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A Study on a Cascade-structured Optical Regenerator Using Wavelength Converters Based on Cross Gain Modulation

by

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Doctoral Dissertation

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Associate professor Hiroyuki Uenohara

For My Parents

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A Study on a Cascaded-structured Optical
Regenerator Using Wavelength Converters
Based on Cross Gain Modulation

Chapter 1

Introduction

1.1 Growth of optical communications

Recently, Internet data traffic is rapidly growing as fiber-to-the-home (FTTH) and asymmetric digital subscriber line (ADSL) services are becoming the preferred infrastructures. Caused by the development of these infrastructures, various rich sets of services such as voice, data and video contents to the users would be provided. The static and predictable data traffic in the circuit-switching network will be changed to be dynamic and unpredictable in the Internet. To handle the routing of the data, photonic network with ultrahigh speed and large capacity is required. In the 1980s, optical communication networks, that employ optical fibers for information transmission instead of coaxial cable, started to be used [1].

The reasons for development of optical communication networks are as follows.

- 1) Optical fiber, which is transmission medium, has large bandwidth, low loss and sufficient linearly transmission line.
- 2) Semiconductor lasers with high output power and narrow spectrum bandwidth under room temperature was developed.

Moreover, using amplification of optical signal by erbium-doped fiber amplifiers (EDFA's) make long distance transmission possible without O/E converters.

The bit rate of optical communication systems was limited to 10 Gbps or less until 1995 in practical level [2]. Recently, to break the limitations of bit rate imposed by the dispersion and nonlinear effects in optical fibers and by the speed of electronic components, wavelength-division-multiplexing (WDM) technique has been developed instead of time-division-multiplexing (TDM) technique [2]. WDM is a technique that several channels are multiplexed in the wavelength domain. WDM lightwave systems were available commercially since 1996. In these days, the capacity of commercial WDM systems exceeded 1.6 Tbps [3]. In 2001, system capacity of more than 10 Tbps has been demonstrated by several laboratories using (1527 – 1563 nm) in C-band, (1570 – 1610 nm) in L-band and (1477 – 1508 nm) in S-band although the transmission distance was limited to below 200 km. [4][5] As indicated in these facts, large capacity and high spectrum efficiency can be achieved in WDM systems. Fig. 1.1 indicates a kind of growth of transmission capacity in optical communication networks [6].

Not only WDM channel increases, but also the bit rate per channel also increases from 10 to 40 Gbps or more to sustain increasing of data traffic. However, the electronic circuits are becoming the bottleneck of the network speed, because power consumption of electric circuit becomes higher as operating at higher bit rate. This is becoming a serious problem for optical networks.

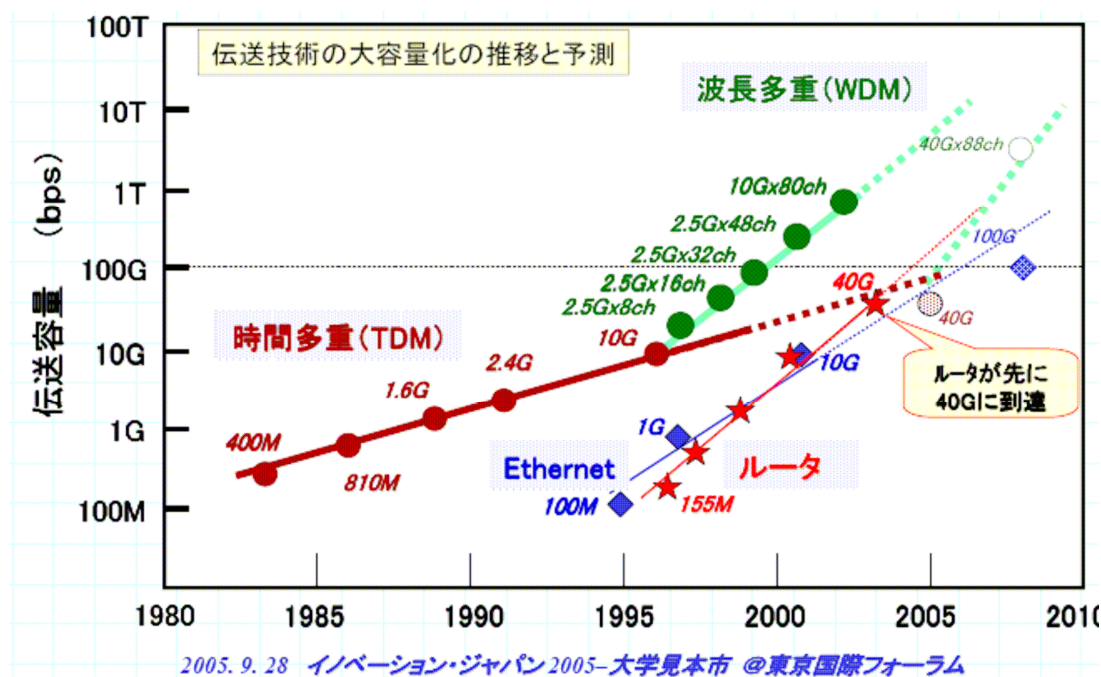


Fig. 1.1 Growth of transmission capacity in optical communication networks. (After Ref. [6])

1.2 Vision of photonic networks

Now that the ubiquitous network society is moving into high gear, future networks must efficiently support various services and transfer data at the required quality. To satisfy these requirements, next-generation IP networks with high-performance optical/electrical switching is desired [7].

Figure 1.2 shows measurement data of traffic volume at Japanese Internet exchange [8]. This shows rapid increase of traffic that exceeds the degree of development of electrical circuits expected by Moore's Law. In addition, this figure shows that the difference between maximum and minimum amount of traffic is becoming large.

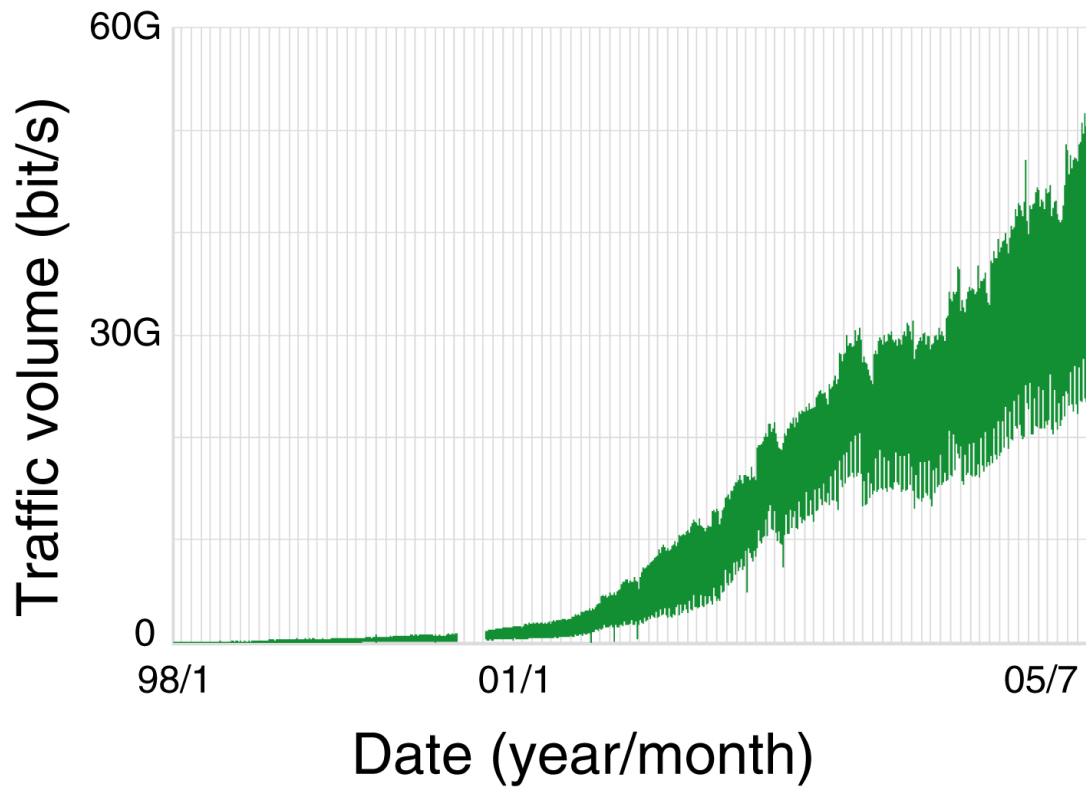


Fig. 1.2 Measurement data of traffic volume in Japan (After Ref. [8])

To handle large and fluctuating traffic, much attention has been paid to photonic network technique [9]. Fig. 1.3 shows the road map of photonic network technique [10]. In the early stage, WDM systems started as point-to-point transmission system. In recent days, as progress of optical switching technology for dynamic and reconfigurable network structure, optical ring networks using optical add-drop multiplexers (OADM's) [11][12] and optical cross connect (OXC) system [9] have been developed. To improve efficiency of fiber and wavelength in photonic network, wavelength conversion technique and optical signal processing are important.

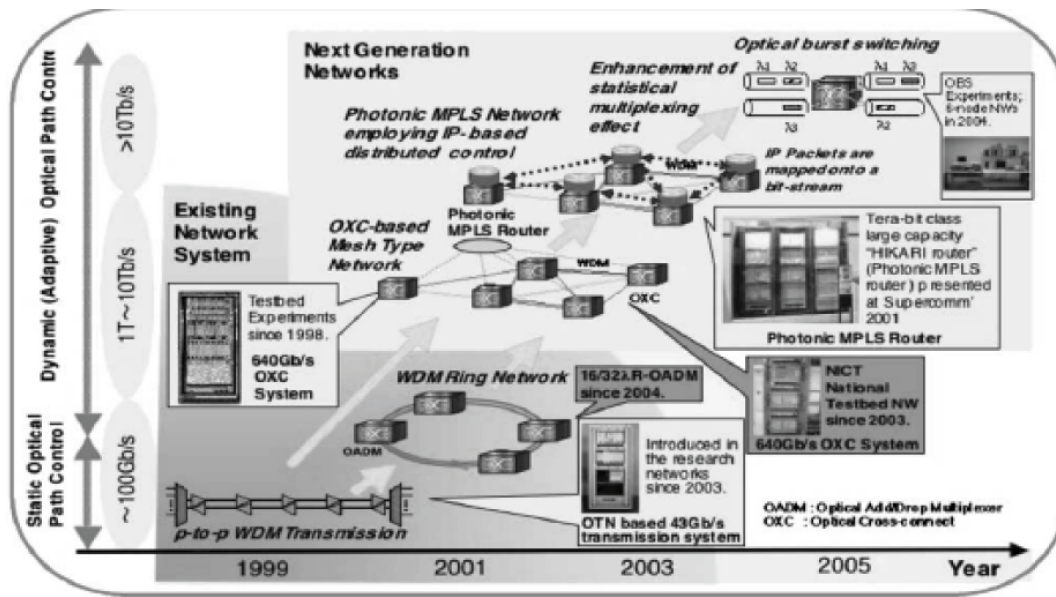


Fig. 1.3 The progress of photonic network technique. (After Ref. [10])

1.3 Role of signal regenerator

In optical communication systems, fiber loss, which reduces the signal power received at receivers, and fiber dispersion, which broadens optical pulses, limit the transmission distance. Additionally, as mentioned in the previous section, increase of bit rate per channel makes signal decision difficult because shot noise, beat noise between signal amplified spontaneous emission (ASE) and beat noise between ASE and ASE increases [13]. Moreover, timing jitter tolerance becomes severe in narrow one-bit time at high bit rate [2]. For long distance transmission, therefore, signal regenerators are necessary to compensate degradation of signal quality. A signal regenerator has two or

three functions:

1. **Reamplifying**

To amplify optical power reduced by fiber transmission (see Fig. 1.4 (a))

2. **Reshaping**

To reshape distorted waveform and to suppress power fluctuation at signal '1' level and '0' level. (see Fig. 1.4 (b))

3. **Retiming**

To compensate timing jitter in optical pulse train generated by various causes such as amplified spontaneous emission, polarization mode dispersion and cross phase modulation, and to align predefined interval time. (see Fig. 1.4 (c))

A regenerator, which has the function of reamplifying and reshaping, is called a 2R regenerator. And a regenerator, which has the function of reamplifying, reshaping and retiming, is called a 3R regenerator. The function of reamplifying, which is called a 1R, is realized by an erbium-doped fiber amplifier (EDFA) in the optical domain.

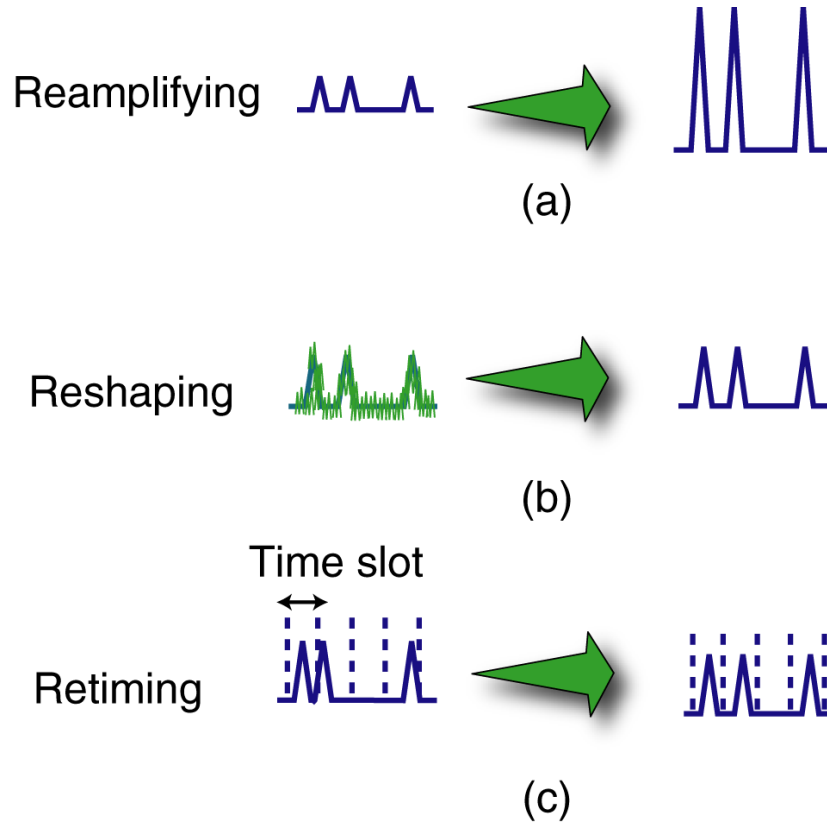


Fig. 1.4 the function of a 3R regenerator
(a) reamplifying (b) reshaping (c) retiming

However, only EDFA systems limit the transmission distance caused by the degradation of signal quality due to ASE noise from EDFA's. Accumulation of ASE induces large beat noise between signal and ASE and beat noise between ASE and ASE.

Beat noise between signal and ASE is expressed as

$$\sigma_{sig-sp}^2 = \frac{2 \cdot (q \cdot \eta \cdot G)^2 \cdot F_n \cdot P_s \cdot B_e}{h\nu} \quad (1.1)$$

where q is the electron charge, η is the internal quantum efficiency of a photodiode, G is the gain of an amplifier, F_n is the noise figure of the amplifier, P_s is the signal power, B_e is the electrical bandwidth and $h\nu$ is the photon energy.

Beat noise between ASE and ASE is expressed as

$$\sigma_{sp-sp}^2 = (q \cdot \eta \cdot G \cdot F_n)^2 \cdot B_o \cdot B_e \quad (1.2)$$

where B_o is the optical bandwidth of an optical band pass filter. In the designed optical fiber communication systems, these beat noises are the major ones. The noise distribution of signal '1' level σ_1 and '0' level σ_0 are thus well approximated by

$$\sigma_1 = \sqrt{\sigma_{sig-sp}^2 + \sigma_{sp-sp}^2}, \quad \sigma_0 = \sigma_{sp-sp} \quad (1.3)$$

Thus, bit error rate can be obtained by

$$BER = \frac{1}{2} \cdot \operatorname{erfc}\left(\frac{Q}{\sqrt{2}}\right) \quad (1.4)$$

with the Q parameter

$$Q = \frac{I_1 - I_0}{\sigma_1 + \sigma_0} \quad (1.5)$$

where I_1 and I_0 are the intensity of signal '1' level and '0' level. erfc stands for the complementary error function defined as

$$\operatorname{erfc}(x) = \frac{2}{\pi} \cdot \int_x^\infty \exp(-y^2) dy \quad (1.6)$$

So it is necessary to suppress the variance of ASE noise for enlarging transmission distance.

Here, signal quality of optical signal with transmission distance is evaluated. OSNR is defined as

$$OSNR = \frac{P_s}{P_{ASE}} \quad (1.7)$$

where P_s is the signal light power and P_{ASE} is the ASE power.

OSNR in optical signal is decreased by ASE from an EDFA. OSNR is expressed as

$$OSNR = \frac{G \cdot P_{in}}{F_n \cdot h\nu \cdot B_o \cdot (G-1) \cdot n} \quad (1.8)$$

where P_{in} is the input signal light power, G is the EDFA gain, F_n is the noise figure of EDFA, $h\nu$ is the photon energy, B_o is the optical bandwidth and n is the number of

amplifier stage.

As discussed earlier, the electrical SNR is dominated by the signal-spontaneous beat noise generated at the photodetector. If only this dominant contribution is included, by using Eqns. (1.1) and (1.8), the electrical SNR is related to OSNR as

$$SNR = \frac{\left(\frac{\eta \cdot q}{h\nu}\right)^2 \cdot P_{in}}{n \cdot \sigma_{sig-sp}^2} = \frac{B_o}{2B_e} \cdot OSNR \quad (1.9)$$

where q is the electron charge, η is the internal quantum efficiency and B_e is electrical bandwidth. SNR relates to Q parameter as

$$SNR = 4Q^2 \quad (1.10)$$

From Eqns. (1.4), (1.8), (1.9) and (1.10), BER is represented as the function of amplifier stage as

$$BER = \frac{1}{2} \cdot \operatorname{erfc} \left(\frac{1}{2 \cdot \sqrt{2}} \cdot \sqrt{\frac{B_o}{2B_e} \cdot \frac{P_{in}}{F_n \cdot h\nu \cdot B_o \cdot (G-1) \cdot n}} \right) \quad (1.11)$$

Figures 1.5 (a) and (b) depicts Q value and bit error rate as a function of amplifier stage, respectively. Parameters used in the calculation are shown in Table I.1. Assuming fiber loss is 0.2 dB/km, EDFA spacing is 100 km, an output power from a transmitter is 2 mW and the amplifier gain is 100. From Fig. 1.5 (b), bit error rate of signal was worse than 10^{-9} at 14 amplifier stage. Q value was lowered from 22 to 10 by 5 amplifier stage transmission, and to 7 by 10 amplifier stage transmission. For long distance transmission, it is necessary to hold Q value constant.

An optical regenerator is required to maintain Q value every 5 – 10 amplifier stage. Optical regenerator makes variance of signal small, and therefore, suppression of degradation of Q value was obtained.

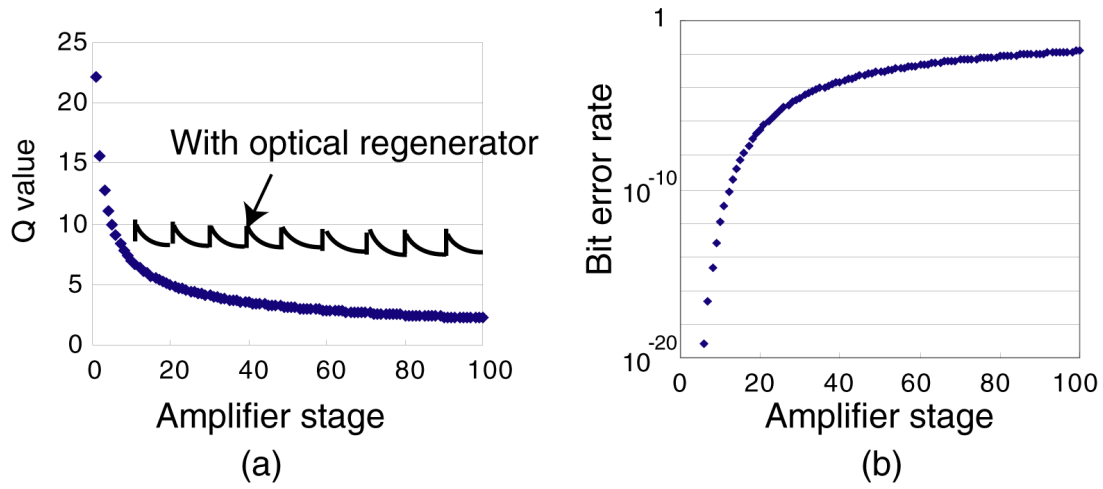


Fig. 1.5 (a) Q value as a function of amplifier stage (b) Bit error rate as a function of amplifier stage.

Table. I.1 Parameters used in amplifier stage calculation

Symbol	Description	Value	Unit
P_{in}	Input light power	$2 \cdot 10^{-3}$	W
F_n	Noise figure	6	dB
B_e	Electrical bandwidth	$1 \cdot 10^{10}$	Hz
B_o	Optical bandwidth	$1.1 \cdot 10^{11}$	Hz
G	Amplifier gain	100	
λ_s	Signal wavelength	$1.55 \cdot 10^{-6}$	m

In addition, I investigate the effect of the extinction ratio of signal in the long-hole transmission system. In this estimation, beat noise between signal and ASE and beat noise between ASE and ASE were considered and the power of signal '0' level was regarded. Thus beat noise between signal '0' level and ASE is expressed as

$$\sigma_{sig_0level-sp}^2 = \frac{2 \cdot (q \cdot \eta \cdot G)^2 \cdot F_n \cdot \frac{P_s}{Ext} \cdot B_e}{h\nu} \quad (1.12)$$

where Ext is the extinction ratio of the signal. Therefore, from Eqn. (1.3), The noise distribution of signal '1' level σ_1 and '0' level σ_0 are thus well approximated by

$$\sigma_1 = \sqrt{\sigma_{sig-sp}^2 + \sigma_{sp-sp}^2}, \quad \sigma_0 = \sqrt{\sigma_{sig_0level-sp}^2 + \sigma_{sp-sp}^2} \quad (1.13)$$

Using the parameter of the Table. I.1, the Q factor against amplifier stage is described in Fig. 1.6. The extinction ratio of the infinite, 30 dB, 20 dB and 10 dB were used as a parameter. Here, compared with the case of the infinite extinction ratio, the difference in Q factor was little in the case of 20 dB and 30 dB. However, the difference between infinite extinction ratio and 10 dB was over fifteen stage around the Q = 6. Next, from Q factor, the stage where BER is less than 1×10^{-9} against the extinction ratio was shown in Fig. 1.7. Compared with the case of the infinite extinction ratio, the difference of transfer stages were less than half in the case of 10 dB extinction ratio. In the case of 20 dB extinction ratio, the difference of transfer stages was about 5 stage. So in this case, the extinction ratio was needed 15-20 dB or more than.

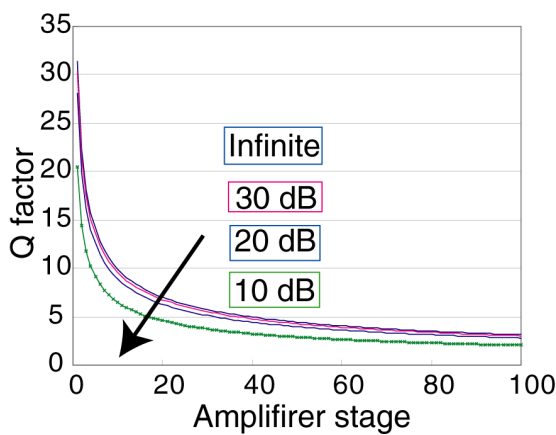


Fig. 1.6 The Q factor against amplifier stage. The extinction ratio was used as a parameter.

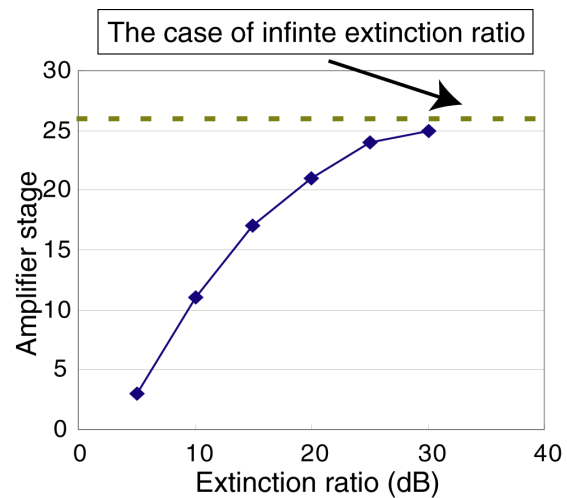


Fig. 1.7 The amplifier stages against the extinction ratio.

Conventionally, 2R or 3R function is achieved by electronic circuits. To operate these functions, optical signal is once converted to electrical signal by an optical-to-electrical (O/E) converter. Then signal is regenerated in electronic circuits, and electric signal is converted to optical signal again. However, a regenerator constructed by electric circuits consumes much electrical power with increasing the bit rate and it does not have a bit rate transparency.

Recently, much attention has been paid to an all-optical regenerator from the viewpoint of eliminating the speed limitation of the electronic circuit, in order to achieve a simple construction eliminating optical-to-electrical or electrical-to-optical converters and also low electronic power consumption. But several issues such as narrow dynamic range for input light power should be resolved for practical use.

1.4 Objective of this study

The purpose of this study is to achieve novel optical regenerators to solve several issues such as narrow dynamic range, polarization sensitivity and so on, for an optical regenerator. To realize this purpose, we use cascaded wavelength converters based on cross gain modulation (XGM) [14]-[16], which simply consists of semiconductor optical amplifiers (SOA's), an optical source and a band-pass filter. A wavelength converter based on XGM has wide dynamic range characteristics such as 7 – 10 dB [17]. However few optical regenerators using XGM have been reported [18], because an input/output characteristic of a single XGM wavelength converter is monotonically decreasing. For reshaping, at least nonlinearity in input/output characteristics corresponding signal '1' level and '0' level are necessary. I would realize the nonlinearity in input/output characteristics by using a cascaded structure.

The purpose of this study is to achieve an optical regenerator by using cascaded wavelength converter based on XGM. The objective of this study are as follows:

1. Investigation of an optical regenerator based on XGM
 - Cross-Gain-modulation-type wavelength-converter-cascaded optical Regenerator (CGCOR)
 - XGM gain-control-type optical regenerator
2. Analysis of operation characteristics of those optical regenerators
3. Realization of these optical regenerators.

The outline of this doctoral dissertation is shown in Fig. 1.8.

In Chapter 2, a wavelength converter based on XGM for all-optical regenerator is investigated. I will investigate reported all-optical regenerators and wavelength converters for all-optical regenerator. Then a wavelength converter based on cross gain modulation will be investigated.

In Chapter 3, a cross gain modulation type wavelength-converter-cascaded optical regenerator (CGCOR) will be proposed. The simulation results of input/output characteristics and dynamic characteristics will be shown. Also, optical regeneration property will be shown in this chapter. The suitable SOA structure for a CGCOR will be discussed.

In Chapter 4, evaluation and discussion of operation performance of a CGCOR from experiments will be described. Input/output characteristics, the change of received sensitivity and relative intensity noise (RIN) will be discussed. Also, dynamic range of a CGCOR will be reported in this chapter.

In Chapter 5, a XGM gain-control-type optical regenerator, which is another type of

all-optical regenerator by using cascaded structure based on XGM, will be proposed. First, I will report its operation principle to solve the several issues such as extinction ratio and frequency chirping. Timing offset between signal light as well as XGM light and filter detuning methods are described. Then the simulation results of input/output characteristics, frequency chirping and effect of regeneration will be reported.

In Chapter 6, evaluation and discussion of operation performance of a XGM gain-control-type optical regenerator from experiments will be written. Input/output characteristics, improvement of received sensitivity, relative intensity noise (RIN) and transmission characteristics will be discussed.

Finally, conclusion of this work will be described in Chapter 7.

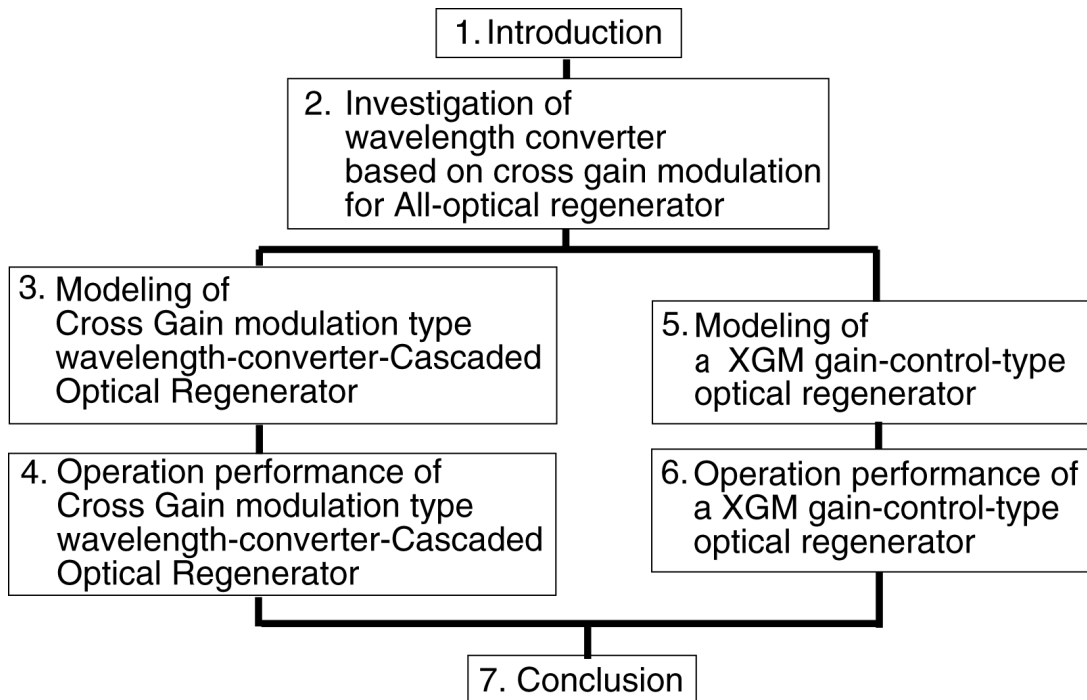


Fig. 1.8 Outline of this doctoral dissertation.

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Chapter 2

Investigation of wavelength converter based on cross gain modulation for all-optical regenerator

2.1 Introduction

Photonic network with ultrahigh speed and large capacity is required due to the growth of the Internet and IP data traffic [1][2]. To realize high throughput and large capacity routing performance [3]-[5], ultrafast wavelength conversion function with simple construction is necessary. Many schemes for realizing wavelength converter have been developed during the 1990s for making wavelength converters [6][7].

Moreover, an all-optical regenerator is a key component to solve the speed limit caused by electronic circuits and to achieve low electric power consumption and efficient data transmission in the photonic network. Several all-optical regenerators reported so far have function of wavelength conversion. First, I will explain reported all-optical regenerators and wavelength converters.

In some all-optical regenerators and wavelength converters, a semiconductor optical amplifier (SOA) is used. For the purpose to use for calculation model, the operation of

wavelength converter based on XGM is investigated experimentally and analytically, because a wavelength converter based on XGM forms the basis of the proposed optical regenerator.

Then wavelength converter based on cross gain modulation is investigated such as input/output characteristics, dynamic operation and signal quality before investigation of all-optical regenerator by using cascaded structure.

2.2 All-optical regenerators and wavelength converters

With the development of photonic networks, optical functional devices without electric circuits have been studied intensively due to its simple structure, flexibility and high efficiency. In particular, all-optical regenerators and wavelength converters without electrical-to-optical conversion have been reported a lot. Some all-optical regenerators consist of wavelength converters. In this section, several types of all-optical regenerators and wavelength converters are compared.

All-optical (2R or 3R) regenerators use various nonlinear phenomena such as cross phase modulation (XPM), self phase modulation (SPM), four-wave-mixing (FWM) and so on. Several all-optical regenerators consist of a wavelength converter, because some of them act as an optical gate or have nonlinearity of input/output characteristics.

Moreover, wavelength conversion technique has become important to realize wavelength routing in high-speed photonic network. Therefore, to achieve optical regeneration and wavelength conversion in node at the same time are preferable. In this, the characteristics of an all-optical regenerator and wavelength converters can be

realized below.

i. SOA

Several all-optical techniques for an optical regenerator make use of some physical phenomena in a SOA [8].

They are (1) gain saturation in a SOA, (2) phase shift by index change and (3) the other scheme employing a SOA as nonlinear medium. Inherently, a SOA has gain characteristics, and it has advantages of its compactness (about 1 mm in size), wide gain bandwidth (over 30 nm) and possibilities for integration with other semiconductor optical devices. Additionally, a SOA can have polarization insensitivity.

i. i. XGM

Although the detail of a wavelength converter based on XGM will be described in the later section, XGM has the advantages of simple construction without interferometers, enough high speed operation, wide dynamic range in input power [9]. Essentially, a long-sized SOA would be able to operate at higher speed. Fig. 2.1 shows a schematic diagram of 100 Gbps wavelength conversion experiment [10]. By using a 2 mm-long semiconductor optical amplifier, wavelength conversion with error free at 100 Gbps could be achieved. However, wavelength conversion based on XGM has the disadvantage such as low extinction ratio and high frequency chirping. Such issues have been investigated [11]-[14].

Some optical regenerators using XGM signal for gain saturation or suppression of pattern effect were reported from several groups [15]-[17], but optical regenerators that bring out wavelength conversion light directly generated by XGM have not been

reported until this study has started to my knowledge. Only calculation of bit-error-rate and possibility of improvement of performance using XGM was reported [18].

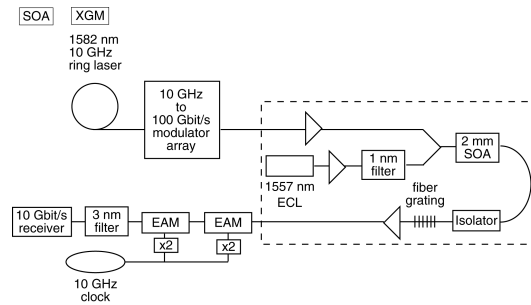


Fig. 2.1 Schematic diagram of 100 Gbps wavelength conversion experiment. (After Ref. [10])

i. ii. Gain saturation

Using gain saturation in a SOA, it seems that power fluctuation could be suppressed [19]. But using carrier density change resulted in gain saturation causes pattern effect. To avoid pattern effect in a SOA, the technique of using other control light were reported [15][17]. An example of that method is shown in Fig. 2.2. An ultra long (4 mm-long) SOA with periodic and a half bit delayed clock makes 3R function by use of gain saturation. Periodic clocked signal works both retiming function and suppression of pattern effect. This concept was demonstrated at a bit rate of 40 Gb/s.

The other scheme to avoid pattern effect is to use a quantum dot SOA due to ultrafast gain recovery [20]. Ultrafast gain nonlinearity of QD SOAs enables compression of '1' level noise without inducing waveform distortion. Due to this property, the Q factors of 40 Gb/s signals degraded with ASE-noise were improved.

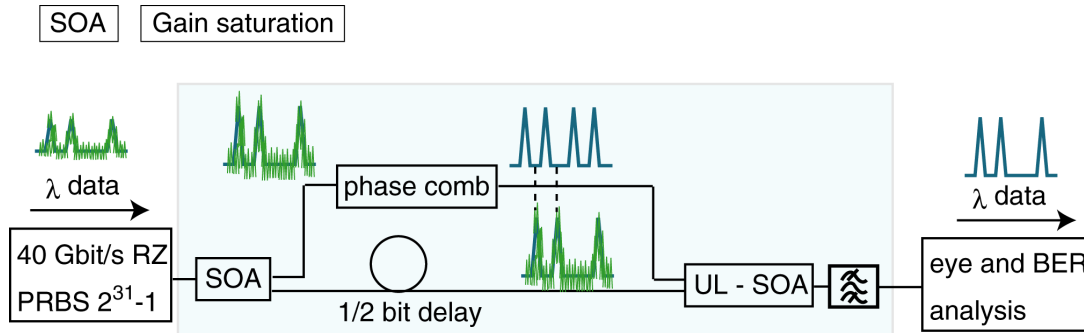


Fig. 2.2 Schematic diagram of optically clocked 3R. (After Ref. [15])

i. iii. XPM

The phase change by XPM associated with the gain modulation is used to control the interference at the output of an interferometer. Here, the optical regenerator based on the symmetric-Mach-Zehnder (SMZ)-type interferometric semiconductor switch structure, which enables to form a rectangular-like switch window with an ultrafast response time, has been studied extensively, because its response time is not limited by the slow semiconductor carrier lifetime (see Fig. 2.3 (a)). 3R regeneration performance at 84 Gb/s using a type of SMZ structure, which is a polarization-discrimination SMZ (PD-SMZ) structure, has been demonstrated [21] (see Fig. 2.3 (b)). In addition, 168 Gb/s wavelength conversion using the Delayed-Interference Signal-wavelength Converter (DISC) was demonstrated [22]. And 12,000 km transmission with keeping good signal quality was also reported [23].

Moreover, a using Sagnac interferometer integrated with a parallel-amplifier structure (SIPAS) was reported for realization of filter-free operation [24] (see Fig. 2.4).

Although they achieved ultrafast operation, the rise time of interferometer structure has the drawback, which is narrow dynamic range in input power [25] (2 – 3 dB). To avoid this problem, All-optical power equalizer added at the input side of the optical regenerator was investigated [17] (see Fig. 2.5).

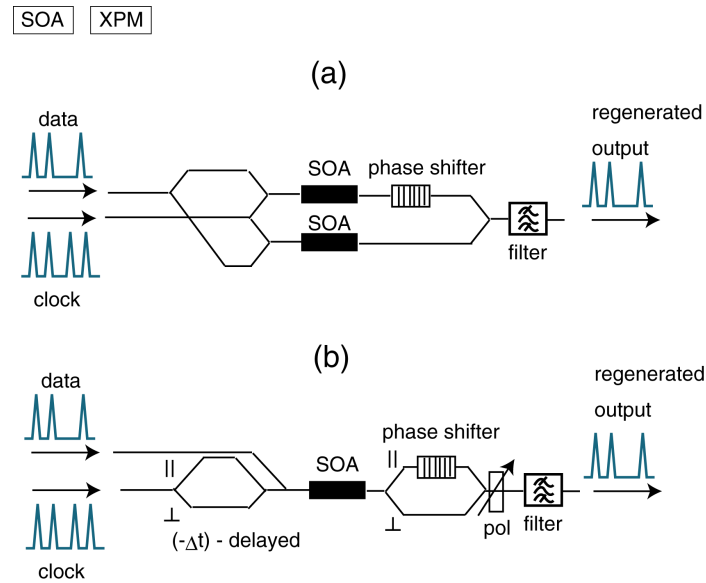


Fig. 2.3 SMZ-type all optical 3R regenerator.

(a) 3R regenerator scheme with SMZ structure (b) 3R regenerator scheme with PD-SMZ structure. (After Ref. [21])

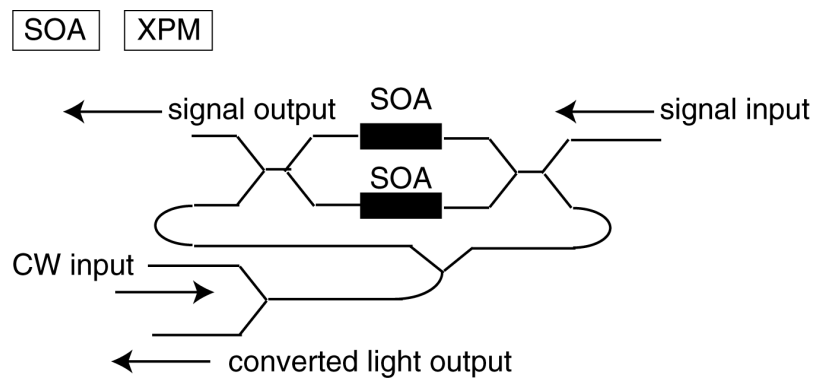


Fig. 2.4 Photograph of SIPAS. (After Ref. [24])

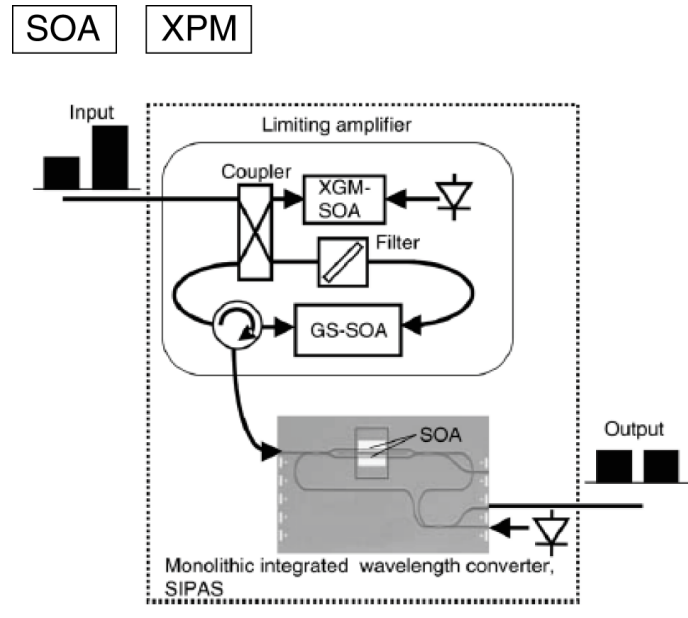


Fig. 2.5 Configuration of the all-optical burst-mode 2R regenerator consisted of SIPAS and limiting amplifier. (After Ref. [17])

i. iv. FWM

In case of a FWM-based optical regenerator, a SOA is used as nonlinear medium. FWM is transparency against modulation formats and high bit rate operation [26]. Under certain conditions, regenerative characteristic appears [27]. However, the nature of the FWM-based regeneration process, which is related to the SOA's gain saturation, sets an upper limit at the operation speed of the whole process due to the limited response of the SOA's carrier dynamics. The Experimental setup is shown in Fig. 2.6. Regenerative properties of wavelength converters based on FWM was investigated.

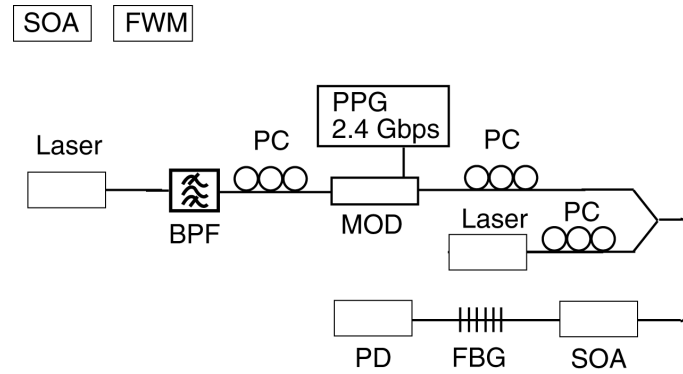


Fig. 2.6 The schematic of wavelength converters based on FWM in SOA's. (After Ref. [27])

ii. Electroabsorption (EA) modulator

An optical 3R regenerator using a wavelength converter based on an EA modulator can be configured with several small and discrete optical modules, and it can operate at high speed (over 80 Gbps) [28-30], although it has no optical gain. Moreover, it can be polarization insensitive by using an EA modulator with low polarization dependency.

ii. i. Cross absorption modulation (XAM)

Electric field into an EA modulator induced by the photo-generated carriers at high input power levels changes the waveguide absorption. Saturation of absorption by signal light power is the operation principle. Consequently, refractive index in an EA modulator can also be changed, so an interferometer is used for enhancing high speed operation.

Using one or two wavelength converters based on cross absorption modulation, an optical 3R regenerator is realized. The CW (in the case of 2R) or clock (in the case of

3R) light is fed into the EA modulator as probe light. The high power signal light is launched and induces a cross-absorption saturation effect in the EA modulator. Therefore, this signal and the probe lights counterpropagate in the EA modulator and interact with each other, and the probe light is then modulated by a loss variation of the EA modulator using two-stage wavelength converters, wavelength of output signal is set to be the same as that of input signal. Fig. 2.7 shows the reported optical signal regenerator. The operation speed up to 100 Gb/s was demonstrated [30].

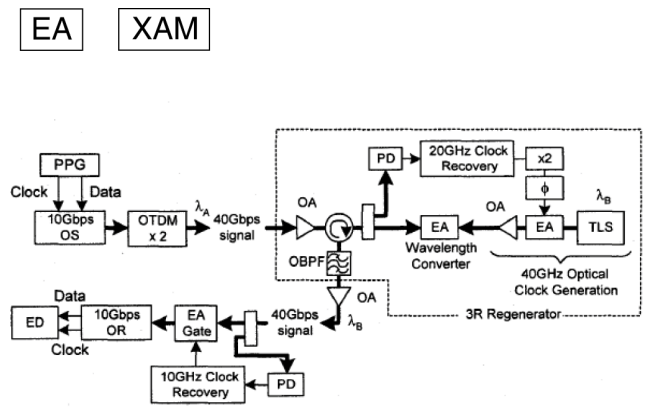


Fig. 2.7 Experimental setup of optical regenerator using XAM in EA modulator. (After Ref. [30])

iii. LD

A laser diode has the characteristics such as self-lasing as well as compactness and production by using mature process. So, these advantages are attractive for an optical regenerator.

iii. i. Injection locking

Injection locking in a LD would be used because step like function in input/output characteristics is obtained [31]. Fig. 2.8 shows principle of an optical regenerator using mode locking in a Fabry-Perot laser. This employs two longitudinal modes. This 2R

optical regenerator is demonstrated at 10 Gb/s. However, wavelength dependency is one of the biggest issues, because each mode has specified wavelength.

In addition, the methods by using transverse [32][33] and polarization [34] in a VCSEL are reported.

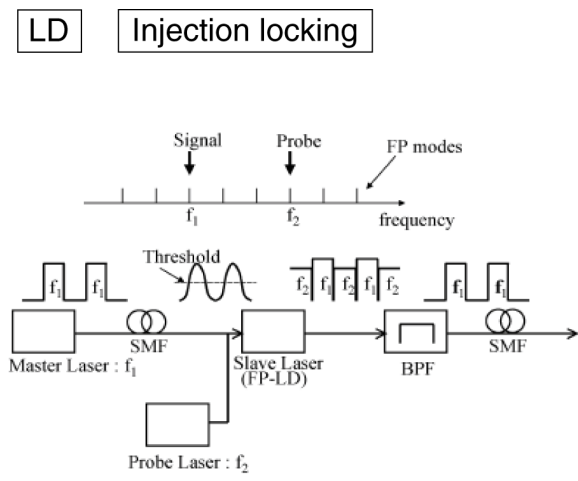


Fig. 2.8 Principle of optical regenerator using two longitudinal modes in FP-LD. . (After Ref. [31])

iv Optical fiber

Nonlinear effect such as FWM or self phase modulation (SPM) in highly nonlinear fibers (HNLF's) is available for an optical regenerator to realize reshaping or retiming. HNLF has much larger nonlinearity than that of a conventional dispersion-shifted fiber. Employing nonlinear effect enables high-speed operation (~ 100 Gbps) [35][36]. However, it is necessary to set polarization for occurring nonlinear effect efficiently, and high power input light was needed to induce nonlinear effect.

iv.i SPM

SPM induces spectral broadening with increasing light power in a HNLF, and using a band pass filter (BPF) makes nonlinearity of input/output characteristics [35]. Figure

2.9 shows a wavelength converter with 3R-regeneration capability based on SPM. This optical regenerator operated at 160 Gb/s, and it has great potential at even higher data rates.

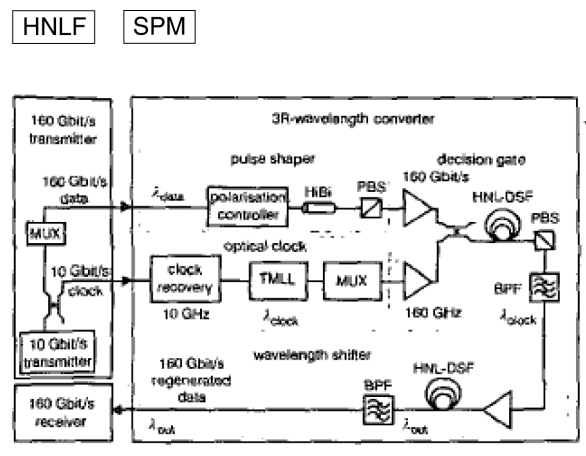


Fig. 2.9 Experimental setup of optical regenerator based on SPM in HNLF. . (After Ref. [35])

iv.ii. FWM

Using pump position tunability in a two-pump FWM system, tunable all-optical wavelength conversion and wavelength multicast technique using orthogonally polarized fiber FWM in a HNL-DSF were reported [36]. A wavelength converter using FWM in a HNLF operated at 10 Gbps.

- v. Comparison of performance between several techniques.

The characteristics of these reported optical regenerators and wavelength converters are summarized in Table II.1. Each of them has advantages and disadvantages. There is no optical regenerator without issues for practical use. Therefore, I investigate a novel optical regenerator to solve issues.

Table. II.1 Performance of optical regenerators

	SOA				EA modulator	LD	HNLF
	XGM	Gain saturation	XPM + Interferometer	FWM	XAM	Injection locking	SPM
Reported speed	40~100 Gbps	40 Gbps	168 Gbps	40 Gbps	100 Gbps	10 Gbps	160 Gbps
Input power dynamic range	○(7~10 dB)	○~△ (4 dB)	△ (2 dB)	○	○	○	○
Conversion efficiency	○	○	○	△	△	○	△
Polarization efficiency	○	○	○	○	○	○/△	△
Extinction ratio	△	△	○	○	○	○	○
Wavelength dependency	○	○	○	○/△	○	△	○
Frequency chirping	△	△	○	△	○	○/△	○
Deveice size	1 mm	1 mm	1 mm	1 mm	100 μm	1 mm	10 km
Ref.	This work	[15]	[21]		[30]	[31]	[35]

2.3 Operation performance of a semiconductor optical amplifier

A semiconductor optical amplifier (SOA) [38] utilizes stimulated emission caused by the population inversion. The population inversion is achieved by current injection to an active region. A SOA has capability to be applied for a booster amplifier, an inline amplifier and a preamplifier, and so on. Moreover, many optical functional devices have been demonstrated as follows; one of them is a wavelength converter based on XGM. To investigate XGM performance, it is necessary to know operation performance of using SOA. So I investigated the characteristics of a SOA experimentally.

In the experiments, conventional 1.55- μm -wavelength polarization-insensitive GaInAsP bulk SOAs with different cavity lengths of 900, 1200 and 1500 μm were used. These SOA has buried-hetero (BH) structure to efficiently confine injection current into an active region. Figure 2.10 shows fiber-to-fiber gain characteristics against output power. Small-signal fiber-to-fiber gains of 900, 1200 and 1500 μm -long of SOA's were 22.1, 24.2 and 25.5 dB, respectively. In this measurement, injection current for 900, 1200 and 1500 μm -long of SOA's were 300, 400 and 500 mA, respectively.

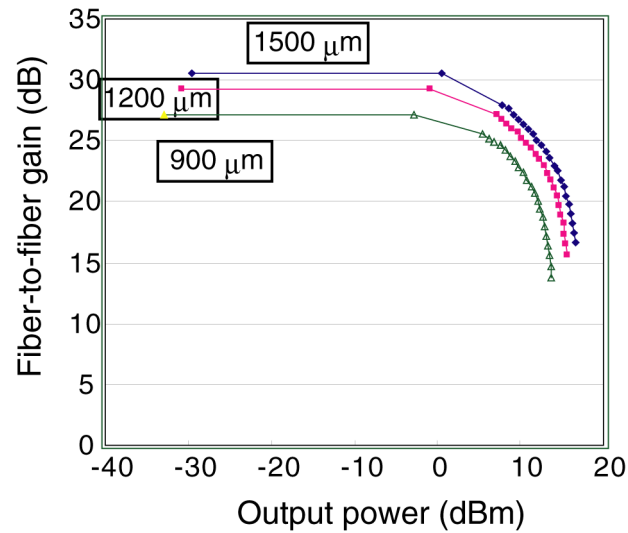


Fig.2.10 Gain characteristics of a SOA used in the experiment.

Next, ASE spectrum in each SOA, which corresponds to gain dependency on wavelength, is shown in Fig. 2.11. In this measurement, injection current for 900, 1200 and 1500 μm -long SOA's were 400, 533 and 667 mA, respectively. The 3 dB bandwidth of ASE spectrum for 900, 1200 and 1500 μm -long SOA's were 48, 32 and 28nm, respectively. All of them have broad ASE spectrum, so SOA operation within wide wavelength can be expected. The wavelength of ASE peak in 900, 1200, 1500 μm were 1525, 1545 and 1557 nm, respectively. Figure 2.12 shows ASE spectrum dependency on injection current. Injection current of 150, 200 and 300 mA was used. The wavelength of ASE peak shifted short wavelength with increasing injection current due to band filling effect. Thus, differential gain becomes large toward in short wavelength. Both gain and differential gain in a SOA affect XGM performance.

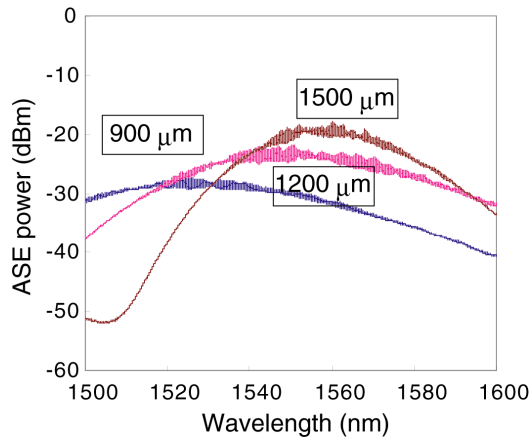


Fig.2.11 ASE spectra of SOA's with cavity length of 900, 1200 and 1500 μm .

Device lengths were used as a parameter.

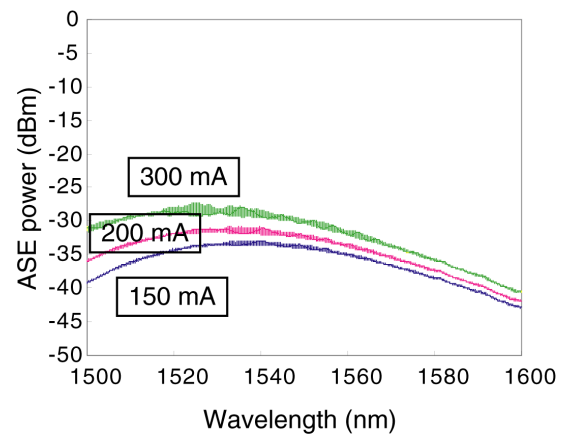


Fig.2.12 ASE spectra of SOA's with cavity length of 900 μm .

Injection currents were used as a parameter.

These SOAs have capability to amplify the high-speed signal (~ 40 Gbps). Figure 2.13 shows input signal, which is modulated at 40 Gbps in RZ format with 2^7-1 pseudorandom bit sequence (PRBS) and mark ratio of 1/2. Here, bit sequence of amplified signal from the 900 μm long SOA is shown in Fig. 2.14. As seen in Fig. 2.14, little pattern effect was occurred.

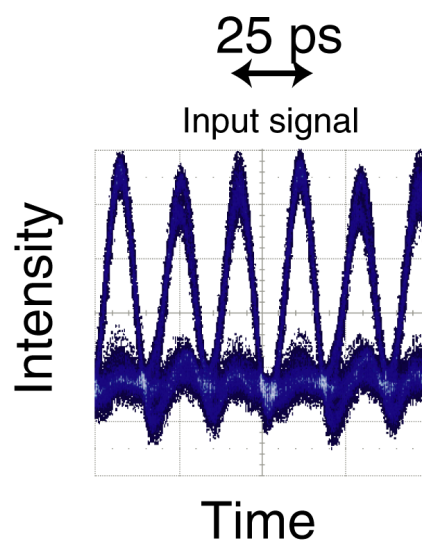


Fig. 2.13 Input signal waveform at a bit rate of 40 Gbps.

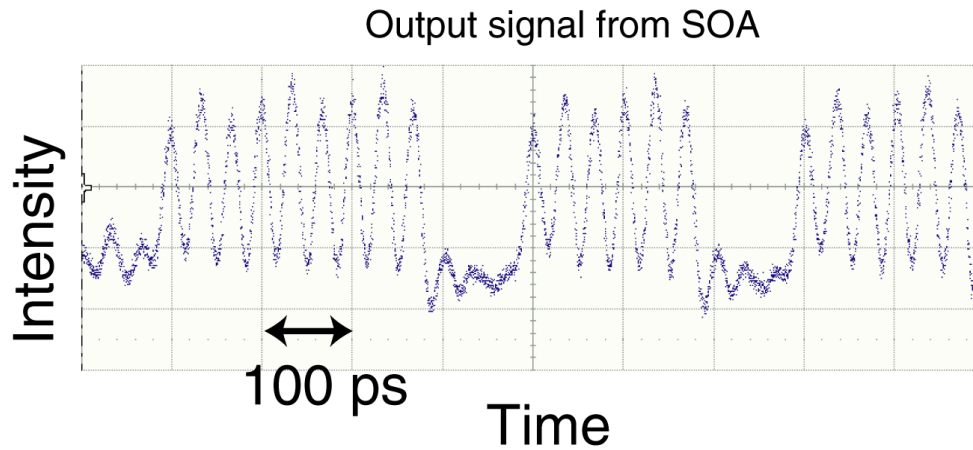


Fig. 2.14 Bit sequence of amplified signal.

2.4 Wavelength converter based on cross gain modulation

In this section, operation performance of wavelength converter based on XGM is investigated. First, principle of XGM is described. Next, the results of measurement and calculation are shown.

2.4.1 Principle of cross gain modulation

First, the principle of wavelength conversion based on XGM is shown in Fig. 2.15. Signal light, whose wavelength is λ_s , injected into a SOA decreases carrier density in s SOA due to the stimulated emission. This causes to decrease optical gain for CW probe light with wavelength of λ_p , which is injected into a SOA at all time. So, the probe light is modulated by the gain variation. And probe light polarity is inverted against signal light polarity. To set transparency wavelength of a band pass filter at λ_p , wavelength converted signal light can be obtained.

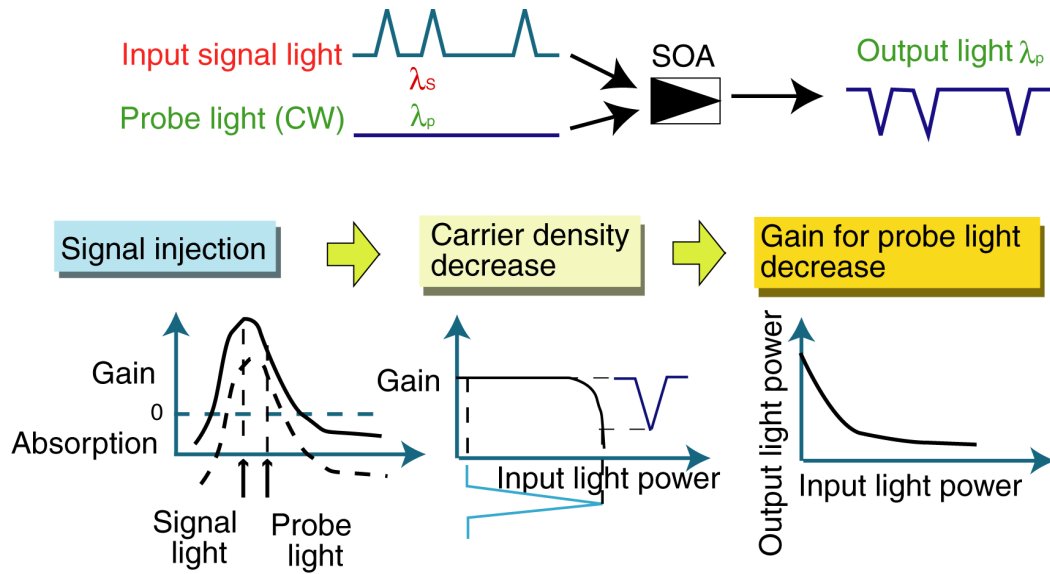


Fig. 2.15 Principle of a wavelength converter based on XGM.

The following equations are simple rate equations in a SOA

$$\frac{dn}{dt} = -\frac{n}{\tau_s} - A_g(n - n_0)\frac{I}{h\nu} + \frac{J}{ed} \quad (2.1)$$

$$\frac{dI}{dz} = \Gamma A_g(n - n_0)I - \alpha I \quad (2.2)$$

where n is the carrier density, n_0 is the transparency carrier density, τ_s is the carrier lifetime, A_g is the differential gain coefficient (cm^2 in unit), I is the optical intensity (W/cm^2 in unit), ν is the optical frequency, J is the injection current density, e is the electron charge, d is the active region thickness, t is time, z is the propagation direction of light, Γ is the optical confinement factor and α is loss coefficient by absorption and scattering. As shown in the schematic of input/output characteristics in Fig.2.15, firstly the wavelength conversion light power decreases with increasing signal light power. Then in the saturation regime, wavelength conversion light power does not change so much when signal light power changes. The steady state of optical intensity is obtained

by solving Eqn. (2.1) under the assumption $\frac{dn}{dt} = 0$, and by substituting it into Eqn. (2.2), next equation can be obtained;

$$\frac{dI}{dZ} = \left(\frac{\Gamma \gamma_0}{1 + I/I_s} - \alpha \right) I \quad (2.3)$$

where $I_s = \frac{h\nu}{\tau_s \cdot A_g}$, $\gamma_0 = A_g \left(\frac{\tau_s \cdot J}{e \cdot d \cdot n_0} \right)$ are saturation optical power and

unsaturated gain coefficient. With optical intensity increasing, gain coefficient decreases and gain saturation occurs according to $\frac{1}{\left(1 + \frac{I}{I_s}\right)}$.

Wavelength converter based on XGM has several advantages. These are shown as follows;

- Sufficient high-speed operation (capability of error free operation up to 100 Gbps)
- Simple structure (interferometer is not necessary)
- High conversion efficiency
- Wide wavelength bandwidth
- Polarization insensitivity

2.4.2 Input/output characteristics

To use nonlinear input /output characteristics of a wavelength converter based on XGM, its input/output characteristics is estimated experimentally. Experimental setup is shown in Fig. 2.16. The wavelength converter based on XGM consisted of a SOA, a 3 dB optical coupler, a tunable laser and a band pass filter (BPF). The tunable laser was

driven under CW condition. Both signal and probe light were coupled together through a 3 dB coupler, and then they were injected into a SOA. The saturation output power was +10 dBm under 400 mA bias current. The gain peak wavelength was 1525 nm without light injection. The SOA had the polarization gain difference of 0.5 dB.

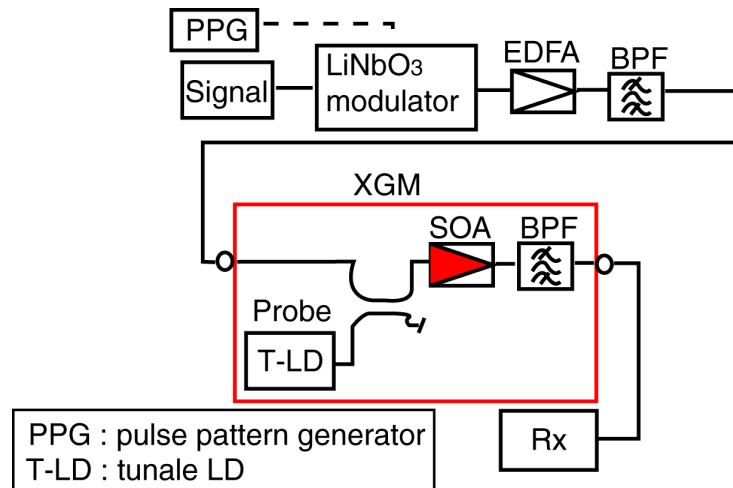


Fig. 2.16 Experimental setup of a wavelength converter based on XGM.

Figure 2.17 shows input/output characteristics of a wavelength converter based on XGM. Input/output characteristics of XGM in case of 900, 1200, 1500 μm -long SOA's are shown in Figs.2.17 (a), (b) and (c), respectively. Injection current is used as a parameter. In this measurement, signal wavelength was 1554 nm. And probe wavelength and power were 1545 nm and -3 dBm, respectively. As shown in these figures, nonlinearity with saturation region was obtained in input/output characteristics, which is dependent on input signal light wavelength, injection current, probe light wavelength and power. From Figs. 2.17 (a) to (c), the condition of high injection current was more saturable because SOA gain becomes large with increasing current. Compared

with three types of SOA's under the condition of the same injection current density, the 1500 μm -long SOA has large nonlinearity. This would be caused by long cross-interaction in the cavity.

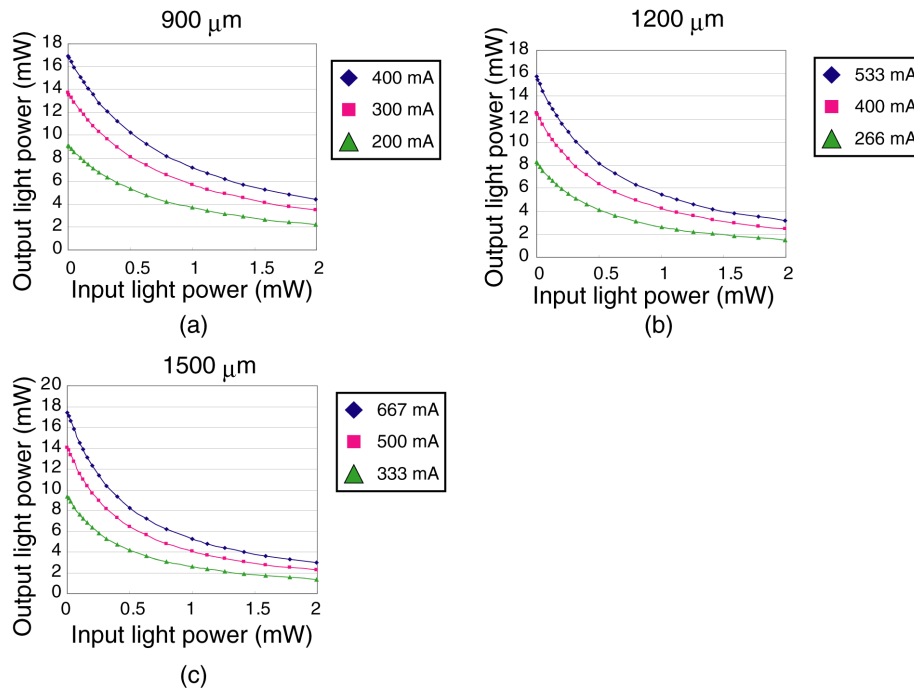


Fig. 2.17 Input/output characteristics of wavelength converter based on XGM.

Injection current was used as a parameter.

(a) 900 μm -long SOA (b) 1200 μm -long SOA (c) 1500 μm -long SOA

To obtain high-speed response, high injection current is preferred. If it is considered that input and output light wavelengths are fixed, probe light power is set to get desired input/output characteristics. Figure 2.18 shows the dependence of input/output characteristics on probe light power. Input signal light and probe light wavelength are 1554 and 1533 nm, respectively. A 1200 μm -long SOA was used. Probe light power of -3, 0 and +3 dBm were used as a parameter. As shown in Fig. 2.18, output power

became large with increasing probe light power. Moreover, less nonlinearity was obtained in the case of higher probe light power.

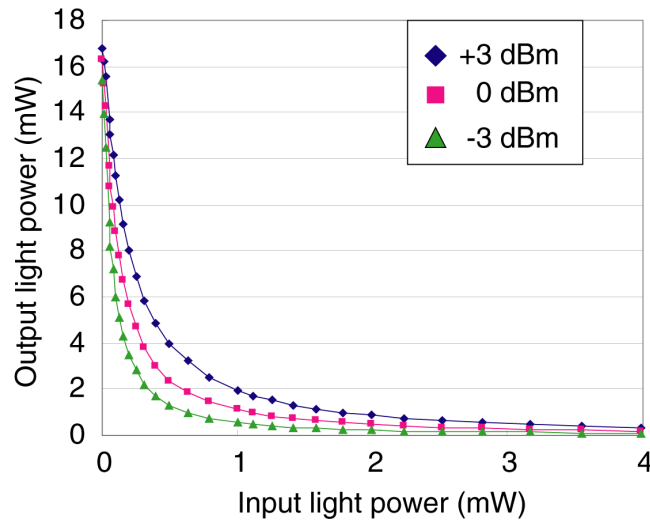


Fig. 2.18 Input/output characteristics of wavelength converter based on XGM.

Probe light power -3 , 0 and $+3$ dBm were used as a parameter.

From the experimental results under several kinds of input parameters, there are tendencies that wavelength converter based on a SOA becomes more saturable in lower probe light power, shorter probe light wavelength and longer signal light wavelength. SOA gain and differential gain depend on input light wavelength. Generally, SOA differential gain for short wavelength is high, because of band-filling effect. Therefore shorter probe light wavelength and longer signal light wavelength cause nonlinearity of input/output characteristics with lower power.

Next, to investigate operation performance of wavelength converter based on XGM,

the time-dependent transfer matrix method (TMM) was used to calculate converted optical waveforms and chirp in a SOA by self-consistently solving the pulse propagation and rate equations [11][13][14]. This helps in designing a cascaded structured optical regenerators, the main target of this study, to taking frequency chirp, the extinction ratio and ASE noise into consideration.

The calculation model of a SOA is shown in Fig. 2.19.

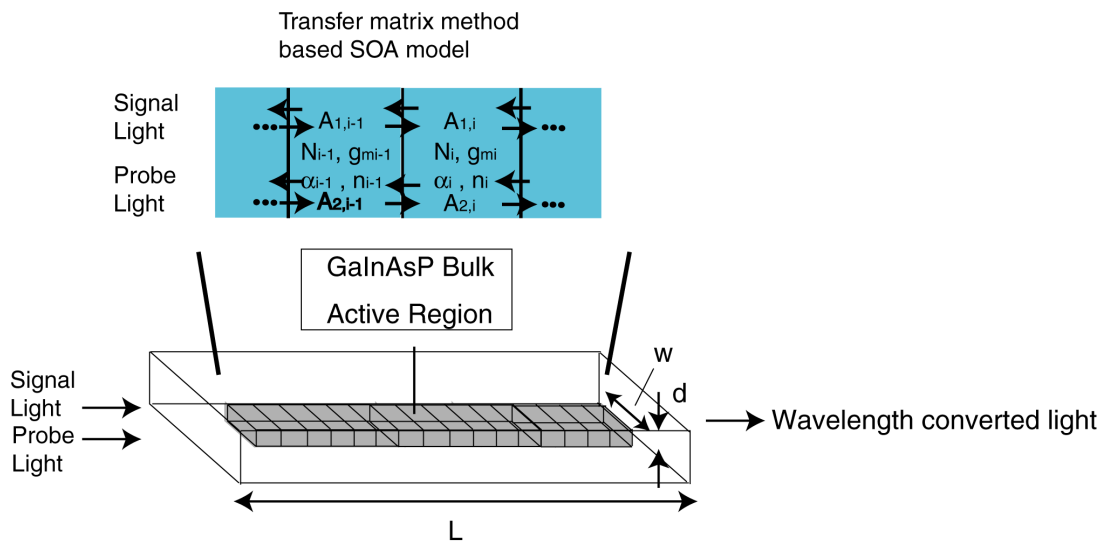


Fig. 2.19 Calculation model of SOA for the wavelength conversion based on XGM

To account for the interaction between carrier density N and photon density S , which is expressed as forward and backward signal light, probe light and ASE, a SOA is divided into several small sections along a propagation axis of light and the rate equation is solved in each section as follows;

$$\frac{\partial N}{\partial t} = \frac{I}{qV} - (c_1 N + c_2 N^2 + c_3 N^3) - v_g (g_x S_x) \quad (2.4)$$

$$\frac{dS_x}{dt} = g_x S + R \quad (2.5)$$

with

$$g_x = \Gamma(g_{m_x} - \alpha_a) - (1 - \Gamma)\alpha_c - \alpha_{scat} \quad (2.6)$$

$$g_{m_x} = \frac{a_0(N - N_0) - a_1(\lambda_x - \lambda_p)^2 + a_3(\lambda_x - \lambda_p)^3}{1 + \varepsilon S} \quad (2.7)$$

$$R = \beta c_2 N^2 v_g A_{cross} h \nu \quad (2.8)$$

$$\lambda_p = \lambda_0 - a_2(N - N_0) \quad (2.9)$$

where I is the injection current, V is the active volume, q is the electronic charge, c_1 , c_2 and c_3 are the non-radiative recombination, the radiative recombination and the Auger recombination rate, respectively, g is the net gain, v_g is the group velocity, R is the spontaneous emission, Γ is the confinement factor, g_m is the net gain, α_a is the loss in an active layer, α_c is the loss in cladding layers, α_{scat} is the scattering loss, a_0 , a_1 , a_2 and a_3 are gain constants, N_0 is the carrier density at transparency, λ is the wavelength of input signal. λ_p is the gain peak wavelength (assumed to shift linearly with carrier density), λ_0 is the wavelength at transparency, ε is the gain compression factor, β is the spontaneous coupling factor, A_{cross} is the cross-sectional area of the active layer and $h \nu$ is the photon energy. Index x refers to different optical input signals, where index s means signal light and p means probe light. And c_1 , c_2 and c_3 are related to recombination constants in Eqn. (2.4). a_0 is the differential gain at gain peak, a_1 determinates gain bandwidth, a_2 is a constant characterizing the gain peak shift and a_3 accounts for the asymmetry of the gain curve.

The average photon density S is calculated by

$$S_x = \frac{|A|^2 + |B|^2}{v_g A_{cross} h \nu_x} \quad (2.10)$$

where A is the forward-traveling wave amplitude and B is the backward-traveling wave amplitude.

The phase of electric field is given by the next equation,

$$\frac{\partial \phi_x}{\partial z} = -\frac{1}{2} \alpha \Gamma g_x + \frac{\sqrt{S_{spon}}}{\sqrt{S_x}} \quad (2.11)$$

with

$$\alpha_x = -\frac{4\pi}{\lambda_x} \frac{dn}{dN} \frac{dg}{dN} \quad (2.12)$$

where ϕ is the phase of electric field, α is the α -parameter, dn/dN is the differential refractive index.

It is important to consider the frequency chirping for calculation of XGM. The chirp of the converted signals is calculated by differentiating its phase with respect to time $\{-1/(2\pi)(d\phi/dt)\}$.

Using calculation parameter was extracted from experimental results. First, λ_p was decided and then a_2 was decided by gain peak wavelength shift with injection current, which is related to Eqns. (2.9) and (2.4). Next, β was decided from ASE power. Then from unsaturated and saturated gain dependency on wavelength, other parameters were decided. Parameters used in the calculation are shown in Table II.2.

Table. II.2 Device parameters used in calculation

Symbol	Description	Value	Unit
Γ	Optical confinement factor	0.194	
L	SOA length	900, 1200 and 1500x10⁻⁶	m
d	Active layer thickness	0.1x10⁻⁶	m
w	Active layer width	1.5x10⁻⁶	m
A_{cross}	Active layer cross section	0.15x10⁻¹²	m ²
V	Active layer Volume	$L \times A_{\text{cross}}$	m ³
β	Spontaneous coupling factor	1.4x10⁻³	
C_1	Non-radiative recombination	1.0x10⁸	s ⁻¹
C_2	Radiative recombination	2.5x10⁻¹⁷	m ³ /s
C_3	Auger recombination	9.4x10⁻¹¹	m ⁶ /s
a_0	Material gain constant	2.25x10⁻²⁰	m ²
a_1		0.0437x10²⁶	m ⁻³
a_2		4.2x10⁻³²	m ⁴
a_3		3.155x10²⁵	m ⁻⁴
N_0	Carrier density at transparency	0.9x10²⁴	m ⁻³
λ_0	Wavelength at transparency	1.652x10⁻⁶	m
vg	Group velocity	7.5x10⁸	m/s
ε	Nonlinear gain compression	1.3x10⁻²³	m ³
dn/dN	Differential refractive index	-1.2x10⁻²⁶	m ³
α_a	Loss in active layer	7x10³	m ⁻¹
α_c	Loss in cladding layer	1x10³	m ⁻¹
α_{scat}	Scattering loss	1x10²	m ⁻¹

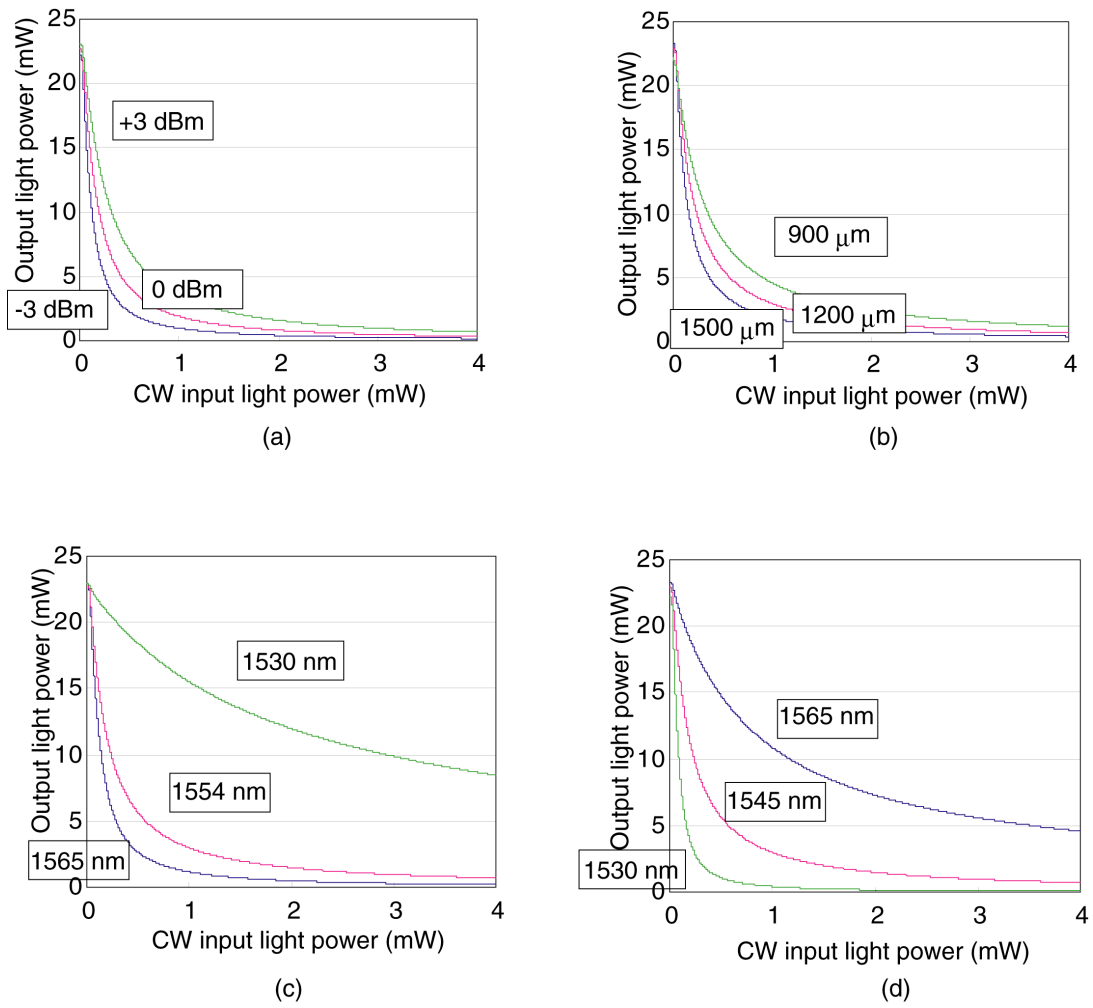
By using these parameters, input/output characteristics of a wavelength converter based on a SOA were calculated. Figs. 2.20 show calculation results. I investigated input/output characteristics dependency on (a) probe light power, (b) cavity length, (c) signal light wavelength and (d) probe light wavelength, respectively.

In Fig. 2.20 (a), input signal light and probe light wavelength were 1554 and 1533 nm, respectively. A 1200 μm -long SOA was used. Injection current was 533 mA. Probe light power of -3, 0 and +3 dBm were used as a parameter.

In Fig. 2.20 (b), input signal light, probe light wavelength and probe light power were 1554 nm, 1545 nm and -3 dBm, respectively. The cavity length of 900, 1200, 1500 μm were used as a parameter. Injection current for 900, 1200 and 1500 μm were 400, 533 and 667 mA, respectively. Each injection current was decided to be the same current density.

In Fig. 2.20 (c), probe light wavelength and power were 1545 nm and -3 dBm, respectively. A 1200 μm long SOA was used. Injection current was 533 mA. Input light wavelength of 1530, 1554 and 1565 nm were used as a parameter.

In Fig. 2.20 (d), input light wavelength and probe light power were 1554 nm and -3 dBm, respectively. A 1200 μm long SOA was used. Injection current was 533 mA. Probe light wavelength of 1530, 1545 and 1565 nm were used as a parameter. As I have already mentioned, the tendencies that wavelength converter based on SOA is become more saturable by lower probe light power, shorter probe light wavelength and longer signal light wavelength have been obtained. SOA gain and differential gain depend on input light wavelength. From Figs. 2.20, these tendencies from calculation agree well with experiments results. Thus, I consider that the calculation model can be available for investigation of wavelength converter based on XGM.



Figs. 2.20 Input/output characteristics of wavelength converter based on XGM using calculation model.

(a) Probe light power dependency (b) SOA length dependency (c) input light wavelength dependency (d) probe light wavelength dependency

2.4.3 Dynamic operation

To investigate operation characteristics of wavelength conversion based on XGM, eye pattern of wavelength conversion light was measured. Experimental setup was the same as that described in Section 2.4.2. Both RZ and NRZ format were used. A RZ signal light was generated using an electro-absorption (EA) modulator integrated with a DFB laser and a LiNbO₃ modulator. In case of NRZ signals, the EA modulator integrated with a DFB laser was directly modulated by a pulse pattern generator. 10 Gbps, $2^{31}-1$ pseudo-random bit sequence was used for both RZ and NRZ signals. The tunable laser was driven under CW condition. We used a SOA with a cavity length of 900 μm . The bias current was 300 mA. Peak signal light power was +9 dBm and signal wavelength was 1554 nm. Probe light power and wavelength were set at 0 dBm and 1545 nm, respectively.

Figures 2.21 (a) and (b) show eye patterns of conversion signal with NRZ and RZ format. Clear eye openings were observed for both cases.

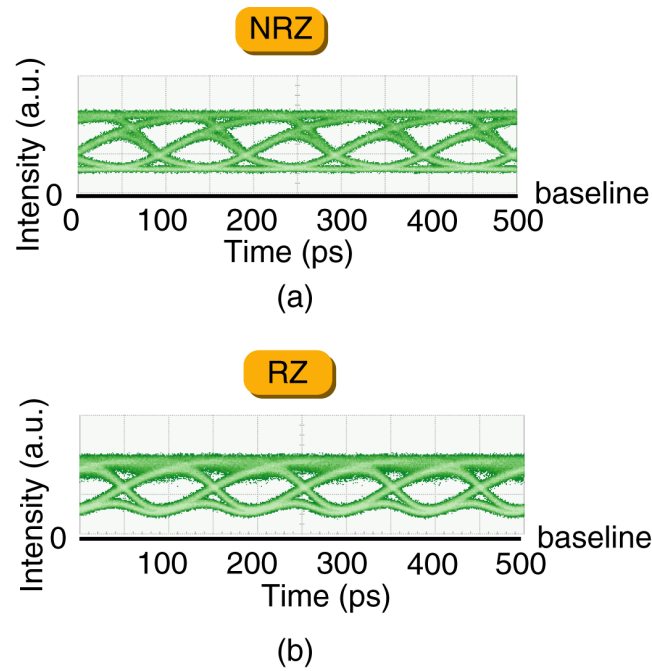


Fig. 2.21 Eye pattern of wavelength conversion light.

(a) NRZ format (b) RZ format

Next, dynamic operation of wavelength conversion was simulated by using SOA model based on transfer matrix method. The data rate of signal was 10 Gbps, PRBS 7-stage and mark ratio of 1/2 was used. The signal and the probe wavelength and power, SOA cavity length and injected current were the same as that used in the experiment. Figures 2.22 show calculated eye pattern of conversion signal. Figures 2.22 (a) and (b) show simulated conversion signal waveform for NRZ and RZ signal. As can be seen in these figures, by calculation model, clear eye opening was obtained, and simulated waveform agreed well with the experimental waveform, qualitatively. Therefore, I considered that this SOA calculation model could be used for investigation of a novel optical regenerator using wavelength converter based on XGM. At the same time, frequency chirping was calculated. The simulation results of its magnitude was about 20

GHz.

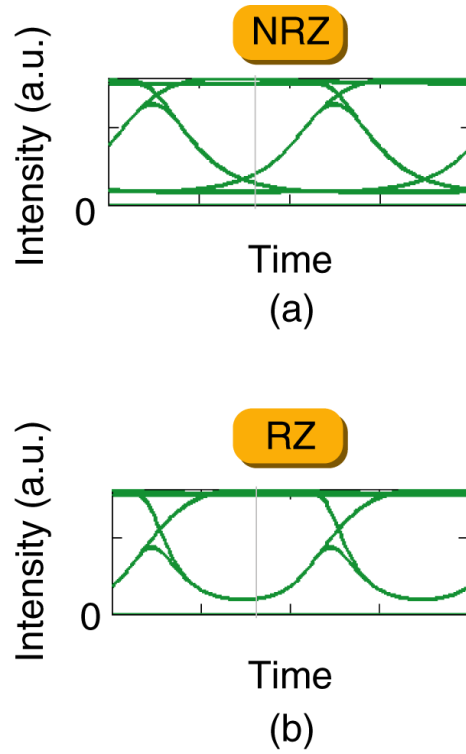


Fig. 2.22 Eye pattern of wavelength conversion light by using calculation model.

(a) NRZ format (b) RZ format

2.4.4 Signal quality

In this section, received sensitivity of wavelength conversion light was evaluated to investigate signal quality of converted output. In addition, much attention has been paid to the selection of the modulation format in terms of signal bandwidth and nonlinear effect under ultrahigh-speed optical network with bit rate over 40 Gbps. Therefore, it is necessary to investigate the dependence of wavelength conversion performance on modulation format. In this experiment, RZ and NRZ format were considered.

Figure 2.23 shows the result of bit error rate (BER) measurement. The wavelength

conversion signal was detected with an OC-192 receiver (OpNext RCV7003CN), and the BER was measured with a BER tester. In Fig. 2.23, peak signal light power of +6, +9, +12, +14 dBm was used as a parameter. Signal and probe light wavelength were 1554 and 1545 nm, respectively. Probe light power was +5 dBm. Signal was modulated at 10 Gbps and with RZ format. The received sensitivity of output powers were dependent on probe peak signal light power. The difference of the received power between the case of back-to-back and the case of output signals were more than 4.7 dB. In the case of +12 dBm peak signal light power, it was obtained minimum received power.

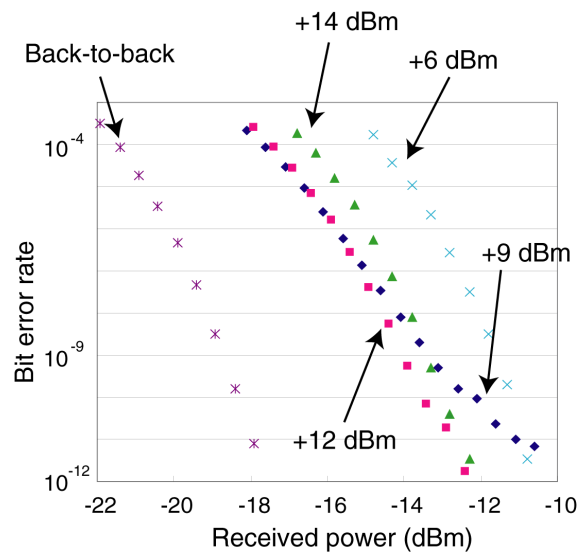


Fig. 2.23 The results of bit error rate measurement.

The dependence of the power penalty on signal light power is shown in Fig. 2. 24. The probe light power is used as a parameter. The power penalty was defined as the difference of optical received power at a BER of 10^{-9} between the wavelength

conversion signal and input signal light. The probe light power was 0 dBm and +5 dBm. The probe light wavelength was fixed at 1545 nm. In each case, there exists an optimized signal light power to minimize the power penalty. At low signal light power range, extinction ratio becomes large with increasing signal light power because of large carrier density change. This results in the improvement of signal quality, i.e., decrease of power penalty. At high signal light power range, on the other hand, rise time becomes long with increasing signal light power, which is dominated by the carrier lifetime. Therefore, the power penalty becomes large with large signal light power. From these considerations, we consider that power penalty would be affected by the carrier density change induced by the modulation format difference. The difference of the minimum power penalty at an optimized signal light power between probe light power of 0 dBm and +5 dBm was 0.1 dB for RZ signal and 2.3 dB for NRZ signal, respectively. The smaller power penalty dependence on probe light power on RZ format indicates that the advantage on either extinction ratio or rise time occurs using RZ format. However extinction ratio on RZ format has little difference from that on NRZ format.

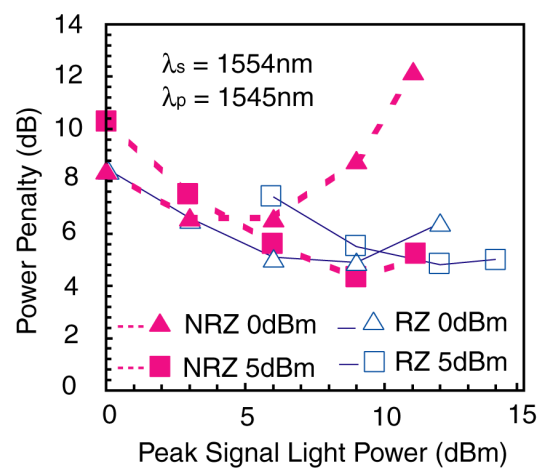


Fig. 2.24 The dependence of power penalty on signal light power with probe light as a parameter. Signal light wavelength was 1554 nm, and probe light wavelength was 1545 nm.

The dependence of minimum power penalty on probe light wavelength is shown in Fig. 2.25. The probe light power was used as a parameter, and it was set at +5 dBm, and 0 dBm. Probe light wavelength of 1535, 1545 and 1562 nm were selected. In case of probe light power of 0 dBm, the power penalty with probe light wavelength of 1535, 1545 and 1562 nm was 4.9, 5.1 and 6.2 dB on RZ format, respectively. Whereas on NRZ format, the power penalty with probe light wavelength of 1535, 1545 and 1562 nm was 7.6, 6.6 and 8.9 dB, respectively. In other words, the difference of power penalty on RZ format and on NRZ format was 0.2 and 1.0 dB between the wavelength of 1535 and 1545 nm, respectively. Furthermore, it was 1.1 and 2.3 dB between wavelength of 1545 and 1562 nm. From Fig. 2.25, it is indicated that the dependence of minimum power penalty on probe light power and wavelength is smaller on RZ format than on NRZ format. I consider main reason for power penalty dependence on probe light wavelength is the difference of differential gain. At longer wavelength, the differential gain is small due to the blue shift of gain peak wavelength, so the small extinction ratio caused by the small differential gain results in the increment of power penalty.

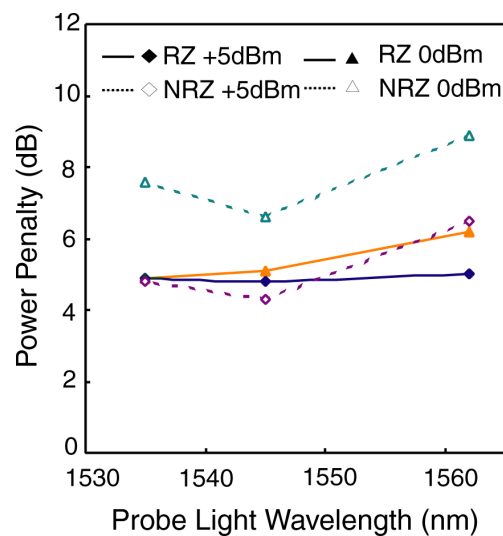


Fig. 2.25 The dependence of power penalty on probe light.

To increase extinction ratio, decrease of probe light power is one of the methods. On NRZ format, power penalty increases under that condition as shown in Fig. 2.25, but the increase of power penalty can be suppressed on RZ format. In order to investigate the origin of these dependency, we measured rise and fall times of wavelength conversion signals. They are shown in Fig. 2.26. In this experiment, we used signal light with repetition frequency of 1.25 GHz and the duty ratio of 1:8. The widths of signal light for RZ and NRZ format were 48 and 100 ps, respectively. In these experiments the signal light wavelength was 1554 nm, and probe light wavelength was 1545 nm. Probe light power was 0 dBm. The rise time is defined as the transient time from 10 % to 90 % between low level and high level, and fall time is defined as that from 90 % to 10 %. The probe light and wavelength were fixed at 1545 nm and 0 dBm, respectively. As can be seen in Fig. 2.26, the rise time on RZ format is short compared with NRZ format. Because rise time is the dominant factor for power penalty degradation, this difference between RZ and NRZ is considered to cause the dependence of power penalty on probe light power as shown in Fig. 2.24 and Fig. 2.25.

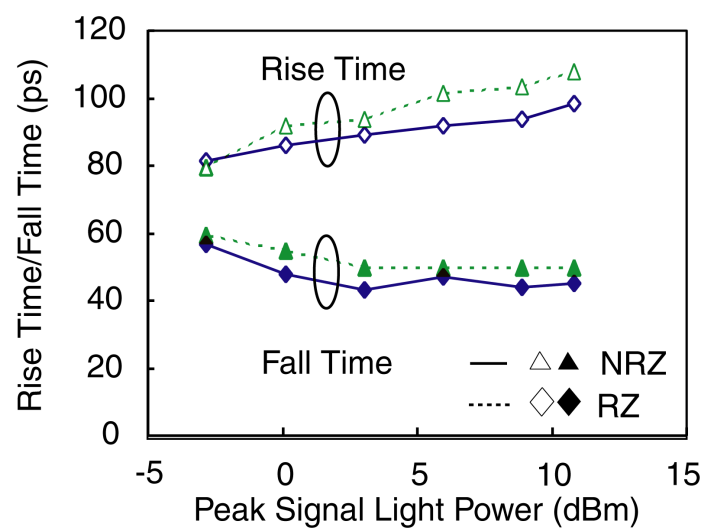


Fig. 2.26 Experimental results of rise and fall time on RZ and NRZ format.

We calculated the XGM wavelength conversion performance to investigate the cause of the power penalty and operation speed dependence by using transfer matrix method. The wavelength of signal and probe light were 1554 nm and 1545 nm, respectively. Probe light power was 0 dBm. The calculated rise and fall time are shown in Fig. 2.27. These results with smaller rise time and fall time on RZ format than that on NRZ format agree qualitatively with experimental results as shown in Fig. 2.26.

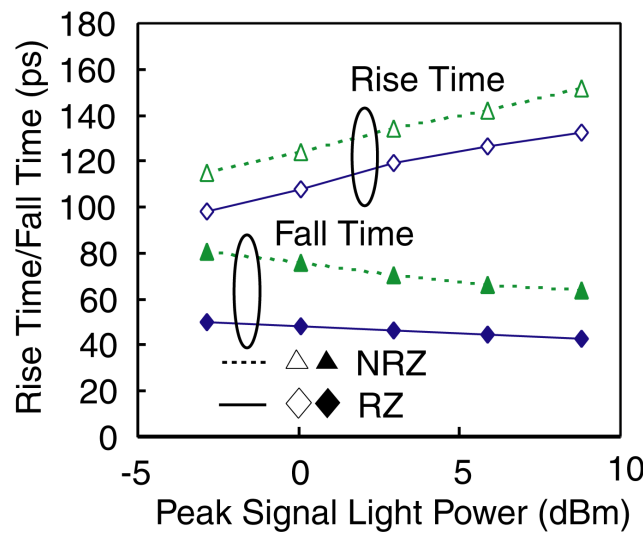


Fig. 2.27 Calculation results of rise and fall time on RZ and NRZ format.

We also calculated the transient response of wavelength conversion signal and carrier density. The signal light used in this calculation, wavelength conversion light and simulated carrier density is shown in Fig. 2.28 (a), (b) and (c), respectively. The peak signal power was +3 dBm for both RZ and NRZ. The wavelength of signal and probe light wavelength were 1554 and 1545 nm, respectively. Probe light power was 0 dBm. As can be seen in Fig. 2.28 (c), the difference of carrier density between the maximum and minimum values for RZ signal is smaller than that for NRZ signal. This small

carrier density change results in the small difference of wavelength conversion signal power on RZ than on NRZ format as shown in Fig. 2.28 (b). On RZ format, signal power should return to zero in each time interval, and then periodic carrier density change occurs in the duration of consecutive “1” patterns. This causes the small change of carrier density on RZ format.

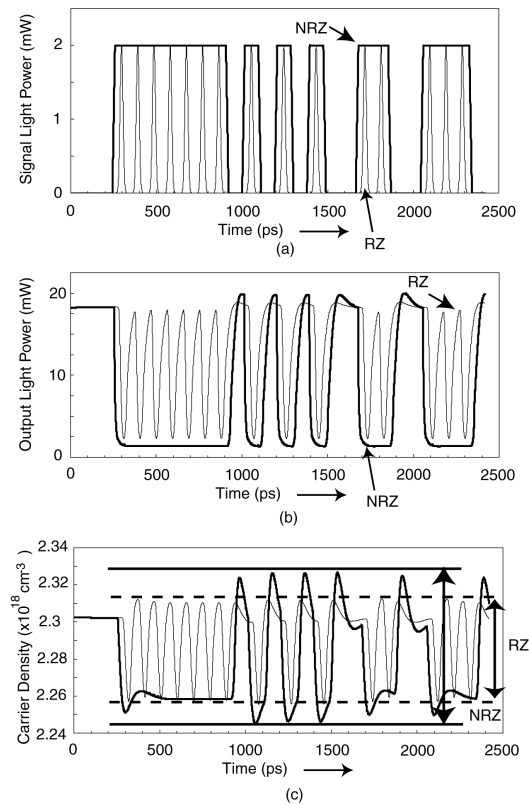


Fig. 2.28 Calculation results of transient response for XGM wavelength conversion for RZ and NRZ signals. (a) Signal pattern. (b) Wavelength conversion light. (c) Carrier density. The wavelength of signal and probe light wavelength were 1554 and

2.5 Summary

In summary, the characteristics of various reported all-optical regenerators and wavelength converters are compared in their performance. To realize an all-optical regenerator for solving several issues, a wavelength converter based on cross gain modulation was chosen.

Then the characteristics of a wavelength converter based on XGM were investigated experimentally. In addition, by fitting experimental results to simulation results, each calculation parameters of a SOA was extracted, and validity of the calculation model was obtained.

Moreover, the difference of characteristics in wavelength conversion between RZ and NRZ signal using XGM in a SOA was investigated. Comparing to NRZ, we obtained small dependence of power penalty on RZ format on probe light power and probe light wavelength. From calculations of carrier density change using rate equation, we have confirmed that this tendency is affected by the difference of carrier density change between RZ and NRZ modulation.

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Chapter 3

Modeling of a Cross Gain modulation type wavelength-converter-Cascaded Optical Regenerator

3.1 Introduction

In this section, I propose a novel optical regenerator, which consists of two-stage wavelength converters based on XGM in SOA's, to solve issues of an optical regenerator such as small dynamic range in input power. First, I will describe the principle of a cross gain modulation type wavelength-converter-cascaded optical regenerator (CGCOR). Next, simulation results are shown. Then, the results of input/output characteristics and effect on signal regeneration are indicated. I will also investigate prospect of capability of a CGCOR. Finally, I will summarize this chapter.

3.2 Principle of a CGCOR

As mentioned in the previous chapter, a wavelength converter based on XGM has the advantage of high-speed operation (~ 40 Gb/s), operation against wide bandwidth (~ 30 nm), polarization insensitivity and large dynamic range (7~10 dB) in input power [1].

But signal polarity is inverted inherently and signal power is decreasing monotonically. For signal reshaping, it is necessary that input/output characteristics have nonlinearity at both signal '1' level and '0' level. By cascading inverse signal polarity and nonlinearity of input/output characteristics, it is possible to realize nonlinearity at both signal '1' level and '0' level. The principle for realizing optical nonlinearity using cascaded XGM-based wavelength converters is shown in Fig. 3.1. There are the following three stages of input/output characteristics.

- (1) At the first XGM-based wavelength converter, while input light power is low, output light power of the first wavelength conversion is reduced as the input light power increases. Under this condition, the light power of the first wavelength conversion is at high level, and it corresponds to the saturation region at the second wavelength converter. The output light from the first wavelength converter in the saturation regime at the second stage wavelength converter causes small power fluctuation at the low input power.
- (2) Next, when the input light power increases gradually, output light power at the first wavelength converter decreases monotonically. Consequently, the input light power at the second wavelength converter becomes within the power range at which the wavelength conversion light power changes.
- (3) Finally, when the input light power increases such that it reaches the saturation regime at the first wavelength converter, the wavelength conversion light power becomes nearly constant. Hence, power fluctuation becomes small at high input light power.

Therefore, the nonlinear characteristics can be achieved.

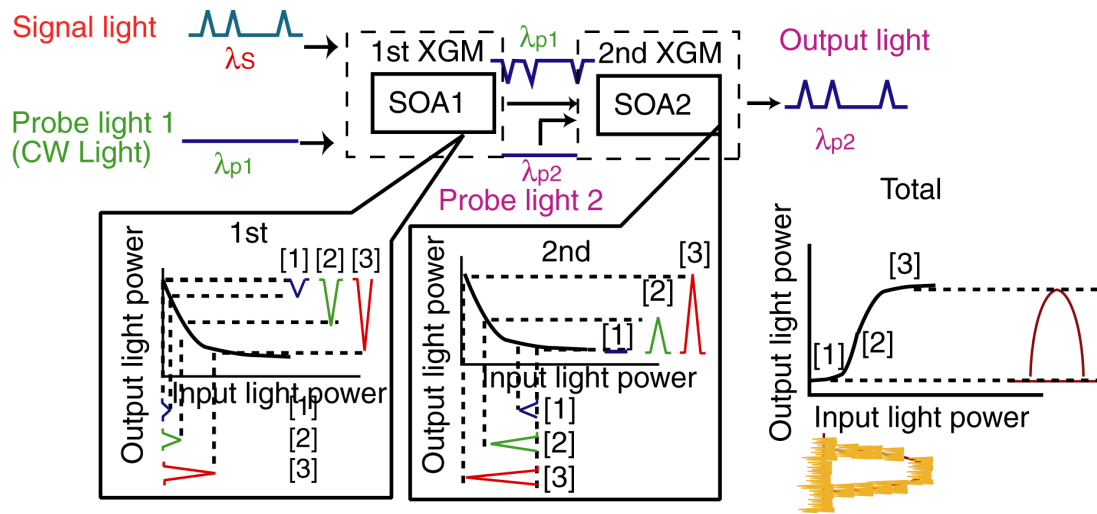


Fig. 3.1 Principle of optical nonlinearity of input/output characteristics in a CGCOR.

By using cascaded structure, polarity of output signal is the same as that of input signal. Additionally, it is possible to set wavelength of output signal to be the same as that of input signal. These are the advantage of a CGCOR over a single wavelength converter based on XGM.

3.3 Input/output characteristics

To evaluate operation performance of a CGCOR, the SOA model was simulated [2]. A CGCOR consists of two wavelength converters based on XGM. So the performance of a CGCOR was easily represented by cascading two SOA models. The using SOA model was based on time-dependent transfer matrix method (TMM) and its calculation parameters were the same as the case of Section 2. The behavior of signal and probe light are obtained by solving Eqns. (2.4)-(2.12). Figure 3.2 shows calculation results of input/output characteristics. The input light wavelength was 1554 nm. The first-stage and the second-stage probe light wavelength were 1533 and 1530 nm, respectively. The

first stage probe light power was -3 dBm, and the second stage probe light power of -8 , -10 and -12 dBm were used as a parameter. The length of the first and the second SOA were 1200 and 900 μm , respectively. Injection current into the first and the second SOA were 533 and 400 mA, respectively, to set current densities of the first and the second SOA to be the same. Wavelength conversion light at the first wavelength converter and another CW probe light were injected into the second SOA for wavelength conversion in the simulation model. From Fig. 3.2, realization of nonlinear characteristic at both low and high level for output light power was verified. When probe light power at the second wavelength converter is too large, gain saturation effect becomes small. This causes optical nonlinearity at low level to become unclear. In case that probe light power is too small, output power becomes low because output signal is originated from amplified probe light with low power.

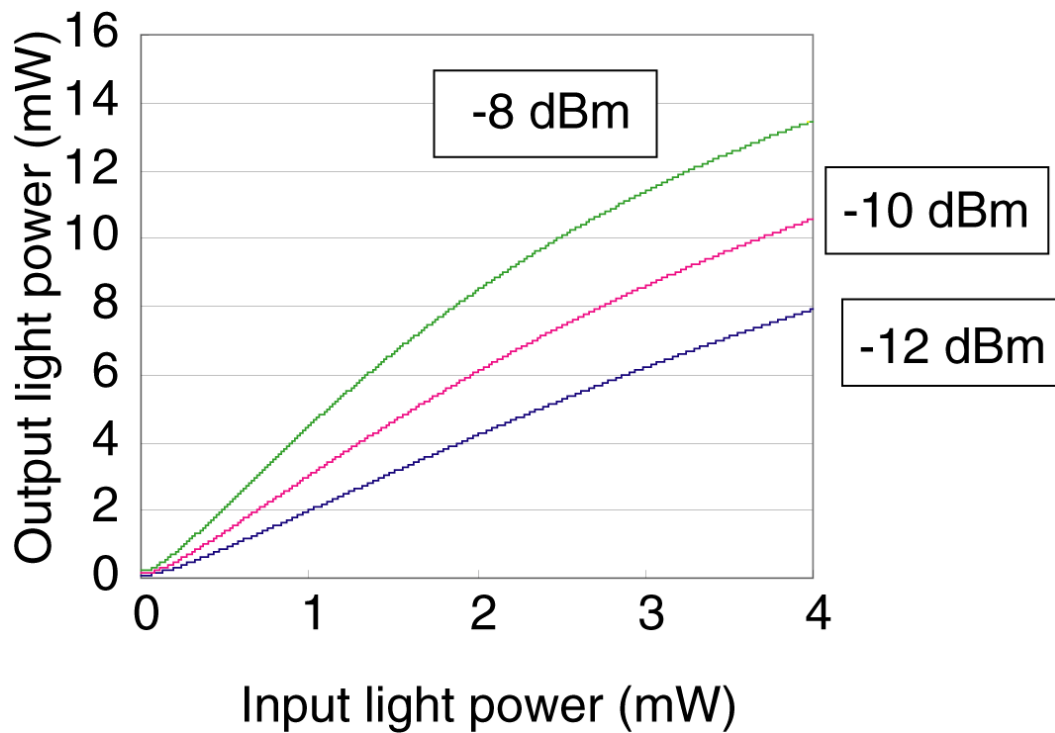


Fig. 3.2 calculation result of input/output characteristics. The second-stage probe light power

From calculation results as indicated in Figs. 2.26 (a) to (d) in the Section 2.4.2, the dependency of input/output characteristics of a wavelength converter based on XGM was investigated experimentally, and the tendency of a CGCOR can be understood by using these results. Figures 3.3 show calculation results. I investigated dependency of input/output characteristics dependency on (a) the second-stage probe light power, (b) the first-stage probe light power, (c) cavity length of the first-stage SOA and (d) SOA cavity length of the second-stage, respectively.

In Fig. 3.3 (a), The second-stage probe light wavelengths of 1565, 1554 and 1530 nm were used as a parameter. Input signal light and the first-stage probe light wavelength were 1554 and 1533 nm, respectively. The first- and the second-stage probe light power were 0 and -13 dBm, respectively. 1200 and 900 μm -long SOA's were used as the first- and the second-stage XGM wavelength converter. Injection current for the first and the second-stage SOA were 533 and 400 mA, respectively.

In Fig. 3.3 (b), The first-stage probe light wavelength of 1565, 1545 and 1535 nm were used as a parameter. Input signal light, the second-stage probe light wavelength were 1554 and 1530 nm, respectively. The first- and the second-stage probe light power were -6 and -10 dBm, respectively. 1200 and 900 μm -long SOA were used as the first- and the second-stage XGM wavelength converter. Injection current for the first and the second-stage SOA were 533 and 400 mA, respectively.

In Fig. 3.3 (c), The cavity length of 900, 1200 and 1500 μm for the second-stage XGM were used as a parameter. Input signal light, the first- and the second-stage probe light wavelengths were 1554, 1533 and 1530 nm, respectively. The first- and the second-stage probe light power were -6 and -10 dBm, respectively. A 1200 μm -long SOA was used as the first-stage XGM wavelength converter. Injection current for the

first-stage SOA was 533 mA. Injection current for 900, 1200 and 1500 μm -long SOA were 400, 533 and 667 mA, respectively. These values were decided so as to set the same current density in each SOA.

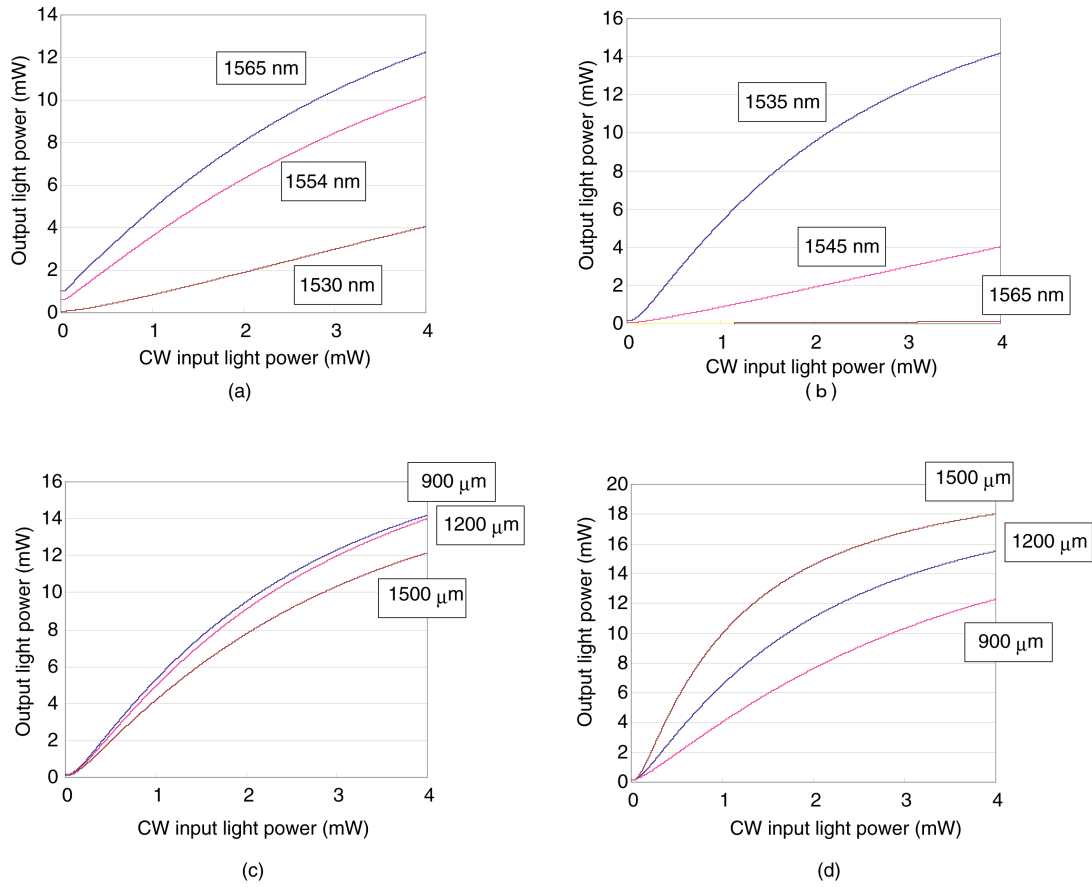
In Fig. 3.3 (d), The SOA length of 900, 1200 and 1500 μm for the second-stage XGM wavelength converter were used as a parameter. Input signal light, the first- and the second-stage probe light wavelength were 1554, 1533 and 1530 nm, respectively. The first- and the second-stage probe light power were -6 and -10 dBm, respectively. A 900 μm length SOA was used as the second-stage XGM wavelength converter. Injection current for the second-stage SOA was 533 mA. Injection current for 900, 1200 and 1500 μm were 400, 533 and 667 mA, respectively. From Figs. 3.3, these tendencies from experiment correspond to calculation results as mentioned in Chapter 4. Thus the calculation model can be used for investigation of a CGCOR.

Here, for quantification of nonlinearity, I use nonlinear parameter γ [3-5], and γ is expressed as

$$\left\{ \begin{array}{l} f(x) = \frac{1}{2 \cdot \tanh\left(\frac{1}{2}b\right)} \cdot \tanh\left\{b\left(x - \frac{1}{2}\right)\right\} + \frac{1}{2} \\ f'\left(\frac{1}{2}\right) = \frac{1}{\gamma} \end{array} \right. \quad (3.1)$$

where b is the constant. The power of input and output was normalized. In this, I decide that the point, where the gradient of nonlinear region in high power side is the same as the gradient of nonlinear region in low power side, is the '1'.

Figure 3.4 shows input/output characteristics. In this, $\gamma = 1, 0.8, 0.6, 0.4, 0.2$ was used as a parameter. In $\gamma = 1$, input/output characteristics represent linear characteristics, and nonlinearity is increasing with decreasing γ , finally input/output characteristics make step function in $\gamma = 0$.



Figs. 3.3 Input/output characteristics of a CGCOR

(a) The second-stage probe light wavelength dependency.

λ_s : 1554 nm, λ_{lp} : 1533 nm, P_{1p} : 0 dBm, P_{2p} : -13 dBm, L_{1st} : 1200 μm , L_{2nd} : 900 μm

(b) The first-stage probe light wavelength dependency

λ_s : 1554 nm, λ_{2p} : 1530 nm, P_{1p} : -6 dBm, P_{2p} : -10 dBm, L_{1st} : 1200 μm , L_{2nd} : 900 μm

(c) SOA length for the second-stage dependency

λ_s : 1554 nm, λ_{lp} : 1533 nm, λ_{2p} : 1530 nm, P_{1p} : -6 dBm, P_{2p} : -10 dBm, L_{1st} : 1200 μm ,

(d) SOA length for the first-stage dependency

λ_s : 1554 nm, λ_{lp} : 1533 nm, λ_{2p} : 1530 nm, P_{1p} : -6 dBm, P_{2p} : -10 dBm, L_{2nd} : 900 μm

For example, experimentally input/output characteristics of XGM gain control optical regenerator and input/output characteristics from Eqn. (3.1) with parameter fitting. In this case, the wavelength for the input, and the probe light in the wavelength converter were 1554 and 1535 nm, respectively. Average power of the input light at the XGM SOA are 5 dB larger than the power of the input light at the gain saturated SOA. The probe light power for the XGM SOA was -4 dBm. The cavity length and bias current of the SOA in the wavelength converter were $1500\text{ }\mu\text{m}$ and 650 mA , respectively. Those of the gain saturated SOA were $900\text{ }\mu\text{m}$ and 400 mA . Here $\gamma = 0.79$ was obtained. I draw these input/output characteristics in Fig. 3.5. From this figure, good approximation was obtained.

I decided the mean value of signal '0' level and '1' level were 0.05 and 0.95. In this parameter, 0.076 standard deviation makes $Q = 6$ (equivalent of bit error rate = 10^{-9}). Here, the signal with $Q = 6$ was input to this function with adding ASE noise equivalent to the ten stages 100 km spacing EDFA. The Q factor of output signal against γ factor was shown in Fig. 3.6. From this figure, $Q = 6$ is maintaining in $\gamma = 0.85$. Therefore more than $g = 0.85$ is required. In addition, the g factor to maintain Q factor with adding ASE noise was shown in Fig. 3.7. The needed g factor was increasing with Q factor increasing, $\gamma = 0.79$ was needed in $Q = 10$.

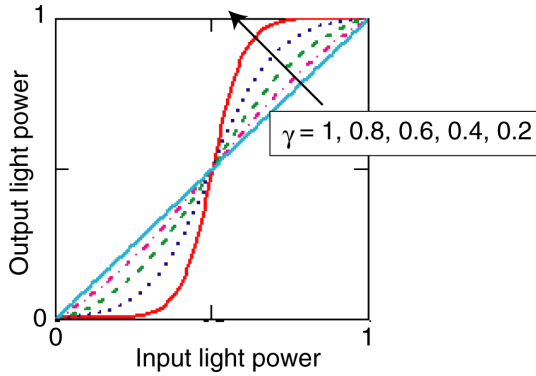


Fig. 3.4 hyperbolic input/output characteristics.
 $\gamma = 1, 0.8, 0.6, 0.4, 0.2$ was used as a parameter

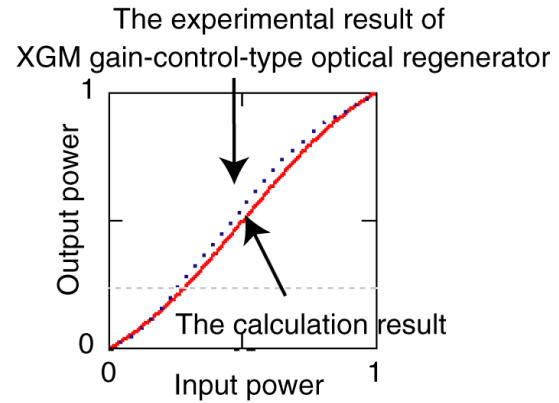


Fig. 3.5 The results of experimental and calculation
 $(\gamma = 0.79)$ Input/output characteristics.

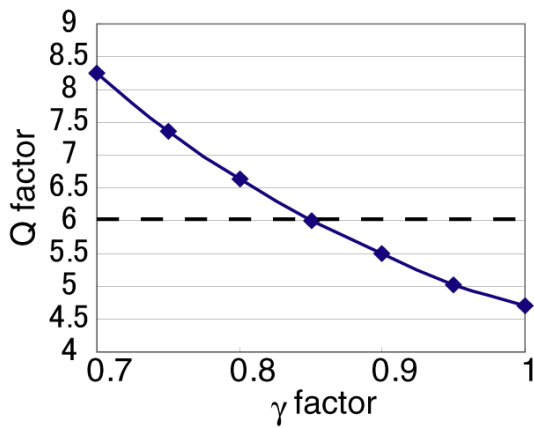


Fig. 3.6 The change of Q factor against γ factor.

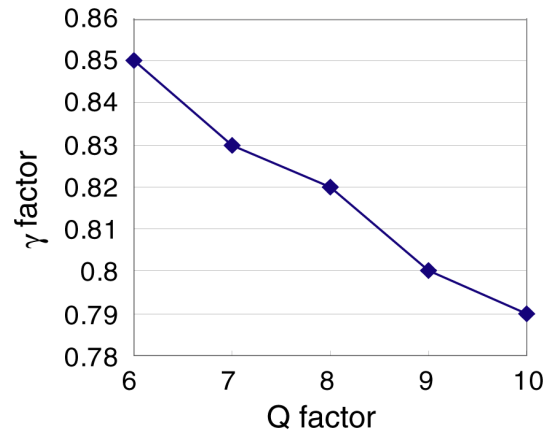


Fig. 3.7 γ factor to maintain Q factor.

3.4 Effect of signal regeneration

In Section 3.3, it was verified that a CGCOR has nonlinear characteristic at both low and high input power region to choose the appropriate first-stage and the second-stage probe light wavelength and other conditions. By applying the nonlinear characteristics, realization of an optical regenerator is expected. To estimate performance of a CGCOR, dynamic operation of a CGCOR was calculated by using SOA model based on transfer matrix method.

The data rate of signal was 10 Gbps, 7-stage PRBS and mark ratio of 1/2 was used.

Figures 3.7 (a) and (b) show the calculation results in the case of NRZ and RZ format, respectively. As can be seen in these figures, clear eye opening was also obtained in a CGCOR. Input signal light and the first- and the second-stage probe light wavelengths were 1554, 1533 and 1530 nm, respectively. The first- and the second stage probe light power were -3 dBm and -10 dBm, respectively. In the case of using NRZ format, average signal power was $+3$ dBm, and in the case of using RZ format, average signal power was 0 dBm.

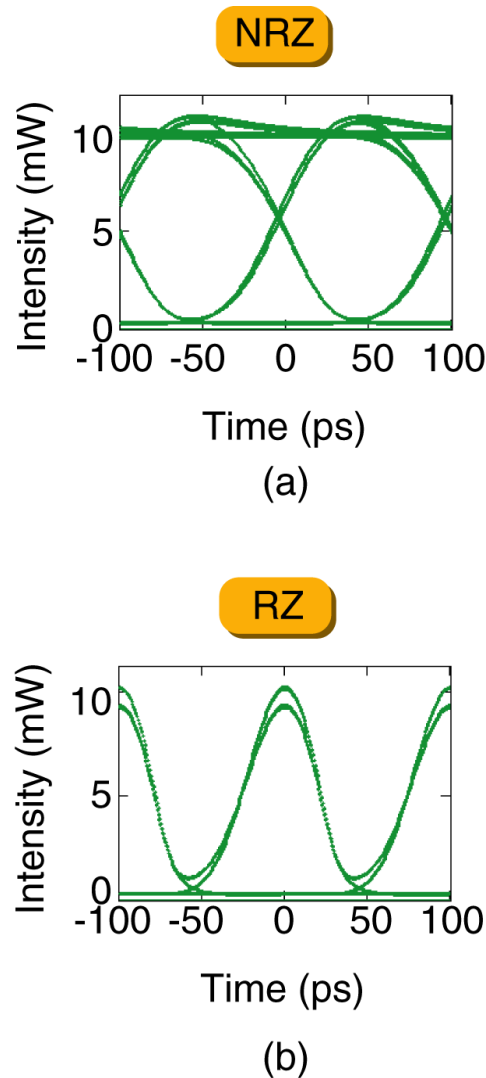


Fig. 3.7 Eye pattern of a CGCOR by using calculation model.

(a) NRZ format (b) RZ format

Next, to estimate signal quality from a CGCOR, several kinds of noises were considered [6][7]. They are described as listed below.

Thermal noise:

At a finite temperature, electrons move randomly in any conductors. Random thermal motion of electrons in a resistor is detected as a fluctuating current even in the absence of an applied voltage. The load resistor in the front end of an optical receiver adds such fluctuations to the current generated by the photodiode. The noise variance is given as follows;

$$\sigma_T^2 = \frac{4k \cdot T_n \cdot B_e}{R} \quad (3.2)$$

where k is the Boltzmann constant, T_n is the absolute temperature and B_e is the electrical bandwidth of the receiver and R is the load-resistor.

Shot noise

Shot noise is caused by the random fluctuation of current consisting of a stream of electrons that are generated at random times. The noise variance is given as

$$\sigma_s^2 = \frac{2q^2 \cdot B_e \cdot \eta}{h\nu_s} \cdot P_s \quad (3.3)$$

where q is the electron charge, η is the internal quantum efficiency, $h\nu_s$ is the photon energy of signal and P_s is the power of signal.

Beat noise between signal light and amplified spontaneous emission (ASE) light

The beating of spontaneous emission with the signal will produce a noise current. The noise variance is as follows

$$\sigma_{s-sp}^2 = 4 \cdot \frac{\eta}{h\nu_s} \cdot P_s \cdot \frac{\eta}{h\nu_{spon}} \cdot P_{spon} \cdot \frac{B_e}{B_o} \quad (3.4)$$

where $h\nu_{spon}$ is the photon energy of ASE, P_{spon} is the power of ASE and B_o is the optical bandwidth.

Beat noise between different ASE light

The beating between different spontaneous emission will also produce a noise current. The noise variance is given as

$$\sigma_{sp-sp}^2 = \left(\frac{\eta}{h\nu_{spon}} \cdot P_{spon} \right)^2 \cdot B_e \cdot \frac{2B_o - B_e}{B_o^2} \quad (3.5)$$

In a saturated SOA, ASE power varies by gain saturation. Therefore, ASE dynamics in calculation model was taken into account. Parameters used in the calculation are shown in Table III.1. Figure 3.8 shows a type of ASE waveform in XGM operation. As shown in Fig. 3.8, ASE waveform is changed by saturation and pattern effect seemed to occur.

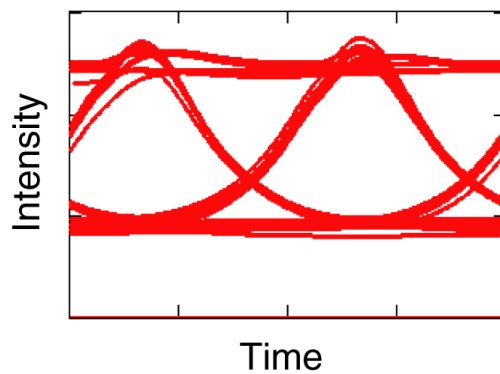


Fig. 3.8 Waveform of a example of calculated ASE.

Table. III.1 Parameters used in noise calculation

Symbol	Description	Value	Unit
k	Boltzmann constant	$1.38 \cdot 10^{-23}$	J/K
T _n	Absoute temprature	300	K
B _e	Electrical bandwidth	$1 \cdot 10^{10}$	Hz
B _o	Optical bandwidth	$1.1 \cdot 10^{11}$	Hz
R	Load-resistor	50	Ω
q	Electron chirge	$1.6 \cdot 10^{-19}$	C
η	Internal quantum efficiency	0.8	

To investigate signal regeneration performance, signal with power fluctuated was utilized. Figure 3.9 shows waveform of the used input signal waveform. Signal power was distributed according to signal power. In this case, Q parameter of the input signal at -16 dBm was 12.9.

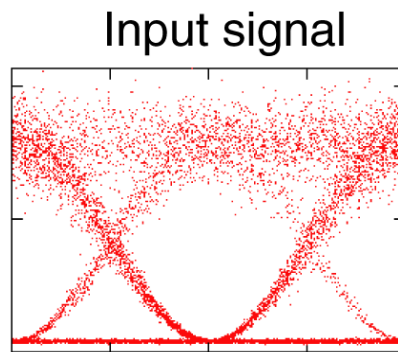


Fig. 3.9 Waveform of input signal. 10Gbps, PRBS 7-stage and NRZ format signal was used.

In this calculation, parameters were the same as used ones in Fig. 3.7 (a). The calculated output signal is indicated in Fig. 3.7. Power fluctuation seen in the input signal was successfully suppressed in the output signal. From this result, I confirmed that a CGCOR has possibility to operate as an optical regenerator.

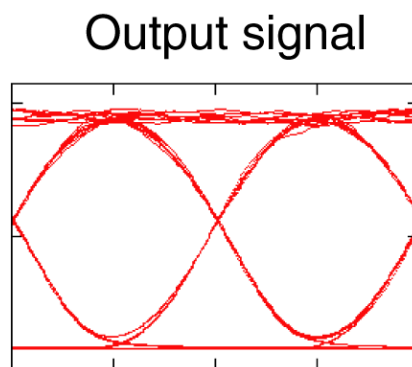


Fig. 3.10 Waveform of output signal from CGCOR. 10Gbps, PRBS 7-stage and NRZ format

3.5 Possibility prospect of a CGCOR

As mentioned in Section 1.3, an optical regenerator was required to maintain Q value. In this Section, transmission characteristics by using a periodic CGCOR was investigated assuming loop structure. ASE power added by an EDFA was defined as

$$P_{ASE} = n \cdot (G - 1) \cdot F_n \cdot B_o \cdot h\nu \quad (3.5)$$

indication of symbols and their values are the same as the case in Section 1.3 [7]. The parameter of a CGCOR and input signal was set at the same as the case of Fig. 3.7 (a). Fiber loss was assumed to be 0.2 dB/km and amplifier gain was 100. CGCOR's were inserted at every 10 EDFA stages. Schematic of calculation model was shown in Fig. 3.11. Figures 3.12 (a), (b), (c), (d) and (e) show the eye pattern at 1000 km, the one at 3000 km without CGCOR's, 1000 km, 2000 km and 3000 km after passing through a CGCOR, respectively. As can be seen from Fig. 3.9 (a) and (b), an EDFA provides power fluctuation of signal. On the other hand, In Fig. 3.9 (c), (d) and (e), power fluctuation caused by ASE is suppressed although overshoot in '1' level and accumulation of power fluctuation are observed. However, extinction ratio in signal is degraded at each CGCOR. Extinction ratio in Figs. 3.9 (c), (d) and (e) were 10.8 dB, 8.32 dB and 6.2 dB, respectively. Degradation of extinction ratio causes eye closing. I consider degrading extinction was a limiting factor for transmission distance.

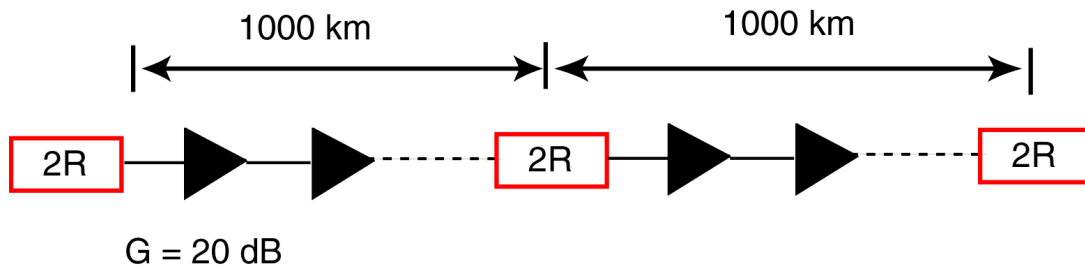


Fig. 3.11 Histogram of eye pattern at signal '1' level and signal '0' level.

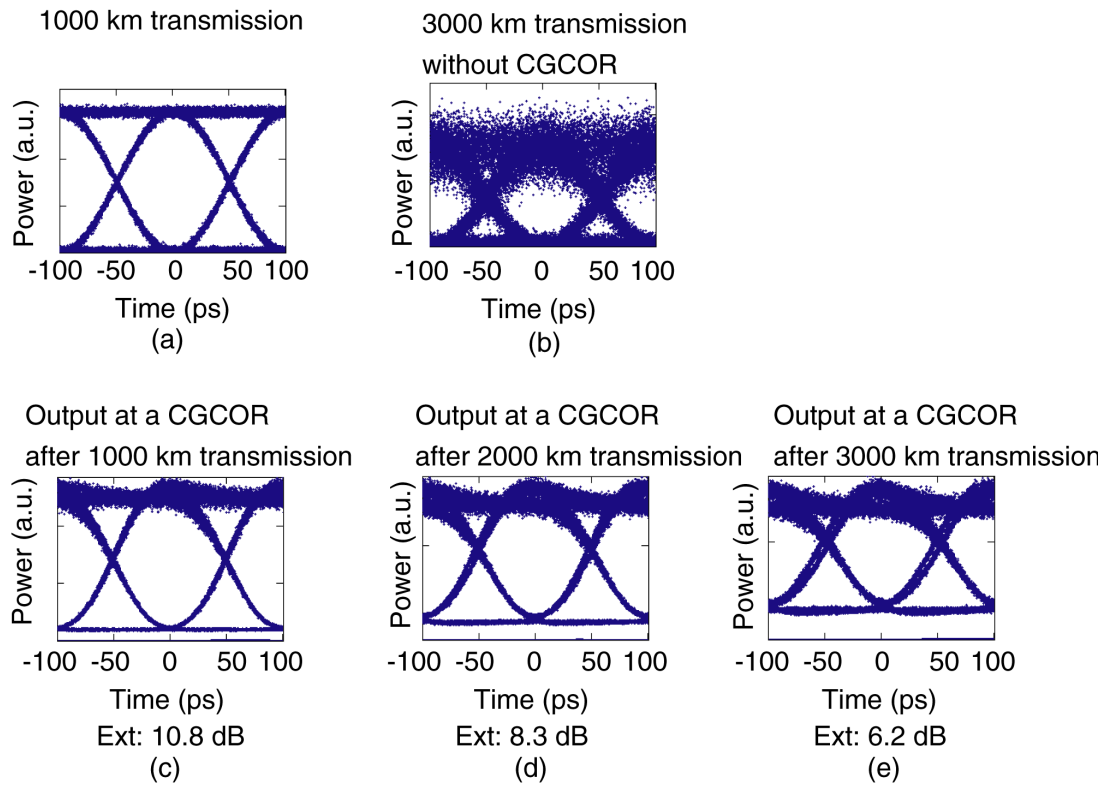


Fig. 3.12 Waveform of signal with transmission.

(a) at 1000 km transmission (b) at 3000 km transmission (c) output at a CGCOR after 1000 km transmission (d) output at a CGCOR after 2000 km transmission (e) output at a CGCOR after 3000 km transmission

In addition, to evaluate eye opening quantitatively, histogram of eye pattern in photocurrent was estimated as shown in Fig. 3.13. The value of the deviation was normalized by the mean value of signal '1' level or signal '0' level. The sampling points were extracted near the decision point with distinguishing between signal '1' level and '0' level. Because of signal overshoot, two peaks were observed in signal '1' level whereas gaussian profile was obtained in the case of transmission without CGCOR's. In the case of using CGCOR's, pattern effect such as overshoot was observed, therefore

accurate comparison between the system using a CGCOR and the system using an EDFA was not able, but the value of the deviation in the case of a CGCOR was less than the case without CGCOR's. At 2000 km transmission after passing through a CGCOR, its variance was large compared with the case of 1000 km. And the difference of variance between the case at 2000 km and at 3000 km was little. It is expected to maintain power fluctuation with transmission.

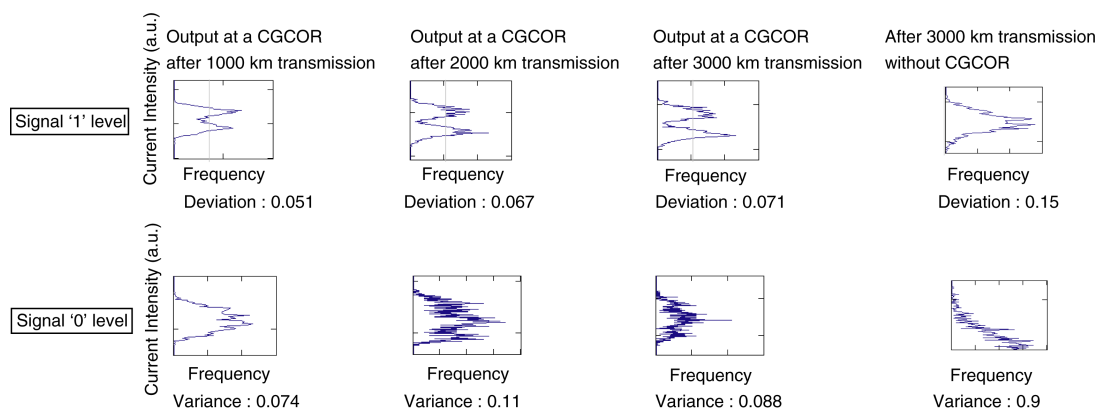


Fig. 3.13 Histogram of eye pattern at signal '1' level and signal '0' level.

Then, dependence of the difference of negative power penalty on waveform was investigated. The second-stage probe light power was used as a parameter. The negative power penalty, which is obtained experimentally, in the case of the second-stage probe light power of -8 , -10 , -12 and -14 dBm is 2.3 dB, 4.1 dB, 3.4 dB and 0.9 dB, respectively. Other parameters are the same as the case in Fig. 3.9. Figures 3.14 (a), (b), (c), (d), (e) and (f) show the eye pattern at 1000 km, the one at 3000 km without CGCOR's, 3000 km after passing through a CGCOR using the second-stage probe light power of -8 , -10 , -12 and -14 dBm, respectively. In Figs. 3.14 (c), (d) and (e), suppression of power fluctuation was observed. In Fig. 3.14 (f), on the other hand, power fluctuation was observed. Therefore, from rough estimation, a CGCOR is

considered to be required more than 2 dB negative power penalties.

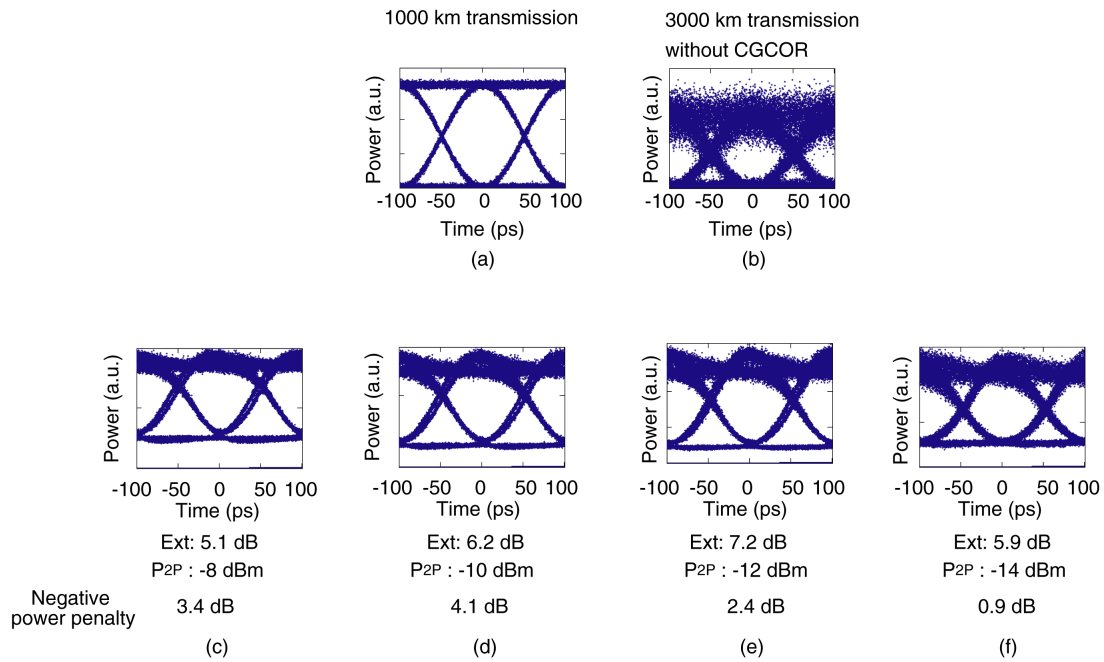


Fig. 3.14 Waveform of signal with transmission.

(a) at 1000 km transmission (b) at 3000 km transmission

output at a CGCOR after 3000 km transmission (c) the second-stage probe light power -8 dBm (d) the second-stage probe light power -10 dBm (e) the second-stage probe light power -12 dBm (f) the second-stage probe light power -14 dBm

Moreover, I investigated the improvement of SNR by using CGCOR as the above condition. Figure 3.15 shows calculation results. Compared to EDFA only system, SNR at 1000 km, 2000 km and 3000 km are improved by 2 dB, 5 dB and 8 dB, respectively. This indicates CGCOR allows transmission distance elongation.

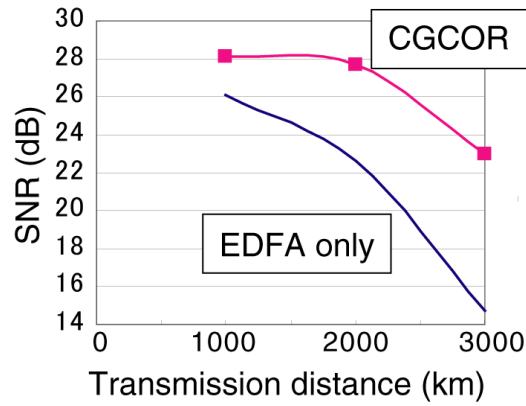


Fig. 3.15 The change of SNR by CGCOR with transmission distance.

3.6 Summary

In this Section, a CGCOR was proposed and its performance was investigated analytically. A CGCOR is expected to have nonlinear input/output characteristics. Then, the operation performance such as input/output characteristics, signal regeneration performance and transmission characteristics was investigated. These depend on probe light wavelength and power, SOA cavity-length and so on. By using nonlinear input/output characteristics, signal regeneration operation for degraded signal would be realized. Then, transmission characteristics for using a CGCOR was investigated. It was seen that power fluctuation of signal was suppressed by a CGCOR. However, degradation of extinction ratio limited the number of cascaded CGCOR's. The degradation of extinction ratio was one of the issues which should be solved for a CGCOR. In addition, by using the parameter of negative penalty from bit error rate experiment, it is considered that a CGCOR is required about 2 dB negative power penalty as the rough target.

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Chapter 4

Operation performance of a Cross Gain modulation type wavelength-converter-Cascaded Optical Regenerator

4.1 Introduction

In Chapter 3, a CGCOR was proposed and its performance was evaluated numerically. In this chapter, I investigate the performance of a CGCOR experimentally. First, input/output characteristics of a CGCOR are investigated to confirm whether nonlinearity in input/output characteristics can be obtained or not. Next, dynamic characteristics are performed by using modulated signal at a bit rate of 10 Gbps in NRZ format. Then, the performance of a signal regenerator is investigated by using degraded signal with ASE. We also propose the scheme for improving functionality of a CGCOR by using sinusoidal probe light. Finally, I will summarize this chapter.

4.2 Input/output characteristics

To investigate the performance of the proposed optical regeneration system called a CGCOR, the optical input/output characteristics were measured. Figure. 4.1 depicts the experimental setup. A pulse pattern generator, a LiNbO₃ modulator, and a bit error rate tester were used for bit error rate measurement. A distributed feedback laser diodes (DFB-LD) was used as a signal light source. The input light wavelength was 1554 nm. The CW probe light for wavelength conversion was emitted from a tunable laser. This input light and CW probe light were injected into the first SOA. The probe light wavelength was 1533 nm. The length of the first SOA was 1200 μm , the gain peak wavelength was 1550 nm and the small-signal gain was 31.5 dB. Injection current into the SOA was 533 mA. Wavelength conversion light at the first wavelength converter and another CW probe light from the other tunable laser were injected into the second SOA for wavelength conversion. The probe light wavelength was 1530 nm. The length of the second SOA was 900 μm , the gain peak wavelength was 1525 nm and the small-signal gain was 28.5 dB. Injection current into the second SOA was 400 mA. The optical power of the wavelength conversion signal was detected by an optical power monitor.

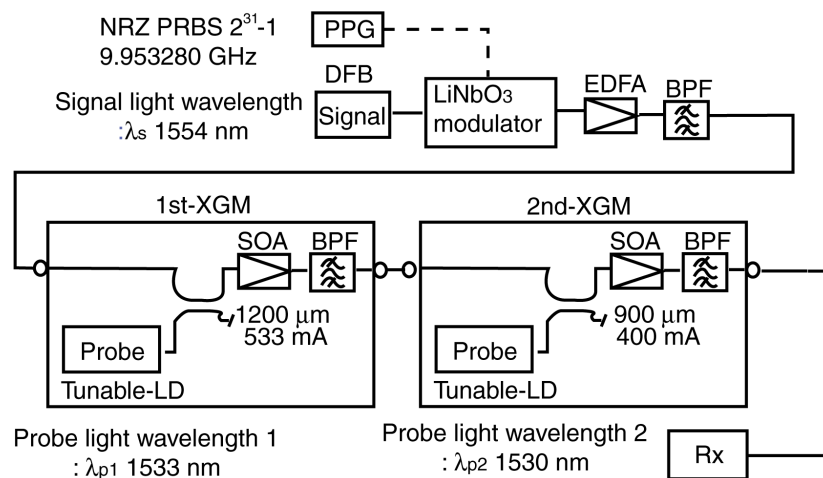


Fig. 4.1 Experimental setup of CGCOR

Figure. 4.2 shows the optical input/output characteristics of a CGCOR. The probe light power at the first wavelength conversion was fixed at -3 dBm. And the probe light power at the second wavelength converter of -8 , -10 , and -12 dBm were selected. As can be seen in the figure, nonlinear characteristic at both low and high level for output light power was achieved. When probe light power at the second wavelength converter is too large, gain saturation effect becomes small. This causes optical nonlinearity at low level to become unclear. In case that probe light power is too small, output power becomes low. In other words, optical gain of the system becomes small. So, the probe light power for the second wavelength converter of around -10 dBm was the optimized value. If the extinction ratio and nonlinearity of a wavelength converter are improved, a larger extinction ratio and sharper nonlinearity performance close to threshold function can be expected.

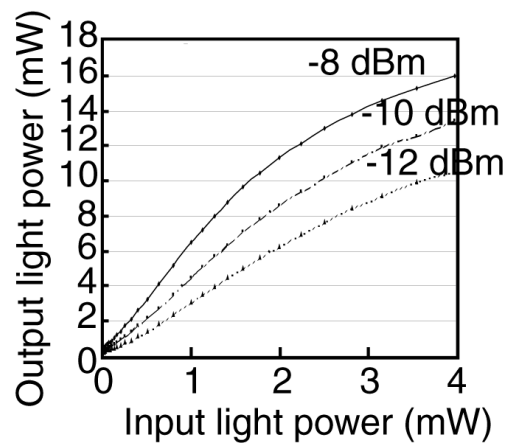


Fig. 4.2 Input/output characteristics of a CGCOR

4.3 Effect of signal regeneration

4.3.1 Dynamic operation performance

Next, the dynamic characteristics and improvement of the received sensitivity by using a CGCOR was investigated.

The experimental setup is the same as that shown in Fig. 4.1. CW light from a DFB-LD was modulated by a LiNbO₃ modulator as the signal light. The signal was 9.95328 Gbps in NRZ format with a $2^{31}-1$ pseudorandom bit sequence (PRBS). The degraded signal was intentionally generated by adding amplified spontaneous emission (ASE) from an erbium-doped fiber amplifier (EDFA) to investigate the noise reduction effect. For this, the average signal power was fixed at as low as -16 dBm and it was amplified with the large optical gain of 23 dB. The amplified signal power was 6.89 mW after passing through an optical band-pass filter. This power was adjusted so that the average signal power was $+3$ dBm at the injection front facet of the first SOA. The probe light power, probe light wavelength and injection current were the same as conditions used for the optical input/output characteristic measurements. Figures 4.3 (a), (b), (c) and (d) indicate the waveforms of the input and output signal lights in case of the second wavelength conversion with probe light power of -8 , -10 and -12 dBm, respectively. Compared to the input signal, the eye pattern of the output signals has opened clearly. And in the case that the second-stage probe light power was -8 dBm, signal '0' level seemed to fluctuate. In the case that the second-stage probe light power was -12 dBm, signal '1' level seemed to fluctuate.

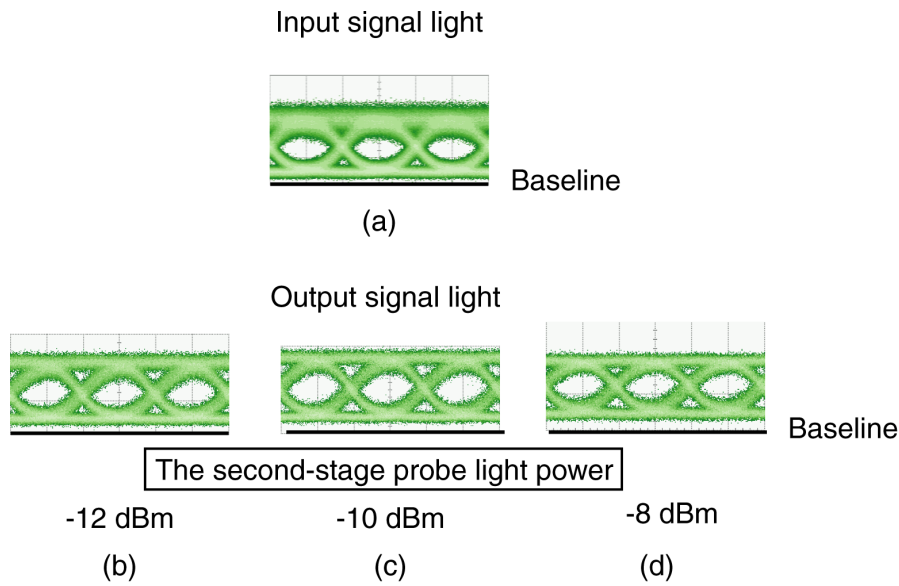


Fig. 4.3 Waveforms of input and output signals

(a) Input signal (b) output signal at -12 dBm second-stage probe light power (c) output signal at -10 dBm second-stage probe light power (d) -8 dBm second-stage probe light power.

4.3.2 Bit error rate measurement

The improvement of the optical received power was verified by performing bit error rate (BER) measurements. Figure 4.4 shows the experimental results. The output signal became error free whereas the error floor was observed for a signal with ASE. In the case that the second-stage probe light power was -10 dBm, the optical received power for output signal at $\text{BER} = 10^{-9}$ was improved by 4.1 dB compared with that for the input signal with ASE noise. We confirmed that the cascaded system has the capability of improving signal quality. The received sensitivity of output signals has dependency on the power of probe light within the range from -8 to -12 dBm. This was considered to be the influence of change of nonlinearity by probe light power. However, we observed the power penalty of 3.7 dB for the output signal power compared with the signal light without ASE. I consider that the noise suppression effect was not

sufficiently large and the output signal transient time between the low and high levels was not sufficiently fast for realizing complete eye opening. In addition, extinction ratio was degraded from 8 dB to 6 dB.

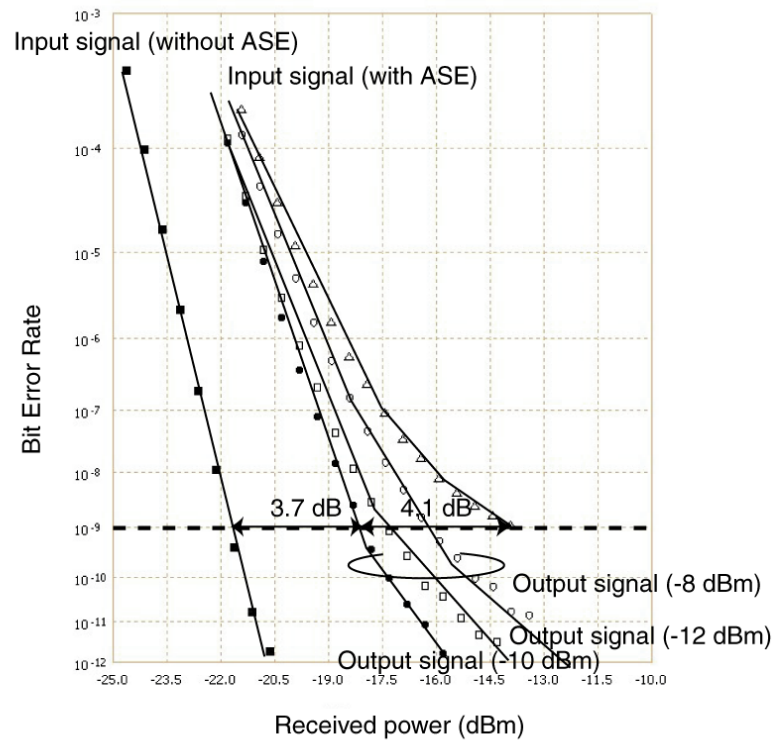


Fig. 4.4 BER results in the case of back-to-back signal without and with ASE, and output signals. The probe light power in the second-stage wavelength converter is used as a parameter.

In this case, the probe light power in the first-stage was fixed at -3 dBm. When the probe light in the first-stage changes, optimal probe light power would be changed.

Figure 4.5 shows the experimental result of other bit error rate measurement in the case of the probe light power in the second-stage XGM wavelength converter was used as a parameter. The probe light power in the first-stage wavelength converter was fixed at 0 dBm, and that in the second-stage wavelength converter was used as a parameter.

The latter was -6, -5, -4 and -3 dBm. In case that the probe light power in the second-stage wavelength converter was -5, -4 and -3 dBm, the negative power penalty of the output signal was obtained whereas error floor was observed for the input signal. The insets in Fig. 4.5 show eye patterns of the input and output signal light in case that probe light power in the second-stage wavelength converter was -4 dBm. Compared to the input signal, eye pattern of the output signal opened clearly. In the case of probe light power of -4 dBm, optical received power at $\text{BER} = 10^{-9}$ was improved by 4.1 dB compared with that for input signal. As can be seen in Fig. 4.5, there exists an optimized probe light power to minimize the optical received power. In case that the probe light power in the first-stage wavelength converter was -6, -3 and +3 dBm, the optimized probe light power in the second stage wavelength converter was -13, -10, and 0 dBm, respectively. The difference of the received power at each optimized condition was within 1 dB.

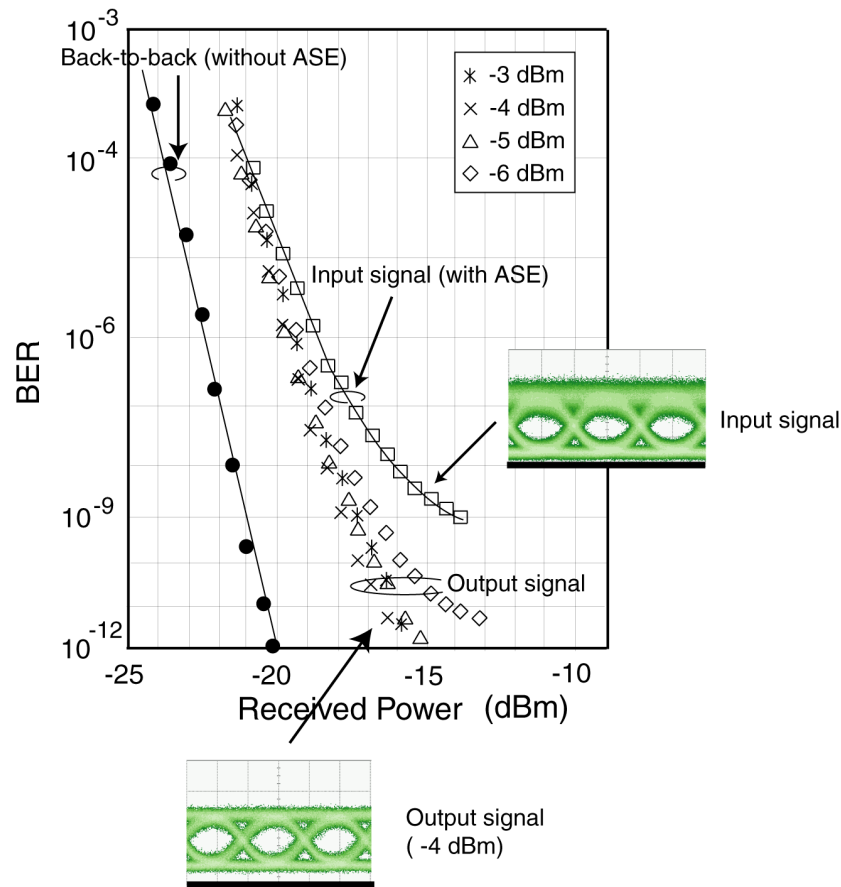


Fig. 4.5 BER results in the case of back-to-back signal without and with ASE, and output signals. The probe light power in the second-stage wavelength converter is used as a parameter.

4.3.3 Relative Intensity Noise measurement

In Section 4.3.2, improvement of received sensitivity could be confirmed. In this Section, the relative intensity noise (RIN) [1] was evaluated to investigate the cause of improvement of optical received power. Experimental setup is shown in Fig. 4.6. In RIN measurements, CW light was used as both signal and probe light. The noise of input and output signal from a CGCOR was detected by GaInAs *p-i-n* photodiode with bandwidth of 25 GHz (New Focus model 1414) and they were measured by using an RF spectrum analyzer (ADVANTEST R3172). In these measurements, the output power was adjusted

by an optical regenerator just in front of the PD to keep input light power received by a PD constant. CW light power was set at +6 dBm as ‘1’ level signal and –10 dBm as ‘0’ level signal, respectively. This power was fixed to use the same condition as BER measurement.

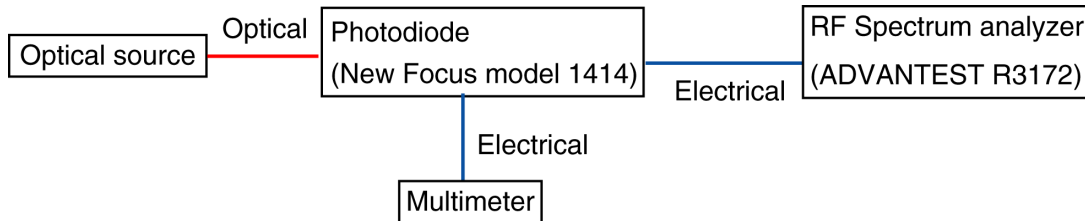


Fig. 4.6 Experimental setup for RIN measurements.

Figures 4.7 (a) and (b) indicate the results of RIN measurements in ‘1’ level and ‘0’ level for input signal and output signal, respectively. In this experiment, probe light power in the first-stage wavelength converter was 0 dBm and probe light power in the second-stage wavelength converter was –4 dBm. RIN suppression between output signal and input signal was observed at both ‘1’ level and ‘0’ level. So, we consider that the reason for improvement of received sensitivity using a CGCOR is caused by RIN suppression.

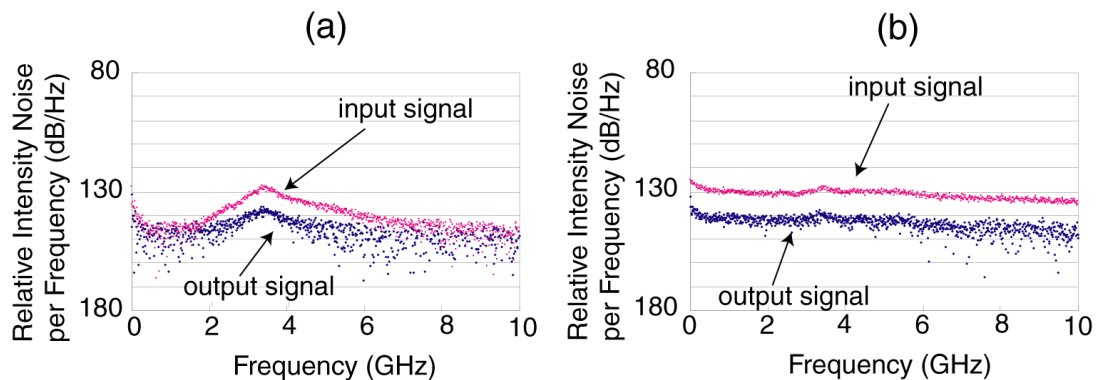


Fig. 4.7 The result of RIN measurements for the input and output signal.

(a) ‘1’ level signal (b) ‘0’ level signal

Figures 4.8 (a) and (b) summarize the dependence of RIN suppression in ‘1’ level and ‘0’ level on the probe light power in the first- and the second-stage wavelength converter, respectively. Probe lights in the first- and the second-stage XGM wavelength converters were used as parameters. Here, RIN suppression is defined as the difference between the peak value of RIN per frequency for output signal and that for input signal. Probe light power in the first-stage wavelength converters were varied from -6 to $+3$ dBm. Probe light power in the second-stage wavelength converter were varied from -14 to 0 dBm. The solid circles represent the optimized probe light power in the second-stage wavelength converter where BER was the best at each probe light power in the first-stage wavelength converter. The numbers on the curve in Figs. 4.8 (a) and (b) indicate the value of RIN suppression with the unit of dB/Hz.

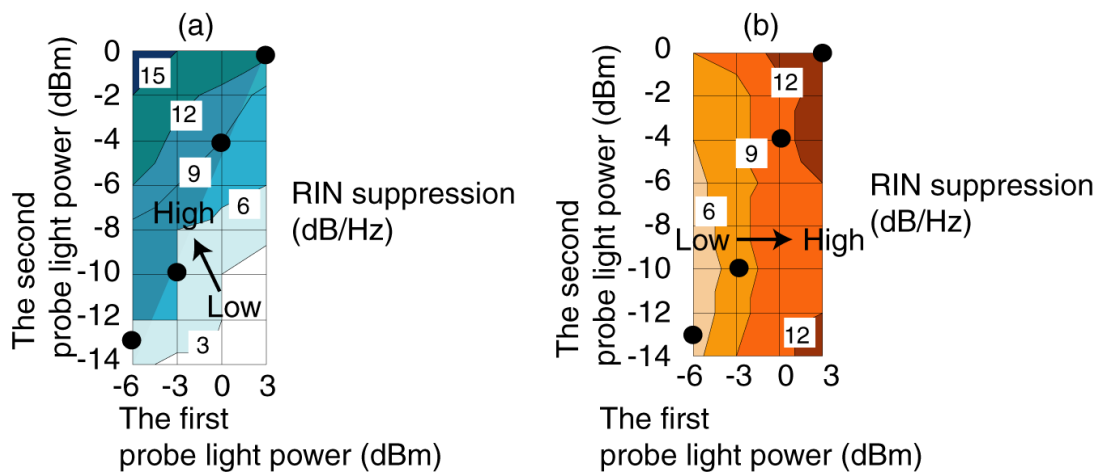


Fig. 4.8 The dependence of RIN suppression on the probe light power in the first- and second-stage wavelength converter.

(a) ‘1’ level signal (b) ‘0’ level signal

At '1' level, the RIN suppression becomes large when the probe light power in the first-stage wavelength converter becomes small and the probe light in the second-stage becomes large. At '0' level, RIN suppression becomes large when the probe light power in the first-stage becomes large. I consider that the main cause of the dependence of the RIN suppression on probe light power is the suppression of carrier density fluctuation in SOA's for wavelength conversion so as not to degrade local CW probe light with low noise characteristics. In case of '1' level, noise is suppressed in the second-stage wavelength converter, because the wavelength converted light in the first-stage wavelength converter, which is injected into the second-stage wavelength converter in low power level. So, small probe light power in the first-stage wavelength converter is effective because the output power is smaller than that for large probe light power and the change of carrier density in the SOA is also small. And large probe light power in the second-stage wavelength converter is also effective because it lowers the initial carrier density due to the stimulated emission and the carrier fluctuation by signal light becomes small. That's why the RIN suppression becomes large towards upper left direction as shown in Fig. 4.8 (a). In case of '0' level, on the other hand, noise is suppressed at the first-stage wavelength converter, because input light power is low originally. It is effective to set large probe light power in the first-stage wavelength converter for suppressing carrier density fluctuation, so the RIN suppression becomes large in the right direction as indicated in Fig. 4.8 (b). As mentioned above, there is trade-off relation for the probe light power in the first-stage wavelength converter between '1' level and '0' level, and this is one of the reason for the optimized condition of the probe light power in the first-stage wavelength converter.

However, the tendency of the optimized conditions in BER measurements (solid

circles in Figs. 4.8 (a) and (b)) cannot be explained completely. Therefore, I paid attention to the extinction ratio as the other dominant factor because the extinction ratio influences signal quality in wavelength conversion based on XGM.

To investigate the effect of the extinction ratio on BER characteristics, it was estimated by it by the eye pattern of the regenerated output signal. The results are shown in Fig. 4.9. The numbers on the curve in Fig. 4.9 indicate the extinction ratio with the unit of dB. The extinction ratio was degraded in spite of the large RIN suppression at upper left area in Fig. 4.8 (a). This is because small output light at '1' level caused by the small probe light and the '0' level signal light at the first-stage wavelength converter can not result in the small '0' level output power at the second-stage wavelength converter. From these results, the optimized probe light power in the first- and the second-stage wavelength converter exists from the upper right to lower left area as shown by the solid circles. I confirmed that the optimized conditions for the probe light power are decided by the extinction ratio as well as RIN suppression in a CGCOR.

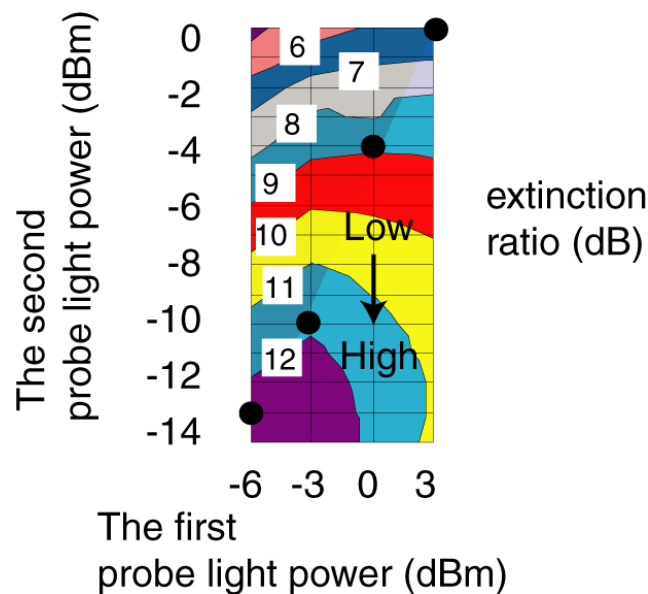


Fig. 4.9 The dependence of extinction ratio on the probe light power in the first- and the second-stage wavelength converter.

4.3.4 Dynamic range

In the previous sections, it was confirmed that a CGCOR had capability of improving received sensitivity. In this Section, dynamic range of a CGCOR, which is one of the main targets in this study, will be investigated.

Experimental set up is the same as that shown in Fig. 4.1. The wavelength for the input light, the probe lights in the first- and the second-stage wavelength converter was 1554, 1533 and 1554 nm, respectively. This indicates the output light wavelength was the same as that of the input signal light. To investigate the capability of optical regeneration by the CGCOR, we performed BER measurements and estimated the improvement of the received sensitivity at the BER of 10^{-9} . Figure 4.10 shows experimental results and waveforms of the input signal with ASE noise and the output signal at input signal power of +4 dBm from the CGCOR. Average input light power of -0.5, +4 and +5.5 dBm was used as a parameter. The probe light power in the first- and the second-stage wavelength converter was fixed at -3 and -12 dBm, respectively. As shown in the inset in Fig. 4.10, the eye pattern of the output signal opened clearly compared to the input signal. Minimum power penalty was obtained at average input signal power of +4 dBm. In this case, the received sensitivity was improved by 1.7 dB from that for the input signal with ASE. Here, power penalty is defined as the difference of the received optical power at $\text{BER}=10^{-9}$ between output signal and input signal without ASE. We observed the negative power penalty of the output signal at each condition whereas error floor was observed for input signals. I also observed that the minimum power penalty was 2 dB. We consider that the power penalty results from the degradation of the extinction ratio, especially from shorter to longer wavelength conversion like the second-stage wavelength converter. I expect that the decrease of

power penalty could be achieved by improving extinction ratio in a wavelength converter.

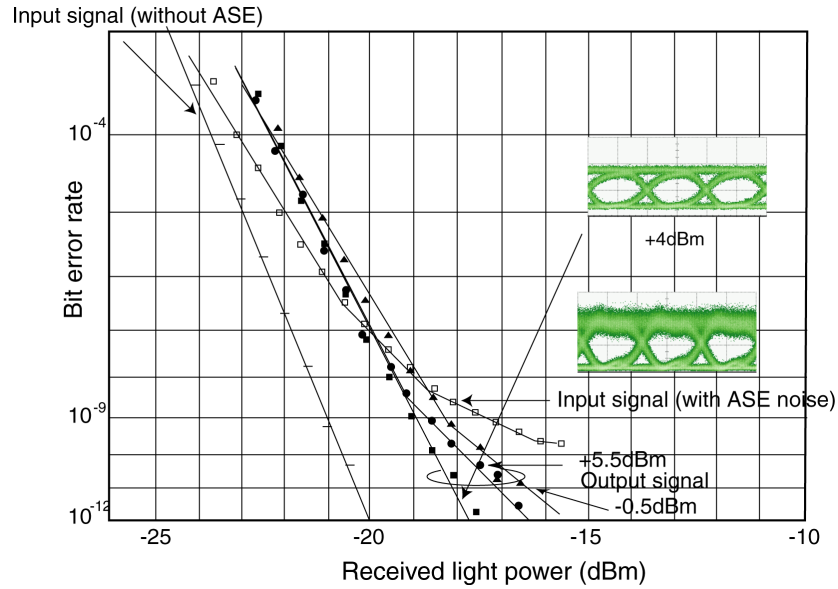


Fig. 4.10 The results of BER measurement for input and output signal from CGCOR. The insets are eye patterns of input signal with ASE and output signal at average input signal power of +4 dBm. Input power of -0.5, +4 and +5.5 dBm are used as a parameter.

Then we estimated the power penalty from the BER results as a function of input light power, and investigated the dynamic range in input light power. The dynamic range is defined as the range of input light power satisfying the difference of the power penalty for the output light from the CGCOR below 1 dB from the minimum power penalty. The results are indicated in Fig. 4.11. In this figure, horizontal solid line indicates the level of the power penalty difference from the minimum value of 1 dB, and horizontal dashed line shows the power penalty level of the input signal with ASE. First, The probe light power was fixed and it was the same condition as for Fig. 4.10. In case that the input signal power was varied from -0.5 to +5.5 dBm, power penalty difference was below 1 dB, and the dynamic range in input light power was 6 dB. In case that input signal power was from -1.5 to +6.5 dBm, the received sensitivity was improved

within the range of 8 dB in comparison with the input light with ASE.

Under the optimized condition of probe light power for each input light power in the first-stage wavelength converter, input signal dynamic range extended over 11 dB as shown by the dotted line in Fig. 4.11. Probe light power in the first-stage wavelength converter was changed from -12 to $+3$ dBm. Probe light power in the second-stage wavelength converter was fixed in order that output signal power from the CGCOR kept constant. The highest input light power limit could not be estimated due to the limit of the experimental setup.

This dynamic range is limited by signal quality of the output signal from a CGCOR. As shown in Section 4.3.3, suppression of the relative intensity noise (RIN) and extinction ratio are the dominant factors for the optimized condition for a CGCOR. Therefore, we consider that they limit the dynamic range in input light power. Fig. 4.12 shows results of RIN measurement against input signal light power. From RIN measurement, we confirmed that, in case that input signal power was -0.5 dBm, which is the low limit of the dynamic range, RIN suppression was weak at '1' level. In case that input signal power was $+5.5$ dBm, which is the high limit of dynamic range, RIN suppression was weak at '0' level. On the other hand, extinction ratio of the output signal was almost the same when input signal power range was from -0.5 to $+5.5$ dBm. Figures 4.13 (a) and (b) show waveforms of output signal at average input signal power of -0.5 and $+5.5$ dBm, respectively. Thus we consider that the limit of low and high input light power is restricted by the degradation of noise suppression effect in '1' level and '0' level in signal, respectively.

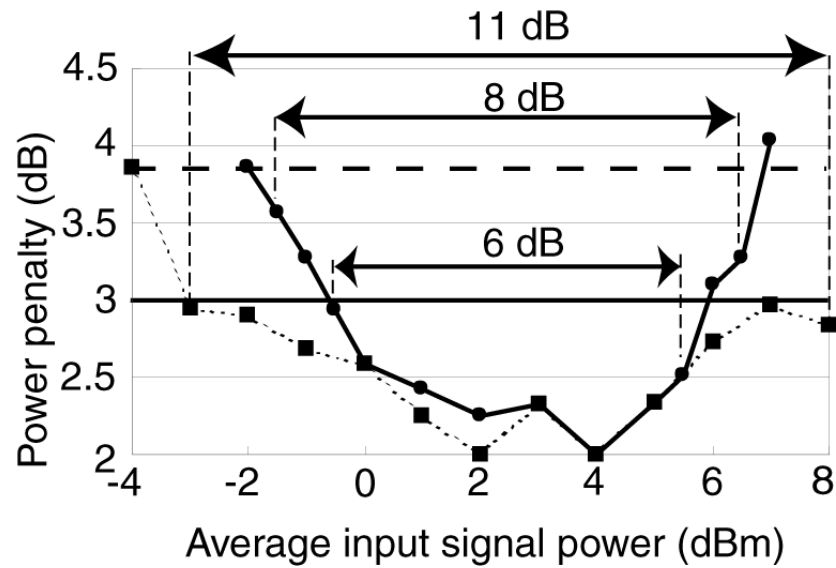


Fig. 4.11 Power penalty of the optical regenerator as a function of average input signal power. The results under the fixed and the optimized probe light power conditions were shown by solid circles and solid rectangles, respectively.

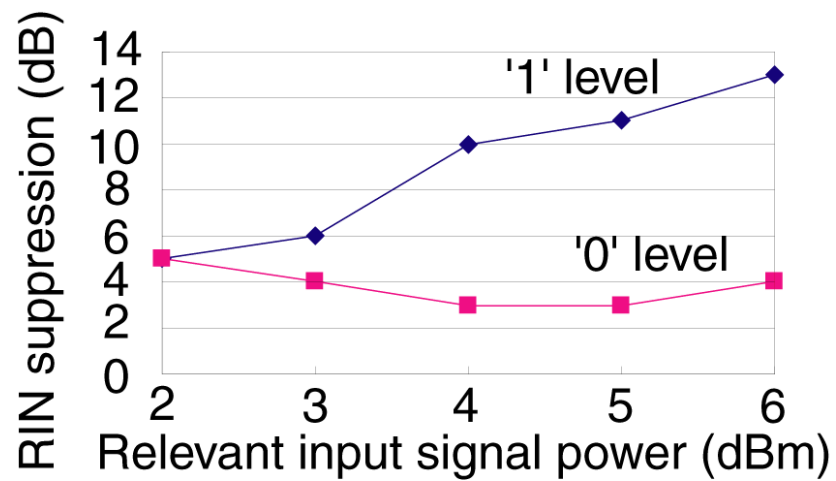


Fig. 4.12 RIN suppression as a function of relevant average input signal power.

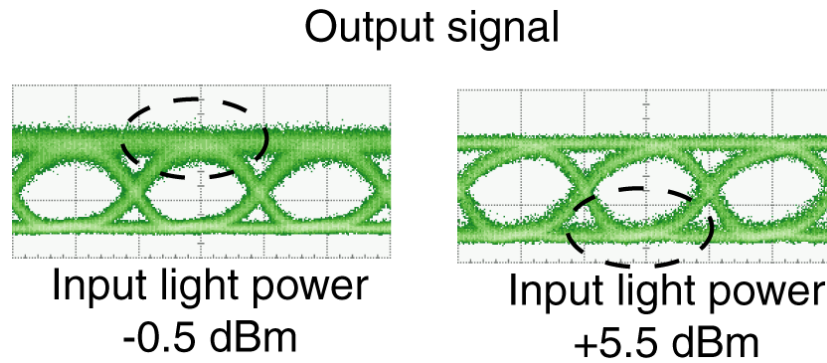


Fig. 4.13 Eye patterns of output signal at average input signal power of -0.5 and $+5.5$ dBm.

4.4 Novel function of a CGCOR by using sinusoidal probe light

In Section 4.3, a CGCOR was investigated from several viewpoints and improvement of received sensitivity could be confirmed. But waveform distortion by pattern effect is one of the big issues, because carrier recovery time of a SOA is slow.

Moreover, many techniques of all-optical modulation format conversion between RZ and NRZ were reported for the purpose of application of future all-optical networks [3].

Therefore, in this section, I propose and demonstrate the improvement of a pattern effect and modulation format conversion from RZ to NRZ by using sinusoidal probe light for a CGCOR. These two effects can be selected by changing offset between signal and probe light timing.

Figure 4.14 shows the principle of improvement of pattern effect and format conversion. We use small sinusoidal modulated probe light in the first-stage wavelength

converter. The modulation frequency was the same as that of the input signal. To suppress pattern effect, peak of the sinusoidal wave is shifted ahead of the signal peak as shown in Fig. 4.14. The leading and trailing portion of the sinusoidal probe light partly overlap those of the first-stage wavelength conversion light so that the sinusoidal probe light make the rise and fall time of the first-stage wavelength conversion light faster in appearance. The faster rise and fall time improve pattern effect because one of the causes of pattern effect is slow rise time of the first- and the second-stage wavelength converters resulted from long recovery time of carrier density.

In RZ – NRZ format conversion, peaks of the sinusoidal wave is adjusted to that of input signal. In this situation, signal ‘0’ level of the first-stage wavelength conversion light extends in the whole time slot. Amplification of the probe light is cancelled by gain reduction due to XGM by signal light injection, so low power region corresponding signal ‘0’ level extends.

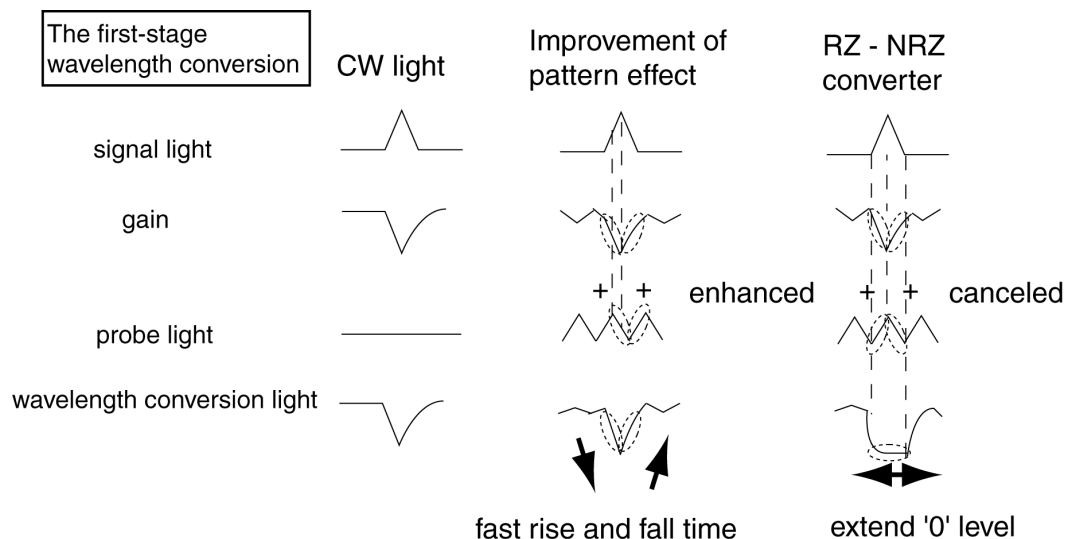


Fig. 4.14 Principle of improvement of pattern effect and modulation format conversion in CGCOR.

Figure 4.15 shows the experimental setup. The architecture of an optical regenerator is basically the same as that of a CGCOR, and it consists of two-stage wavelength converters based on XGM in SOA's.

Signal with 9.95328 Gbps, RZ format was used. The wavelength for the input light, the probe light in the first- and the second-stage wavelength converter were 1554, 1533 and 1530nm, respectively. The probe light in the first-stage wavelength converter was modulated in sinusoidal waveform by an electroabsorption modulator (EAM). Electrical clock was supplied from pulse pattern generator. The CW probe light was used in the second-stage wavelength converter. Average power of the input light, the first- and the second-stage probe light were 0, -1 and -10 dBm, respectively. The extinction ratio of the sinusoidal probe light in the first-stage wavelength converter was 3 dB. The cavity length and bias current for the SOA in the first-stage wavelength converter were 1200 μm and 533 mA, respectively. Those for the SOA in the second-stage wavelength converter were 900 μm and 400 mA.

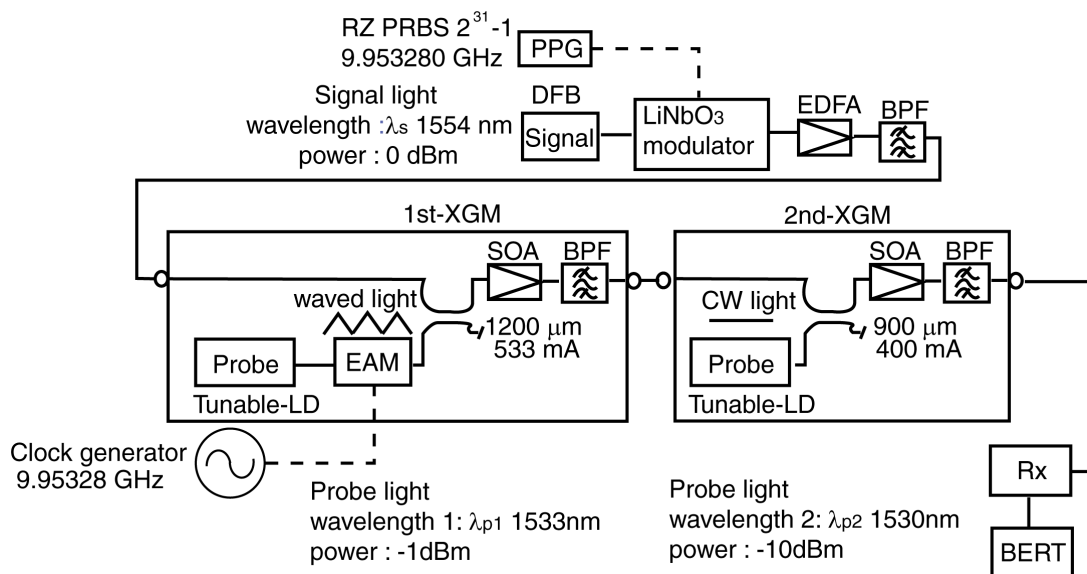


Fig. 4.15 Experimental setup for improvement of pattern effect and modulation format conversion in CGCOR.

We observed the output waveforms and measured bit error rate of output signal. Figure 4.16 shows the experimental results. For suppression of pattern effect, the peak of sinusoidal probe light was about 19 ps ahead of the input signal peak. Improvement of pattern effect for the RZ-like output signal compared to output signal with CW probe light was observed at the boundary of time slot. For RZ-NRZ conversion, on the other hand, the peak of the probe light was nearly adjusted to the input signal peak. The NRZ-like waveform was obtained as shown in the inset in Fig. 4.16. And no degradation by using sinusoidal probe light was observed because no noticeable difference of received power between CW probe and sinusoidal probe light.

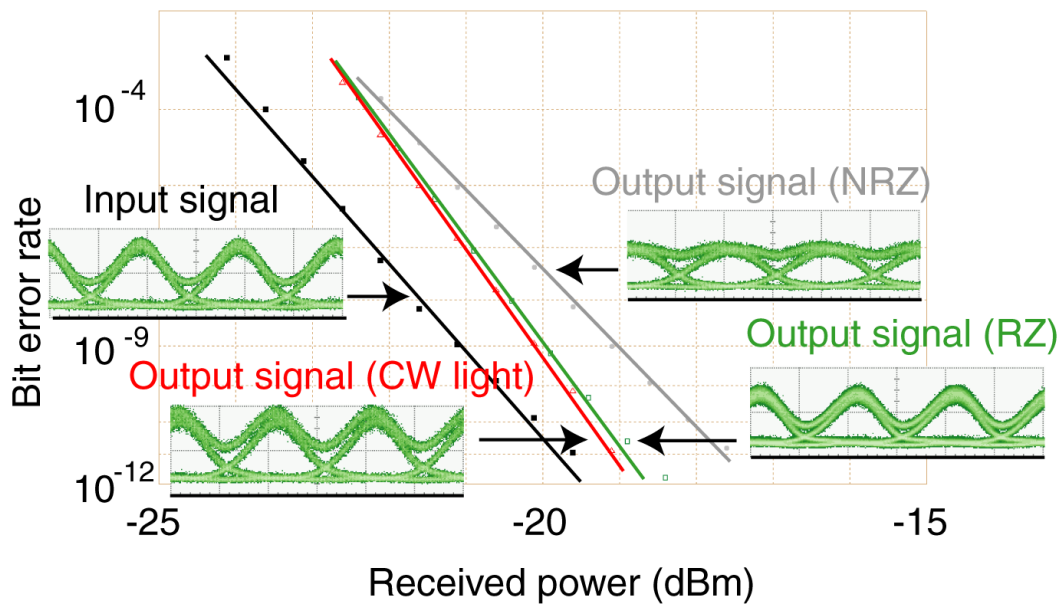


Fig. 4.16 The results of bit error rate measurement.

We also investigated the power penalty against offset between signal and the first-stage probe light. Figure 4.17 shows the experimental results. Power penalty is defined as the difference of the received optical power at $\text{BER}=10^{-9}$ from the RZ-like output signal. Less than 1 dB power penalty was observed when input signal was input about 20 ps ahead or behind the optimized condition.

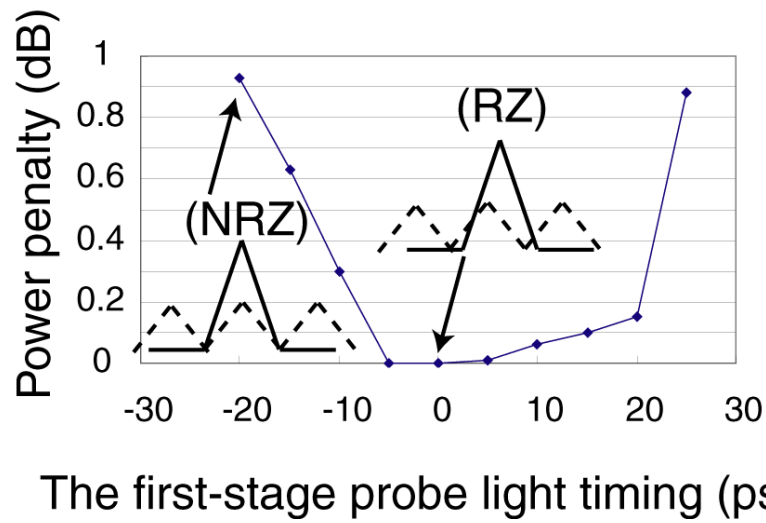


Fig. 4.17 Power penalty against the first-stage probe light timing.

4.5 Summary

In summary, the characteristics of a CGCOR such as input/output characteristics, signal regeneration performance and dynamic range were investigated experimentally. In input/output characteristics, nonlinearity was observed. As a result, optical received power at $\text{BER} = 10^{-9}$ was decreased by 4.1 dB from degraded input signal, in the case that the first- and second-stage probe light power was -3 and -10 dBm, respectively. The cause of improvement of received sensitivity was the noise suppression effect. This was estimated by RIN measurements. Then, it was confirmed the optimized conditions were dominated by both RIN suppression and extinction ratio. Moreover, dynamic range in input light power by a CGCOR was investigated. The dynamic range in input light power of 6 dB was achieved. And the received sensitivity was improved within the range of 8 dB in comparison with the input light. In addition, input signal dynamic range was over 11 dB under the optimized probe light conditions. These indicate the CGCOR has the capability of operating in wide range of input signal light power. In addition, novel function by using offset scheme of sinusoidal probe light for a CGCOR was proposed and investigated improvement of pattern effect and modulation format conversion from RZ to NRZ. As improvement of pattern effect, No degradation by using sinusoidal probe light was observed between both output signals using CW probe and sinusoidal probe. These two effects were switched only by the offset between the sinusoidal probe light in the first-stage wavelength converter 20 ps. Moreover, little power penalty was observed within ± 20 ps offset.

A CGCOR has large dynamic range and large noise suppression effect. I consider that a CGCOR is applicable in the situation that signal with large noise and the number of optical regenerators and transmission distance are limited.

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Chapter 5

Modeling of a XGM gain-control-type optical regenerator

5.1 Introduction

In Chapter 3 and 4, operation performance of a CGCOR was investigated numerically and experimentally, and nonlinearity in input/output characteristics, improvement of received sensitivity and 6 dB dynamic range have been achieved. However, The issues of degrading extinction ratio and frequency chirping in a CGCOR remain. That is, (1) extinction ratio and (2) frequency chirping degradation causes power penalty against low-noise signal, and frequency chirping results in waveform distortion by wavelength dispersion of optical fibers. Therefore, it is necessary to have not only nonlinearity in input/output characteristics to enlarge dynamic range, but also high extinction ratio and low frequency chirping. To improve characteristics of all-optical regenerators, other type of an optical regenerator consisting of a wavelength converter based on XGM and a gain saturated SOA is proposed and investigated.

First, the principle of a novel optical regenerator, which is named a XGM gain-control-type optical regenerator, is explained. Next, by using SOA model based on

transfer matrix method, the investigation of input/output characteristics and the performance of an optical regenerator by calculation is described. Then, a novel approach to lower the effect of frequency chirping is investigated. The method of filter detuning and injection timing offset into a gain saturated SOA between original signal and XGM signal. And transmission characteristics using these methods is discussed.

5.2 Principle of a XGM gain-control-type optical regenerator

The proposed optical regenerator consists of a wavelength converter based on XGM and a gain saturated SOA. Figure 5.1 shows a schematic view of a XGM gain-control-type optical regenerator and principles of realizing nonlinearity in input/output characteristics. At first, signal light is divided into two. One of them is used for wavelength conversion based on XGM to generate logically inverted signal light. This XGM light is injected into a gain-saturated SOA at almost the same timing. ‘1’ level of input signal with high power is input into a SOA together with ‘0’ level of XGM signal with low power, and ‘0’ level of input signal with low power is input into a SOA together with ‘1’ level of XGM signal with high power. In this method, either signal or XGM signal has high intensity at all time and it is in gain saturation regime. The similar configuration was successfully done as an optical power equalizer, in which a gain saturated SOA and the inverted-mode signal as a burst-mode limiting amplifier and to reduce the pattern effect, respectively, and power dynamic range of 8 dB was achieved [1]. By injecting original signal and additional XGM signal at the same time, fluctuation of carrier density in this method could be less than that in the case of

conventional gain saturation.

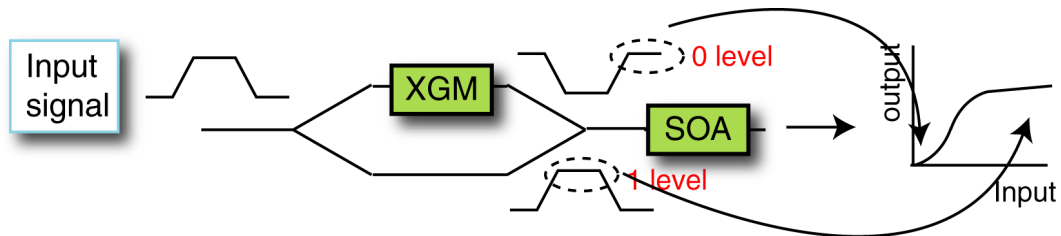


Fig. 5.1 The schematic view of a XGM gain control type optical regenerator.

However, frequency shift from blue-chirp to red-chirp is still observed at the leading edge and the trailing edge of output signal.

In order to suppress the effect of frequency chirping, filter detuning method [2]-[6] and timing offset method [7] are introduced. Figure 5.2 shows their principle. By inputting signal slightly earlier than the XGM signal to a gain saturated SOA, red-chirp portion moves from the trailing edge to low power side because increase of total input signal occurs later than the trailing edge of input signal and subsequent carrier density change is caused after the trailing edge of input signal. In addition, by detuning the center wavelength of a band pass filter toward shorter wavelength, the power of red-chirp component can be reduced. By these two schemes, frequency chirping can be suppressed, and improvement of transmission characteristics can be expected.

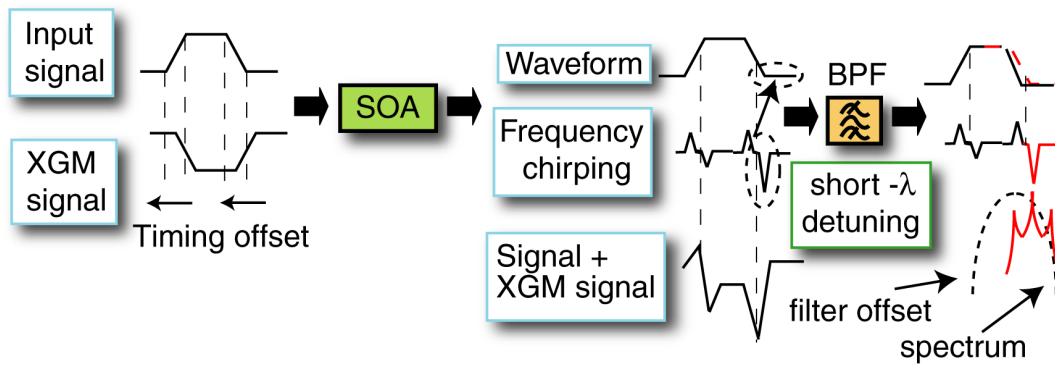


Fig. 5.2 The principle of the frequency chirping control method.

5.3 Input/output characteristics

To realize an optical regenerator, nonlinear input/output characteristics is necessary. To investigate input/output characteristics of a XGM gain-control-type optical regenerator, operation performance was calculated using the SOA model. The SOA model is the same model using in Chapter 2 and Chapter 3 and using time-dependent transfer matrix method to solve Eqns. (2.4)-(2.12). Figure 5.3 shows the calculation result of input/output characteristics. Signal with 10 Gbps, NRZ format was used. The wavelength for the input, and the probe light in the wavelength converter were 1554 and 1535 nm, respectively. Average power of the input light at the XGM SOA are 5 dB larger than the power of the input light at the gain saturated SOA. The probe light power for the XGM SOA was -4 dBm. The cavity length and bias current of the SOA in the wavelength converter were 1500 μm and 650 mA, respectively. Those of the gain saturated SOA were 900 μm and 400 mA. As can be seen in Fig. 5.3, nonlinear characteristics could be obtained at both low power region of less of than 0.05 mW, and at high power region of more than 0.2 mW.

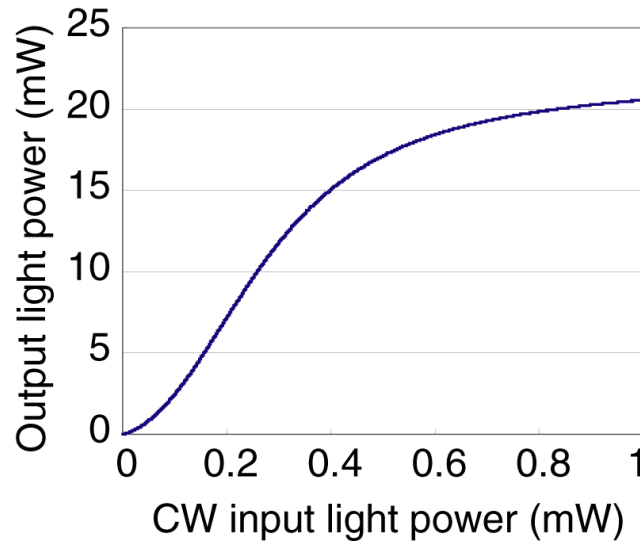


Fig. 5.3 Calculation result of input/output characteristics.

5.4 Effect of signal regeneration

In Section 5.3, it was verified that XGM gain-control-type optical regenerator has nonlinear characteristic at both low and high power region. Then, performance of XGM gain control type optical regenerator was investigated. Figures 5.4 (a), (b), (c) and (d) show input and output signal waveform in the case of using XGM gain control light, CW control light and input signal only, respectively. In Fig. 5.4 (b), the input signal was modulated at a bit rate of 10 Gbps and 7-stage PRBS in NRZ format. The wavelength for the input, and the probe light in the wavelength converter were 1554 and 1540 nm, respectively. Average power of the input light at the XGM SOA and a gain saturated SOA were -1 and -6 dBm, respectively. The probe light power for the XGM SOA was -4 dBm. The cavity length and bias current of the SOA in the wavelength converter

were 1500 μm and 650 mA, respectively. Those of the gain saturated SOA were 900 μm and 400 mA, respectively. In Fig. 5.4 (c), CW control light was injected into a gain saturated SOA. CW control light power was set at 3.25 mW as peak power of XGM gain control light. Other parameters were the same as the case of Fig. 5.4 (b). In Fig. 5.4 (d), only signal light was injected into a SOA. The input signal power was -11 dBm. Other parameters were the same as the case of Fig. 5.4 (b). As can be seen in Fig. 5.4 (b), clearly eye opening was achieved although slight overshoot was seen. In addition, extinction ratio of the output signal was almost the same as that of the input signal. To compare the case of Fig. 5.4 (b) with the case of Fig. 5.4 (c), the method using XGM gain control light could increase output power of signal '1' level because total input power is lower and the optical gain is larger. Moreover, in the case of using CW control light, extinction ratio decreases because SOA gain for signal '1' level is smaller than that of '0' level caused by gain saturation. As can be seen in Fig. 5.4 (d), without any control light, signal light of -11 dBm causes strong waveform distortion by gain saturation. Therefore, XGM gain control light is considered to be effective to suppress carrier fluctuation.

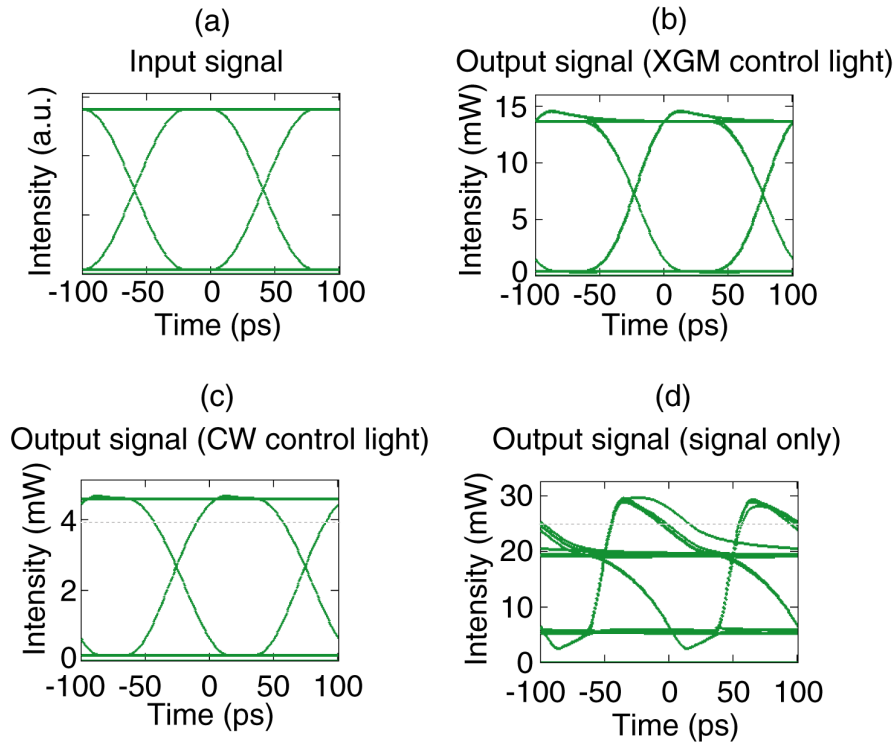


Fig. 5.4 Calculated eye patterns of input and output signals. (a) input signal (b) output signal in the case of using XGM control light (c) output signal in the case of using CW control light (d) output signal in the case of signal light only

To observe the effect of XGM gain control signal, Fig. 5.5 shows progression of the two optical signals along a SOA. Carrier density in a SOA was also shown. The lights and carrier density obtained at one-third, two-thirds and the end of a SOA were indicated in these figures. At the front end, when signal '1' level was injected into a SOA, XGM signal suppresses the carrier density change because extinction ratio of XGM signal was low and XGM signal with low power is added. Suppression of carrier density change helps to avoid overshoot of signal light. At one-third, carrier density increases with decreasing XGM signal. This is because power of XGM signal was higher than power of signal light. The refractive index in a SOA increases with decreasing carrier density. Therefore, the refractive index increases with increasing

input signal at the front side of a SOA. When two signals propagate along a SOA, the change of the signal light power dominates the change of carrier density at the two-thirds. This is because the gain of signal light is larger than the gain of XGM signal light because the wavelength of signal is longer than XGM signal light. At the backside, the refractive index decreases with increasing signal power opposite the case of the front side. In this way, the change of refractive index balances between at the front side and backside. And, this is considered to be one of the reason to suppress frequency chirping.

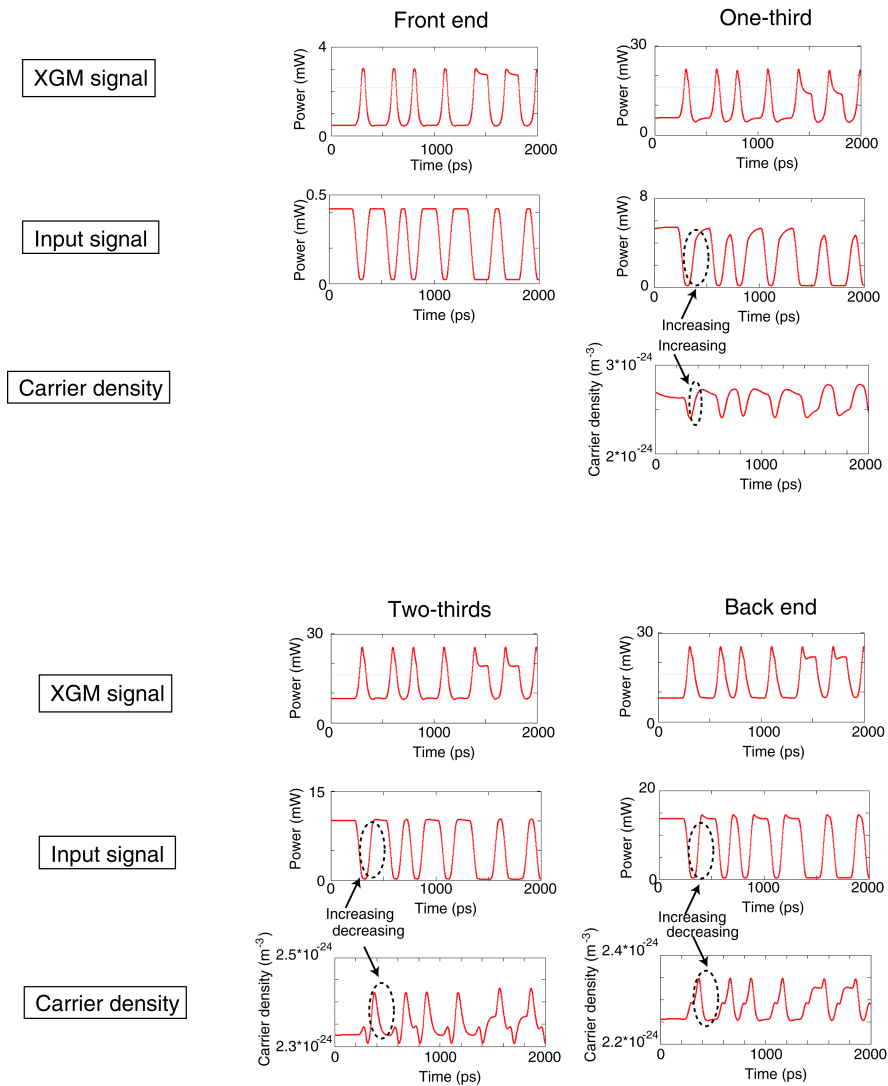


Fig. 5.5 SOA dynamic response at front end, one-third, two-third and back end

To investigate signal regeneration performance of a XGM gain-control-type optical regenerator, dynamic operation with power fluctuated input signal was calculated by solving SOA model. Figures 5.6 (a) and (b) show the input and output signal waveforms, respectively. The parameters such as input signal power, wavelength and so on, were the same as the case of Fig. 5.4 (b). The way how to include noises were described in Section 3.4. As can be seen in Figs. 5.6, noise level of output signal can be suppressed compared with input signal.

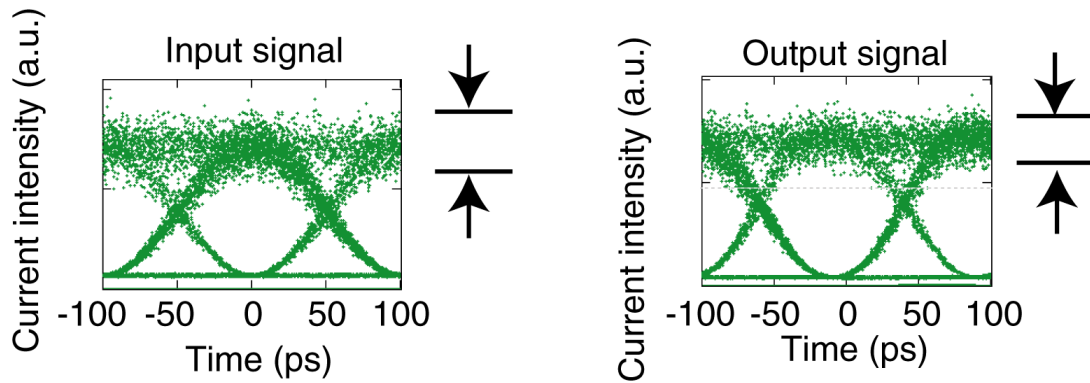


Fig. 5.6 Calculated eye patterns of input and output signals. (a) input signal (b) output signal

5.5 Effect of filter detuning and timing offset scheme

In the case of a CGCOR, transmission distance is limited by large frequency chirping, which occurs waveform distortion caused by wavelength dispersion. To lower the effect of frequency chirping, the filter detuning scheme and the timing offset scheme are introduced. In this Section, improvement of transmission characteristics is investigated by calculation. The calculation SOA model based on transfer matrix method takes the phase of signal and probe lights into consideration. Thus it is possible to investigate these schemes in frequency domain.

5.5.1 Effect of filter detuning

To reduce the power of frequency chirped component, the filter detuning scheme was investigated. In this Section, the calculation using SOA model based on transfer matrix method and filter profile is done to evaluate their effect.

The parameters used in this calculation was the same as the case in Section. 5.3. Here, phase of output signal light was also calculated. Then optical field of output signal was represented as the following equation.

$$E_{output}(t) = \sqrt{P_{output}(t)} \cdot \exp[-i\phi(t)] \quad (5.1)$$

where E_{output} is the optical field of output signal, P_{output} is the power of output signal and ϕ is the phase of output singal. By using Fourier-transformation, the spectrum of output signal is obtained from Eqn. (5.1).

Filter profile is simply assumed super-Gaussian as depicted in the following.

$$f(\lambda) = \frac{1}{\sqrt{2\pi} \cdot \sigma} \cdot \exp\left[-\frac{(\lambda - \mu)^2}{2\sigma^2}\right]^3 \quad (5.2)$$

where μ and σ are the mean value and variance, respectively.

The filter profile of the calculation model and filter of an actual use for experiment are shown in Fig. 5.7. In this case, μ and σ are 1553.57 nm and 0.40622, respectively. As can be seen in Fig. 5.7, good approximation was obtained. Therefore, I used this function for evaluation of the filter detuning scheme.

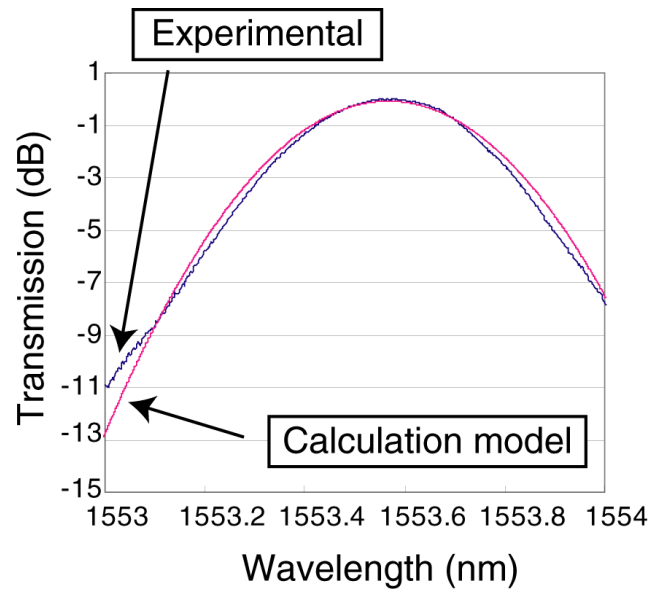


Fig. 5.7 Wavelength profile of calculation model and experimental filter.

Then, the optical field through the filter $E_{filter\ detuning}$ in frequency domain is represented by the next equation.

$$E_{filter\ detuning}(\lambda) = E_{output}(\lambda) \cdot f(\lambda) \quad (5.3)$$

and the optical field through the filter in time domain is obtained by using inverse Fourier transform.

Here, filter detuning is defined as

$$\Delta\lambda = \lambda_{filter} - \lambda_o \quad (5.4)$$

where λ_{filter} is the transparency center wavelength of the filter and λ_o is the wavelength of the output light. The direction of plus is defined as a longer wavelength side.

Figure 5.8 (a) shows the optical spectra of input and output signal. Input signal was

assumed to be a transform-limited pulse. Figure 5.8 (b) shows spectrums of filtered output signals, and filter wavelength at center, -0.3 nm detuning and +0.3 nm detuning was used as a parameter. In Fig. 5.8 (a), the spectrum of the output signal broadened by comparison with input signal. In Fig. 5.8 (b), the cutting of spectrum by filtering was observed. Next, by using inverse Fourier transform for these spectra, the effect of filter detuning on waveform was investigated.

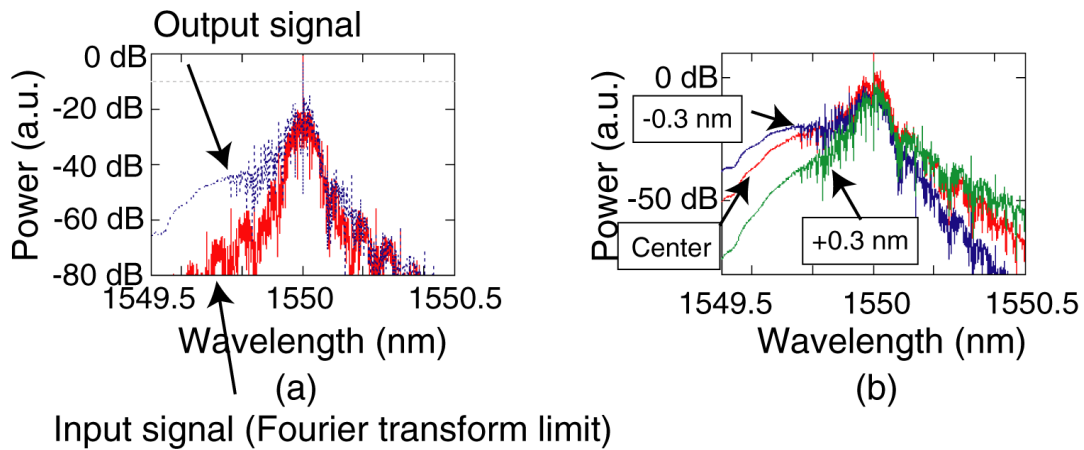


Fig. 5.8 Spectrum of signals. (a) Spectrum of input and output signals (b) spectrum of filtered output signals. The filter wavelength at center wavelength, -0.3 nm detuned and +0.3 nm detuned was used as a parameter.

Figure 5.9 (a) shows waveforms of filtered output signals. The output waveforms in case of filter wavelength at output signal wavelength, -0.3 nm detuning and $+0.3$ nm detuning were evaluated. Figure 5.9 (b) shows frequency chirping of the output signal. By ± 0.3 nm filter detuning, output power was attenuated to about half. When the filter wavelength shifted toward 0.3 nm shorter wavelength than the output signal wavelength, the rise time and fall time become faster. On the other hand, in case of 0.3 nm longer wavelength detuning, rise time and fall time become longer. From Fig. 5.9 (b), in this condition, blue-chirp was occurred at the leading edge, and red-chirp was occurred at the trailing edge. Therefore, shorter wavelength detuning increased the power at leading edge and decreased the power at leading edge. This helped rise and fall time became faster.

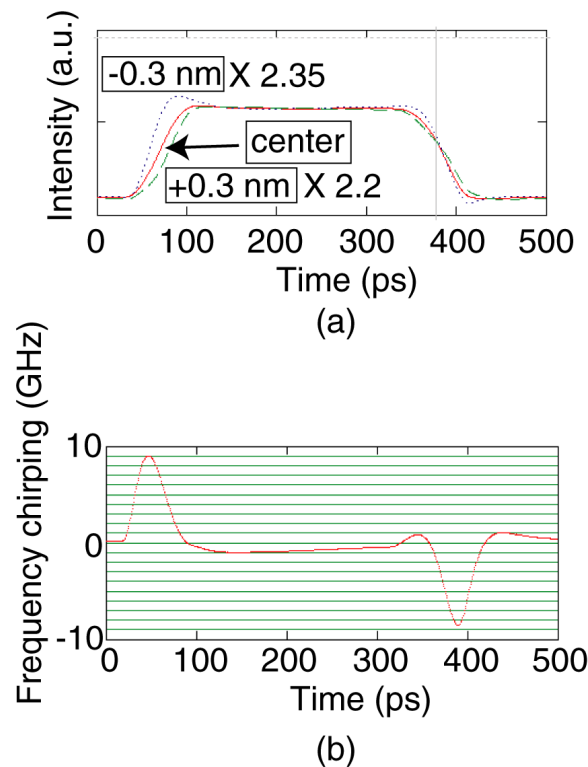


Fig. 5.9 Spectrum of signals. (a) Spectrum of input and output signals (b) spectrum of filtered output signals. The filter wavelength at center, -0.3 and $+0.3$ nm was used as a parameter.

5.5.2 Effect of timing offset between input signal and XGM signal

To shift the red chirp component into the region that is lowering the effect of the frequency chirping, the timing offset scheme was proposed. The red chirp component is caused by increasing XGM signal, from trailing edge to low power side. To investigate the effect of the timing offset scheme, the operation of a XGM gain-control-type optical regenerator was calculated.

In this, timing offset is defined as

$$\Delta t = t_{XGM} - t_{signal} \quad (5.5)$$

where t_{signal} is the injection timing of signal light for a SOA and t_{XGM} is the injection timing of XGM signal light for a SOA. The direction of plus means that the signal is ahead of XGM signal.

Calculation results of the chirping characteristics are shown in Figs 5.10 (a), (b) and (c) in the case of offset 0, +21 ps and +27 ps, respectively. In Figs 5.10, each solid circle indicates the data point at which the chirp was 0. In the case of ‘offset 0’, large red-chirp occurred at the trailing edge of output signal. Here, at the trailing edge, blue-chirp and red-chirp are induced by decreasing the input signal and increasing the XGM signal. In the cases of timing offset +20 ps and +27 ps, it was observed that red-chirp component moved to low power region. By inputting signal slightly earlier than the XGM signal, red-chirp moved from the trailing edge to low power side, so the effect of wavelength dispersion becomes small. This method is expected to improve transmission distance caused by frequency chirping in a gain saturated SOA.

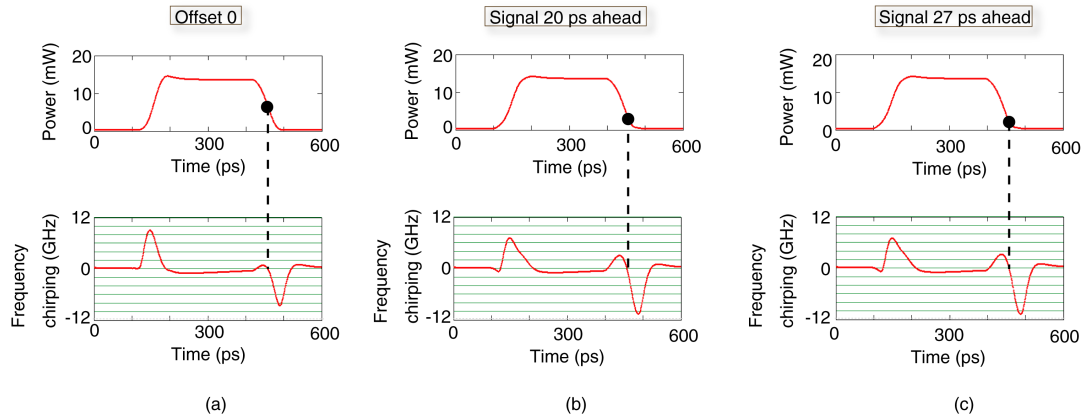


Fig. 5.10 Waveforms and frequency chirping. (a) the case of offset '0' (b) the case of signal 20 ps ahead (c) the case of signal 27 ps ahead

5.6 Transmission characteristics

Frequency chirping in optical signal affects waveform in signal transmission due to wavelength dispersion. Waveform distortion by wavelength dispersion limits the transmission distance of optical communication. A XGM gain-control-type optical regenerator has been investigated to realize optical regeneration for suppressing the influence of frequency chirping. In this Section, transmission characteristics of output signal from XGM gain-control-type optical regenerator by using the filter detuning and the timing offset schemes are investigated. The waveform of signal after fiber transmission was calculated.

In fiber transmission, only second order group velocity dispersion (GVD) was taken into consideration. By using Fourier-transformation, the optical field of signal in frequency domain was obtained. In this, transfer function of optical fibers $H(\omega)$ is described simply as below.

$$H(\omega) = \exp \left[-i \cdot \frac{\beta_2 \cdot L}{2} \cdot (\omega - \omega_c)^2 \right] \quad (5.6)$$

with

$$\beta_2 = \frac{D \cdot \lambda_c \cdot 10^{-6}}{2\pi \cdot c} \quad [\text{ns}^2/\text{km}] \quad (5.7)$$

where D is the dispersion parameter [ps/nm/km], λ_c is the carrier wavelength, L is the transmission distance and $\omega_c = 2\pi c/\lambda_c$ is carrier angular frequency. Thus the optical field after the transmission $E_{\text{transmission}}$ in frequency domain is represented by next equation.

$$E_{\text{transmission}}(\varpi) = H(\varpi) \cdot E_{\text{output}}(\varpi) \quad (5.8)$$

and by using inverse Fourier transform, the optical field after the transmission in time domain is obtained.

Calculation results of waveform change after fiber transmission are shown in Figs. 5.11 (a) to (c) in the case of offset '0', +20 ps and +27 ps, respectively. In these calculations, single mode fibers were assumed, and dispersion parameter was set at 16 ps/nm/km, to consider single mode fiber. In all cases, waveforms became distorted along fiber transmission. In the case of Fig. 5.11 (a), eye was closed at 40 km transmission. In the cases of Figs. 5.11 (b) and (c), on the other hand, eye patterns were still opened after 40 km. Therefore, lower waveform distortion due to waveform dispersion by using timing offset can be expected.

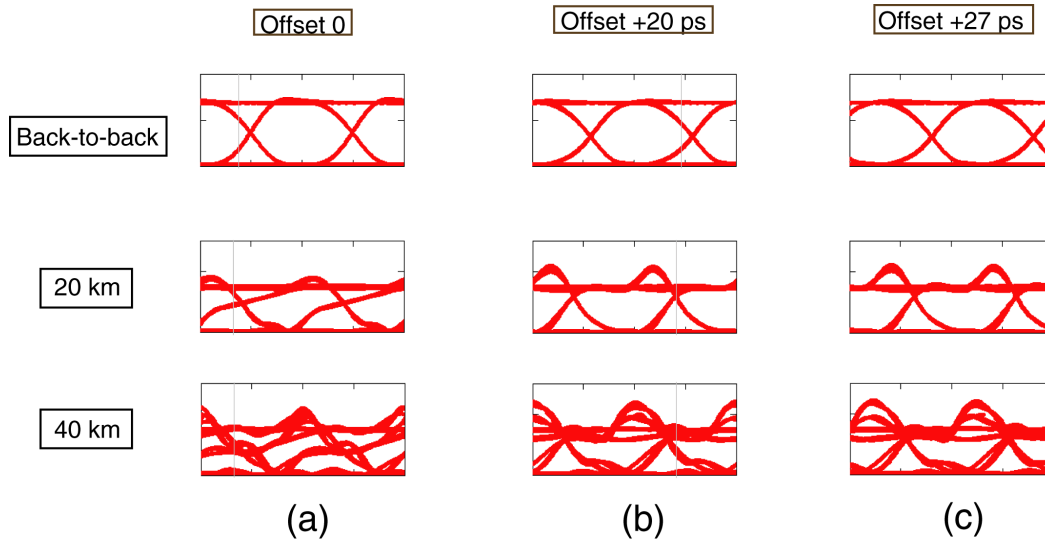


Fig. 5.11 Transmission characteristics of output signal from XGM gain control type optical regenerator. (a) the case of offset '0' (b) the case of offset +20 ps (c) the case of offset +27 ps

5.7 Prospect of ability of a XGM gain-control-type optical regenerator

Just like Section 3.5, transmission characteristics was estimated using loop structure. Fiber loss of 0.2 dB/km and amplifier gain of 100 were assumed. A XGM gain-control-type optical regenerator was inserted at every 10 EDFA stages. In this calculation, fiber dispersion was not taken into account. The parameters of a XGM gain-control-type optical regenerator and input signal were set to be the same as the case of Fig. 5.6. Figures 5.12 (a), (b), (c), (d) and (e) show the eye patterns at transmission after 1000 km, 3000 km without a XGM gain-control-type optical regenerator, at a XGM gain-control-type optical regenerator after 1000 km transmission, at a XGM gain-control-type optical regenerator after 2000 km transmission and at a XGM gain-control-type optical regenerator after 3000 km transmission, respectively. From

Figs. 5.12 (a) and (b), it seems that waveform was more influenced by ASE than that described in Chapter 3, because input power of -6 dBm was lower than the case of a CGCOR. As can be seen in Fig. 5.12 (b), eye is obviously closing after 3000 km transmission without regenerators. On the other hand, from Figs. 5.12 (c), (d) and (e), the power fluctuation was suppressed and eye opens although 3000 km transmission. Here, degradation of extinction ratio was a severe issue for a CGCOR. In the case of a XGM gain-control-type optical regenerator, extinction ratio in the case of (c), (d) and (e) were 16 dB, 18.3 dB and 11.5 dB, respectively. The degradation of extinction ratio was not seen in the case of a XGM gain-control-type optical regenerator, although extinction ratio in the case of (e) lowers caused by signal '1' level power fluctuation by the influence of beat noise between signal and ASE.

In addition, like the case of a CGCOR, power histograms near the decision point are shown in Fig. 5.13. In the case of a XGM gain-control-type optical regenerator, the fluctuation at both signal '1' level and '0' level increases with transmission distance while a CGCOR was almost constant. This reason is considered that a XGM gain-control-type optical regenerator does not suppress complementally the effect of accumulation of ASE.

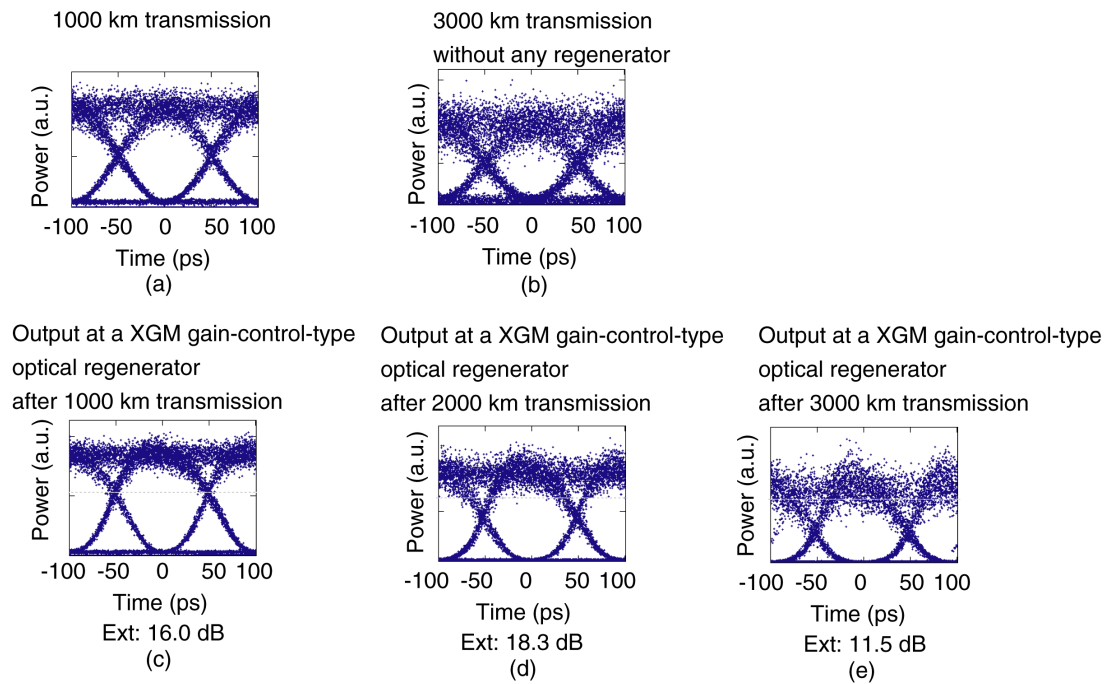


Fig. 5.12 Waveform of signal with transmission.

(a) at 1000 km transmission (b) at 3000 km transmission (c) at a XGM gain-control-type optical regenerator after 1000 km transmission (d) at a XGM gain-control-type optical regenerator after 2000 km transmission (e) at a XGM gain-control-type optical regenerator 3000 km transmission

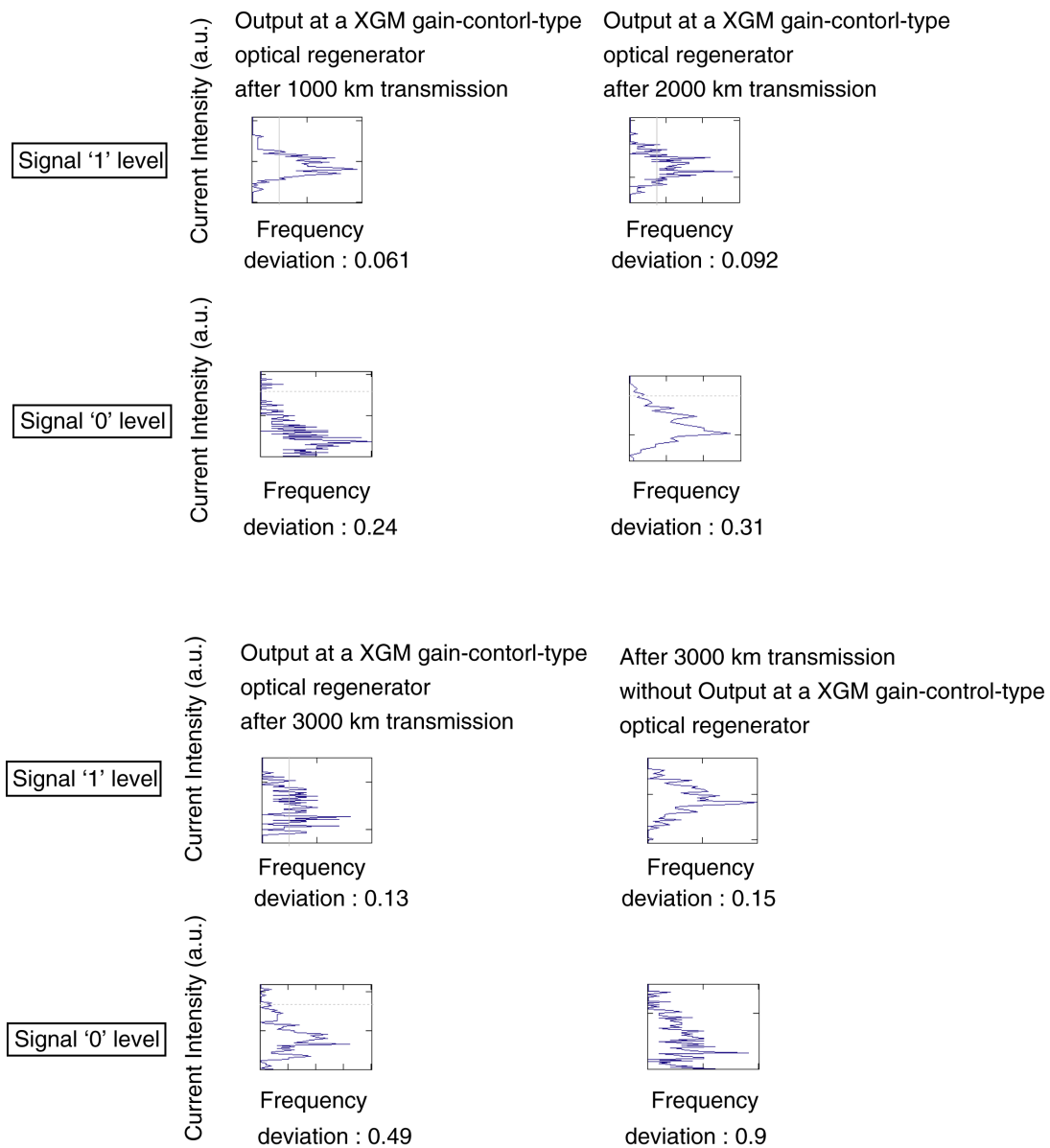


Fig. 5.13 Histogram of eye pattern at signal '1' level and signal '0' level.

Then, dependence of the difference of negative power penalty on waveform was investigated like the case of in Chapter 3. The probe light power and signal light power were used as a parameter. The negative power penalty, which was obtained experimentally, in the case of the signal power of -6 , -7 , -9 and -12 dBm and probe light power of -4 , -5 , -7 and -10 dBm is 4.0 dB, 2.9 dB, 2.1 dB and 1.2 dB, respectively. Other parameters are the same as the case in Fig. 5.12. Figures 5.14 (a), (b), (c), (d), (e) and (f) show the eye patterns at 1000 km, the one at 3000 km without a XGM gain-control-type optical regenerator, 3000 km after passing through a XGM gain-control-type optical regenerator using the signal power of -12 , -9 , -7 and -6 and probe light power of -10 , -7 , -5 , -4 dBm, respectively. In Figs 5.14 (c), (d) and (e), suppression of power fluctuation was observed. On the other hand, in Fig. 5.14 (f) power fluctuation was observed at signal '1' level. And, in the case of Fig. 5.14 (d), power was slightly more fluctuated the case of Fig. 5.14 (e) and (f). Therefore, from rough estimation, a XGM gain-control-type optical regenerator for more than 3 dB negative power penalties was required. Compared with the case of a CGCOR, extinction ratio was not degraded. Therefore, the dominant factor for transmission distance is ASE. Especially, beat noise between signal and ASE became large in the case of the long distance transmission. Therefore noise suppression for signal '1' level is important for a XGM gain-control-type optical regenerator.

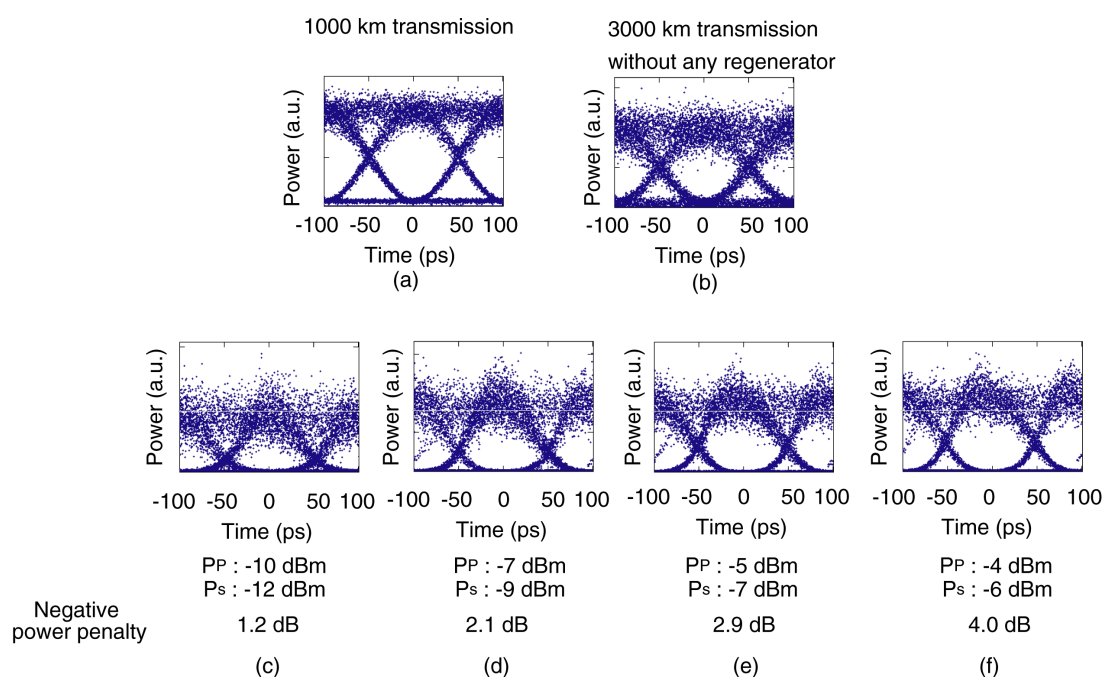


Fig. 5.14 Waveform of signal with transmission.

(a) at 1000 km transmission (b) at 3000 km transmission

output at a CGCOR after 3000 km transmissison (c) the signal and probe light power -12 and -10 dBm (d) the signal and probe light power -7 and -9 dBm (e) the signal and probe light power -7 and -5 dBm (f) the signal and probe light power -4 and -6 dBm

Moreover, I investigated the improvement of SNR by using XGM gain-control-type optical regenerator as the above condition. Figure 5.15 shows calculation results. Compared to EDFA only system, SNR at 1000 km, 2000 km and 3000 km are improved by 2 dB, 5 dB and 8 dB, respectively. This indicates XGM gain-control-type optical regenerator allows transmission distance elongation.

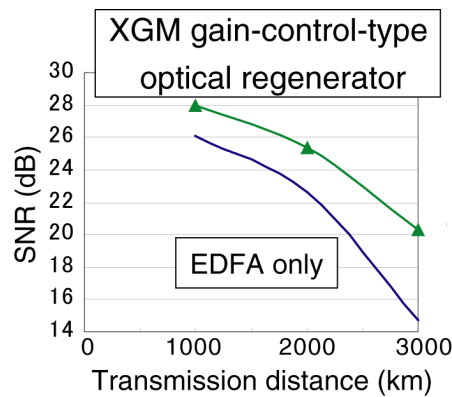


Fig. 5.15 The change of SNR by XGM gain-control-type optical regenerator with transmission distance.

5.8 Summary

In summary, a XGM gain-control-type optical regenerator was proposed and its characteristics were investigated to solve the issues for a CGCOR such as the degradation of extinction ratio and frequency chirping numerically. Then, the operation performance such as input/output characteristics, signal regeneration performance was investigated. Moreover, the techniques of the filter detuning and timing offset schemes were investigated. Then transmission characteristics for consideration of the effect of frequency chirping or noise caused by ASE were evaluated. It was observed that a XGM gain-control-type optical regenerator has nonlinear input/output characteristics. By using nonlinear input/output characteristics, signal regeneration operation for degradation signal was investigated. By using a XGM gain-control-type optical regenerator, suppression of power fluctuation of degraded signal occurred. Also, it was observed that the schemes of the filter detuning and the timing offset lowered the effect of frequency chirping. Then, transmission characteristics considering fiber dispersion by

using a XGM gain-control-type optical regenerator were investigated. The effect of lowering the frequency chirping by the filter detuning and the timing offset methods was confirmed by the signal transmission simulation, and it was confirmed that XGM gain-control-type optical regenerator has possibility to transmission over 40 km with SMF. In addition, optical regeneration performance of XGM gain-control-type optical regenerator for accumulation of ASE would suffices 3000 km transmission under the bad condition for system without optical regenerators. In addition, using the parameter of negative penalty obtained from bit error rate experiments, a XGM gain-control-type optical regenerator with about 3 dB negative power penalty was required. Moreover, the degradation of the extinction ratio was not observed. Therefore, XGM gain-control-type optical regenerator has capability to solve the issues such as extinction ratio and frequency chirping.

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Chapter 6

Operation performance of a XGM gain-control-type optical regenerator

6.1 Introduction

In Chapter 5, a XGM gain-control-type optical regenerator was proposed and investigated numerically. From calculations, I could obtain the possibility that a XGM gain-control-type optical regenerator would have nonlinearity in input/output characteristics and it improved received sensitivity. Moreover, combination of a chirp-control method with the filter detuning and the timing offset methods could have the perspective that transmission characteristics would improve in a gain saturated SOA. In this Chapter, the characteristics of a XGM gain-control-type optical regenerator is investigated.

6.2 Input/output characteristics

For the first step of the investigation of the performance of a XGM gain-control-type optical regenerator, the optical input/output characteristics were measured. Figure 6.1 depicts the experimental setup of an optical regenerator using a gain saturated SOA and

a wavelength converter based on XGM.

Signal with 9.95328 Gbps, NRZ format was used. The extinction ratio of the input signal light was 12.1 dB. The degraded signal was intentionally generated by superimposing amplified spontaneous emission (ASE), caused in an erbium-doped fiber amplifier, to investigate the noise reduction effect. The wavelength for the input, and the probe light in the wavelength converter were 1554 and 1535 nm, respectively. Average power of the input light at the input facet of a XGM SOA and a gain saturated SOA were -1 and -6 dBm, respectively. The probe light power for the XGM SOA was -4 dBm. Average power of the wavelength conversion light was 2.6 dBm at the input side of a gain saturated SOA. The cavity length and bias current of the SOA in the wavelength converter were $1500\text{ }\mu\text{m}$ and 650 mA, respectively. Those of the gain saturated SOA were $900\text{ }\mu\text{m}$ and 400 mA. 3dB-bandwidth of the band-pass filter at the output side of the gain saturated SOA was 0.5 nm.

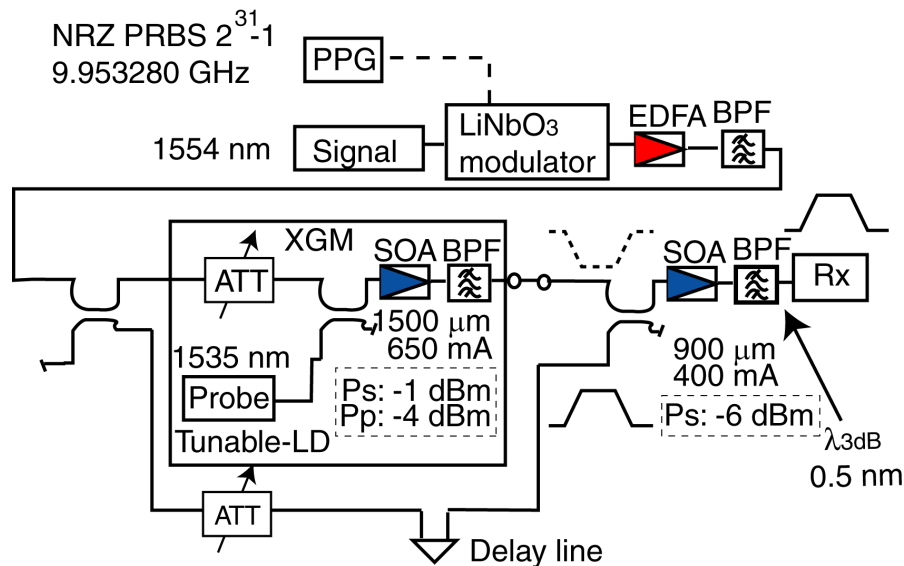


Fig. 6.1 Experimental setup of XGM gain control type optical regenerator.

Figure 6.2 (a) shows input/output characteristics of the proposed optical regenerator under CW condition. The enlarged figure is indicated in Fig. 6.2 (b). In this measurement, center wavelength of a filter was shifted 0.3 nm toward shorter wavelength than the signal light wavelength.

The horizontal axes in Figs. 6.2 (a) and (b) indicates the CW input signal light power at the input facet of the gain saturated SOA, and the vertical axes indicate the CW output power. As can be seen in Figs. 6.2, nonlinear characteristics were observed at both low power region of less of than 0.05 mW, and high power region of more than 0.2 mW.

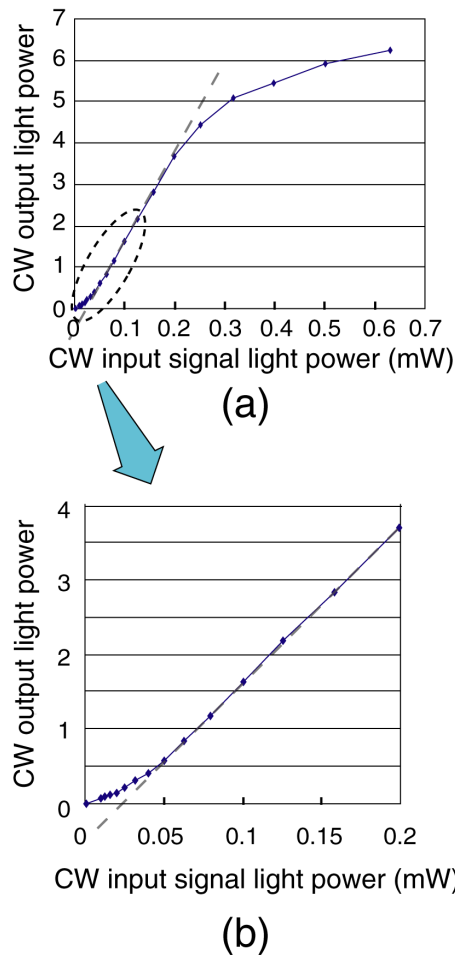


Fig. 6.2 (a) CW input/output characteristics of the XGM gain control type optical regenerator (b) The enlarged figure of the (a)

Figure 6.3 indicates total input light power injected into a gain saturated SOA as a function of signal light power. At both low and high input power region, total input power level is higher than the other region so that larger gain saturation occurs. Therefore, output power increment is suppressed, and S-shaped characteristics can be obtained.

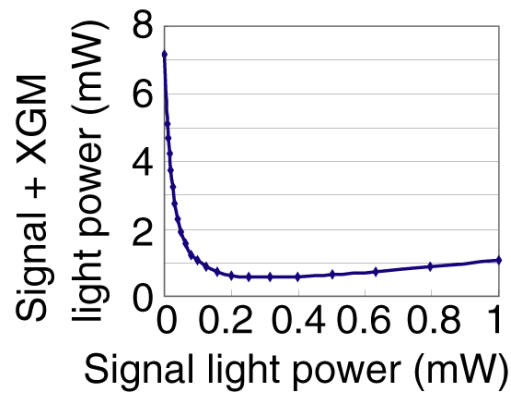


Fig. 6.3 Total input signal light power into a gain saturated SOA as a function of signal light power.

6.3 Dynamic characteristics

In the previous section, nonlinearity in input/output characteristics was confirmed in a XGM gain-control-type optical regenerator. And the validity of simulations as shown in Chapter 5 could be verified. Then, the effect of the filter detuning and the timing offset on frequency chirping control was investigated.

6.3.1 Effect of filter detuning

Although fluctuation of carrier density in a XGM gain-control-type optical regenerator can be suppressed comparing with normally gain saturation scheme, using a gain saturated SOA causes frequency chirping in signal transient time to some extent. By using a band pass filter (BPF) in optical frequency domain, the power in frequency chirping component is changed.

Filter detuning was defined in Chapter 5 as

$$\Delta\lambda = \lambda_{\text{filter}} - \lambda_o \quad (6.1)$$

Figures 6.4 (a), (b), (c) and (d) show eye patterns of input, output signals with the offset of -0.3 nm, 0 nm and +0.3 nm, respectively. Compared to input signals, which is degraded by adding ASE, suppression of power fluctuation was observed for every cases of filter detuning. In addition, extinction ratio of output signals was not degraded against input signal. However, when the filter wavelength shifted toward shorter wavelength than the output signal wavelength, the rise time became faster. On the other hand, in case of longer wavelength detuning, rise time became longer.

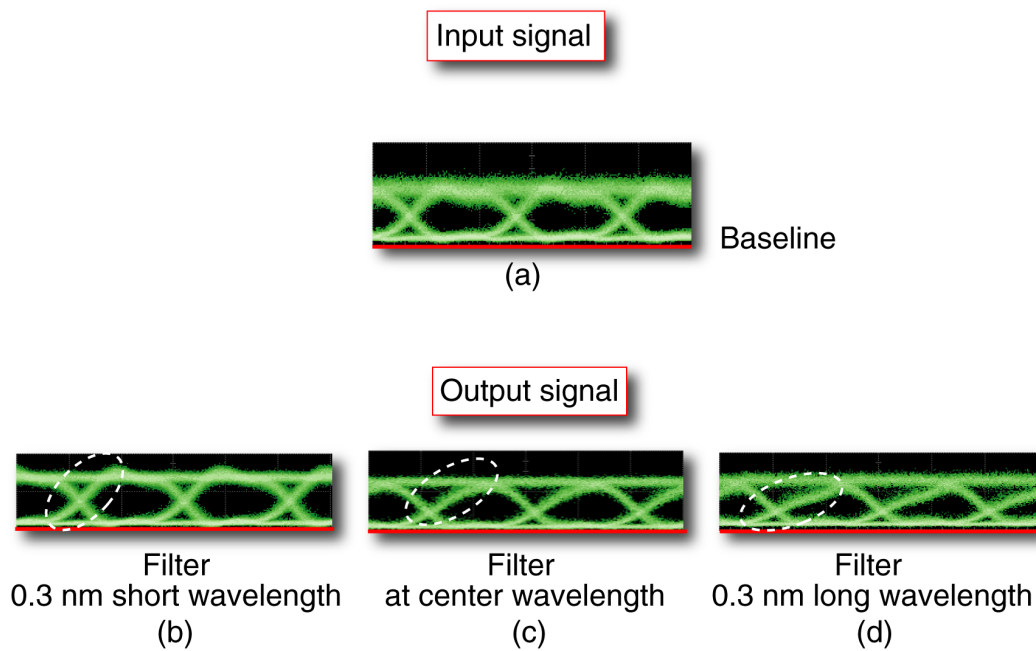


Fig. 6.4 Eye patterns of input and output signals.

(a) input signal (b) output signal at 0.3 nm shorter (c) output signal at center wavelength (d)

Figure 6.5 represents rise time as a function of offset of filter detuning scheme. Rise time decreased from 94 ps to 48 ps when filter wavelength shifted from 0.3 nm longer to 0.3 nm shorter wavelength. So, the shorter wavelength detuning is effective for improving the rise time of output signal.

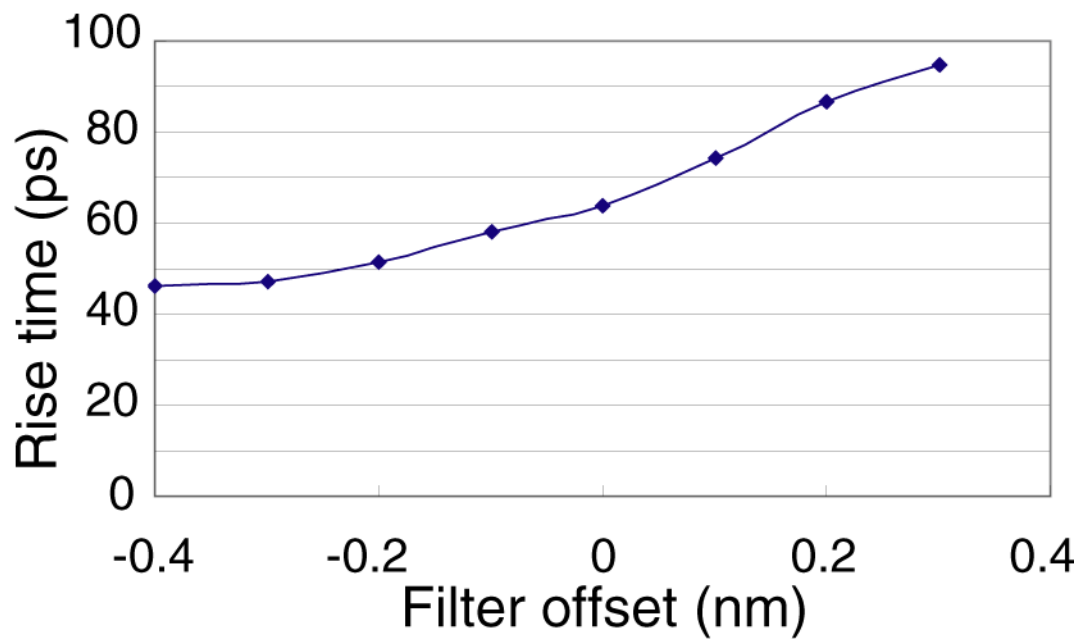


Fig. 6.5 Rise time of output signal as a function of the filter detuning.

Figure 6.6 shows optical spectra of input signal and output signals using a BPF with the offset of 0 and -0.3 nm. Spectrum of output signals broadened toward shorter wavelength against spectrum of the input signal. These measured spectra agreed calculation results shown in Figs. 5.7. By filter detuning for short wavelength detuning, it was observed that intensity in the long wavelength side decreased. Consequently filter detuning affected waveform in the time domain.

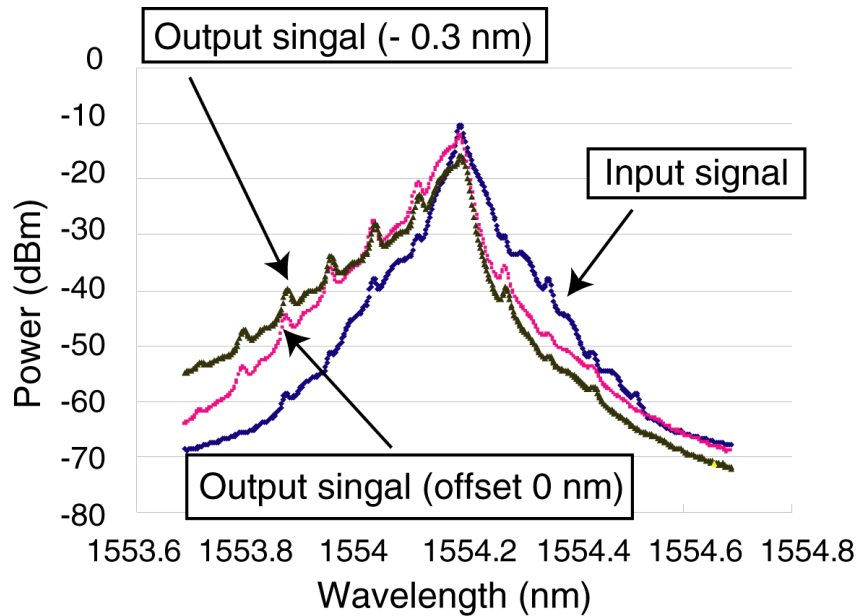


Fig. 6.6 Spectrum of signals. Input signal and output signal with BPF at offset 0 nm and - 0.3 nm were used.

Then, to verify the effect of chirp control on signal quality by the filter detuning scheme, output signal chirping was measured. Measured data of the chirping characteristics are shown in Figs. 6.7 (a) and (b) in case of filter detuning of 0 and -0.3 nm offset, respectively. In these figures, each solid circle indicates the data point at which the chirp was 0. In these measurements, an optical chirp test set (ADVANTEST Q7607) and a sampling oscilloscope (Agilent 86100B) were used. In terms of chirping characteristics, frequency shift from blue-chirp to red-chirp was observed at the leading edge and the trailing edge of output signal. At the leading edge, both blue-chirp and red-chirp were induced by decreasing the XGM signal and increasing the input signal, respectively. At the trailing edge, blue-chirp and red-chirp are induced by decreasing the input signal power and increasing the XGM signal power. When the center wavelength

of a band pass filter was detuned 0.3 nm toward shorter wavelength, the power of red-chirp region was reduced. From this, filter detuning has capability for lowering the effect of frequency chirping.

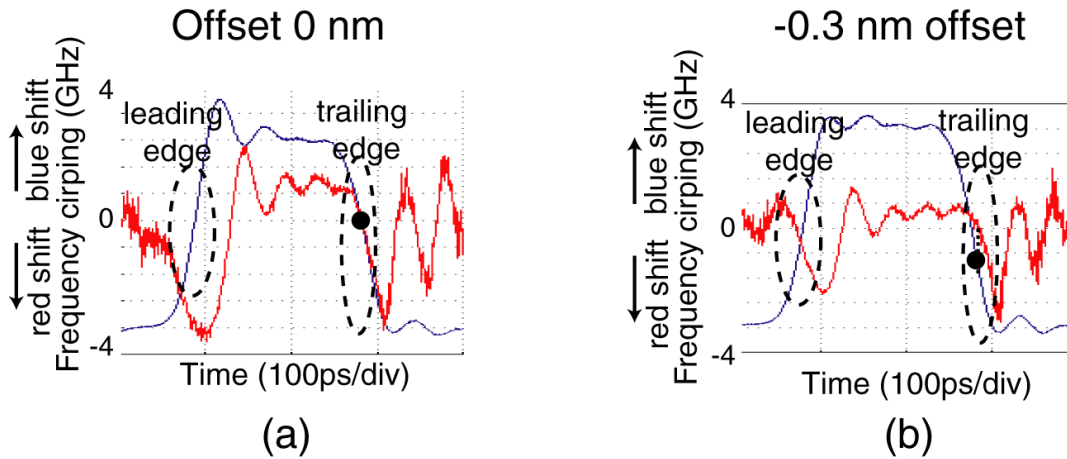


Fig. 6.7 Measurement data of the chirping characteristics.
(a) BPF set at center wavelength (b) BPF set a 0.3 nm shorter.

6.3.2 Effect of timing offset scheme

In this Section, the effect of timing offset scheme on frequency chirping is investigated. By delaying input XGM timing into a SOA, the red shift of frequency chirping in the trailing edge, which occurred by increasing XGM signal power in the leading edge in XGM signal, moves from signal trailing edge transient to '0' level base line. This reason is that the change of carrier density in a SOA, which correlates with the change of refractive index, becomes shifted. These were discussed in 5.5.2.

Figures 6.8 (a) and (b) show eye patterns of output signals at timing offset 0 and +21 ps. In this experiment, the BPF was set at 0.3 nm shorter than signal light wavelength. As shown in Figs. 6.8 (a) and (b), eye opening was clearly observed in back-to-back

condition although degraded input signal was used. This tendency against signal timing from -6 ps to $+36$ ps was verified. The reason for operating against wide range of timing offset seemed that gain saturation of a SOA compensate the difference of timing offset.

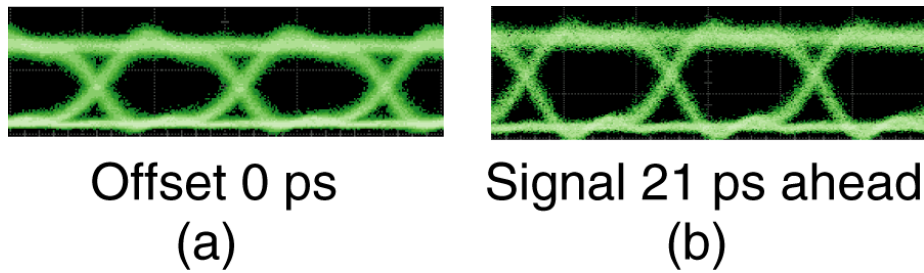


Fig. 6.8 Eye patterns of output signals.

(a) offset 0 ps (b) signal 21 ps ahead.

Then, to verify the effect of timing offset scheme on chirping control, output signal chirping was measured.

Timing offset was defined in Chapter 5 as

$$\Delta t = t_{XGM} - t_{signal} \quad (6.2)$$

Measured data of the chirping characteristics are shown in Figs. 6.9 (a), (b) and (c) in the case of offset 0, $+21$ ps and $+27$ ps. As the same in Fig. 6.7, each solid circle indicates the data point at which the chirp was 0. In the case of ‘offset 0’, large red-chirp occurred at the trailing edge of output signal. At the leading edge, both blue-chirp and red-chirp are induced by decreasing the XGM signal power and increasing the input signal power, respectively. At the trailing edge, blue-chirp and red-chirp were induced by decreasing the input signal and increasing the XGM signal. By inputting signal

slightly earlier than the XGM signal, red-chirp moved from the trailing edge to low power side, so the suppression of wavelength dispersion effect and the resultant improvement of transmission distance can be expected. Transmission characteristics will be discussed later.

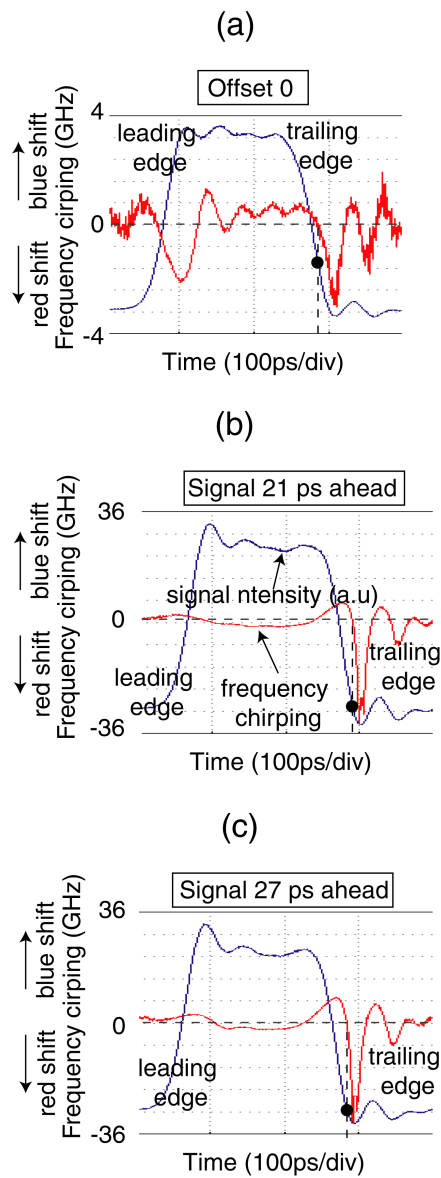


Fig. 6.9 Measurement data of the chirping characteristics
(a) offset 0 ps (b) signal 21 ps ahead (c) signal 27 ps ahead

In addition, 40 Gbps operation of a XGM gain-control-type optical regenerator was tried. Figures 6.10 (a) and (b) show input signal and output signal from a XGM gain control type optical regenerator. Input signal was modulated at a bit rate of 40 Gbps, 7-stage PRBS and RZ format. As can be seen in Figs. 6.10 (a) and (b), eye patterns of output signal from a XGM gain control type optical regenerator opened clearly without pattern effect. Therefore a XGM gain-control-type optical regenerator has capability to operate at 40 Gbps. I considered that a wavelength converter based on XGM limits the operation speed of a XGM gain-control-type optical regenerator. In Figs. 6.11 (a) and (b), bit sequence of output signal from a XGM gain-control-type optical regenerator and XGM signal, respectively. Although pattern effect was observed in wavelength converted light, no pattern effect was occurred in output signal from a XGM gain control type optical regenerator. It is no need for XGM signal to operate exactly at 40 Gbps because that XGM signal act as assisting light. This was reported by NTT Laboratories [1]. Therefore, operating speed isn't limited by XGM speed.

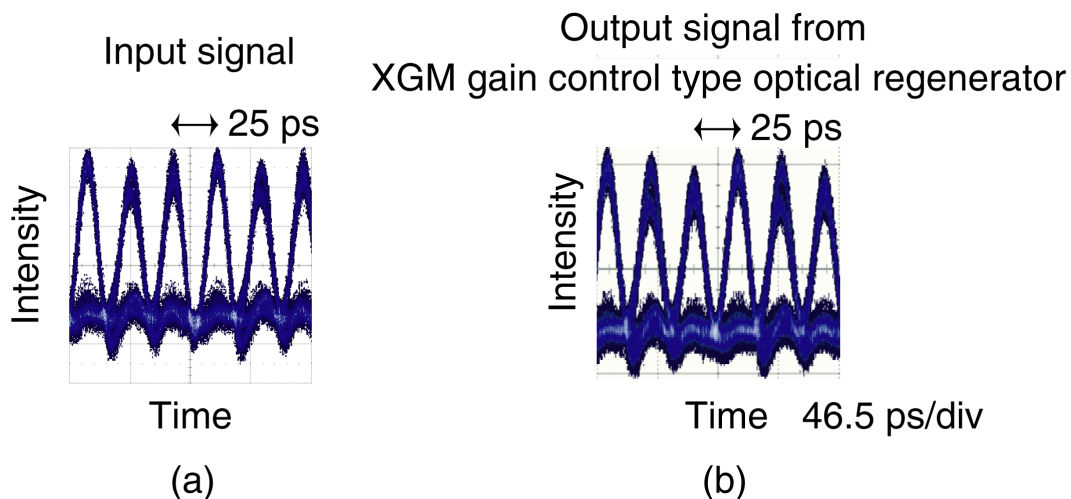


Fig. 6.10 Eye patterns of input and output signals at 40 Gbps.

(a) input signal (b) output signal from XGM gain control type optical regenerator

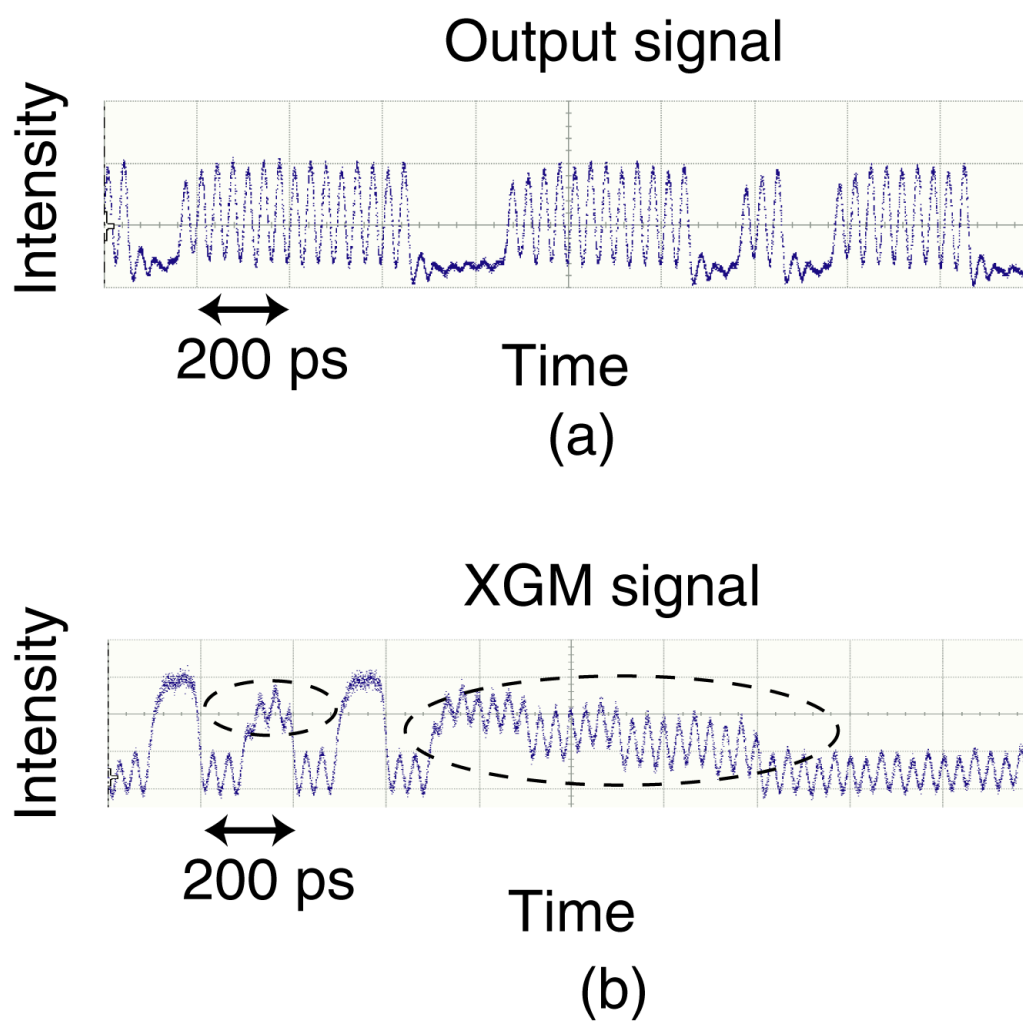


Fig. 6.11 Bit sequence at 40 Gbps.

(a) Output signal from XGM gain control type optical regenerator (b) wavelength conversion light

6.4 Effect of signal regeneration

In a XGM gain control type optical regenerator, eye opening at 10 Gbps was clearly observed, and it is expected to improve received sensitivity. So, in this section, signal quality of output signal is investigated, and the offset of a XGM gain-control-type optical regenerator on received sensitivity is discussed.

6.4.1 Bit error rate measurement

To investigate the regeneration performance, bit error rate of output signal was measured.

At first, the effect of rise time by filter detuning was investigated. In Fig. 6.12, the results for output signals in the cases of a BPF set at the signal wavelength and 0.3 nm shorter, input signal with ASE noise and signal without ASE noise are plotted. In case of output signal, input timing between signal and XGM signal was set to be the same. Insets are input and output waveforms. Improvement of received sensitivity of the output signal using filter detuning was observed whereas error floor was observed for input signal and the output signal in the case of a BPF set at the signal wavelength. Signal sensitivity was improved more than 4 dB. Rise time in the case of -0.3 nm was 47.4 ps and in the case of 0 nm offset was 63.7 ps. So, the decrease of rise time by using filter detuning scheme have influenced on improvement of received sensitivity.

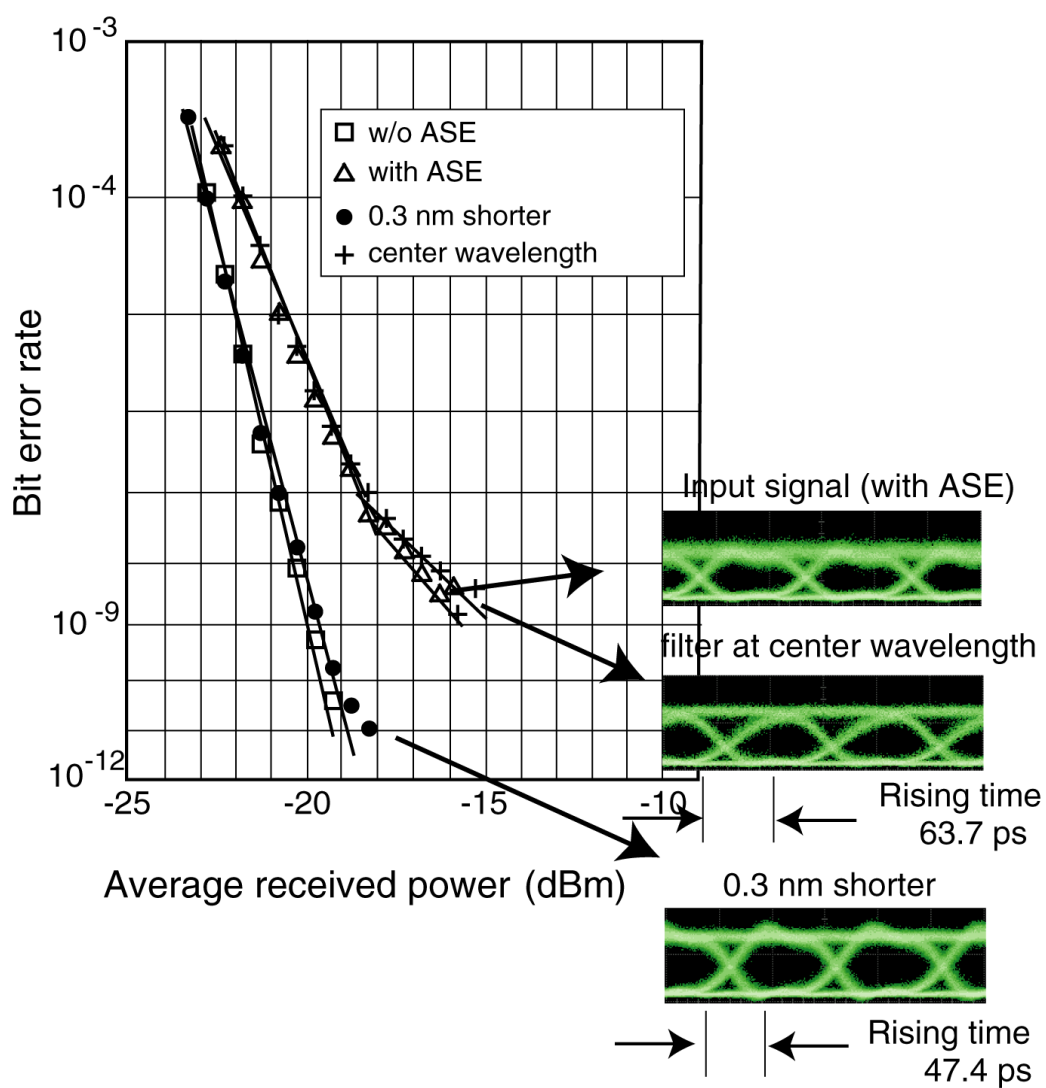


Fig. 6.12 BER results of input and output signal. Insets are input and output waveforms

Next, the effect of timing offset was discussed. In the previous Section, eye opening were clearly observed against wide range of timing offset under back-to-back condition. Therefore, it is expected that the effect of timing offset is little in that condition. Figure 6.13 indicates results of the power penalty as a function of signal light timing. Positive and negative signs mean that input signal is injected ahead and behind the XGM signal. Power penalty is defined as the difference of the optical received power at $\text{BER} = 10^{-9}$ between output and input signal without ASE. As shown in Fig. 6.13, power penalty was almost the same against signal timing from -6 to 36 ps.

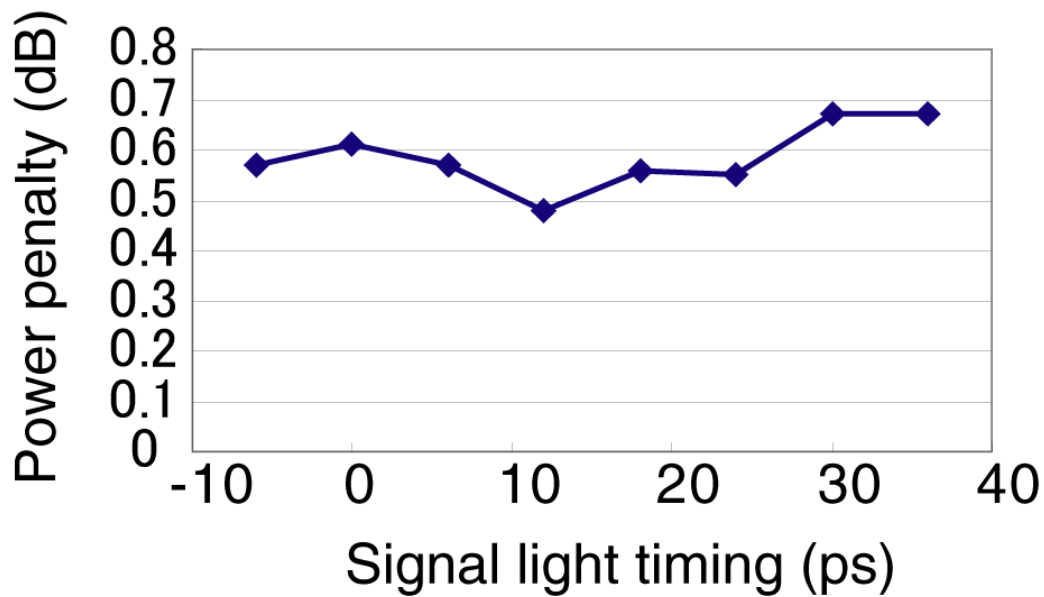


Fig. 6.13 Power penalty against signal light timing.

6.4.2 Relative intensity noise measurement

To investigate the cause of sensitivity improvement, relative intensity noise (RIN) was measured, just like a CGCOR described in Section 4.3.3. Experimental setup was the same as that shown in Fig. 4.6 except input optical power. CW light power was -3 dBm as '1' level signal and -15 dBm as '0' level signal, respectively. The other parameters such as signal light wavelength and probe light wavelength were the same as the case of BER measurement. Figures 6.14 (a) and (b) indicate the results of RIN measurements in '1' level and '0' level for input signal and output signal, respectively. RIN suppression compared between output signal and input signal was observed at both '1' level and '0' level. Therefore, the suppression of intensity noise is considered to be the main cause of received sensitivity improvement in a XGM gain-control-type optical regenerator as well as a CGCOR. Figure 6.15 shows RIN suppression ratio. Here, RIN suppression is defined as the difference between the peak value of RIN per frequency for output signal and that for input signal. Input signal power was used as a parameter. The numbers on input/output characteristics indicate the results of RIN suppression. It was seen that noise suppression was obtained under the condition that nonlinearity was observed.

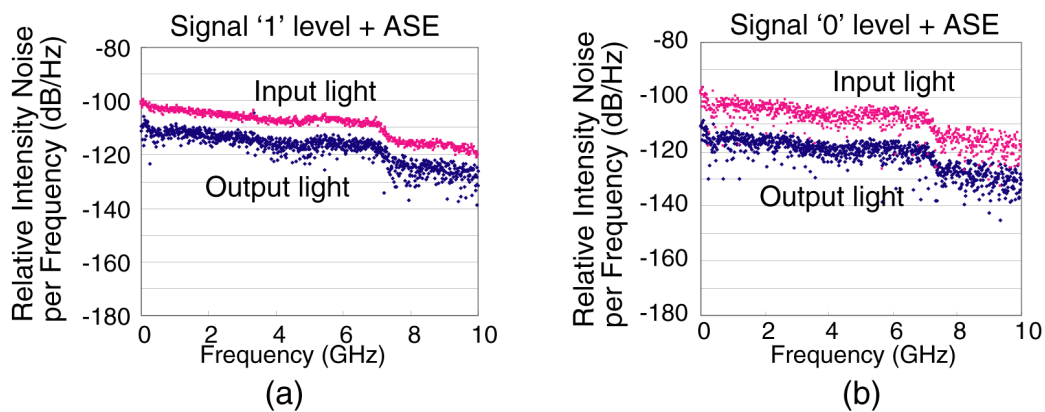


Fig. 6.14 Results of RIN measurement.

(a) signal '1' level (b) signal '0' level.

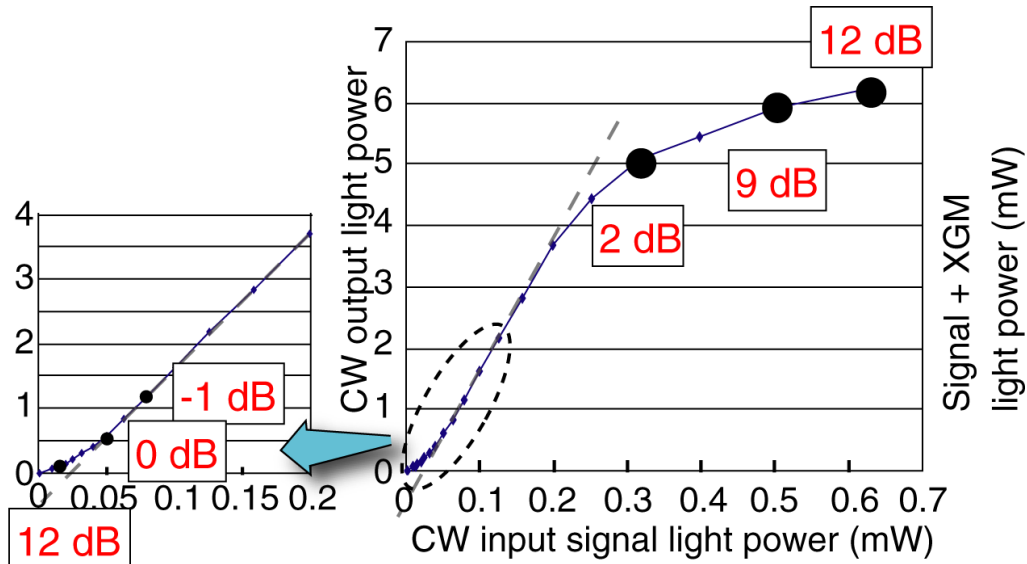


Fig. 6.15 RIN suppression. Value as a function of input light power. It is plotted on curve of input/output characteristics.

6.4.3 Dynamic range and OSNR tolerance

To show the regeneration capability, which is one of the most important points for an optical regenerator, input signals with several OSNR were input into a XGM gain-control-type optical regenerator, and BER was evaluated. Experimental setup was shown in Fig. 6.16. To investigate OSNR tolerance, ASE light source was used. By controlling the power of ASE light source, OSNR of the input signal was varied. The band-pass filter at the output side of the gain saturated SOA was set at 0.3 nm shorter from 0 nm offset, and +21 ps offset. Other parameters such as signal light wavelength and probe light wavelength were the same as the case of Section 6.4.1.

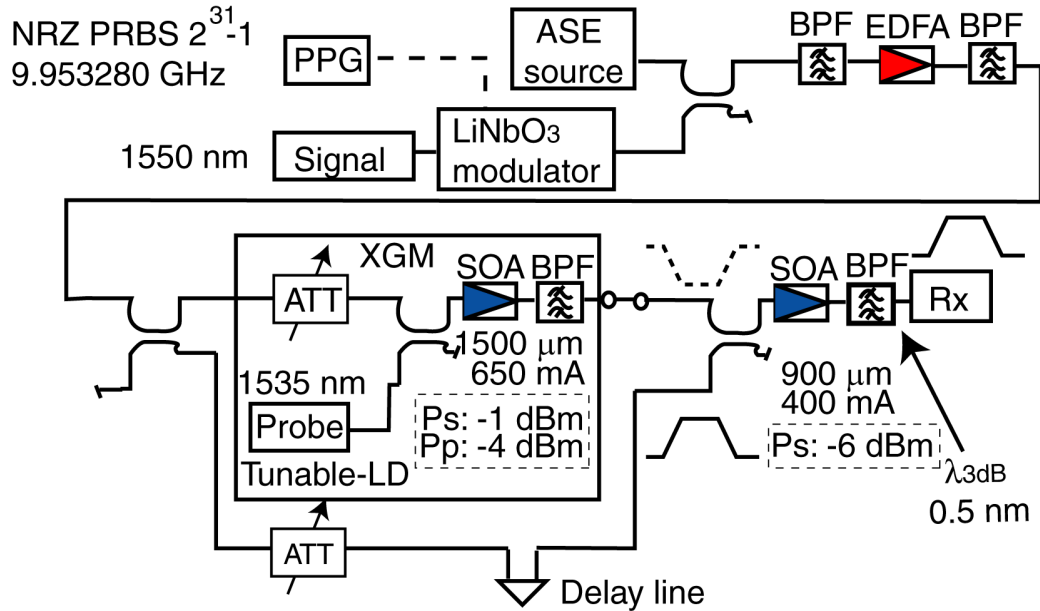


Fig. 6.16 Experimental setup for OSNR tolerance.

Figures 6.17 (a) and (b) show the results of BER measurement for input and output signals, respectively. OSNR was used as a parameter. As shown in Figs. 6.17, the received sensitivity of both input and output signal was degraded with decreasing OSNR, although degrading of output signal was more moderate than input signal. Figure 6.18 shows received sensitivity and sensitivity improvement ratio against OSNR of input signal. The sensitivity improvement ratio is defined as the difference of the received optical power of output signal at $\text{BER}=10^{-9}$ from that of input signal. As can be seen in Fig. 6.18, while the OSNR was from 16 dB to 40 dB, difference of the received sensitivity of output signal was within 1 dB. This means a XGM gain-control-type optical regenerator has OSNR tolerance.

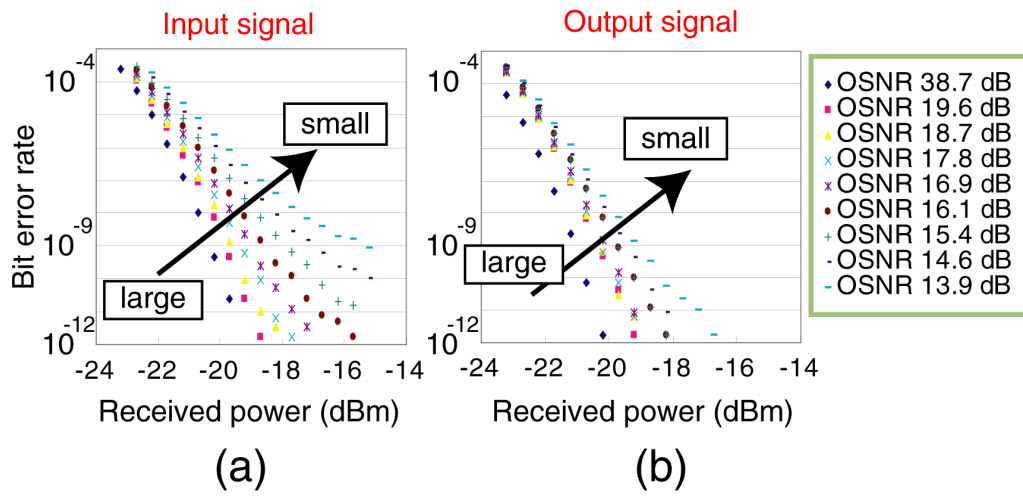


Fig. 6.17 the results of BER measurement.

(a) input signal (b) output signal

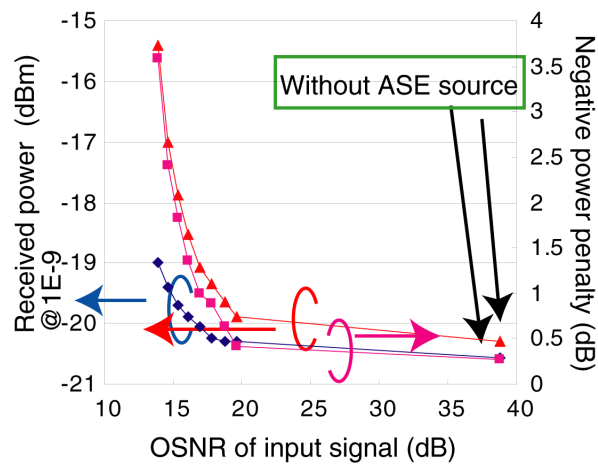


Fig. 6.18 Received power of output signal and sensitivity improvement ratio against OSNR of input signal.

Then, dynamic range of a XGM gain-control-type optical regenerator in input power against various OSNR was investigated. BER was measured for various input signal power against each OSNR. The result was shown in Fig. 6.19. Here, power penalty is

the difference of the received optical power at $\text{BER}=10^{-9}$ from minimum received power of output signal against each OSNR. When input signal of OSNR was 38.7 dB, which is the case without ASE, difference of received sensitivity was within 1 dB till the average input signal power was down to -11 dBm for low power side. However, received sensitivity was degraded when input signal power was -4 dBm. This was caused by pattern effect induced by input signal with high power. Consequently, when OSNR decreased, degradation of received sensitivity for high power side could be seen. It was considered that lowering the effect of noise suppression for signal '1' level was the reason.

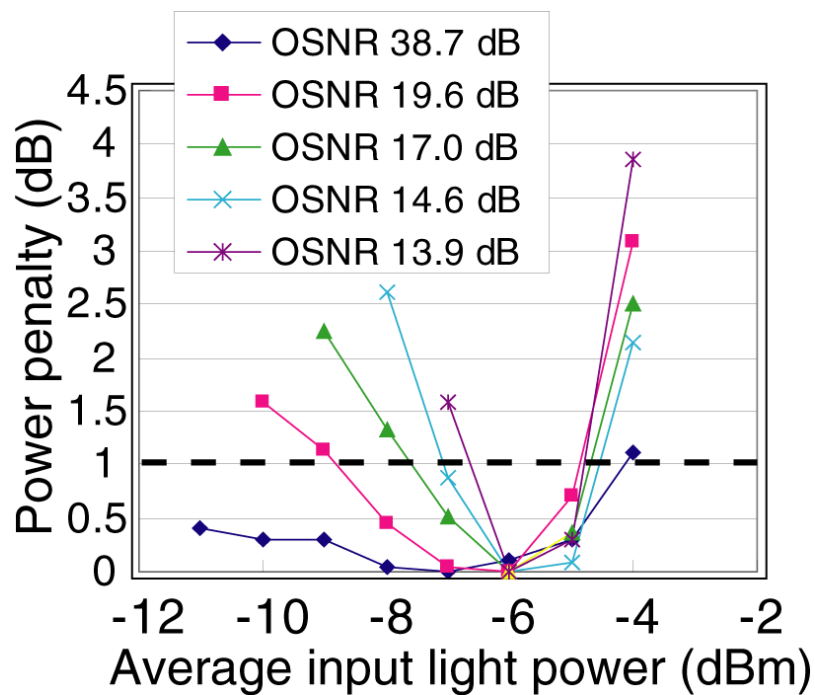
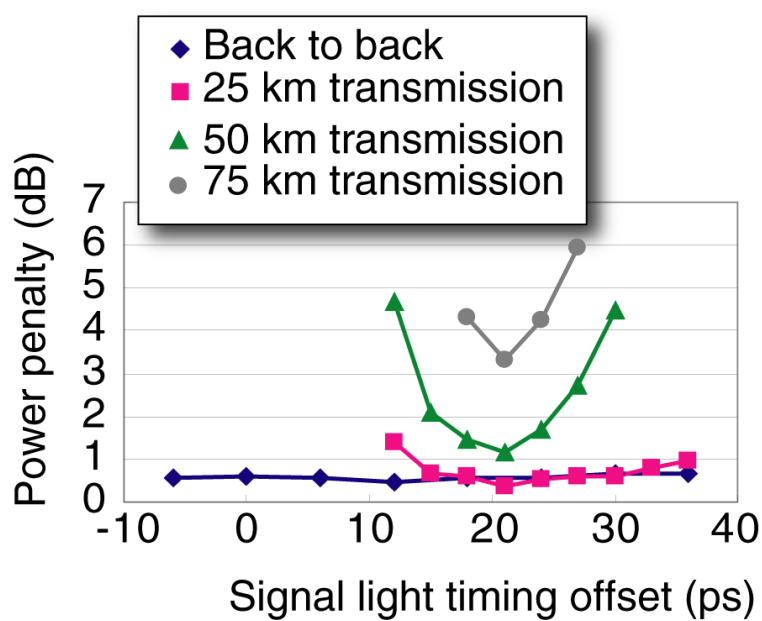


Fig. 6.19 The dependency of power penalty against average input light power. OSNR of input light power was used as a parameter.

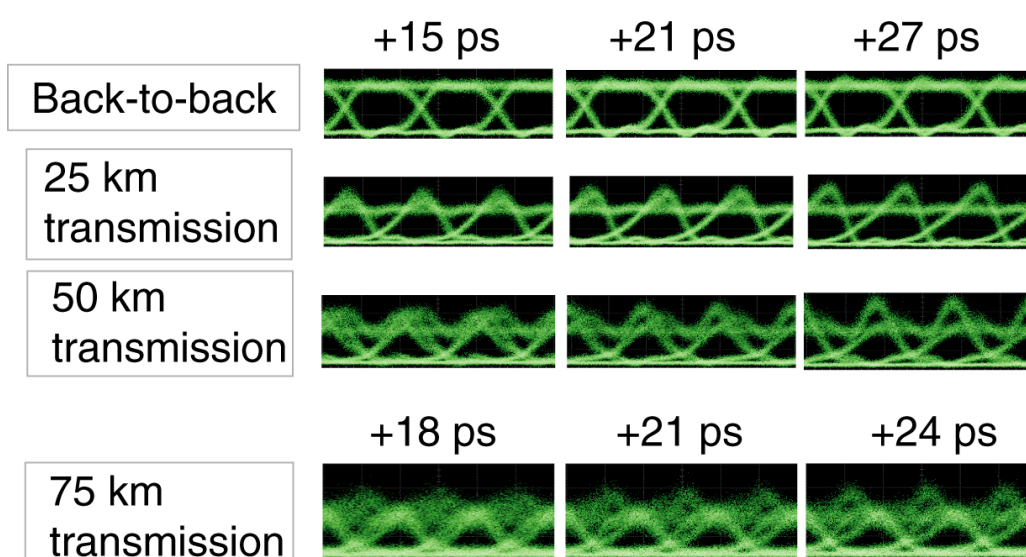
6.5 Transmission characteristics

To verify the effect of filter detuning and timing offset scheme on transmission characteristics, transmission experiments were performed. Experimental setup and parameters of an optical regenerator were the same as that described in section 6.4.1. Figures 6.20 (a) and (b) indicate results of the power penalty and waveforms as a function of signal light timing offset, respectively. Positive and negative signs mean that input signal is injected ahead and behind the XGM signal. Transmission distance was used as a parameter. Here, power penalty is defined as the difference of the optical received power at $\text{BER} = 10^{-9}$ between output and input signal without ASE. Only in the case of 75 km transmission, the optical received power at $\text{BER} = 10^{-7}$ was used, because BER didn't reach 10^{-9} level in this case. We observed BER of less than 10^{-12} with the distance of less than 50 km.

Under back-to-back condition, power penalty was almost the same against signal timing from -6 to 36 ps. And waveform didn't change drastically. But with increasing transmission distance, signal timing influenced on power penalty and waveform. This results from residual frequency chirping dependent on signal timing. In case of timing offset of 21 ps, the minimum power penalty was obtained at 25 , 50 and 75 km.



(a)



(b)

Fig. 6.20 Transmission performance.

(a) Power penalty against signal light timing offset and (b) waveforms. Transmission distance is used as a parameter.

6.6 Discussion of a XGM gain-control-type optical regenerator capability

In Section 6.4, signal regeneration performance for input signal with various OSNR was discussed. In this Section, transmission characteristics is simulated for investigation of required optical regenerator performance from experimentally obtained negative power penalty in a XGM gain-control type optical regenerator. Figures 6.21 (a), (b), (c) and (d) shows waveform obtained by calculation by using input signal of (a) OSNR = 40 dB, (b) OSNR = 20 dB, (c) OSNR = 17 dB, (d) OSNR = 14 dB and (e) OSNR = 11 dB, respectively. Here, negative power penalty in the case of OSNR = 38.7 dB, 19.6 dB, 16.7 dB and 13.9 dB was about 0.3 dB, 0.4 dB, 1.8 dB and 3.6 dB, respectively, from BER experiment described in Fig. 6.18. For the case of OSNR = 11 dB, I did not experiment. Input signals immediately were first injected into a XGM gain-control-type optical regenerator, then fiber transmission was assumed with a regenerator setting at every 1000 km. Comparison between input signals and output signal from the first optical regenerator, suppression of power fluctuation was seen from the case of each input signal whereas output signals has difference depended on input signal OSNR. With transmission, similar waveforms were shown in the case of the 2000 km transmission without an optical regenerator for each OSNR input signal, because ASE noise from EDFA's became dominant factor. By using the optical regenerator, noise suppression, especially in signal '0' level, was observed. Between input signals with OSNR = 11 dB and OSNR = 40 dB, the waveforms at 2000 km transmission after passing through the third-stage XGM gain-control-type optical regenerator almost the same although the waveforms of OSNR = 11 dB at the first-stage has larger power

fluctuation than the case of OSNR = 40 dB and the received sensitivity was different in BER experiment between output signal using input signal of OSNR = 38.7 dB and 13.9 dB. Therefore a XGM gain-control-type-optical regenerator has possibility to operate for various OSNR from 10 dB by using multiple stages of XGM gain-control-type optical regenerators. As can be seen in these figures, signal '1' level fluctuation caused by the beat noise between signal and ASE was observed. For long distance transmission, it is necessary for a XGM gain-control-type optical regenerator to suppress signal '1' level power fluctuation with no pattern effect occurring.

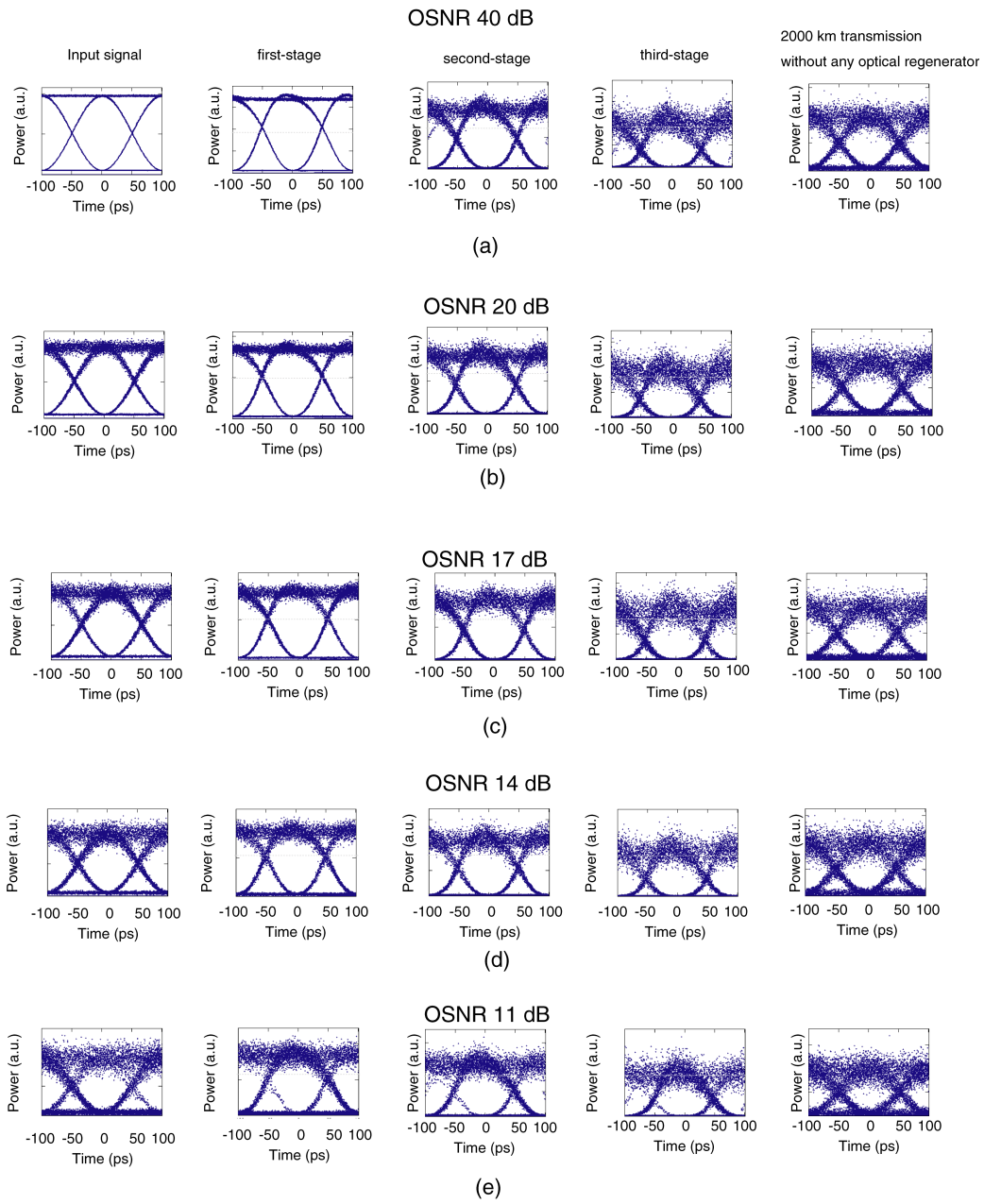


Fig. 6.21 Cascaded the optical regenerator performance. OSNR of input signal was parameter.
 (a) OSNR = 40 dB (b) OSNR = 20 dB (c) OSNR = 17 dB (d) OSNR = 14dB (e) OSNR = 11 dB

6.7 Summary

In summary, we have investigated the XGM gain-control-type optical regenerator in experiment. For this optical regenerator, not only input/output characteristics and signal regeneration performance, but also lowering the effect of the frequency chirping by the filter detuning scheme and timing offset scheme was verified. Using a filter detuning scheme, rise time changed from 94 ps to 48 ps and received sensitivity was improved by fast rise time. Then, a timing offset scheme was investigated in chirp measurement and it was observed that red-chirp was shifted toward lower power region. By using this optical regenerator, the degraded signal sensitivity was improved over 4 dB. Moreover, transmission of regenerated signal was reached up to 50 km by using the filter detuning scheme and the timing offset scheme. In addition, received sensitivity and dynamic range for several OSNR were observed. At one-stage XGM gain-control-type optical regenerator, received sensitivity and dynamic range was degraded for input signal with low OSNR. However, by using multiple stage, a XGM gain-control-type optical regenerator has possibility to operate even for low OSNR input.

A XGM gain-control-type optical regenerator has the advantage for lowering frequency chirping effect against conventional gain saturation. I consider XGM gain-control-type optical regenerator is applicable for the optical regenerator with multiple stages.

Reference

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Chapter 7

Conclusion

In this dissertation, two types of the cascade-structured optical regenerators using wavelength converters based on cross gain modulation have been described. One is the cross gain modulation type wavelength-converter-cascaded optical regenerator (CGCOR), and the other is the XGM gain-control-type optical regenerator. I investigated these optical regenerators in analytically and experimentally. The calculation parameter was extracted from wavelength conversion experiments in Chapter 2. The tendency of calculation results correspond the tendency of experiment.

The study on a cascade-structured optical regenerator using wavelength converter based on cross gain modulation is concluded as follows.

I. A cross gain modulation type wavelength-converter-cascaded optical regenerator

As a wavelength converter based on XGM, a CGCOR was proposed. By cascaded-structure, nonlinearity in input/output characteristics at both signal '1' level and '0' level was realized and signal polarity was maintained. Moreover, output signal

wavelength can be the same as input signal wavelength.

From calculations using SOA model based on transfer matrix method and experiments, I confirmed nonlinear input/output characteristics in low power region and high power region. The input/output characteristics depended on several parameters such as wavelengths and power of an input signal and probe signal because a SOA had dependency on wavelength and power. Therefore, not only parameters of light, but also parameters of a SOA such as injection current or cavity length influenced input/output characteristics.

By using nonlinear input/output characteristics, it is expected to operate as optical regenerator. I investigated the effect of signal regeneration in a CGCOR using degraded input signal by adding ASE and at the bit rate of 10 Gbps in NRZ format. In bit error rate (BER) measurements, optical received power at $\text{BER} = 10^{-9}$ decreased by 4.1 dB from degraded input signal. The cause of this improvement of signal regeneration is considered to be due to noise suppression from relative intensity noise (RIN) measurements. From the result of RIN measurement, noise suppression effect would be caused by not only its nonlinear input/output characteristics but also the effect of signal transfer into local CW probe light with low noise. Moreover, I obtained that optimized condition for the first- and the second-stage probe light was dominated by the extinction ratio as well as RIN suppression of signal '1' level and '0' level.

In addition, novel function by using offset scheme of sinusoidal probe light for a CGCOR was proposed and improvement of pattern effect and modulation format conversion from RZ to NRZ was investigated.

An All-optical regenerator has several issues to be solved. One of them is the dynamic range in input power. Thus the dynamic range of a CGCOR was investigated

and the dynamic range of 6 dB under the fixed condition and 11 dB under the optimize probe light were achieved. It has been mentioned that a wavelength converter based on XGM is 7-10 dB, therefore the dynamic range of a CGCOR is nearly the same as that of a XGM wavelength converter.

Then, transmission characteristics for using a CGCOR was investigated by calculation. A CGCOR has the effect of noise suppression with transmission under the condition of more than 2 dB negative penalties. However, the extinction ratio degraded with lapping the stage. In addition, occurring large frequency chirping is expected in a CGCOR. The degradation of extinction ratio and frequency chirping are issues of a CGCOR.

By using cascade-structure, compared with XGM wavelength converter, CGCOR is improved as follows;

- Nonlinearity at low power region and high power region equivalent to signal '0' level and '1' level
- Suppression of reduction of eye opening by monotonically degradation and nonlinearity
- Compensation for pattern effect of XGM wavelength conversion light by latter SOA
- Polarity of output signal is same as one of input
- It is possible that output signal wavelength is same as input one.

A CGCOR has large dynamic range and large noise suppression effect. I consider that a CGCOR is applicable in the situation that signal with large noise and the number of

optical regenerators and transmission distance are limited.

II. A XGM gain-control-type optical regenerator

To solve the issues such as the degradation of extinction ratio and the frequency chirping, a XGM gain-control-type optical regenerator was proposed and its operation performance was investigated. By using polarity inverted signal generated from a wavelength converter based on XGM and gain saturated SOA, nonlinear input/output characteristics was obtained in calculations and experiments. The output signal is processed from input signal and not CW light, and gain saturation is occurred at not lonely signal '1' level but also signal '0' level, so it is expected that the degradation of the extinction ratio does not occur.

To lower the effect of frequency chirping, the filter detuning scheme and the timing offset scheme were investigated. In a filter detuning scheme, not only the decreasing of red chirp power at the trailing edge, but also the increase of blue chirp power at the leading edge were caused. Therefore, rise time changed from 94 ps to 48 ps by the -0.3 nm detuning and received sensitivity was improved by fast rise time. By using these schemes, the power of red chirp at the trailing edge was decreased.

By using this optical regenerator, the degraded signal sensitivity was improved over 4 dB. Moreover, transmission of regenerated signal was reached up to 50 km by using the filter detuning scheme and the timing offset scheme. In addition, received sensitivity and dynamic range for several OSNR input signal were observed. At one-stage XGM gain-control-type optical regenerator, received sensitivity and dynamic range was

degraded against input signal with degraded OSNR degraded. However, by using multiple stages, a XGM gain-control-type optical regenerator has possibility to operate for low OSNR.

By using cascade-structure, compared with gain saturation, XGM gain-control-type optical regenerator is improved as follows;

- Nonlinearity at low power region by XGM signal, causing maintaining extinction ratio
- Suppression of variation of the carrier density by using XGM signal
- Decreasing of the effect of frequency chirping by the method of XGM timing offset.

A XGM gain-control-type optical regenerator has the advantage for lowering frequency chirping effect against conventional gain saturation. I consider XGM gain-control-type optical regenerator is applicable for the optical regenerator with multiple stages.

Last, I indicate the performance of these two cascade-structured optical regenerator with other all-optical regenerator in Table. VII.1.

Table. VII.1 Performance of optical regenerators

	SOA				EA modulator	LD	HNLF
	XGM gain-control-type optical regenerator	CGCOR	XPM + Interferometer	FWM	XAM	Injection locking	SPM
Reported speed	40~Gbps	10~ Gbps	168 Gbps	40 Gbps	100 Gbps	10 Gbps	160 Gbps
Input power dynamic range	○~△(1~7 dB)	○ (6 dB)	△ (2 dB)	○	○	○	○
Conversion efficiency	○	○	○	△	△	○	△
Polarization efficiency	○	○	○	○	○	○/△	△
Extinction ratio	○	△	○	○	○	○	○
Wavelength dependency	○	○	○	○/△	○	△	○
Frequency chirping	○	△	○	△	○	○/△	○
Deveice size	1 mm	1 mm	1 mm	1 mm	100 μm	1 mm	10 km
Ref.	This work	This work	[21]		[30]	[31]	[35]

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- [2] H. Takeda and H. Uenohara, “Novel optical signal regeneration system using cascaded wavelength converter based on cross-gain modulation in semiconductor optical amplifier” Jpn. J. Appl. Phys, Vol. 42, no12A, pp. L1446-L1448, 2003
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