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論 文 要 旨

THESIS SUMMARY

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要旨（英文 800 語程度）
Thesis Summary（approx.800 English Words ）

The vertical-cavity surface-emitting laser (VCSEL) is a key light source in energy-efficient and high-speed optical interconnects in data centers and supercomputers. VCSELs have also been used in absorption spectroscopy, optical PC mouse applications and local area networks and so on. VCSELs have various merits such as low power consumption, ultra-fast modulation, low threshold current, small-foot print and low-cost in mass-fabrication. However, there still remain key challenges such as higher speed modulation of over 40 Gbps with low power consumption of below 100 fJ/bit for energy-efficient data center photonics. The resonance frequency of VCSELs determines the intrinsic modulation bandwidth of VCSELs. Since the resonance frequency increases as the square root of the drive current above threshold, high current densities may be required to increase the modulation bandwidth, which makes a difficulty in long term reliability. Therefore it has been practically hard to go beyond 40 Gbps in conventional VCSELs.

Recently, a Photon-Photon Resonance (PPR) effect has been used in single-mode edge emitting semiconductor lasers in order to increase their 3-dB modulation bandwidths far beyond the relaxation oscillation frequency.

In order to realize such an effect, we also studied coupled cavity VCSEL in which cavities are transversely coherently coupled. The author showed a possibility of bandwidth enrichment of conventional VCSEL by exploiting the photon-photon resonance effect. The world's fastest 980 nm VCSEL was achieved by exploiting the PPR effect. Although, the modulation speed was preliminary limited by the photo-detector limitation. In spite of the fact that, the 3-dB cut off frequency of over 29 GHz for the multi-mode TCC VCSEL could be observed. We also showed that by well designing of the shape of oxidation in TCC VCSEL, we can control the phase to be always in out-of-phase regime. As a result we could see 25 Gbps clear eye opening even at elevated temperature (0-60 ° C). We also fabricated a quasi-single mode (QSM) transverse-coupled cavity VCSEL with a smaller bow-tie shape aperture, which makes

current injection unnecessary in a feedback cavity. We demonstrate the modulation-bandwidth enhancement of a quasi-single mode VCSEL with a passive optical-feedback-cavity. The 3-dB modulation bandwidth can reach at 27 GHz, which is 3 times larger than a conventional VCSEL without optical feedback. Clear eye opening of large signal modulations at 36 Gbps is obtained. We also carried out the numerical simulation for further bandwidth enhancement. The modeling shows a prospect of the bandwidth enhancement beyond 40 GHz by optimizing optical feedback parameters. In order to realize a 40 Gbps modulation speed, we endeavored to combine this upshot with others possible effects. For this matter, we synthesized this phenomenon with push-pull effect. Author experimentally obtained 40 Gbps eye opening with mixed effects, while using only PPR effect eye was completely closed at this speed. Low extinction ratio in this measurement was mostly due to the lack of electrical amplifier to increase the modulation swing, while the total injected current was 20 mA for the combined cases, we could only apply voltage swing of 300 mV<. Although, this problem could be easily solved by increase of voltage swing to higher, but the current density for realizing the speed beyond 40 Gbps would be still too large. For this reason, we tried to combine the PPR effect with QCSE in electro-absorption modulator. Preliminary we reached up to 25 Gbps eye opening with high extinction ratio, while the voltage swing was the lowest ever reported (<400 mV_{pp}) and the size of device was also the smallest ever made (8 μm long).At the same time, we obtained 30 GHz small signal response for the composed phenomena (PPR and QCS effects), while some un-known noises raised up after 12 GHz, we could not reach higher bit rates at this experiment. In order to obtain the small signal noise free, further optimization of PPR effect is required. We also showed a possibility of spatial mode multiplexer/demultiplexer based on tapering of the hollow waveguide. The modeling results indicate that the cross talk between channels should be small enough to be used in practical application. Moreover, we proposed a highly efficient out-of-plane optical coupler based on a tapered hollow waveguide. Modeling shows low polarization and wavelength dependences in a 35 nm wavelength window (C-band). The relative lateral displacements per spot size of the vertical output for the entire C-band are less than 0.13 and 0.38 for TE and TM input modes, respectively. At the same time, the polarization-dependent insertion loss is below 1.35 dB for both TE and TM input modes. This device functions as a spot size converter, via taper angle modification, which can be used for a variety of applications such as out-of-plane coupling of VCSELs, detectors and so on. At last in order to realize green optical interconnect going beyond 1 Tbps, we propose a composition of taper hollow waveguide with the TCC VCSELs.