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Low-voltage electro-absorption optical modulator based on slow-light Bragg reflector waveguide

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We report on slow-light GaInAs/GaAs electro-absorption modulators with a Bragg reflector waveguide. We fabricated 20∼100 μm long compact modulators composed of triple GaInAs/GaAs quantum wells sandwiched by highly reflective Bragg reflectors. A large group index of 20 enables us to reduce the size of the modulators. We demonstrated 6 dB intensity modulation with a voltage swing V_{pp} below 0.5 V for 50 μm long devices. Shorter devices, for example with a length of only 20 μm, also showed an extinction ratio over 4 dB for sub-volt driving. Characterizations on wavelength dependence were also carried out experimentally. © *2013 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4789533]

Electric interconnects are confronting with development bottlenecks in large capacity data centers and super-computers. Much attentions are paid on optical interconnects with lower power consumptions, larger bandwidths, and higher connection densities.[1] Directly modulated vertical cavity surface emitting lasers (VCSELs) have been intensively developed for use in optical interconnects since they offer low-power consumption and small footprints. Their modulation speed is limited by their relaxation oscillation frequency. While high-speed direct modulations of VCSELs with small oxide apertures beyond 40 Gbps have been reported so far,[2] there have been still challenges in reliabilities for small oxide aperture VCSELs. An external modulator with low driving voltages can go beyond the direct modulation of VCSELs for higher speeds. However, the power consumption in modulators strongly depends on the modulator voltage swing hence low-voltage modulators are highly needed for low-power consumptions. There have been reports demonstrating modulators with a driving voltage below 1 V.[3–8] However, they are always at a cost of either narrow optical bandwidths or long device lengths. Also, there exists a fundamental difficulty in light source integration in small footprints. Electro-absorption (EA) modulators employing the quantum-confined Stark effect (QCSE) have shown good results in obtaining broad optical bandwidths and high-speed operation.[9–11] But there have been difficulties in getting a modulator voltage below 1 V in particular for miniature EA modulators. Both low-voltage operations and the miniaturization resulting in a low parasitic capacitance are needed to realize low-power consumptions and high-speed operations at the same time. If we could manage in reducing the light group velocity v_g in EA modulators, QCSE will be significantly enhanced thanks to the higher light-matter interaction brought by the slowing light effect. In this case, requirements in low driving-voltages (also voltage swing), large extinction ratios and high-speed operations can be fulfilled at the same time.

Slowing light has been a heat research focus in various photonic devices.[12] Miniature modulators based on photonic crystals with slowing light have been demonstrated.[13,14] In our group, we have demonstrated various functional devices based on slow-light Bragg reflector waveguides[15], such as optical modulators, optical switches, amplifiers, and beam scanners.[16–21] The slow-light inside the waveguide, which has a much lower group velocity v_g, can strongly interact with quantum wells, and hence we see a potential in obtaining a large ER with an ultra-short modulation length. An early device was fabricated with a dielectric top-mirror.[16] The modulator length is as small as 20 μm. However, the driving voltage is still not low enough (1 ∼ 2 V).

In this paper, we report a low driving-voltage and miniature EA modulator with a Bragg reflector waveguide operating at 980 nm-wavelength band. High-speed operation is very promising from the modulator's extremely small volume.

The ultra-compact modulator is fabricated on a VCSEL epitaxial wafer. The pair numbers of GaAlAs distributed Bragg reflectors (DBR) are 20 and 40 for the top- and bottom-mirror, respectively. An InGaAs/GaAs active region, which contains three quantum wells (3QW), provides electro-absorption. Oxidization-type confinement layer realizes a lateral optical confinement and a low parasitic capacitance. A schematic cross-section view of this waveguide-type modulator is illustrated in Fig. 1. "Slow-light" propagation is excited

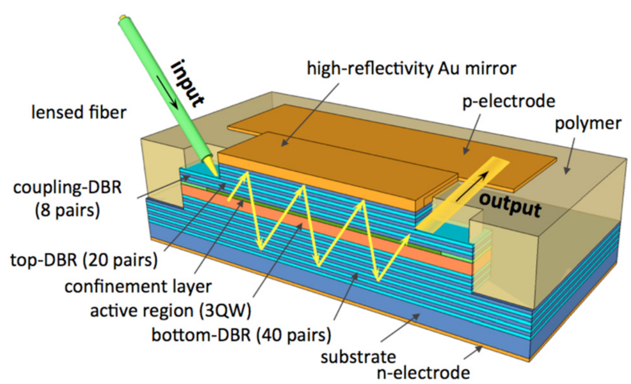

FIG. 1. A schematic cross-section view of the slow-light Bragg reflector waveguide modulator.

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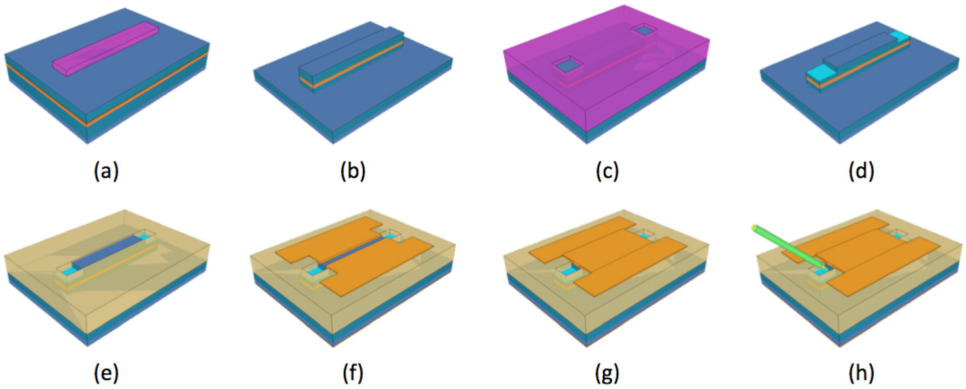

FIG. 2. Fabrication process: (a) resist patterning by lithography; (b) dry-etching to form the waveguide structure; (c) resist patterning by lithography; (d) dry-etching to form the coupling and out-coupling regions; (e) polymer patterning by lithography; (f) p- and n-type electrodes deposition and lift-off; (g) device completion after high-reflectivity gold mirror deposition; (h) lensed-fiber coupling.

applying a tilt-fiber coupling scheme[22] from a lensed fiber at the coupling region, where 8 pairs of a top-DBR are remained. Out-coupling region has the same structure as the input-coupling region and both were formed by dry etching. Polymer (AL-X2010, Asahi Glass) is used to protect the waveguide sidewalls from current leakage. A brief flow chart of the fabrication process is illustrated in Fig. 2. Top-view photos for 20 μm and 50 μm long devices are shown in Fig. 3(a). The waveguide width (non-oxide aperture) is 3 μm.

After slow-light is excited inside the waveguide, it propagates in a zigzag route. The loss of this propagation is very low because both the top- and bottom-mirrors have high reflectivity of over 99.9%. When we apply a negative bias voltage V_b on the device, electro-absorption takes place in the active region and the intensity decreases along the propagation direction. As a result, output intensity is decreased when a larger negative bias is applied. To be noted here, the cutoff wavelength and photo luminance (PL) peak of this epi-wafer are approximately 980 nm and 950 nm, respectively. In this slow-light Bragg reflector waveguide, the modulation efficiency is much higher than conventional waveguide modulators with the same device length. This slow light propagation scheme allows an ultra-low driving voltage, while the modulator length is significantly decreased.

The waveguide structure is the same as our beam steering device in Ref. 20. We are able to obtain the propagation constant β of a slow-light mode from a beam steering angle θ as $\beta = 2\pi \times \sin\theta/\lambda$. The group index n_g is obtained from the dispersion of the propagation constant. Figure 4 shows the measured wavelength dependence of a group index for TE mode. The simulation result is also plotted by a solid line. A group index of over 20 in the wavelength range of 960 ~ 980 nm is large enough to make a modulator length five times shorter than conventional waveguide modulators.

The extinction ratio (ER) is a key parameter for modulators. We used a near-field pattern (NFP) measurement system to make characterizations. Figure 3(b) shows the NFPs when V_b is 0 V and -1.0 V. Output intensity is clearly modulated. Some reflected lights can be observed at the input-coupling region due to an imperfect coupling. For example, before and after inputting a 300 μW TE-polarized 965 nm light, the photo-current change in the device is $\sim$130 μA at -1.2 V bias. A coupling efficiency is approximately 3 dB here. The minimum insertion loss we obtained in experiment is $\sim$8 dB, which counts for the coupling loss, a propagation loss and an out-coupling loss. The major loss in coupling and out-coupling can be improved by further optimizing the fiber coupling scheme.[22] The only intrinsic loss of propagation is in fact not large thanks to the high top-mirror reflectivity and extremely short device length. The change in the spot sizes

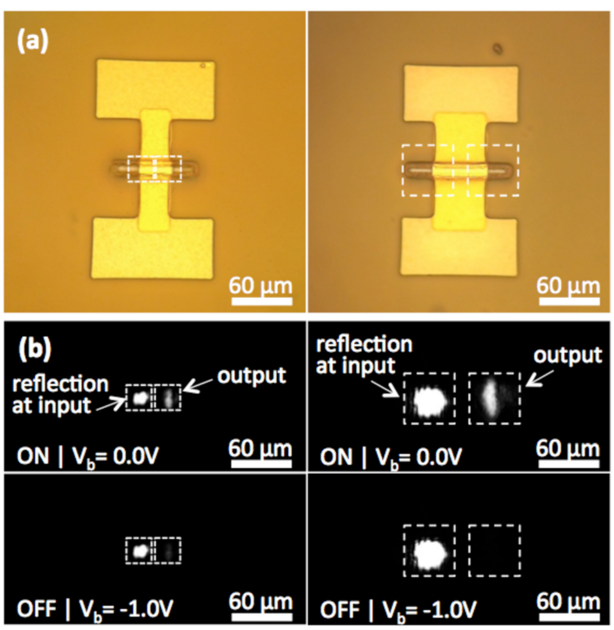

FIG. 3. (a) Top-view photos of the fabricated devices: 20 μm long modulator (left), and 50 μm long modulator (right); (b) Measured near-field patterns at different bias voltages.

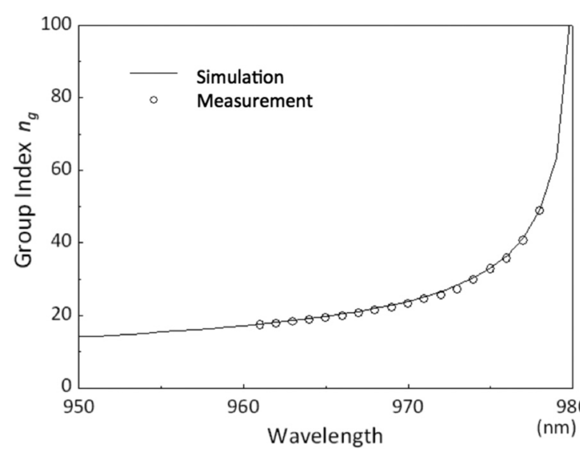

FIG. 4. Measured wavelength dependence and calculation of group index for TE-polarized input.

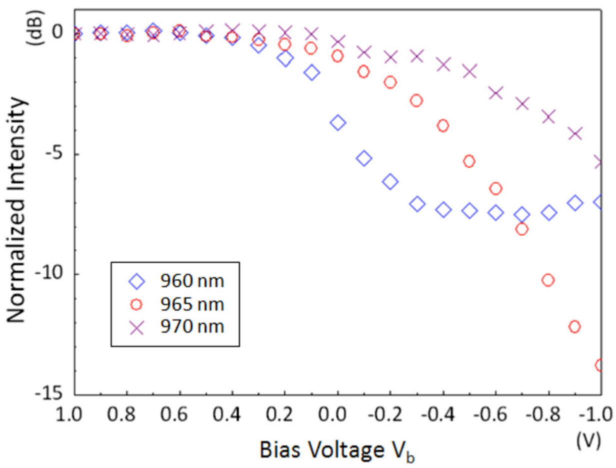

FIG. 5. Intensity versus bias voltage of a 50 μm device for different input wavelengths.

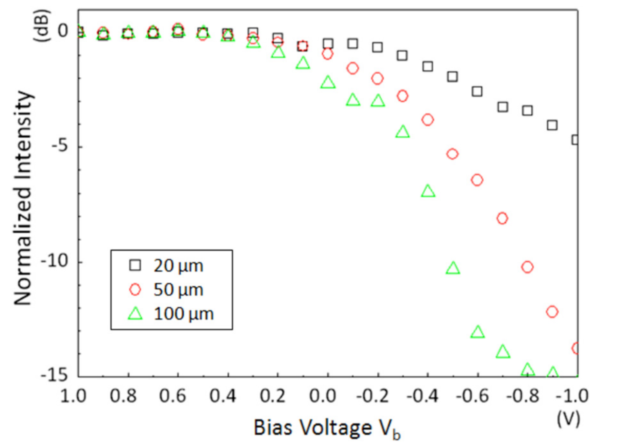

FIG. 6. Intensity versus bias voltage for devices with different lengths at the wavelength of 965 nm.

and shapes in Fig. 3(b) are due to the difference in camera focusing points, which were adjusted during measurements in order to capture clear and separate reflection light and output. We tried to see the static modulation dependence on wavelength. A 50 μm long modulator was measured with input wavelengths of 960, 965, and 970 nm, respectively. Output intensities for different V_b are shown in Fig. 5, normalized referring to the intensity when $V_b = 1.0$ V. For a positive bias larger than 0.5 V, the intensity almost keeps constant because there is a built-in potential inside the waveguide. When the bias is decreased, especially to negative values, output intensity is significantly weakened. For shorter wavelengths, a faster light extinction can be observed because it is nearer to the PL peak wavelength of QWs. At the wavelength of 960 nm, 5.4 dB ER is obtained with a V_{pp} of 0.4 V (+0.1 V ~ −0.3 V). Higher ER cannot be reached due to some remained light at the out-coupling region, which is caused by the poor coupling. The current waveguide structure, fiber insertion angle and position are optimized for longer wavelengths. By using a wafer with shifted PL peak or modifying the waveguide structure, higher ER is expected. At a wavelength of 965 nm, an ER as large as 12.9 dB is observed with a V_{pp} of 1.0 V (0.0 V ~ −1.0 V), even though the modulation efficiency is slightly poorer than that of 960 nm. The wavelength dependence comes from the dispersion of the group index and QCSE. The optical bandwidth of the present device is estimated to be several nanometers, which could be expanded by optimizing the detuning from the PL-peak wavelength and the cut-off wavelength.

We also investigated modulators with different device lengths. Three devices with lengths of 20, 50, 100 μm were tested and compared. We show the measured results in Fig. 6. We successfully obtained an ER over 4 dB on a device as small as 20 μm in length with a V_{pp} of 1.0 V (0.0 V ~ −1.0 V). Longer devices require lower driving voltage. For the 100 μm device, we successfully achieved 6.0 dB ER with a V_{pp} as low as 0.2 V (−0.3 V ~ −0.5 V). 14 dB ER was obtained with a V_{pp} of 1.0 V (+0.2 V ~ −0.8 V). Longer device can provide lower driving voltage and higher ER. However, so far the slow-light propagation loss is still not low enough, thus the maximum device length is limited by the increased insertion loss. By further increasing the top-mirror reflectivity as well as lowering the material absorption in waveguide, low-loss propagation will be possible and longer devices can be made for reducing modulator voltages.

The VCSEL-based slow light modulators we demonstrated this time are with lengths from 20 to 140 μm (including coupling/out-coupling regions) and a width of 3 μm. The devices' volumes are extremely small thus high-speed modulation is very prospective thanks to small parasitic capacitance. Our next goal is to further reduce the device volume and electrode size for testing high-speed modulations. The device can be potentially integrated with a VCSEL,[18] which may provide high-speed modulation and low power consumption at the same time for use in large-scale optical interconnects.

In conclusion, we fabricated an ultra-compact modulator based on a slow-light Bragg reflector waveguide. Modulator length varies from 20 μm to 100 μm in this experiment. A low voltage swing V_{pp} was obtained thanks to the low group velocity of slow-light. For a 50 μm device, an extinction ratio ER of 5.4 dB was achieved with a V_{pp} as low as 0.4 V. The voltage swing is in a comparable level of directly modulated VCSELs or even lower. 14 dB ER was obtained keeping the V_{pp} no larger than 1.0 V. Modulators of longer lengths can provide the same ER with a smaller V_{pp}. Wavelength dependence was also investigated. Input signal with a wavelength closer to the photo luminance peak of QWs showed more efficient modulation, which can be explained by the nature of quantum confined stark effects. The proposed modulator has an extremely small device volume, which shows its great potential for use in low-power consumption and high speed optical interconnects.

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