Modeling and Experiment on Low Voltage Slow-Light Electro-absorption Modulators for High-speed and Low Power Consumption Optical Interconnect

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Abstract

Optical interconnects offer significant advantages for future high performance computers and large scale data centers. The development of low-voltage and high-speed modulators would be a challenge for further increase of the link capacity with low power consumption. we present the modeling and the experiment toward ultra-low voltage (<500mV) and small footprint (<50μm) electro-absorption modulators. We fabricated Bragg reflector waveguide slow light modulators with GaInAs/GaAs QW electro-absorption. We present the modeling and the measurement on their static characteristics including their near-field patterns with different applied voltages. While extinction ratios are lower than the modeling, sub-volt modulation can be seen for miniature devices below 100μm. In addition, we calculated the power consumption by simple circuit of modulator. As a result, a possibility of low power consumption below 100fJ/bit is presented.

Introduction

Optical interconnects are attractimg great interest for use in data centers and supercomputers. High-speed VCSELs have played a major role for reducing the power consumption in massively parallel interconnects. The development of low-voltage and high-speed modulators would be a challenge for further increase of the link capacity to go beyond 40Gbps. In order to reduce power consumption, low-voltage operation is a key issue. Low voltage swing modulators have been reported so far [1-3], however, there still remain difficulties in their size, optical bandwidth and so on. We proposed and demonstrated a slow-light modulator with a Bragg reflector waveguide [4] based on VCSEL technologies, enabling us to make a modulator smaller [5]. Recently, we presented a possibility of ultra-low voltage operation in our slow light modulators [6]. In addition, we are also able to integrate the modulator with a VCSEL laterally [7]. In this paper, we present the modeling and the experiment toward ultra-low voltage (<500mV), small footprint (<50μm), and potentially low power consumption (<100fJ/bit) electro-absorption modulators.

Device Structures

The schematic cross-section views of our two types slow-light modulators are shown in Figs. 1 (a) and (b). Its basic structure is the same as that of 980nm InGaAs/GaAs VCSELs. An input light is coupled through a lensed fiber with a tilt angle to the slow-light waveguide, which will also be directly coupled form a VCSEL for future work [7]. A so-called 'slow-light' mode is excited inside the waveguide and travels in a zigzag route as schematically shown in Fig. 1. It can promote stronger electro-absorption in QWs thus the device can be made smaller thanks to slowing light. The number of distributed Bragg reflectors (DBR) on the top- and bottom-mirror, which determines the mirror reflectivity, is 20 and 40, respectively. 9 pairs of top-mirror DBR are left after etching at the fiber coupling region [6]. It is designed for a high coupling efficiency. The reflectivity of the top-mirror is so designed as to radiate a portion of light from the surface. If we apply a reverse bias voltage on the device, the increased electro-absorption due to quantum confined stark effect (QCSE) decreases the radiated intensity [6].

In this paper, we focus on especially low voltage operation and miniaturization of the device. While there is tradeoff between low voltage and device length, it is noted that the reduction of the device length leads to the reduction of the paracitic capacitance, and therefore the miaturization will lead to high-speed operations.

We discuss two types (Radiation Type and Waveguide Type) of modulators as shown in Fig.1. The reflectivity of the top-mirror is designed to radiate a portion of light from the surface in Radiation Type. If we apply a reverse bias voltage, the increased electro-absorption due to quantum confined stark effect (QCSE) decreases the propagation distance and hence the total radiation intensity. On the other hand, the output can also be

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taken only at the end of the modulator in Waveguide Type by depositing Au film on the surface as shown in Fig. 1(b).

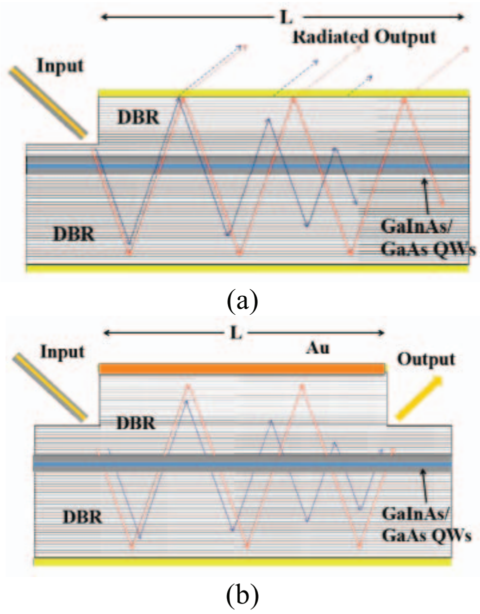

Fig.1 Schematic structures of slow light electro-absorption modulator with Bragg reflector waveguide: (a) Radiation Type and (b) Waveguide Type.

Modeling

We carried out the device modeling for these two types of modulators, and discuss the miniaturization and low voltage operation of our modulators. The calculation is based on the electro-absorption data of 980nm GaInAs QWs [8]. The radiaiton loss though the top DBR was calculated by the full-vectorial waveguide simulator (FIMMWAVE by Photon Design), which is based on the mode matching method [9]. The operating wavelength is assumed to be 995nm, which is about 15nm detuned from the absorption peak of QWs. The group index is around 20, thus the device length can be shortened by a factor of 6 thanks to slowing light.

Figure 2 shows the calculated output intensity (insertion loss) as a function of reverse-bias voltages for two types of modulators. The blue line shows the result for a 100μm long rariation-type device, while the black and red lines show that of waveguide-type devices with a device length of 30μm and 80μm, respectively. The insertion losses at 0V bias voltage are 3-5dB. The result shows a possibility of an ultra-low bias voltage operation of below 0.5V for a 80μm long device length with 5dB extinction ratio. Moreover, an ultra-compact modulator of below 30μm can be expected with a low bias voltage swing of 1.0 V. Further optimization can be expected by adjusting the operating wavelength. The result indicates a potential of a sub-volts swing with a device length below 100μm for getting an extinction ratio of over 5dB.

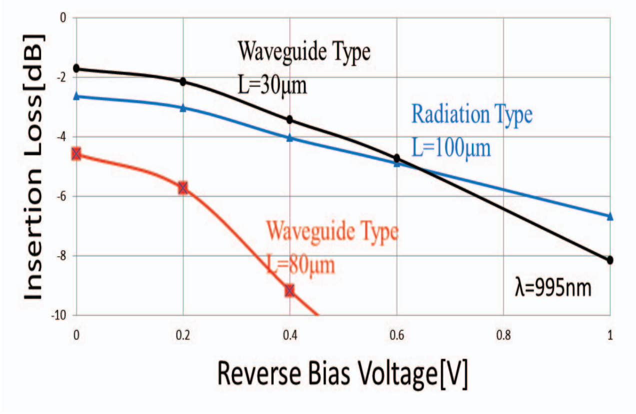

Fig. 2 Calculated output intensity as a function of reverse bias voltages for two types of slow light modulators. The wavelength detuning from PL peak wavelength is assumed as 15nm.

Measurement

We fabricated radiation-type slow light modulators. Figure 3 shows the top view and the schematic cross-section view of the device. The number of pairs of top DBR is 20, and the number of pairs of the bottom DBR is 40. The absorption layer is GaInAs/GaAs 3QWs with aPL peak wavelength of 980nm. Input light from a tunbale laser source is coupled to slow light modulator through a lensed fiber. In the coupling area, the top DBR which was partly etched off to reduce the reflectivity. The increased electro-absorption due to QCSE by appling reverse bias voltage decreases the radiation intensity, so we measured the radiation intensity from the surface of the device.

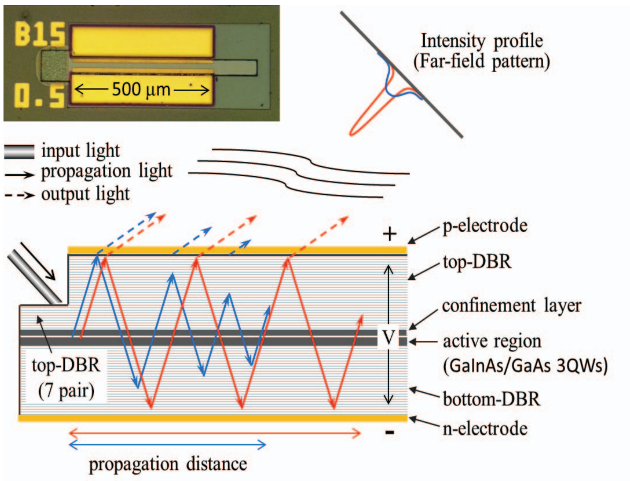

Fig. 3 Top view and the schematic cross-section view of a fabricated slow light modulator.

We measured their near-field patterns with different voltages as shown in Fig. 4. Clear decrease in propagation distance can be seen with applying a reverse bias voltage. The integrated intensity and the intensity at a fixed distance from the input (80μm in this case) offer the experimental data for Radiation Type and Waveguide Type modulators. Those are plotted as a function of reverse bias voltages in Fig. 5. The red line shows the measurement results of a 80μm long waveguide type modulator, and the blue line shows that of a 100μm long radiation type modulator. While extinction ratios are lower than the modeling, sub-volt modulation can be demonstrated for miniature devices below 100μm.

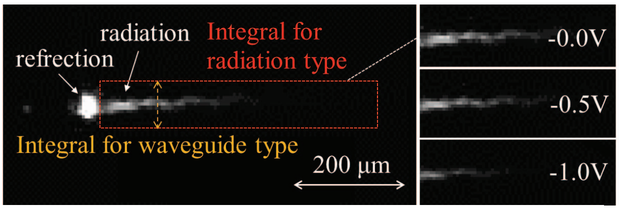

Fig. 4 Measured near-field patterns with different reverse bias voltages.

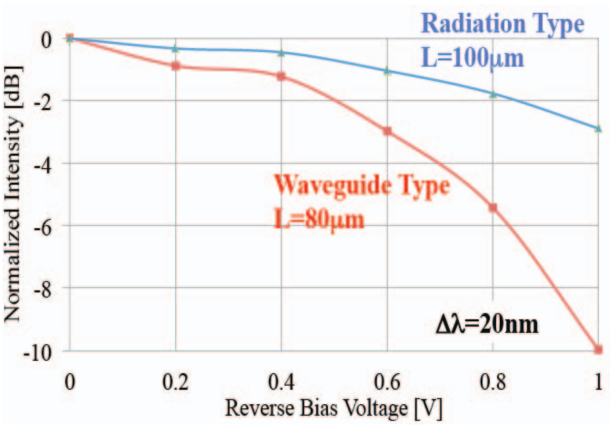

Fig. 5 Measured output intensity as a function of reverse bias voltages for two types of slow light modulators. The intensity was normalized by the intensity at V=0V. The wavelength detuning is 20nm. The data were obtained from the near-field patterns shown in Fig. 4.

We also measured the wavelength dependence for the waveguide type modulator in the same way as shown in Fig. 6. The amount of detuning wavelength from the PL peak wavelength is varied from 11nm to 19nm. The result indicates sub-volt modulation can be expected for getting an extinction ratio of over 5dB in the 10nm wavelength band. This wavelength window is enough for the laterally integrated structure with a VCSEL in the same chip.

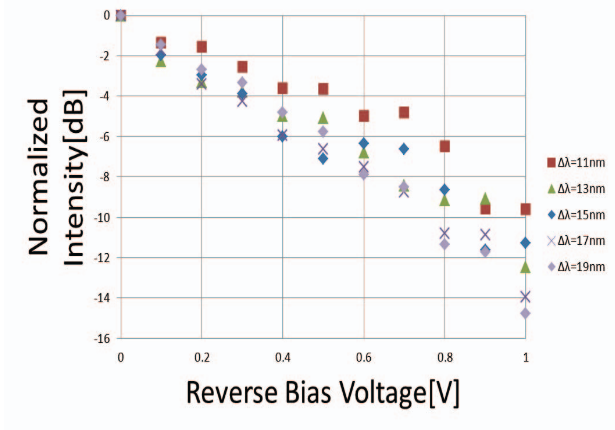

Fig. 6 Measured wavelength dependence for waveguide type modulator. The intensity was normalized by the intensity at V=0V. The wavelength detuning is from 11nm to 19nm. The data were obtained from the near-field patterns.

Discussion

We show a simple equivalent circuit model of an electro-absorption modulator in Fig. 7. The power consumption of this circuit is expressed by the following equation. C is the parasitic capacitance, V is the modulation voltage, I_p is the photocurrent, B is the modulation speed and R is the termination resistance.

$$P = \frac{1}{2}\left(\frac{V}{RB} + \frac{I_p}{B} + CV\right)V \qquad (1)$$

Here we assume the following parameters: a device length of 50μm, a width of 20μm, a depletion layer thickness of 300nm, a termination load resistance of 50 Ω, a bit rate of 40Gbps. While we could estimate power consumption of 120fJ/bit, we can expect the possibility of the low power consumption of less than 100fJ/bit..

Conclusions

We carried out the modeling and experiment on Bragg reflector waveguide slow light modulators with GaInAs/GaAs QW electro-absorption. Our modeling and preliminary experiment show a possibility of sub-volts swing modulation with small footprint. We estimate that the optical band is more than 10nm, and the energy consumption per bit is as low as 100fJ/bit, which can boost the speed beyond 40Gbps and can reduce the total transmitter energy in optical interconnects.

The integration with a low threshold VCSEL can meet the demand for high-speed and low power consumption optical interconnections in large-scale data centers and supercomputers.

Achnowledgement

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