Silicon Waveguide Grating Modulators

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Silicon waveguide grating modulators are such silicon modulators with waveguide gratings introduced to the modulation regions. As a kind of period optical structure, the waveguide gratings in the modulator will generate slow light effect to increase the light-matter interaction. Through this approach, the modulation efficiency can be enhanced and a more compact modulator footprint can be obtained. Simultaneously, silicon waveguide grating modulators can be fabricated under CMOS process which have lower process requirements than silicon photonic crystal modulators. While maintaining high-speed performance and CMOS compatibility, silicon waveguide grating modulators have ultra-compact footprint compared with conventional silicon Mach-Zehnder modulators, which will play an important role in future high-density optoelectronic integration.

silicon photonics slow-light effect electro-optic modulators

1. Introduction

For two-dimensional photonic crystal, the fabrication is still relatively challenging under the standard CMOS manufacturing process, which has relatively higher requirements on the process. The photonic crystal structure has a low tolerance to the fabrication process. If there is a small deviation in the parameters during the process, the performance will change obviously, and the structural quality is indeed prone to deviation in the fabrication, thus causing difficulty for large-scale wafer manufacturing. In order to avoid process limitations and take the advantage of CMOS compatibility for silico modulators, silicon slow-light modulators based on waveguide gratings have been proposed and fabricated theoretically and experimentally in recent years.

2. All-Silicon Waveguide Grating Modulators

In 2011, A. Brimont et al. demonstrated a silicon slow-light modulator with Mach–Zehnder interferometer to explore the effects of introducing grating structures into silicon modulator waveguides. The slow-light effect changes the group index, and they illustrated that the modulation efficiency changes with the group index experimentally. In fact, the modulation efficiency of the modulator is enhanced by the increase of the group index. When the group index increases up to 22, the modulation efficiency achieves a value of 0.45 V·cm. Meanwhile, the EO bandwidth of two modulators with slow-light phase-shifter lengths of 0.5 mm and 1 mm can reach 16 GHz and 11 GHz, respectively [1]. For slow-light phase-shifters of 500 μm, the modulator achieves an eye diagram of 40 Gb/s with 6.6 dB extinction ratio at quadrature, with an enhanced modulation efficiency of 0.85 V·cm and on-chip insertion loss of 6 dB [2]. For 1 mm slow-light phase-shifters, the high modulation efficiency of 0.6 V·cm allows the modulator to work from 5 Gb/s with 1 Vpp up to 25 Gb/s with 3 Vpp. The low drive voltages make the device more suitable for the application of CMOS transceivers, but the insertion loss is relatively high, reaching 12 dB [3]. It can be seen that the modulation efficiency has been significantly improved, thus the footprint can be reduced to the order of several hundred microns, and achieve a favorable eye diagram at high speed, while containing the length of 1 mm is beneficial for achieving a low drive voltage. It is worth noting that the waveguide grating modulator is very suitable for manufacturing under CMOS fabrication process. As early explorations into the introduction of waveguide grating structure in silicon modulators, these results demonstrate experimentally that the slow-light effect brought by waveguide grating can enhance the performance of silicon modulators under CMOS fabrication process.

In 2015, M. Caverley et al. reported a silicon modulator with quarter-wave phase-shifted Bragg grating resonator on the SOI platform. With a length of 155 μm, the modulator has two ports, through port and reflect port. The modulated output signal is mainly obtained from the reflect port, which has a spectral response of a sharp notch, and the modulator demonstrates the EO bandwidth of 26 GHz, and achieves the OOK eye diagram of 32 Gb/s with a bit error ratio (BER) of less than 10^{-10} of 25 Gb/s. However, the spectrum of the modulator is very narrow, and its operation is affected by the wavelength, which affects its practical application [4]. In 2016, K. Bédard et al. demonstrated a dual phase-shift silicon modulator with Bragg grating structure. The silicon waveguide grating modulator achieves an OOK signal up to 55 Gb/s with MMSE equalization and up to 50 Gb/s without equalization, while PAM-4 signal is illustrated at 60 Gb/s. However, although the modulation speed is high, this modulator has a long length of 825 μm with a narrow spectrum, which is insufficient to illustrate advantages compared to conventional silicon MZMs and MRMs [5].

It can be seen that the slow-light effect introduced by the grating structure in the silicon modulators improves the modulation efficiency, thereby reducing the energy consumption. In order to study the effect of silicon modulator assisted by waveguide grating on reducing energy consumption specifically, in 2018, R. Hosseini et al. investigated the slow-light effect on improving the energy efficiency of the modulator and compared it with conventional methods by increasing doping concentration. Considering the trade-off between the modulation efficiency and loss, the loss–modulation efficiency product figure of merit was proposed. Under the condition of the similar energy reduction, the loss-modulation efficiency product of the slow-light waveguide is smaller than that of the high-doping modulator. The research has shown the ability of the slow-light structure to reduce the energy consumption theoretically [6]. However, the analysis of the model is not comprehensive enough, and the influence of the waveguide parameters on various performance parameters of the modulator is not illustrated in detail.

Due to the introduction of the grating structure into the modulator waveguide, the parameters and period of the grating will have a significant impact on the performance of the modulator. Through establishing a quantitative model, the different parameters of the grating will be related to the performance of the modulator directly. Therefore, establishing a precise simulation model of a silicon slow-light modulator assisted with waveguide grating will guide the specific design. In 2019, O. Jafari et al. demonstrated the design of silicon integrated Bragg grating resonators modulator. In each arm of the Mach–Zehnder interferometer, a series of Bragg gratings resonators are introduced to enhance the phase modulation ability based on slow-light effect. Therefore, the designed silicon Bragg gratings modulator has stronger phase modulation capability than that of conventional silicon MZMs, while holding a large optical bandwidth compared to silicon MRMs. They established a complete theoretical model to explore the effect of different Bragg parameters, including NOP and NOR (NOP: number of periods of the resonator mirrors on each side; NOR: number of resonators), on the device performance. Therefore, the modulator was optimized according to the modulation efficiency, efficiency factor, enhancement factor, and optical bandwidth. Through the simulation modeling, the variation law of the performance of the device with the structural parameters was more completely and intuitively reflected, which has reference significance for the practical design of the device. In particular, according to the dynamic response model of the modulator based on the coupled-mode theory, the large-signal analysis was performed using the finite-difference time domain and the OOK eye diagram up to 110 Gb/s, showing the ultra-high-speed operation potential of the modulator [7]. Furthermore, focus on the efficiency–speed tradeoff in silicon slow-light modulators, they established a comprehensive model for the EO response of lumped-electrode slow-light modulators. Meanwhile, for the silicon slow-light modulators with traveling-wave electrodes, they used the finite-difference time-domain method to show that the efficiency and speed can both be improved under an optimized slow-light effect. The relationship between the EO bandwidth and enhancement factor is demonstrated in Figure 14D. However, the additional loss caused by slow-light waveguide limits the application of such modulators [8].

Meanwhile, optimizing the PN junctions is also the method to improve the modulation efficiency for the silicon modulator. The modulation efficiency can be improved by introducing interleaved PN junction, and combining these two structures to further optimize silicon modulators has also become an attractive research point. In 2019, M. Passoni analyzed this composite structure theoretically. Based on the silicon slow-light modulator with the waveguide grating structure in **Figure 1**A, the interleaved PN junctions with the same period as the grating were introduced into the modulation arm, to achieve optimal matching between the electromagnetic field and the depletion regions of the PN junction, thereby further improving the performance of the modulator. The bandwidth of the modulator was increased by the interleaved PN junction, because the spatial matching between the field of the grating and the depletion region is independent for wavelength. According to the simulation results, the modulation efficiency was improved compared to the conventional silicon modulator, with 0.1–0.5 V·cm over a bandwidth of 20–30 nm, as shown in **Figure 1**C. The research illustrates the trade-off between modulation rate, loss, and energy consumption. However, the optimization of the device was not enough, and further optimization should be able to get better results [9]. Furthermore, they developed the full simulation of the silicon slow-light modulator with interleaved PN junction along the waveguide axis, as in **Figure 1**B. The simulation investigated the optical modulation amplitude (OMA), which accounts for loss and modulation efficiency, further elaborating the trade-off among modulation efficiency, cutoff frequency, optical modulation amplitude, insertion loss, and dissipated energy per bit. **Figure 1**D demonstrates the comparison of modulation efficiency, IL (Lπ), for phase-shifters in four different conditions. After introducing the structure of the interleaved PN junction, the optical bandwidth is wider than the slow-light bandwidth. Under the condition of 1 V reverse bias, the modulator can achieve an energy below 0.5 pJ/bit and a bandwidth of tens of nanometers with a length below 0.5 mm (**Figure 1**E). This simulation demonstrates that a suitable design of interleaved PN junction will enhance the performance of silicon slow-light modulator for reducing power dissipation [10].

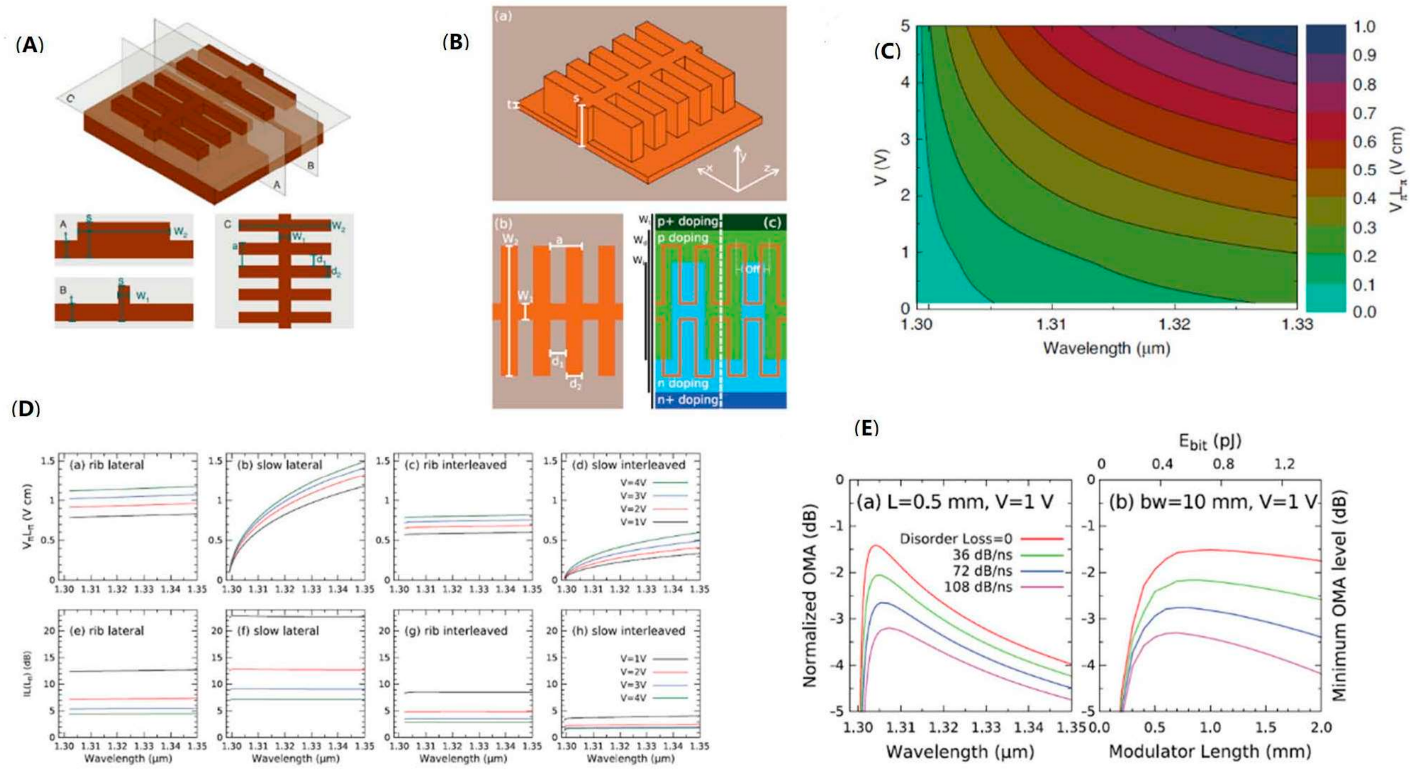

Figure 1. The model of silicon waveguide grating modulator with interleaved PN junction. (**A**) Structure of the slow-light waveguide grating [9]. (**B**) Schematic of the slow-light waveguide with interleaved PN junctions [10]. (**C**) Modulation efficiency change with wavelength and bias voltage [9]. (**D**) The comparation of VπLπ, IL (Lπ) for phase-shifters in four conditions: rib waveguide with lateral PN junction; slow-light waveguide with lateral PN junction; rib waveguide with interleaved PN junction; slow-light waveguide with interleaved PN junction [10]. (**E**) Normalized OMA variation with different parameters of the silicon slow-light modulator [10].

On the basis of the previous exploration of simulation research, the practical experimental performance research of silicon waveguide grating modulators has also made progress in recent years. In 2020, O. Jafari et al. demonstrated a silicon slow-light modulator assisted by phase-shifted Bragg gratings experimentally, which was fabricated under CMOS process. The integrated Bragg grating resonators enhanced the phase modulation efficiency significantly, and a small-signal Vπ × L of 0.18 V·cm was obtained, which is an extremely high value for an all-silicon modulator. These experimental data prove the significant effect of the slow-light structure on improving the modulation efficiency of the modulator. Meanwhile, the modulator shows an EO bandwidth of 28 GHz and an optical bandwidth of 2.9 nm, with a length of 162 μm, which is much smaller than that of conventional silicon MZMs. The optical bandwidth is larger than that of the silicon modulators with waveguide grating reported before, which should provide an operating temperature range larger than 40 °C and illustrate the advantage compared to silicon MRMs. Meanwhile, OOK modulation is demonstrated at 30 Gb/s with a BER below the 7%-overhead FEC threshold. However, in general, although the modulation efficiency and footprint of the modulator have both achieved ideal values, the EO bandwidth of the modulator is still not large enough and the high-speed performance is limited, while the optical bandwidth also has a certain space for optimization for a more stable working condition [11].

Furthermore, based on the slow effect introduced by the structure of integrated Bragg grating resonators above, a segmented slow-light modulator was designed for PAM-4 signal transmission. This segmented modulator has a compact footprint of 570 μm, low energy consumption of 73 fJ/bit, high modulation efficiency of 0.51 V·cm, large EO bandwidth of 40 GHz up. A high-speed PAM-4 signal is generated by driving the segmented phase-shifter without an electrical digital-to-analogue converter (DAC), and 90 Gb/s PAM-4 is achieved over a spectral operation of 2 nm. This experimental result demonstrates the potential of silicon waveguide grating modulators to transmit complex signal, and also illustrates the possibility of co-designing silicon waveguide grating modulators as a unit for complex functions under CMOS fabrication process [12].

Meanwhile, in 2021, O. Jafari et al. designed a silicon mode-conversion modulator, combing the structure of asymmetric Bragg grating with lateral and interleaved PN junctions (C-LI) to enhance the phase modulation ability. Under the mode conversion brought by an asymmetric Bragg grating, the modulator can work in reflection mode. Meanwhile, after employing the lateral and interleaved PN junction, the modulator gains a 67% improvement in the phase modulation. The modulator achieved 45 Gb/s with a BER below the 7% forward-error-correction (FEC) threshold and 55 Gb/s with 20% . The modulator has a length of 290 μm, a low loss of 2 dB, and a low power consumption of 226 fJ/bit, but the EO bandwidth is only 11.2 GHz, which limited the high-speed performance. Although the absolute performance of this modulator is limited, the idea of introducing mode conversion based on Bragg gratings and different PN junction profiles is instructive, which will also generate inspiration for designing other new devices based on the effects introduced by grating structures [13].

3. Silicon-Based Hybrid Waveguide Grating Modulators

As discussed above, all-silicon waveguide grating modulators demonstrated the advantages of compact footprint, high modulation efficiency, and low energy consumption. Meanwhile, the silicon-based hybrid waveguide grating modulator has been investigated to enhance the performance further based on the properties of other material and the benefits of slow-light effect, such as hybrid lithium niobate waveguide grating modulator.

In 2021, X. Huang et al. reported a sub-millimeter-long hybrid silicon-rich nitride and thin-film lithium niobate modulator based on Bragg grating waveguides. This modulator is based two 800 μm Bragg grating waveguides, which serve as phase-shifters. By operating at the band edge of Bragg grating, the modulation efficiency is greatly enhanced with slow-light effect, increasing the light–matter interaction time. Using this modulator, an insertion loss of 1.9 dB and a modulation efficiency of 0.67 V·cm were experimentally demonstrated with 60 Gb/s data transmission [14].

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