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High Efficiency Single-Sideband Modulator using Coupled Bragg Grating Resonators on Thin-Film Lithium Niobate

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Abstract: We demonstrate an efficient single-sideband thin-film lithium niobate modulator with periodically cascaded Bragg gratings. The device achieves the highest modulation efficiency that has been reported (0.19 V/cm) with a compact phase-shifter length (542 μm).

1. Introduction

Lithium niobate ($LiNbO_3$, LN) has emerged as a prominent photonic material due to its exceptional and versatile features, including a broad transparency window (~0.35–5 μm), robust electro-optic behavior (γ33=30.8 pm/V), and low optical loss [1]. The development of wafer-scale, high-quality thin-film lithium niobate (TFLN) on insulators has captured the interest of integrated optics researchers. TFLN not only retains the outstanding physical properties of LN but also significantly improves optical field confinement and augments element integration density [2]. However, in order to achieve low-drive voltage compatibility with Complementary Metal-Oxide-Semiconductor (CMOS) circuits, the scalability of these devices has been confined to the centimeter range, preventing large-scale integration on the TFLN platform. To enhance modulation efficiency, two typical approaches are often considered: increasing electric field intensity and reducing the speed of light. Nevertheless, due to loss restrictions, the former has an upper limit to the feasible modulation efficiency, making an order-of-magnitude improve nearly unachievable [3]. The latter strategy, which attempts to delay light to extend the time of light-matter interaction, can result in a significant improvement in modulation efficiency in optical systems such as photonic crystals [4]. However, photonic crystals are extremely sensitive to the changes in geometric parameters [5]. To mitigate this sensitivity to manufacturing errors, the Bragg grating have been introduced as an alternative to replace photonic crystals [6].

Therefore, in this work, we introduce a high efficiency TFLN modulator based on a periodically cascaded Bragg grating that induces a slow light effect within the modulator arm. Taking advantage of the substantial increase in group delay at the passband edge, we achieve a remarkable modulation efficiency of 0.19 V·cm with a compact length of 542 μm. Furthermore, we explore single-sideband (SSB) modulation through the intrinsic filtering effect of the cascaded Bragg grating.

2. Structure and Design

The configuration of the TFLN modulator is visually presented in Fig. 1(a). The Mach–Zehnder interferometer (MZI) modulator is composed of interconnected Bragg resonators and multi-mode interferometers. Lateral spacing of gold traveling-wave electrodes is achieved within a ground-signal-ground layout, and the modulator operates utilizing a single-drive push-pull configuration. The Bragg grating has been intricately designed to possess a duty cycle of 50% and a uniform period of 0.42 μm, ensuring its central wavelength in proximity to 1550 nm. The waveguide width is set at 1.1 μm, complemented by a sidewall etching depth of 0.15 μm. A series of Bragg gratings is strategically arranged to create a coupled Bragg grating resonator, inducing a slow light effect. Within the coupled Bragg grating resonators, each independent resonator encompasses a pair of Bragg grating mirrors and a phase shifter with half a period. In this context, the grating comb parameter Np is set to 25, and the number of grating cascades, denoted as Nr, is also 25.

Notably, at the band gap edge of the grating structure, a distinct and narrow slow light resonance emerges. In this scenario, light in proximity to the edge of the reflection peak undergoes partial reflection and partial transmission. As this reflected light traverses the grating and returns to the input, the principle of reciprocity dictates that it will be reflected once more [7]. Consequently, light positioned at the border of the reflection peak oscillates back and forth within the grating, resulting in stronger interactions and an associated increase in group delay. This corresponds to an elevated group refractive index, consequently enhancing the modulation efficiency.

Furthermore, the inherent filtering characteristics of the Cascade Bragg grating can be exploited to selectively isolate one half of the sideband, leaving only a single sideband intact, facilitating the formation of SSB modulation.

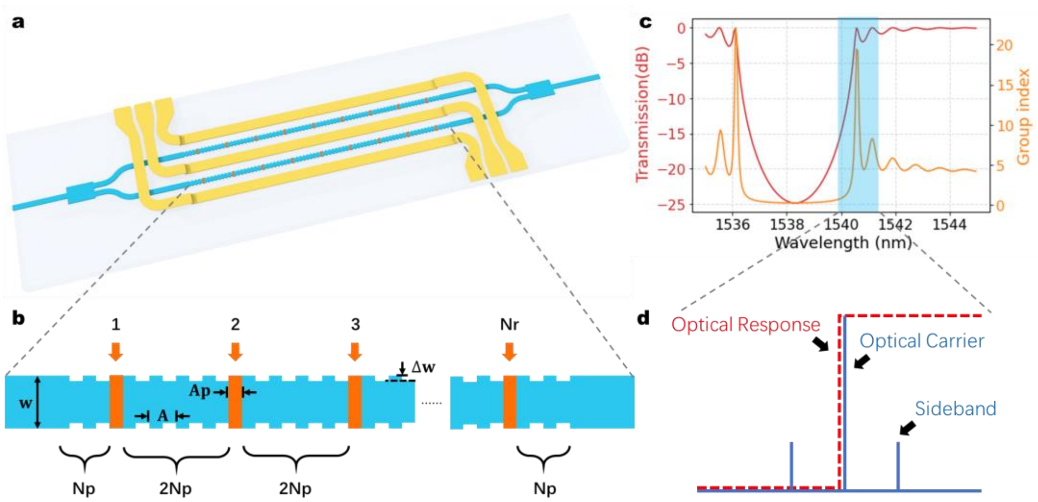

Fig. 1. (a) 3D schematic of the TFLN modulator. (b) A detailed description of the Bragg grating structure for the modulation area. (c) The relationship between the transmission spectrum and the corresponding group refractive index. (d) The concept of a single-sideband modulation.

3. Device Fabrication

The devices are fabricated on an TFLN wafer from NANOLN corporation. The substrate employed is a 400 nm X-cut TFLN wafer, featuring a 4.7-μm-thick buried silicon dioxide (SiO_2) layer. Additionally, a ridge waveguide is formed through the etching of 200 nm of LN, integrated into the structure. The structure was first patterned by electron beam lithography and etched using inductively coupled plasma (ICP) dry etching process. Afterward, 800-nm-thick SiO_2 was deposited on the waveguide by plasma-chemical vapor deposition (PECVD) and etched by ICP reactive ion etching technology. Finally, a 600-nm-thick Ti/Au was deposited by electron beam evaporation and lifted off to form the electrodes. Fig. 2 show microscope images and SEM images of the fabricated device.

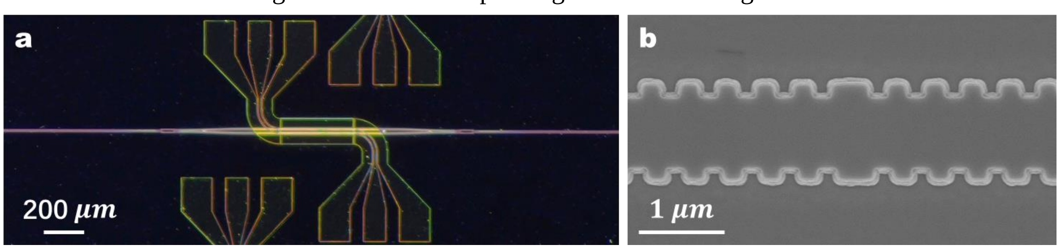

Fig. 2. (a) Microscope images and (b) SEM images of the fabricated device.

4. Device Characterization

4.1 Half-wave voltage

We employed an Arbitrary Waveform Generator (GW Instek AFG-3051) to generate a 1 MHz triangular wave as the driving electric signal and use a photodetector to convert the optical signal generated by the modulator into an electrical signal, and the resulting signals were observed in real-time using an oscilloscope (Rohde & Schwarz RTO1044). The final results are shown in Fig. 3(a). A half-wave voltage of 3.55 V was attained over a compact 542.75 μm phase-shifter length, corresponding to a remarkable modulation efficiency of approximately 0.192 V·cm.

4.2 Electro-optic Response

We also characterized the electro-optic (EO) response, as shown in Fig. 3(b). We established a testing setup employing a vector Network Analyzer (Rohde & Schwarz ZNB40) and examined the EO responses at five discrete points in close proximity to the 1551.6 nm, which is associated with the highest modulation efficiency. The 3-dB bandwidth of these response curves exceeds 40 GHz. The overshoot in the electro-optic S21 response is the result of the interference effect between the resonant light and the waveguide input light. 8]

4.3 Single-Sideband Demonstration

We utilized a microwave source (Ceyear 1465F-V) to load the RF signal onto the modulator, and subsequently assessed the SSB suppression effect using a high-precision spectrometer (APEX AP2683B). Additionally, we employed a 4 mm-long Mach-Zehnder Interferometer (MZI) modulator of common design to compare the filtering effect. Spectral results were obtained through both the conventional design modulator (in Fig. 3(c)) and the cascaded Bragg grating modulator (in Fig. 3(d)). It confirms the narrow-band filtering effect inherent to the cascade Bragg gratings, which effectively filters out extraneous sidebands, thereby facilitating the formation of SSB modulation. However, due to the compact length of the device, the strength of the sideband is constrained. A longer device can be fabricated to achieve a lower half-wave voltage, thereby increasing the sideband strength.

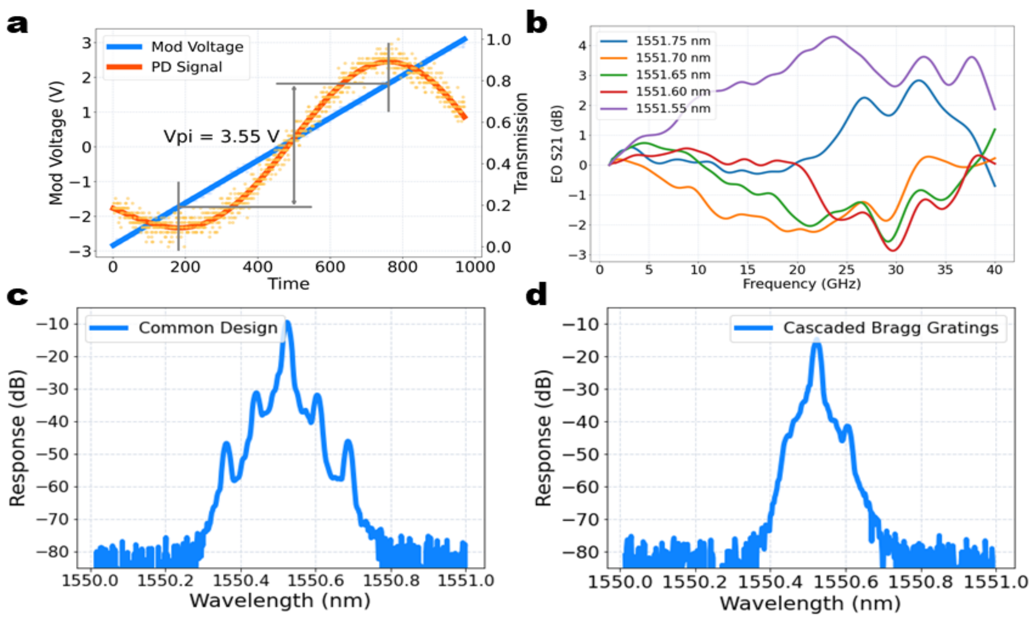

Fig. 3. (a) Normalized optical transmission of the device as a function of the applied voltage, depicting a Vπ of 3.55 V. (b) EO response of the device with different wavelengths. Spectrum of output of different modulators (c) the common design modulator and (d) the cascaded Bragg grating modulator.

5. Conclusions

We experimentally demonstrated a slow light TFLN modulator that exhibits exceptional modulator efficiency and a high 3-dB EO bandwidth. The modulator arms incorporate a periodically cascaded Bragg grating, effectively slowing down the light and yielding a remarkable enhancement in modulator efficiency. Our measurements indicate a voltage-length product of 0.19 V·cm within a compact length of 542 μm. The measured 3-dB EO bandwidth exceeds 40 GHz. Furthermore, we have explored the potential of SSB modulation based on the asymmetric filtering capabilities of the Bragg grating.

6. References

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