High-performance hybrid silicon and lithium niobate Mach–Zehnder modulators

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Abstract *Hybrid Lithium Niobate (LN) and Silicon photonic (SiPh) integration platform has emerged as a promising candidate for future optical modulators. In this paper, we discuss the technologies for realizing hybrid LN/SiPh platform. Various functional devices derived from the Mach-Zehnder interferometer configuration are also reviewed.*

Introduction

The exponential growth of global information volume has contributed to increasing demand for optical communicated networks with higher capacity and lower cost. Photonic integrated circuit (PIC) is a key enabling technology to such networks because it provides high functionality, high performance, and low power consumption [1]. Since the first serious proposal for a PIC in 1969 [2], tremendous progress in the key building blocks including laser diode, optical amplifier, electro-optical modulator, filter, and detector have been achieved.

As one of the key building blocks, the electro-optic (EO) modulator can be realized by several approaches [3]–[5], of which the Pockels effect is often the optimal mechanism. Crystals which lack inversion symmetry are classified generally as “non-centrosymmetric” and display Pockels effect, also known as the linear EO effect, in which the refractive index will change proportional to the strength of the applied electric field. This allows for high operating speed and linear pure phase modulation which is a primary requirement for optical modulation in analog systems [6].

Lithium Niobate (LN), a kind of non-centrosymmetric crystal, has been the most successful material for EO modulator due to its strong Pockels effect, large transparency window, and low absorption loss. But for conventional LN modulators whose waveguides are formed on the surface of a bulk crystal wafer by mean of Ti-diffusion or proton exchange, the low index contrast between core and cladding leads to large modal cross-sectional sizes and large waveguide bending radii, in turn resulting in low modulation efficiency as well as large device size. The emergence of LN-on-insulator (LNOI) materials provides an efficient approach to increased modulation efficiency [7], [8]. The rib waveguides etched into the LN thin film layer bonded on the buried silicon dioxide layer offer a high index contrast that ensures a compact mode size. As a result, the modulator electrodes can be placed more closely to the waveguide thus increase the modulation efficiency without inducing additional optical loss. Modulators based on this technology have been demonstrated with excellent performance [9]–[14].

The development of the PIC has been focused on the platforms that can achieve scalable monolithic integration of the photonic circuits incorporating diverse functional components. Silicon photonics (SiPh) is one of the most attractive approaches [15]. The main motivations behind SiPh lies with the possibility of large wafer size, high volume throughput, and cost reduction because of the fabrication infrastructure of SiPh is compatible with CMOS technology. In addition, the high index contrast of the silicon-on-insulation (SOI) platform promises very compact footprint. SiPh technology now offers an almost complete suite of passive photonic devices such as filters, splitters, (de)multiplexers, and waveguides with proven performances [16]–[18]. These compact and low loss components provide reliable support for interconnection of subassembly and operation of integral on-chip PIC systems.

As the absence of Pockels effect in Si makes it is impossible to realize a pure phase modulator, SiPh modulators based on the free-carrier dispersion effect in p-n junctions have been intensely investigated [19], [20]. This technology has demonstrated impressive devices operating at high data rates up to 100 Gbps [21], but their performance has been limited by the additional insertion loss and signal distortion induced by intrinsic absorption and nonlinearity of the plasma dispersion effect.

Recently, the hybridization of LN membranes onto SOI PIC, which combine the scalability of SiPh and the high EO performance of the LN, has attracted considerable interest

[22]–[27]. In this paper, we will review the hybrid LN on SiPh (LN/SiPh) platform and the multitude of modulator configurations realized on this platform for different applications.

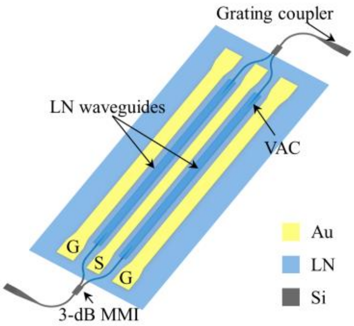

Fig. 1: A typical figure caption

Device Structure

Previously, we have demonstrated high-performance hybrid Si and LN Mach-Zehnder interferometric modulators (MZMs) operating in a travelling-wave electrodes (TWE) [27]. Fig. 1 shows the schematic of the hybrid Si/LN MZM, consisting of two waveguide layers and VACs. The Passive Si components including shallow etched grating coupler, 3-dB multimode interference (MMI), and Si waveguides, serving as input and output circuits, are mature and scalable thanks to the SiPh technology. This avoids the design and fabrication waveguide components in the LN layer, which can be complicated by the index anisotropy and the typically slanted sidewall angel. By placing the task of routing light on the underlying Si, only simple straight LN waveguides need to be fabricated. As a result, the top waveguides can be formed along the y axis of the x-cut LN membrane to access the largest attainable EO coefficient $r_{33} \approx 31$ pm/V.

Light coupled from the Si grating coupler is split into two optical paths and transferred to the two parallel LN waveguides through VACs. The travelling wave electrodes (TWE) arranged in a ground-signal-ground (GSG) configuration provide electric field at opposite direction across the two waveguides where the Pockels effect is utilized to induce an optical phase difference. This phase difference results in constructive or destructive interference at the output MMI, and thereby to achieve intensity modulation of output signal.

Results

After chip fabrication, the SOI substrate is bonded on a printed circuit board (PCB) as shown in Fig. 8. Characterizations of EO modulator mainly consist of insertion loss, optical extinction ratio (OER), half-wave voltage, modulation bandwidth, linearity, and high-speed digital data transmission. Here, these metrics are discussed in detail.

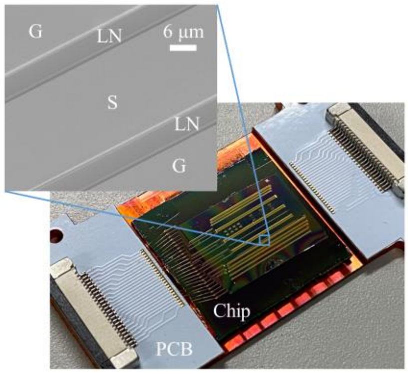

Fig. 2: Optical image of fabricated chip. The inset is the SEM image of TWE formed in GSG configuration.

1. Insertion loss and OER

In general, the insertion loss is comprised of propagation loss in Si and LN, coupling loss between Si/LN, and the insertion loss of MMI. As discussed in Section II, the integral losses of LN waveguides, the VAC and the relatively short Si waveguides are all quite small, leading to a total insertion loss of 1.8 dB. To the best of our knowledge, the insertion loss of 1.8 dB is the lowest value ever achieved in modulators operating above 40 Gb/s on Si. OER values of more than 40 dB are also readily achieved thanks to the accurate split ratio of the SiPh MMI coupler and the highly balanced insertion loss values of both arms.

2. Half-wave voltage and EO bandwidth

The half-wave voltage is the voltage required to switch a MZM between on- and off- state. For a device length of L, the half-wave-voltage-length product, $V_\pi L$, is often used to quantify the modulation efficiency. $V_\pi L$ often conflicts with the modulation bandwidth leading to a trade-off in device design. As reported in [27], we achieved a wide bandwidth of over 70 GHz but with a relatively high V_π of 5.1 V.

As mentioned in last Section, the EO bandwidth is related to the performance of electrodes. Based on an optimized electrode design, here we present a 9-mm-long device with similar bandwidth as [27], while V_π is decreased to 3 V. The EO modulation frequency response characterized by vector network analyzer (VNA) is shown in Fig. 9 as blue solid lines and the simulated results as dashed yellow lines. The result matches well with theoretical calculations. In this device, the width of LN waveguides is optimized in order to minimize propagation loss.

The $V_\pi L$ of the present device is slightly larger than that reported in [27] because we sacrifice the modulation efficiency for better EO bandwidth

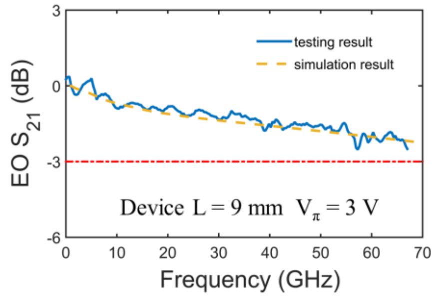

Fig. 3: Measured EO frequency response of the 9-mm-long modulator.

performance.

Conclusion

Optical modulator is a key device at the heart of the optical communication links. Benefitting from the heterogeneous integration of LN with SiPh, functionality EO devices include modulators and switches can be achieved in this platform with very compact size, low loss, low drive voltage, large E-O modulation bandwidth, large optical bandwidth and high linearity. The platform is also amenable to further integration of laser source, photodetectors, as well as high-speed electronic drivers, offering fully integrated solutions for future datacom and interconnect applications. Hence the hybrid LN/SiPh platform is a prime candidate for modulation and switching solutions on SiPh PICs.

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