A Hybrid Lithium Tantalite-Silicon Photonics Platform for Electro-Optic Tuning

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***Abstract*—High-efficiency and ultralow-power electro-optic tuning devices are key components in photonic integrated circuits. Silicon photonic technology is considered to be promising for large-scale and low-cost integration. However, silicon does not exhibit any Pockels effect, and the electro-optic tuning based on free-carrier dispersion suffers from challenges such as high power consumption, and large optical propagation loss. Here, a new hybrid lithium tantalite-silicon platform is proposed for ultra-low-power electro-optic tuning based on the Pockels effect. Benefitting from the strong Pockels coefficients of lithium tantalite thin film, an EO tunable lithium tantalite-silicon hybrid microring is demonstrated. The quality factor and extinction ratio are 17000 and 10 dB, respectively. The linear bidirectional wavelength tuning efficiency is measured as 12.8 pm/V. The proposed platform extends the toolbox of silicon photonics technology, which pave a way for high-speed modulators and phase shifters in optical communication and optical phased array.**

Keywords—electro-optic tuning, hybrid waveguide, silicon photonic, lithium tantalite, Pockels effect

I. INTRODUCTION

Programmable optical units have emerged as crucial building blocks for optical phased arrays [1], photonic matrix multiplication [2], optical communication [3], and other photonic integrated circuits (PICs). To realize it, various physical effects and integrated platforms are exploited. Low power consumption, fast response, and complementary metal-oxide-semiconductor (CMOS) compatibility are critical considerations for technological adoption in the programmable PICs. Silicon (Si) platform allows for reliable, large-scale, and low-cost integration due to its CMOS process [4]. Generally, thermo-optic (TO) tuning by microheater and electro-optic (EO) tuning by free-carrier dispersion on a silicon waveguide are typical methods for programmable optical units [5, 6]. However, the TO tuning presents high power consumption (0.1 mW ~ 100 mW), slow tuning response, and large thermal crosstalk. For the EO tuning, high power consumption is still required, and the increased optical propagation loss by free-carrier absorption will deteriorate the tuning performance. Recently, some second-order nonlinear thin-film materials are employed to achieve the electric filed-driven modulation of the refractive index rather than electric current flow or doped regions in the waveguide, such as lithium niobate (LN) [7], lead zirconate titanate (PZT) [8], barium titanate (BTO) [9], Zr-doped hafnium oxide (HfO_2) [10], aluminum nitride (AlN) [11], silicon carbide (SiC) [12], and other organic spin-coating material [13].

In [14], based on the Pockels effect of the directly-etched LN waveguide, the wavelength tuning efficiency can reach 25 pm/V. However, it is not compatible with CMOS processes. In [15], benefitting from the large Pockels coefficients (~ 1000 pm/V) of the BTO, the wavelength tuning efficiency of 25 pm/V can be achieved. However, the BTO thin film lacks high integration yield and stability in the fabrication process. It is still challenging for high wavelength tuning efficiency and CMOS-compatible fabrication process.

Lithium tantalite (LT) is one of the most attractive EO materials, as it has a high Pockels coefficient (~ 27.4 pm/V), wide wavelength transparency (0.28 μm ~ 5.5 μm), and high optical damage threshold [16]. The development of LT thin film on insulator (LTOI) provides a potential for the Pockels effect-based tunable devices.

In this paper, we propose and demonstrate a hybrid integrated LT-Si photonic platform, which can avoid directly etching the LT thin film and provide an alternative to achieve large-scale and low-cost integration. The EO tunable 100-μm-radius microring resonator with gold micro-electrodes based on the hybrid platform is demonstrated. Due to the Pockels effect of the LT thin film, the wavelength tuning efficiency of 12.8 pm/V can be achieved. The quality factor (Q) and extinction ratio (ER) are 17000 and 10 dB, respectively. To the best of our knowledge, the experimental tunable microring resonator based on the LT-Si hybrid platform has not been reported elsewhere. Our demonstration of the hybrid LT-Si tunable device opens up a new way for the integrated high-speed EO modulators and switches in the PICs, which provides an alternative for the programmable optical units.

II. DEVICE DESIGN AND FABRICATION

A. Device design

The proposed hybrid LT-Si platform consists of 100-nm-thick amorphous silicon (a-Si) layer, a 20-nm-thick

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silicon oxide layer, and a LTOI wafer with a 0.6-μm-thick LT (n: ~2.17) layer and a 0.5-μm-thick silicon oxide layer (Purchase from *Soitec*). To avoid etching LT thin film, the waveguide, grating, and microring patterns are defined on the 100-nm-thick a-Si layer. The cross-section and guided transverse electric (TE) fundamental mode of the proposed hybrid waveguide are shown in Fig. 1(a) and 1(b). The gold electrodes are beside the upper a-Si waveguide, and the electrodes gap is 5.1 μm. The finite element method is used to calculate the mode properties. The effective mode index of the 1.1-μm-wide upper a-Si waveguide of the hybrid waveguide is calculated as 2.19. The light confinement factor in the LT layer can reach >50 %. The confinement factor and EO overlap factor can be optimized by adjusting the thickness of the LT, upper a-Si layer, and electrodes gap [10]. Therefore, the design of the hybrid waveguide can take advantage of the strong EO effect in the LT layer. Based on the hybrid waveguide, the proposed tunable microring resonator is illustrated in Fig. 1(c). To obtain the critical coupling condition with a large ER, the coupling gap between the access waveguide and ring is designed from 80 nm to 200 nm.

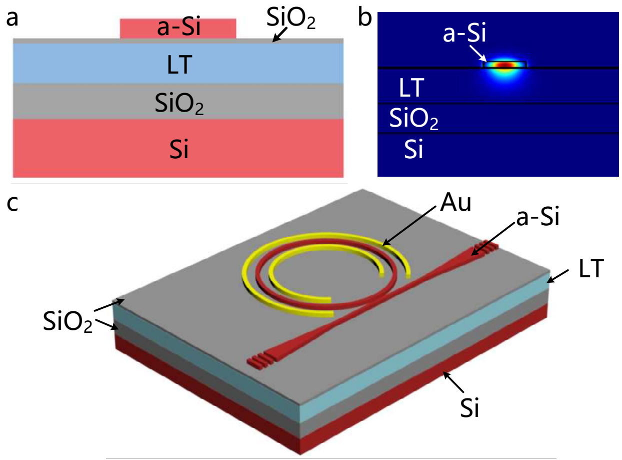

Fig. 1. (a) Cross section of the hybrid LT-Si waveguide. (b) Simulated mode profile of the hybrid LT-Si waveguide. (c) Tunable microring resonator on LT-Si platform.

B. Deviceice fabrication

To demonstrate the EO tuning of the proposed platform, the microring resonators with gold electrodes are fabricated and characterized. The plasma-enhanced chemical vapor deposition (PECVD, Oxford) is employed to deposit 20-nm-thick silicon oxide and 100-nm-thick a-Si, the reason for depositing 20-nm-thick silicon oxide is to prevent cracking caused by depositing a-Si directly on LTOI wafers. Then, the designed patterns consisting of waveguides, gratings, and rings are defined on the resist (AR-P6200.09) by electron-beam lithography (EBL, Vistec EBPG 5200$^+$). The patterns are transferred to the a-Si layer by inductively coupled plasma (ICP) dry etching (SPTS DRIE-I). Eventually, 250-nm-thick gold electrodes and pads are fabricated by electron beam evaporation and patterned by the lift-off process. The optical microscope images are shown in Fig. 2.

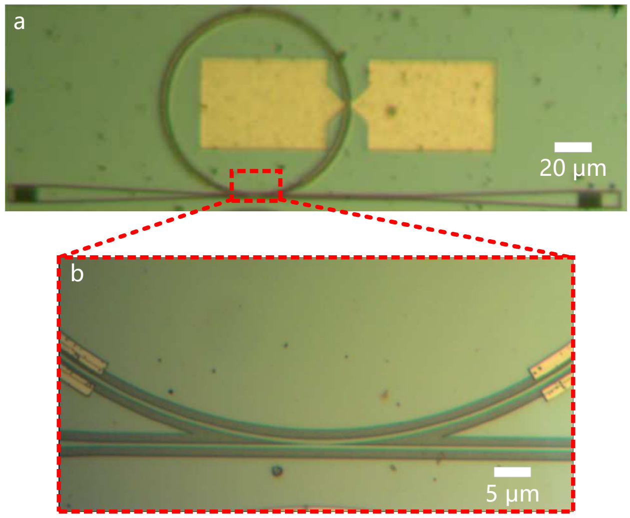

Fig. 2. (a) Optical microscope image of the tunable LT-Si integrated microring resonator. (b) Magnified picture of the optical coupling region.

III. Experimental Results

To achieve the EO tuning performance of the fabricated device, the transmission spectra of the microrings are measured with the applied electric field. As shown in Fig. 3(a) and 3(b), the Q and ER of the proposed device are 17000 and 10 dB, respectively. The resonance wavelengths shift by applying different voltages from -6 V to 6 V. The fitting wavelength tuning efficiency is 12.8 pm/V. Although our tuning efficiency is slightly smaller than [14] based on the LN-etched waveguide, the proposed hybrid LT-Si waveguide provides a promising solution to achieve reliable and large-scale integration for EO material.

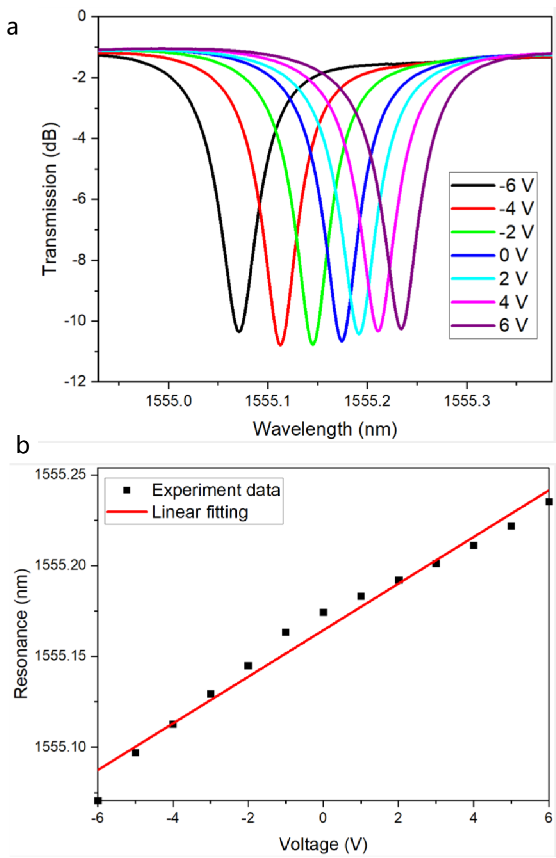

Fig. 3. (a) Measured transmission spectra of the fabricated device by applying voltages. (b) Linear fitting wavelength tuning efficiency.

IV. Conclusion

We have presented a highly promising EO tuning method on a hybrid integrated LT-Si platform. As an example of the tuning potential for the hybrid platform, we fabricate the tunable microring resonators. Due to the Pockels effect of the LT layer, the wavelength tuning efficiency is measured as 12.8 pm/V. The tuning results indicate the strong EO effect in the LT layer, which provides an attractive direction for high-speed EO modulators and switches in the programmable optical units.

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