Integrated Visible-Light Liquid-Crystal Phase Modulator

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Abstract: An integrated liquid-crystal phase modulator for applications within the visible wavelength range is demonstrated. A threshold voltage of ±1.2V is shown and 24π phase shift is achieved within ±2.5V in a 500-µm-long modulator.
OCIS codes: (130.3120) Integrated optics devices; (130.4110) Integrated optics modulators; (130.0250) Optoelectronics.

1. Introduction

Integrated photonics systems at visible wavelengths have many wide-reaching potential applications, including image projection systems, underwater optical communications, and optogenetics [1-2]. Generally, these visible-light integrated systems are based on silicon-nitride waveguides since silicon nitride has a low absorption coefficient within the visible spectrum and is CMOS compatible. However, silicon nitride has a low thermo-optic coefficient and does not exhibit any significant electro-optic properties, which makes integrated phase tuning at visible wavelengths a challenge.

As a solution, nematic liquid crystals, with strong birefringence in the visible spectrum, can be integrated and used for phase modulation. Integrated liquid-crystal-based devices, including slot waveguide phase shifters [3], ring resonators [4-5], and switches and tuners [6], have been explored. However, these demonstrations have been largely limited to the infrared wavelength range. In this work, an integrated visible-light liquid-crystal phase modulator is experimentally demonstrated with a ±1.2V threshold voltage and 24π phase shift within ±2.5V in a 500-µm-long modulation region.

2. Liquid-Crystal Theory

In the proposed liquid-crystal modulator, phase modulation is achieved via the birefringence of the liquid crystal. In a nematic liquid-crystal media, the index of refraction varies based on the orientation of the media's molecules. Thus, the index can be actively tuned by applying an electric field across the liquid-crystal region to orient the molecules in the direction of the field and cause a change in the index of refraction. The resulting phase shift due to this change in refractive index is given by

$$\Delta\phi = \frac{2\pi L \Delta n_{\text{eff}}}{\lambda_0}, \tag{1}$$

where L is the length of the liquid-crystal region, Δn_{eff} is the change in effective refractive index, and λ_0 is the free-space operating wavelength. Here, the transverse-electric mode is used and the molecules are aligned in plane with the surface of the chip.

3. Liquid-Crystal Phase Modulator Structure and Fabrication

The integrated liquid-crystal phase modulator consists of a silicon-nitride waveguide, liquid crystal deposited into an oxide trench, a top glass chip with a liquid-crystal alignment layer, and metal electrodes for applying an electric field across the liquid crystal. The devices are fabricated in a 300-mm wafer-scale CMOS-compatible process at the Colleges of Nanoscale Science and Engineering (CNSE) SUNY-Poly. A cross-sectional diagram of the device as fabricated by CNSE is shown in Fig. 1a. The 200-nm-thick silicon-nitride waveguide is recessed within the silicon

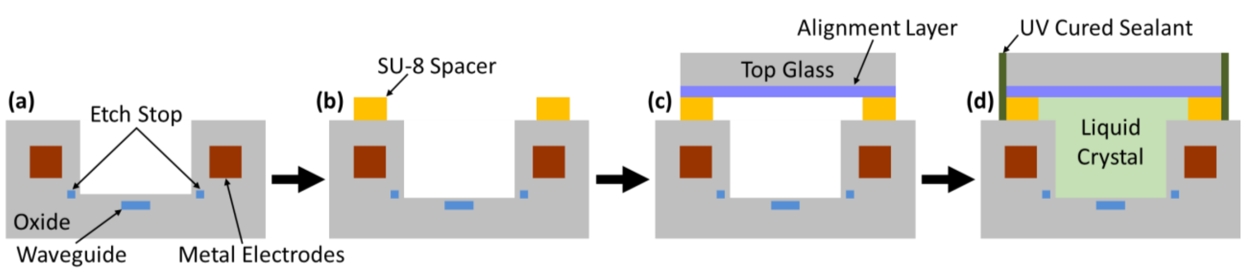

Fig. 1. Cross-sectional diagram of the phase modulator device (a) as received from CNSE-SUNY, (b) after in-house etch to expose the top of the waveguide and deposition of the SU-8 spacer layer, (c) after the top glass chip with an alignment layer is epoxied to the chip, and (d) after the liquid crystal is injected into the cavity and sealed with the UV-cured epoxy.

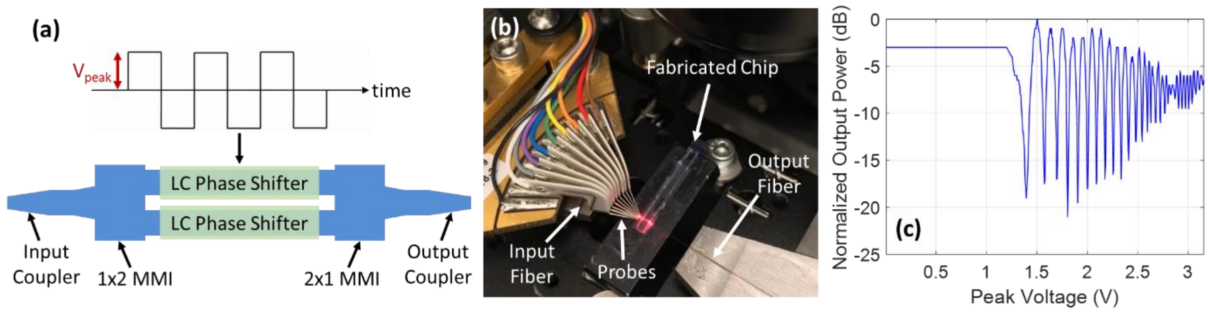

Fig. 2. (a) Diagram showing the integrated Mach-Zehnder-interferometer (MZI) test structure and modulation scheme. (b) Photograph of the fabricated chip and experimental setup. (c) Experimental results showing normalized output power versus peak voltage applied to one arm of the MZI.

dioxide cladding, a trench is etched above the waveguide using a second silicon-nitride etch-stop layer, and metal electrodes are placed along both sides of the trench. Further fabrication and packaging are then done at the MIT fabrication facilities as back-end steps. First, an anisotropic dry etch is performed to etch away the excess oxide on top of the waveguide. Exposing the top of the waveguide is an important fabrication step, because it allows the mode to maximally interact with the liquid crystal, hence allowing for the largest phase shift for a set modulator length. Next, an SU-8 resist spacer layer is deposited around the device, as shown in Fig. 1b. Then, a glass chip, with a polyimide alignment layer on the bottom side, is epoxied on top of the spacer layer, as shown in Fig. 1c. The alignment layer is used to anchor the liquid-crystal molecules. Finally, 5CB nematic liquid crystal is injected into the formed cavity via capillary action and the cavity is sealed off with UV-cured epoxy, as shown in Fig. 1d.

4. Characterization Setup and Experimental Results

To enable characterization of the device, the liquid-crystal phase modulator is fabricated in an integrated Mach-Zehnder-interferometer (MZI) test structure, as shown in Fig. 2a. A 632.8-nm-wavelength HeNe laser is coupled into the chip from an input fiber to the integrated silicon-nitride waveguide using an input edge coupler. A 1x2 multimode interference (MMI) splitter is used to transition from a single waveguide to the two arms of the MZI. A 500-µm-long liquid-crystal phase modulator is placed in each arm of the MZI. Finally, a 2x1 MMI is used to combine the two arms back into a single waveguide and a second edge coupler is used to couple the light from the chip to an output fiber that is fed into a power meter. A photograph of the fabricated and packaged chip and the experimental setup is shown in Fig. 2b.

To characterize the device, electronic probes are used to apply a 10kHz square wave with a variable peak voltage across the electrodes of the phase modulator in one arm of the MZI, as shown in Fig. 2a. (Note that no voltage is applied across the second phase modulator in the MZI; the liquid-crystal molecules in this modulator are maintained in a constant orientation via the alignment layer.) As shown in Fig. 2c, as the peak voltage applied to the liquid-crystal modulator is varied, phase modulation is achieved, which results in amplitude modulation at the output of the MZI test structure. Using this method, a threshold voltage of ± 1.2V is measured and 24π phase shift is achieved in ± 2.5V.

5. Conclusion

In this work, an integrated visible-light liquid-crystal phase modulator has been experimentally demonstrated. A low threshold voltage of ± 1.2V is shown and 24π phase shift is achieved within ± 2.5V in a 500-µm-long modulation region. This device enables integrated visible-wavelength modulation for a variety of applications, including visible image projection systems, underwater communications, and optogenetics [1-2].

This work was supported by the Defense Advanced Research Projects Agency (DARPA) VIPER program (Grant No. FA8650-17-1-7713), DARPA E-PHI program (Grant No. HR0011-12-2-0007), and a National Science Foundation Graduate Research Fellowship (Grant No. 1122374).

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