Integrated Liquid-Crystal-Based Modulators: Packaging Processes and Evaluation Techniques

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***Abstract*—We discuss fabrication processes, important considerations, and evaluation techniques for successful packaging of liquid crystal (LC) into silicon-photonics platforms, enabling compact and power-efficient integrated modulators. We demonstrate an LC-packaging fabrication process, microscopy-based LC-alignment evaluation techniques, a heat-based LC-realignment procedure, and UV-exposure effects on modulator performance.**

Keywords—silicon photonics, liquid crystal, integrated modulators

I. Introduction to Integrated LC Modulators

Integrated liquid-crystal-based (LC-based) modulators have emerged as a promising solution for compact and power-efficient on-chip modulation [1-4]. These modulators leverage the large birefringence and electrically tunable refractive index of LC media by integrating LC into silicon-photonics platforms. This enables the optical mode in the modulator waveguides to strongly interact with the integrated LC media, such that tuning the LC refractive index via an external electric field has a significant effect on the effective refractive index and profile of the optical mode. This strong interaction enables compact and power-efficient phase and amplitude modulators on the order of tens of microns long [3,4].

Integrated LC-based modulators have proven to be especially pertinent for visible-light integrated systems, since visible light is traditionally difficult to modulate on chip due to materials constraints. For example, typical visible-light heater-based silicon-nitride phase modulators are on the order of hundreds of microns to several millimeters long and use excessive power [5]. As a solution to the challenge of compact and power-efficient integrated visible-light modulation, we have recently shown the first integrated visible-light LC-based phase and amplitude modulators [3,4].

In this paper, we discuss fabrication processes, important considerations, and evaluation techniques for successful LC packaging. First, we describe our developed 300-mm-wafer silicon-photonics foundry platform and chip-scale LC-packaging process. Second, we demonstrate evaluation techniques for analyzing LC misalignment using both standard and polarizing microscopes. Third, we develop a procedure to improve packaged LC alignment by transitioning the LC between temperature-dependent phases. Finally, we demonstrate the significant effects that LC misalignment and UV exposure can have on device performance.

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II. Integrated LC Packaging Process

In general, our integrated LC-based modulators consist of a silicon-nitride bus waveguide recessed within a silicon-dioxide cladding to weakly confine and guide the light, LC deposited into a silicon-dioxide trench above the waveguide to enable strong interaction between the optical mode and the LC media, metal electrodes for applying an electric field across the LC region, and a top glass chip with a mechanical alignment layer to anchor the LC molecules.

To demonstrate these LC-based modulators, we developed a custom wafer-scale fabrication process and a chip-scale LC-packaging process. The modulators are fabricated in a CMOS-compatible 300-mm-wafer silicon-photonics process at the State University of New York Polytechnic Institute's (SUNY Poly) Albany NanoTech Complex. Figure 1a shows our typical modulator cross section, as received from SUNY. To integrate LC into this platform, we perform further chip-scale fabrication and packaging in house at the Massachusetts Institute of Technology (MIT) fabrication facilities as back-end steps. This process consists of five steps: (i) we perform a reactive-ion etch to bring the trench closer to the waveguide; (ii) we pattern an SU-8 photoresist spacer layer; (iii) we position and epoxy a glass chip with an alignment layer on top of the SU-8 spacer layer; (iv) we inject LC into the formed cavity (we use commercially available 5CB LC); and (v) we seal the cavity with UV-cured epoxy. The final cross section of our typical modulator after LC packaging is shown in Fig. 1b. (Additional details on the fabrication and packaging process can be found in [3].)

III. Integrated LC Packaging Considerations and Evaluation Techniques

As a critical next step, we established a technique for evaluating the success of the LC packaging process using a polarizing microscope. Specifically, we used the polarizing microscope to evaluate if the LC properly filled into the cavity and uniformly anchored to the alignment layer. In general, a polarizing microscope can be used to image a birefringent sample with a polarized light source impingent on the sample and a polarization-selective analyzer after the sample [2]. Here, we design the polarizing microscope such that the polarization of the incident light is parallel to the expected LC alignment direction, the incident light travels through the LC-filled cavity of the packaged chip, reflects off the bottom of the LC region, and the reflected light travels through a polarization analyzer that is oriented perpendicular to the LC alignment direction, as shown in Fig. 1c. If the LC is aligned properly, the incident light

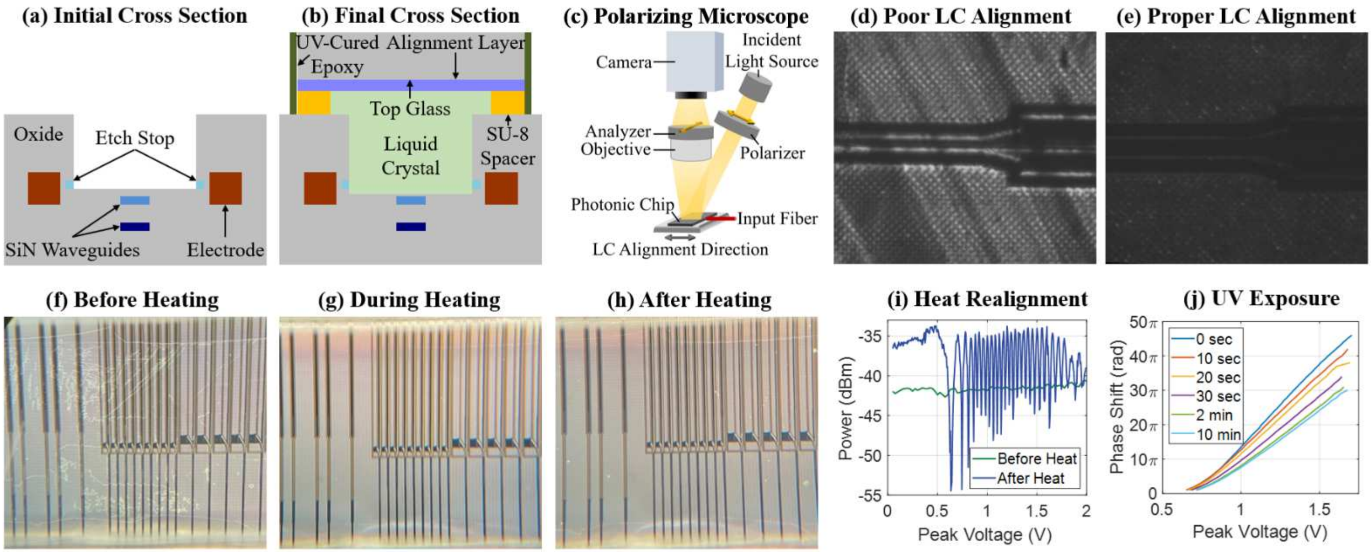

Fig. 1. Cross-sectional simplified diagrams of our typical LC-based modulator (a) as fabricated by SUNY Poly and (b) after the in-house post-processing packaging steps (not to scale). (c) Simplified diagram of the polarizing microscope used to evaluate LC alignment (not to scale). Micrographs taken using the polarizing microscope demonstrating (d) poor LC alignment and (e) proper LC alignment after packaging. Micrographs taken using a standard microscope of the packaged LC region (f) before heating, (g) during heating, and (h) after heating and cooling back down. (i) Experimental results showing output power of an integrated LC-based phase modulator in an MZI test structure versus peak voltage applied to one arm of the MZI before (green) and after (blue) heating. (j) Experimental results showing phase shift of an integrated LC-based phase modulator as a function of peak voltage for varying UV exposure times.

will undergo no polarization rotation, and the analyzer will block the reflected light, resulting in a dark image. However, if the LC molecules are misaligned, the polarization of the incident light will change as it travels through the LC-filled cavity, and the analyzer will no longer block all the reflected light, resulting in a bright image. Examples of a poorly filled cavity, where the LC molecules are misaligned, and a properly filled cavity, where the LC molecules are uniformly aligned, are shown in Fig. 1d-e.

Next, we developed a heat-based technique to reorient the LC molecules in a packaged chip, since non-uniform LC misalignment can significantly degrade device performance. We achieve this LC molecule reorientation by transitioning the LC between temperature-dependent phases. We heat the chip to bring the LC to its isotropic state and then slowly cool it back down to its nematic state, which allows for the LC molecules to properly and uniformly anchor to the alignment layer. Before heating, the LC region is visibly misaligned, as shown in Fig. 1f. During heating, the LC transitions to the isotropic state, making the LC region optically clear, as shown in Fig. 1g. After the chip is cooled down, the LC returns to its nematic state and the molecules properly anchor to the alignment layer, resulting in an optically-clear LC region, as shown in Fig. 1h.

To demonstrate the importance of proper alignment of the LC molecules and the impact of this heat-based reorientation technique, we experimentally characterized an integrated LC-based phase modulator in a Mach-Zehnder-interferometer (MZI) test structure [3] on a packaged chip. We couple a 632.8-nm off-chip laser into the MZI, vary the peak voltage of a 10-kHz square wave on one arm of the MZI, and measure the power output of the MZI. Initially, the LC was poorly filled into this cavity, resulting in the output power remaining constant with applied voltage, implying that no phase modulation is occurring. Then, we used the heat-based reorientation technique to improve the LC molecule alignment and retested the MZI, successfully confirming the expected amount of phase modulation. Results of modulation before and after heating are shown in Fig. 1i, highlighting the significant impact that LC alignment and reorientation via heating can have on device performance.

Finally, we explored the effect of UV exposure on integrated LC-based modulators. This is an important consideration since some steps in the packaging process use UV-cured epoxy. Specifically, we characterize performance of the integrated LC-based phase modulator in the MZI test structure under increasing UV exposure. We expose the chip to 365-nm-wavelength light of intensity 2.5 W cm^{-2} for increasing durations, up to 10 minutes. As shown in Fig. 1j, the UV exposure results in significant degradation in the device performance. This result confirms that precautions must be taken during packaging steps that require UV exposure.

IV. Conclusions

In this paper, we discussed fabrication processes, important considerations, and evaluation techniques for successful LC packaging. This work facilitates wide-spread use and higher-yield integration of LC into silicon-photonics platforms, enabling compact and power-efficient on-chip modulation.

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