Tunability Dependence of All-Optical Liquid Crystal Delay Line on Laser Polarization and Incidence Angle

Jinfeng Li,*[1,2]

[1]Beijing Key Laboratory of Millimeter Wave and Terahertz, Beijing Institute of Technology, Beijing, 100081, China,
[2]Electrical and Electronic Engineering Department, Imperial College London, London SW7 2AZ, United Kingdom

Received September 4, 2023; accepted November 15, 2023; published December 31, 2023

Abstract—This work experimentally investigates the optical manipulation of trans-cis swaps and, resultantly, their optical/electromagnetic imprints as a driver for realizing the tunable delay lines in the microwave X band (8-12 GHz) regime utilizing the polarization and incident angle dependencies of azo-admixed liquid crystals (LCs). Measurement results confirm that the tuning efficacy of the azo-LCs-based delay line is highly dependent on the polarization of the laser beam concerning the rubbing and filling directions of LCs. The achievable differential phase shift is maximized when the laser light beam is polarized parallel to the rubbed direction and the LCs filling direction.

The paradigm shift from light-controlling-light to light-controlling-microwaves has opened new avenues for research and development. The field of liquid crystals (LCs) optoelectronics and microwave (MW) interactions [1] has witnessed remarkable advancements in recent years, with the pursuit of developing all-optically addressed MW tunable devices [2] emerging as the next significant breakthrough. These devices can potentially revolutionize various applications, e.g., communication systems, radar technology, imaging, navigation, and signal processing. In this context, this paper presents a cutting-edge all-optically controlled X-band 0-π variable delay line (phase shifter) that harnesses the unique properties of LCs admixed with azobenzene (azo) dyes.

Integrating LCs and azo dyes in an all-optically controlled delay line offers a promising platform for achieving precise and dynamic control over MW signals. LCs exhibit a fascinating combination of fluidic behavior and long-range molecular order [3], making them highly suitable for manipulating electromagnetic waves. On the other hand, azobenzene dyes [4] possess photochemically reversible trans-cis isomerization properties (Fig. 1) [2], allowing for optical control over their molecular orientation. Understanding the fusion of LCs and azo dyes (i.e., azo LCs) and how to optimally (efficiently) realize (maximize) the tuning functionality would provide invaluable information for establishing low-loss phase shifters at the MW and millimeter-wave regimes of interest.

* jinfengcambridge@bit.edu.cn

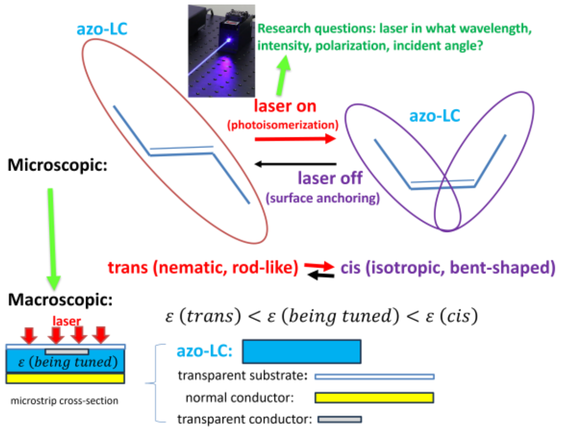

Fig. 1. Principle of trans-cis swap optically in azo-LCs for realizing MW tunable delay lines as we first developed [2].

Among various stimuli for enabling LCs' dielectric tunability (e.g., electric field, magnetic field, temperature variation, and light), using light exhibits unique advantages, e.g., compactness (free of biasing circuits [5] that occupy the device's footprint, which reduces the cost and maintenance as well), and allowing high precision control.

In particular, the state of azo-admixed LCs phase shifter can be between trans nematic and cis isotropic, depending on the orientation of the LCs molecules. In the trans nematic state, the azo-admixed LCs molecules are aligned in a particular direction and the material exhibits anisotropic properties. In the cis isotropic state, the azo-admixed LCs molecules are randomly oriented, and the material behaves like an isotropic liquid. The orientation of the azo-admixed LCs molecules can be controlled optically using a polarized light source (laser pulse) of a particular wavelength, power density, and illumination duration. A combination of these laser control parameters switches the azo-admixed LCs material between the trans nematic and cis isotropic states.

This experimental investigation aims to maximize the tuning efficacy of the all-optically addressed LCs MW phase shifter, which paves the way for optimizing the tuning efficiency in a later stage. We explore other research opportunities depending on specific transmission line structures by investigating how to arrange the initial rubbing alignment concerning the MW signal to be transmitted. Comparing inverted microstrip and coplanar waveguide (CPW)-related structures, inverted microstrip has demonstrated suitability and practicality [2] in LCs surface anchoring alignment and efficient all-optical driving. In contrast, these essential steps are technically demanding to perform on CPW and enclosed CPW-related structures due to the trenches (deep channels) presented. As such, inverted microstrip topology is continued to be employed in this work. With azo-LCs planar alignment by rubbing (surface anchoring), effective dielectric constant at the light-off state represents the molecules perpendicularly interacting with the MW polarization (electric field). Effective dielectric constant at the light-on state represents the molecules' directors in the isotropic state when interacting with the MW polarization. Equations (1) and (2) symbolize the two extreme states of the effective dielectric constants at light-off and light-on conditions, respectively. For LCs that are uniaxial, Eq.(3) corresponds to the dielectric constant at the isotropic (average) state with the perpendicular and parallel states.

$$\varepsilon_r(light\ off, trans)=\varepsilon_r(\perp), \tag{1}$$

and upon excitation:

$$\varepsilon_r(light\ on, cis)=\varepsilon_r(isotropic), \tag{2}$$

where:

$$\sqrt{\varepsilon_r(isotropic)}=\frac{2\sqrt{\varepsilon_r(\perp)}+\sqrt{\varepsilon_r(\parallel)}}{3}. \tag{3}$$

The laser and material systems are set up as per our prototype [2]. GT3-24002 (trade name of MW nematic liquid crystals) admixed with azo dye CPND-7 (10wt%) are employed. Through a series of measurements based on our first microstrip delay line prototype excited by a blue diode laser at 465 nm, amongst other topics, we investigate the effect of the laser polarization on the mechanically rubbed direction (i.e., the deviation of these two directions), aiming to understand its influence on the controllable phase shift produced in the LCs delay line. By measuring the phase shift at each polarized angle of the laser illumination (i.e., the deviation between the laser polarization and the rubbing direction as depicted in Fig. 2) while assuming a constant incidence angle of 0° (the laser device is fixed to be perpendicularly placed if facing the delay line device's plane), we were able to determine the optimal (and worst) condition for the maximum (and minimum) tuning efficacy, as quantified by the measurement results in Fig. 3 for X band (8 GHz, 10 GHz, and 12 GHz).

Furthermore, our investigation presented in Fig. 4 below revealed an intriguing relationship between the incident angle and the controllable phase shift. Note that the difference between perpendicular and orthogonal here represents our experiments on polarization dependency and incident angles dependency, respectively. Perpendicular (as a particular case of orthogonality) indicates the intersection at a right angle in a 2D plane (same plane).

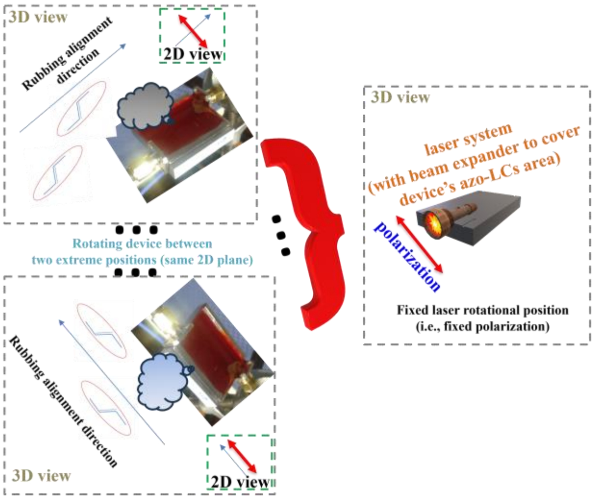

Fig. 2. Core experimental approach in polarization study (2D view represents fixed laser polarization relative to rubbing alignment direction that is rotating with device's rotation in the same 2D plane).

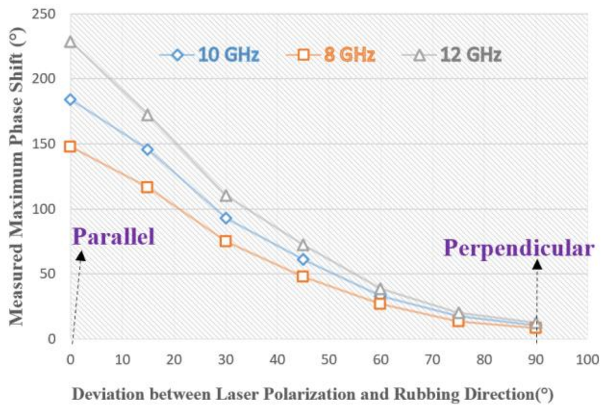

Fig. 3. Experimentally measured differential phase shift at X band with dependency on the deviation between laser beam polarization and rubbing direction (i.e., LC filling direction).
Measurement results based on setup maintaining laser driving current of 3 A and incident angle of 0°.

In contrast, the orthogonal situation entails the possibility of any number of dimensions or orientations (i.e., not necessarily at the same plane). Based on our above polarization experiment insights (i.e., laser parallel polarization with the rubbing direction results in the maximum tunability), the incident angle experiments (as per Fig. 4) were carried out in two scenarios, as shown in Figs. 4 and 5, respectively. In Fig. 4, the movement of the laser source is within the same 2D plane concerning the device's rubbing direction. In Fig. 5, the position variations of the laser result in diverse planes concerning the rubbing direction of the azo-LCs delay line. Measured maximally achievable phase shift (differential) for both cases are shown together in Fig. 6.

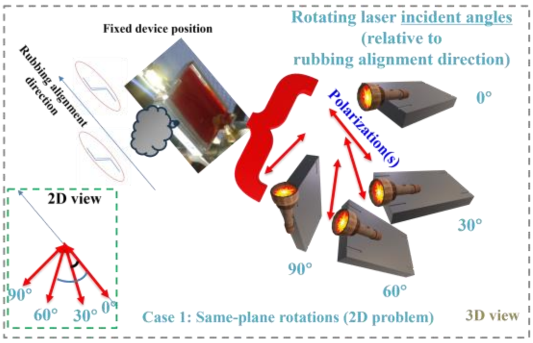

Fig. 4. Core experimental approach in incident angle study (2D view represents resulting laser polarizations rotated in same 2D planes relative to fixed rubbing alignment direction). Measurement results based on setup maintaining laser driving current of 3 A.

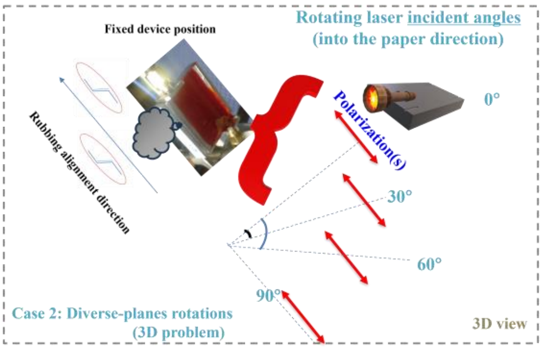

Fig. 5. Core experimental approach in incident angle study (2D view represents resulting laser polarizations rotated in diverse planes relative to fixed rubbing alignment direction). Measurement results based on setup maintaining laser driving current of 3 A.

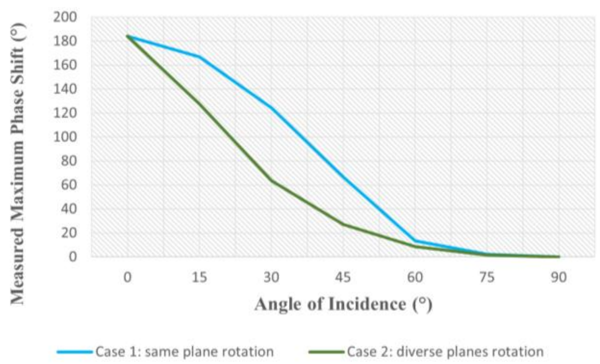

Fig. 6. Experimentally measured differential phase shift at 10 GHz versus incident angles. Measurement results based on setup maintaining laser driving current of 3 A and delay line device position fixed.

For both cases of the incident angle experiments, we observed at larger angles of incidence (from 0° to 90°), assuming a fixed device position (i.e., fixing the rubbing alignment direction), a smaller phase shift was obtained due to the suppressed interaction between the laser beam and the azo LCs molecules. In contrast, as the angle of incidence reduced (from 90° to 0°), we observed an elevated phase shift due to the increased interaction between the laser beam and the LCs. With the increase of the incident angles, the decrease of the phase-shifting capability in case 2 (diverse planes rotation) is more pronounced and is saturated earlier. Instead, case 1 (same plane rotation) exhibits a less sensitive decline response.

In conclusion, the field of LCs optoelectronics and MW interactions has seen advancements in recent years, with the development of all-optically addressed MW tunable devices being the next giant leap. In this context, this paper presents a cutting-edge all-optically controlled X-band 0-π delay line solution that utilizes LCs admixed with azobenzene (azo) dyes. Specifically, we experimentally investigated the effect of laser polarization regarding the mechanically rubbed direction on the controllable phase shift produced. Measuring the phase shift of the LCs delay line at each polarized angle of the laser illumination (assuming the same incidence angle), we were able to determine the condition for maximum tuning efficacy, i.e., when the laser polarization, the rubbing direction, and the LCs filling direction are aligned parallel to each other. We also observed the controllable phase shift varied with the incident angle, i.e., at larger angles of incidence (assuming the same polarization), we observed a smaller phase shift due to the mitigated interaction between the laser beam and the azo LCs molecules. Contrarily, as the angle of incidence reduces, we observed an elevated phase shift due to the increased interaction. Overall, our investigation demonstrates the importance of optimizing the polarization and incident angles regarding the mechanically rubbed direction when manipulating all-optically driven LCs MW optoelectronic devices for maximum tuning efficacy. The transferrable implications from the delay line can be applied to other optically driven LCs devices (e.g., tunable filters and modulators that rely also on photochemically reversible trans-cis isomerization of the azo-LCs materials) and pushing it forward to close the THz gap [6].

The author acknowledges the National Natural Science Foundation of China under Grant 62301043.

References

[1] T. Sakamoto, *Optoelectronic Circuits for Control of Lightwaves and Microwaves* (London, IntechOpen 2011).
[2] J.F. Li, Eng. Lett. **28**, 3 (2020).
[3] J.P.F. Lagerwall, G. Scalia, Curr. Appl. Phys. **12**, 6 (2012).
[4] S. Kim, K. Seiji, Crystals **9**, 12 (2019).
[5] J.F. Li, *ICEPT* (Guangzhou, IEEE 2020).
[6] U. Chodorow, J. Parka, O. Chojnowska, Phot. Lett. Poland **4**, 3 (2012).

