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Response Time Improvement of Liquid Crystal Reflectarray Using Chiral Dopant with Polar Group

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***Abstract*—In this letter, a response-time-improvement method for liquid crystal reflectarrays (LCRAs) is proposed by doping a small amount of chiral molecules with a polar group into nematic liquid crystals (NLCs). The dopant introduces additional intermolecular interactions that accelerate molecular relaxation and thus shorten the decay time, while an overdrive (OD) voltage is applied to mitigate the rise-time increase. LC cells with various chiral-dopant concentrations are characterized, where it is found that the concentration of 0.5 wt% yields the shortest effective decay time. An LCRA prototype using this concentration was fabricated and measured, achieving a significantly reduced decay time, while the rise time is effectively shortened by the OD technique. This work represents the first investigation of chiral-dopant effects on both rise and decay times within a reflectarray configuration, providing guidance for high-speed chiral LCRA design.**

***Index Terms*—Liquid crystal (LC), chiral dopant, reflectarray (RA), response time.**

I. Introduction

FUTURE wireless communication demands high data rates and large system capacity, requiring high-gain antennas and efficient beamforming [1]. Intelligent reflecting surfaces (IRSs) enhance electromagnetic (EM) signals in target regions with low power consumption [2], and reflectarrays (RAs) are a representative implementation [3]. In addition, phase-tunable materials can modulate the EM-wave phase by adjusting their physical properties [4]–[7], which is suitable for embedding in RA to realize beam forming.

Nematic liquid crystals (NLCs) are widely used phase-tunable materials whose elongated molecules reorient under an electric field, producing dielectric anisotropy. In liquid-crystal reflectarrays (LCRAs), the reflection phase is tuned by adjusting the LC permittivity through a simple bias network. Previous studies on LCRAs employed a thick LC layer with alignment films on both sides to ensure low loss and a large phase-variation range [8]–[10]. However, the anchoring forces from the alignment films hardly reach the central region of the LC layer, so when the bias voltage is removed, molecular relaxation relies mainly on elastic restoring forces, resulting in a long decay time.

Some studies have aimed to shorten the response time of LCRAs [11], [12]. One approach embeds a polymer network into the LC layer [11], which increases intermolecular interactions, thereby reducing the decay time. However, the polymer network reduces the effective LC volume, thereby reducing the permittivity anisotropy and narrowing the reflection-phase variation range. Another approach uses overdrive (OD) and underdrive techniques [12]. OD shortens the rise time by applying a brief high-voltage pulse, whereas underdrive momentarily removes the bias to accelerate relaxation. While OD can reduce the rise time to the millisecond level, underdrive provides only limited improvement in decay time.

In this letter, we propose for the first time a doping method that introduces a small amount of chiral dopant with a polar group into the nematic liquid crystal (NLC) to improve the decay time of LCRAs. The dopant induces additional intermolecular interactions that promote the formation of a helical tendency within the LC, enhancing molecular relaxation in the central region of the LC layer and thereby shortening the decay time. Meanwhile, unlike non-polar chiral dopants, the presence of a polar group allows the dopant molecules to reorient under the bias voltage, suppressing the formation of helical structures during voltage application and thus preventing an increase in rise time. The remainder of this letter is organized as follows. Section II introduces the chiral LC material and identifies the optimal doping concentration through capacitance measurements. Section III presents the measured performance of fabricated LCRA prototypes with and without the chiral dopant, demonstrating that the proposed method significantly reduces the decay time. In addition, the overdrive (OD) technique is applied to further shorten the rise time, greatly improving the overall response time. Finally, Section IV concludes this work.

II. Response Time Improvement by Chiral Dopant with Polar Group

A. Chiral liquid crystal

Chiral molecules play an important role in LC materials, particularly in converting nematic LCs into cholesteric LCs with a helical structure [13]. Because chiral molecules lack mirror symmetry, doping them into an LC induces interactions that cause successive small molecular rotations, which

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accumulate into a continuous helical structure along the spiral axis, as illustrated in Fig. 1. This helical configuration can be described by continuum theory [14], where the distortion energy of a chiral LC is given by:

$$F_d = \frac{1}{2}K_1(\nabla\cdot\mathbf{n})^2+\frac{1}{2}K_2(n\cdot\nabla\times\mathbf{n}+q_0)^2+\frac{1}{2}K_3(n\times\nabla\times\mathbf{n})^2 \quad (1)$$

where K_1, K_2 and K_3 are the splay, twist, and bend constant of the LC, respectively, while $\mathbf{n}$ is the alignment direction of the LC molecules. $q_0 = \frac{2\pi}{P}$, where P is the pitch, defined as the distance along the helical axis corresponding to a complete 360° rotation of the LC molecules. In the absence of external disturbances, LC will naturally tend to their minimum distortion energy state. According to the equation, when LC has no splay ($\nabla \cdot \mathbf{n} = 0$), no bend ($n \times \nabla \times \mathbf{n} = 0$) and has a twist which fits $(n \cdot \nabla \times \mathbf{n}) = -q_0$, the distortion energy becomes minimum (i.e., the equilibrium conformation of chiral LC is twisted).

Since the anchoring forces of the alignment films cannot effectively reach the central region of the thick NLC layer, a chiral dopant is introduced to induce an inherent helical tendency. After the bias voltage is removed, the LC molecules in the central region undergo accelerated reorientation, driven by intermolecular interactions that restore the helical configuration, thereby reducing the decay time.

However, this inherent helical tendency also increase the rise time. When a bias voltage is applied, the LC helical structure begins to unwind under the electric field while the molecules reorient along the field direction. This unwinding process significantly prolongs the rise time. In particular, non-polar chiral dopants, which lack a dipole moment, cannot reorient with the electric field; thus, the intermediate helical state unwinds much more slowly, leading to a substantial increase in rise time.

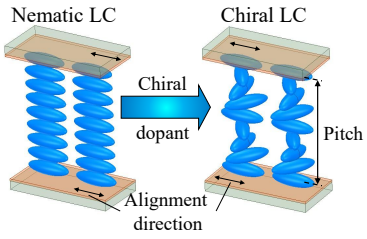

Fig. 1. Structure of nematic and chiral LC.

B. LC doped with chiral molecules substituted by a cyano group

In this letter, TD1020 was employed as the nematic host LC, and C2913 [(S)-4-cyano-4'-(2-methylbutyl)biphenyl] was selected as the chiral dopant with polar group for the experiments. For comparison, the non-polar chiral dopant cholesteryl nonanoate (CN) was also employed in the experiments. The chiral molecular structure of polar dopant C2913 and non-polar dopant CN are shown in Fig. 2(a). Because one of the hydrogen atoms on the benzene ring is substituted by a cyano group, the C2913 molecule exhibits polarity and can be reoriented under an applied bias voltage. This reorientation suppresses the formation of helical structures, thereby mitigating the slow rise time.

By doping chiral molecules into the NLC host at different weight percentages (wt%), the helicity of the LC molecules can be tuned, thereby affecting both rise and decay time of the chiral LCs. In this letter, C2913 was doped into TD1020 at concentrations of 0.2–0.6 wt% to optimize the decay time. Since the permittivity of LC varies under bias voltage, the response time can be evaluated by monitoring the capacitance variation of an LC cell with parallel electrode plates. The LC cell was fabricated using two glass substrates (25 mm × 20 mm, thickness: 0.7 mm), each with a 10 mm × 10 mm indium tin oxide (ITO) electrode printed on the inner surface. The LC layer thickness between substrates was maintained at 50 μm. Capacitance measurements were performed using a LCR (inductance-capacitance-resistance) meter IM3536 (provided by HIOKI Corporation, Japan) with a high speed power amplifier 4005 (provided by NF Corporation, Japan) under a 1 kHz, 70 V bias voltage. The capacitance value was recorded at intervals of 10 ms, enabling accurate evaluation of the response time of the LC cells. Fig. 2(a) and Fig. 2(b) show the measured rise and decay time of the nematic host TD1020, C2913-doped TD1020 LCs (0.2–0.6 wt%) and 0.5wt% CN-doped TD1020 LC for comparison, obtained from the normalized capacitance response under a 70 V bias voltage. The rise time is defined as the duration for the normalized capacitance to increase from 0 to 0.9 after the voltage is applied, while the decay time is defined as the duration for it to decrease from 1 to 0.1 after the voltage is removed.

The measured rise and decay time are summarized in Table I. For C2913-doped LCs, the decay time decreases continuously as the chiral dopant concentration increases; however, once the concentration exceeds 0.5 wt%, the normalized capacitance begins to rebound after reaching its minimum. Furthermore, the pitches of 0.4 wt%, 0.5 wt%, and 0.6 wt% C2913-doped LCs were measured using the Grandjean–Cano cell [15], [16] as 60 μm, 48 μm, and 41 μm, respectively. The rebound occurs when the pitch becomes smaller than the LC layer thickness. This rebound arises from the transient planar (TP) state [17], [18] which is an intermediate state between the homeotropic (H) state and the planar (P) state. In the TP state, the LC molecules with permittivity anisotropy, exhibit high twist energy and a gradual reconstruction of the helical structure, leading to the rebound phenomenon [19]–[21]. At 0.5 wt%, the rebound is only about 0.05, which has a negligible impact on decay time measurement. In contrast, at 0.6 wt%, the rebound exceeds 0.15, which significantly affects the decay time measurement. When the additional time required for this rebound to stabilize is considered, the effective decay time increases significantly. Therefore, the optimal doping concentration for the LCRA design is 0.5 wt%, which provides the shortest effective decay time.

Higher chiral concentration generally increases the rise time. However, the 0.5 wt% C2913-doped LC has a pitch close to the LC layer thickness, forming a nearly complete helix that requires more time to unwind, giving a longer rise time. In contrast, 0.4 wt% and 0.6 wt% C2913-doped LCs have

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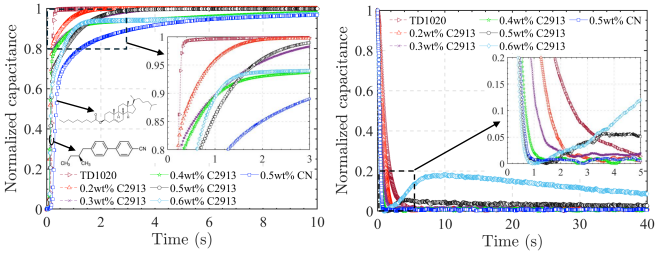
TABLE I
RISE TIME AND DECAY TIME OF TD1020, C2913-DOPED TD1020 AND CN-DOPED TD1020 LCS.

	TD1020	0.5 wt% CN	0.2 wt% C2913	0.3 wt% C2913	0.4 wt% C2913	0.5 wt% C2913	0.6 wt% C2913
Risetime (s)	0.27	3.33	0.56	1.04	1.08	1.27	1.06
Decaytime (s)	2.38	0.54	1.62	1.12	0.66	0.51	30.3

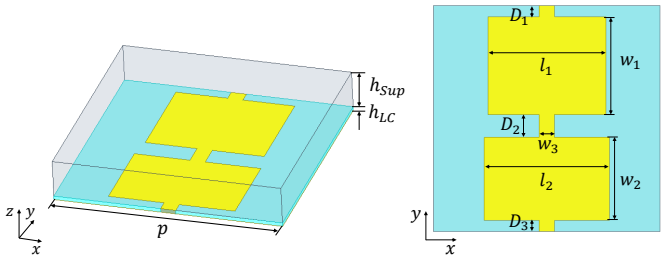
Note : Rise time and decay time of TD1020, 0.5 wt% CN-doped TD1020 and 0.2 wt% to 0.6 wt% C2913-doped TD1020.

mismatched pitches, producing distorted helices, leading to a "fast-then-slow" reorientation. As a result, a non-monotonic rise time trend is produced, making the rise time of 0.5 wt % C2913-doped LC longer than that of 0.4 wt% and 0.6 wt% C2913-doped LCs. To further compare C2913-doped LC with CN-doped LC at the same 0.5 wt% concentration, the shorter rise time is observed in the C2913-doped LC. This is attributed to its polar group, which suppresses the formation of helical structures under bias voltage.



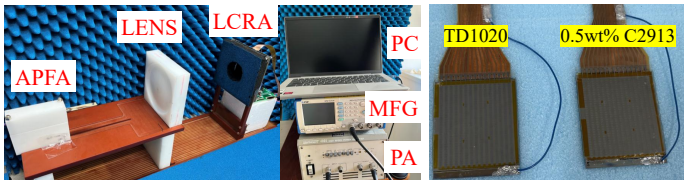
(a) (b)

Fig. 2. (a) Rise time of TD1020, 0.2-0.6 wt% C2913-doped TD1020 and 0.5 wt% CN-doped TD1020; (b) Decay time of TD1020, 0.2-0.6 wt% C2913-doped TD1020 and 0.5 wt% CN-doped TD1020.



(a) (b)

Fig. 3. (a) Perspective view, (b) top view of the proposed LCRA unit cell structure. The parameters are p=3 mm, h_{sup}=0.5 mm, and h_{LC}=0.05 mm, L_1=1.56 mm, L_2=1.66 mm, w_1=1.30 mm,w_2=1.10 mm, w_3=0.20 mm, D_1=D_3=0.15 mm, D_2=0.30 mm.



(a) (b)

Fig. 4. (a) The measurement system; (b) The prototypes of the proposed LCRAs.

III. EXPERIMENT

Two prototype LCRAs each of which is a 15 x 17 unit array filled with 0.5 wt% C2913-doped TD1020 and TD1020 are fabricated separately for experimental verification. The TD1020 used in experiment, whose relative permittivity and loss tangent under full and zero bias voltage are $\varepsilon_{r\perp} = 2.48$, $\tan\delta_{\perp} = 0.015$, $\varepsilon_{r//} = 3.05$, $\tan\delta_{//} = 0.01$. The unit cell of LCRA is shown in Fig. 3. The upper layer of the LC is non-alkali glass material (ε_r=5.4, $\tan\delta$=0.007), and the lower layer of the LC is the metallic ground plane. The reflection phase and magnitude of LCRAs are measured by lens-load printed antipodal fermi antenna (APFA) [22], using the vector network analyzer (VNA) P5008A, and the low-frequency bias voltages are generated by a computer-controlled multi-function generator (MFG) WF1974 and amplified by high speed power amplifier (PA) 4005 provided by NF Corporation, as shown in Fig. 4. The VNA is controlled by a computer which enables the continuous recording of the reflection phase of the LCRA after the bias voltage is applied or removed to measure the response time of the LCRAs.

The frequency responses of the reflection magnitude and phase for two LCRA prototypes under zero bias voltage and full bias voltage of 70 V with frequency of 1 KHz are shown in Fig. 5(a) and (b), respectively. The maximum reflection phase variation for TD1020-based LCRA is 418° at 48.75 GHz, while that of the LCRA doped with 0.5 wt% C2913 is 471° at 49.95 GHz. LCRA with 0.5 wt% C2913-doped LC was also analyzed using full-wave electromagnetic simulation. By fitting the simulated frequency responses to the measured results, the relative permittivity and loss tangent of the 0.5 wt% C2913-doped LC under zero-bias and full-bias conditions were extracted as $\varepsilon_{r\perp} = 2.16$, $\tan\delta_{\perp} = 0.035$, $\varepsilon_{r//} = 3.00$, and $\tan\delta_{//} = 0.03$. The introduction of the chiral dopant enhances the permittivity anisotropy of the LC, thereby enabling a larger reflection phase variation in the LCRA. The reflection phase of the LCRAs under different bias voltages is shown in Fig. 5(c). Both LCs reached their fully biased state under 70 V and remain stable. However, the threshold voltage increases from 5.8 V (undoped TD1020) to 13.9 V (0.5 wt% C2913-doped TD1020) due to the helical structure induced by the chiral dopant. Therefore, a higher bias voltage is required to suppress this induced helical structure and reorient the LC molecules.

Fig. 6(a) presents the measured decay time of the LCRAs with and without 0.5 wt% C2913-doped under 70 V (fully biased state) and 22 V (intermediate state where LCRA with 0.5 wt% C2913-doped LC achieved a reflection phase of 180°). The decay time for the LCRA is defined as the time required for the reflection phase to change from 100% to 10%

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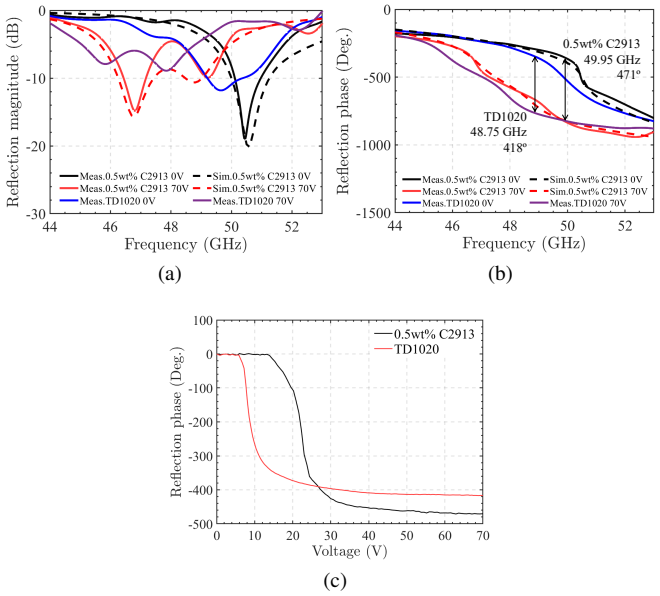

Fig. 5. Frequency responses of (a) reflection magnitude and (b) reflection phase of the LCRA with TD1020 and 0.5 wt% C2913-doped TD1020; (c) reflection phase versus applied bias voltage for TD1020 and 0.5 wt% C2913-doped TD1020.

of its maximum variation after the bias voltage is removed, which occurs 1 s after the start of the measurement. The decay time of both the fully biased state and the intermediate state of 0.5wt% C2913-doped TD1020 are reduced as compared to that of the undoped TD1020. Under the bias voltage of 70 V, the decay time is reduced from 2.42 s to 0.56 s, and under the bias voltage of 22 V, it is reduced from 2.03 s to 0.33 s. During the relaxation process of 0.5 wt% C2913-doped LC under 70 V, a rebound is observed, consistent with the normalized-capacitance measurement that was caused by the TP state. The maximum rebound value for 0.5 wt% C2913-doped LCRA is 17.1°, which is within the acceptable range and has relatively little impact on beam scanning. The experimental results confirm that the proposed chiral doping method significantly reduces the decay time, and the measured values are consistent with the LC decay time obtained from capacitance measurements of the LC cells.

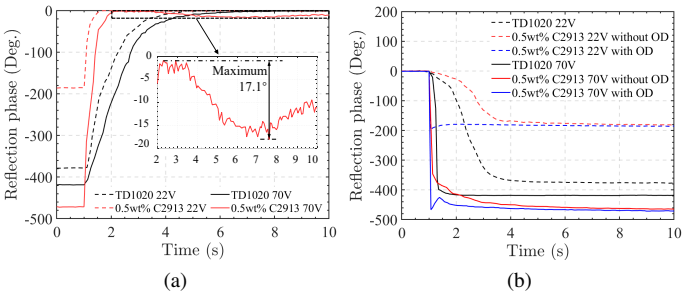

Fig. 6. (a) decay time, (b) rise time of LCRA with TD1020 and 0.5 wt% C2913-doped TD1020.

Fig. 6(b) presents the measured rise time of LCRAs with TD1020 and 0.5 wt% C2913-doped TD1020 with and without overdrive (OD) technique. The rise time for LCRA is defined as the duration required for the reflection phase to increase from 0% to 90% of its maximum variation after the voltage is applied, which occurs 1 s after the start of the measurement. Compared to the undoped TD1020 LCRA, the 0.5 wt% C2913-doped LCRA exhibits a longer rise time owing to the helical structure induced by the chiral dopant. Under the bias voltage of 70 V, the rise time increases from 0.34 s to 1.35 s, and under the bias voltage of 22 V, it increases from 2.11 s to 2.97 s. This issue is addressed in this letter by employing the OD technique to shorten the rise time. In the case of OD, for the fully biased state, a short-duration high voltage of 200 V is applied for 70 ms, followed by a steady voltage of 70 V. For the intermediate state, 200 V is applied for 30 ms, followed by a steady voltage of 22 V. By applying the OD technique, the rise time for both states are significantly reduced to below 70 ms. The OD technique significantly shortens the rise time, effectively eliminating the trade-off between decay time improvement and rise time degradation, thereby enabling a faster overall response for LCRA operation.

TABLE II
COMPARISONS WITH PRIOR WORKS

	[9]	[11]	[12]	This work
Frequency (GHz)	37.5	100	100	49.95
Technology	Conventional LC	LC + PN	LC + OD	PCDM + OD
LC thickness (mm)	0.2	0.045	0.075	0.05
Phase range (deg.)	338	180	360	471
Rise time (s)	1.05	0.012	0.05	<0.07
Decay time (s)	6.05	0.21	5	0.56

Note : LC + PN = liquid crystal + polymer network; LC + OD = liquid crystal + overdrive; PCDM + OD = polar chiral doping method + overdrive.

Table II provides a comparison between the proposed LCRA and several previously reported designs. As shown, by combining the OD method with the proposed doping method, the response time of the LCRA is significantly improved while achieving a wider phase variation range of 471°.

IV. CONCLUSION

In this letter, a doping method using a chiral dopant with a polar group is proposed to reduce the response time of LCRAs. The chiral dopant accelerates molecular relaxation to reduce decay time, while its polar group suppresses helical formation under bias voltage, thereby mitigating the rise-time increase. Capacitance measurements identify 0.5 wt% C2913-doped LC as the optimal concentration, and the fabricated 15 × 17 LCRA prototype achieves a 471° reflection-phase range at 49.95 GHz with significantly reduced decay time, while the rise time is effectively shortened by the OD technique. By combining the proposed doping method with the OD technique, a substantial improvement in LC response time is achieved, demonstrating strong potential for high-speed beam-scanning LCRA applications.

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REFERENCES

[1] W. Saad, M. Bennis, and M. Chen, "A vision of 6g wireless systems: Applications, trends, technologies, and open research problems," *IEEE Network*, vol. 34, no. 3, pp. 134–142, 2020.

[2] D. Pozar, S. Targonski, and H. Syrigos, "Design of millimeter wave microstrip reflectarrays," vol. 45, no. 2, pp. 287–296, 1997.

[3] E. Basar, M. Di Renzo, J. De Rosny, M. Debbah, M.-S. Alouini, and R. Zhang, "Wireless communications through reconfigurable intelligent surfaces," *IEEE Access*, vol. 7, pp. 116 753–116 773, 2019.

[4] A.-L. Franc, O. H. Karabey, G. Rehder, E. Pistono, R. Jakoby, and P. Ferrari, "Compact and broadband millimeter-wave electrically tunable phase shifter combining slow-wave effect with liquid crystal technology," *IEEE Transactions on Microwave Theory and Techniques*, vol. 61, no. 11, pp. 3905–3915, 2013.

[5] D. A. Connelly and J. D. Chisum, "Dynamically reconfigurable microwave circuits leveraging abrupt phase-change material," *IEEE Transactions on Microwave Theory and Techniques*, vol. 68, no. 10, pp. 4188–4205, 2020.

[6] O. G. Vendik, "Insertion loss in reflection-type microwave phase shifter based on ferroelectric tunable capacitor," *IEEE Transactions on Microwave Theory and Techniques*, vol. 55, no. 2, pp. 425–429, 2007.

[7] M. Sazegar, Y. Zheng, H. Maune, C. Damm, X. Zhou, J. Binder, and R. Jakoby, "Low-cost phased-array antenna using compact tunable phase shifters based on ferroelectric ceramics," *IEEE Transactions on Microwave Theory and Techniques*, vol. 59, no. 5, pp. 1265–1273, 2011.

[8] Y. Cui, H. Sato, Y. Shibata, T. Ishinabe, H. Fujikake, and Q. Chen, "A low-cost structure for reducing reflection loss in intelligent reflecting surface of liquid crystal," *IEEE Antennas and Wireless Propagation Letters*, vol. 22, no. 12, pp. 3027–3031, 2023.

[9] X. Li, H. Sato, H. Fujikake, and Q. Chen, "Development of two-dimensional steerable reflectarray with liquid crystal for reconfigurable intelligent surface applications," *IEEE Transactions on Antennas and Propagation*, vol. 72, no. 3, pp. 2108–2123, 2024.

[10] Y. Cui, H. Sato, K.-D. Xu, H. Fujikake, and Q. Chen, "A method of dual-bias voltage supply for reducing reflection loss in reconfigurable intelligent surfaces of liquid crystal," *IEEE Antennas and Wireless Propagation Letters*, vol. 23, no. 11, pp. 3529–3533, 2024.

[11] R. Guirado, G. Perez-Palomino, M. Caño-García, M. A. Geday, and E. Carrasco, "mm-wave metasurface unit cells achieving millisecond response through polymer network liquid crystals," vol. 10, pp. 127 928–127 938, 2022.

[12] R. Guirado, G. Perez-Palomino, M. Ferreras, E. Carrasco, and M. Caño-García, "Dynamic modeling of liquid crystal-based metasurfaces and its application to reducing reconfigurability times," *IEEE Transactions on Antennas and Propagation*, vol. 70, no. 12, pp. 11 847–11 857, 2022.

[13] V. G. Guimarães, A. Svanidze, T. Guo, P. Nepal, R. J. Twieg, P. Palffy-Muhoray, and H. Yokoyama, "Synthesis and characterization of novel bio-chiral dopants obtained from bio-betulin produced by a fermentation process," *Crystals*, vol. 11, no. 7, 2021.

[14] P. G. de Gennes and J. Prost, *The Physics of Liquid Crystals*, 2nd ed. Oxford University Press, 1993.

[15] F. Grandjean, "Sur l'existence de plans différenciés équidistants normaux à l'axe optique dans les liquides anisotropes (cristaux liquides)," *CR Seances Acad. Sci. Paris*, vol. 172, p. 71, 1921.

[16] R. Cano, "Étude du pouvoir rotatoire des cristauxliquides cholestériques," *Bulletin de Minéralogie*, vol. 90, p. 333–351, 1967.

[17] I.-A. Yao, J.-J. Wu, and S.-H. Chen, "Study of the transient phenomenon during homeotropic to planar transition in cholesteric liquid crystal cells," *Japanese Journal of Applied Physics*, vol. 43, no. 4R, p. 1488, apr 2004.

[18] E. K. Omori, R. Ferreira de Souza, R. T. de Souza, and R. S. Zola, "Winding up dynamics for matched and unmatched elastic constants in chiral nematic liquid crystals," *Soft Matter*, vol. 21, pp. 5969–5979, 2025.

[19] P. Watson, J. E. Anderson, V. Sergan, and P. J. Bos, "The transition mechanism of the transient planar to planar director configuration change in cholesteric liquid crystal displays," *Liquid Crystals*, vol. 26, no. 9, pp. 1307–1314, 1999.

[20] H. Lu, M. Zhu, Y. Cao, C. Ma, L. Qiu, J. Zhu, and M. Xu, "Fast-relaxation, dye-doped cholesteric liquid-crystal smart window with a perfect planar state," *Dyes and Pigments*, vol. 208, p. 110795, 2023.

[21] J. W. Doane, "Transient dielectric study of bistable reflective cholesteric displays and design of rapid drive scheme," *Applied Physics Letters*, 1995.

[22] H. Sato, Y. Takagi, and K. Sawaya, "High gain antipodal fermi antenna with low cross polarization," *IEICE Trans. Commun*, vol. E94.B, no. 8, pp. 2292–2297, 2011.

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