Dynamic Modeling of Liquid Crystal-Based Metasurfaces and Its Application to Reducing Reconfigurability Times

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Abstract—This article describes and validates for the first time the dynamic modeling of liquid crystal (LC)-based planar multiresonant cells, as well as its use as bias signals synthesis tool to improve their reconfigurability time. The dynamic LC director equation is solved in the longitudinal direction through the finite-element method, which provides the z- and time-dependent inhomogeneous permittivity tensor used in an electromagnetic simulator to evaluate the cell behavior. The proposed model has been experimentally validated using reflective cells for phase control (reflectarray) and measuring the transient phase, both in excitation and relaxation regimes. It is shown how a very reduced number of stratified layers are needed to model the material inhomogeneity and that even a homogeneous effective tensor can be used in most of the cases, which allows a model simplification suitable for design procedures without losing accuracy. Consequently, a novel bias signal design tool is proposed to significantly reduce the transition times of LC cells and hence of electrically large antennas composed of them. These tools, similar to those used in optical displays, are experimentally validated for the first time at mm- and sub-mm wave frequencies in this work, obtaining an improvement of orders of magnitude.

Index Terms—Dynamic modeling, intelligent reflecting surface, liquid crystal (LC), metasurface, overdrive, reconfigurable intelligent surfaces (RIS), reflectarray antenna, stratified media.

I. INTRODUCTION

LIQUID-CRYSTAL (LC) technologies are starting to be studied at mm-wave bands in order to develop tunable devices that work properly at those frequency ranges. Because of its birefringence, by applying a low-frequency electric field to a cavity containing nematic LC, its electromagnetic properties can be varied and therefore the device response changes [1]. This phenomenon has been widely used in optics to develop LC displays and other devices such as spatial phase modulators [2], but its potential use at mm-wave frequencies has only started to flourish [3].

This varying behavior is related to a continuous change on the electric permittivity, which can be leveraged to vary the resonant frequency or beam of an antenna [4], [5], [6], [7], to sweep the shift in phase shifters [8], [9], [10], [11] or to tune the different elements in a reflectarray antenna [12], [13], [14], [15], [16], to name a few. Very recently, the use of nematic LC as the key phase-shifting element of the upcoming reconfigurable intelligent surfaces (RIS), planar devices able to manipulate electromagnetic propagation, has been proposed [17], [18], [19], as it is one of the few tunable technologies with moderate cost capable of keeping the pace of the high frequencies (>100 GHz) expected in future network generations beyond 5G. Moreover, since the LC fills an entire cavity and its behavior can be locally modified, a pixel-wise active element implementation is avoided. This, together with the fact that these manufacturing procedures are widely common in optics, especially when developing electrically large planar devices with thousands of cells, makes this technology a very attractive solution for developing RIS panels. Alternative solutions to switch a beam in a metasurface, such as mechanical steering [20] or unit cells based on varactor diodes [21], although being commercially available, are either of much higher cost or exhibit frequency limitations, as Table I shows.

Nevertheless, the relatively large losses and the slow switching times between states are the main weaknesses of such LC-based devices, as detailed in Table I. Even though LC manufacturers are starting to develop novel composites

| Strategy | Speed | Freq. range | Cost | Efficiency | Energy |
|----------|-------|-------------|------|------------|--------|
| Mechanical | s | Wide       | High | Low        | High   |
| Varactor | μs | Limited    | Medium | High      | Medium |
| LC       | s | Wide       | Low  | High       | Very low |

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specifically designed to present low losses at microwave and mm-wave frequencies [3], current mm-wave LC devices provide reconfigurability times in the order of the seconds. However, to be fully implantable in future ultra-reliable low-latency communication networks, improving these times until they are at least comparable to the channel coherence time is of utmost importance due to the stringent dynamic requirements of upcoming communication protocols.

A number of strategies have been reported in optics to improve transition times, such as the use of polymerizable compounds [22], [23] or dual-frequency LC [24], [25], [26], especially for decay time. Another strategy to reduce transition times is to employ sophisticated excitation signals by leveraging LC dynamics [27], [28], [29]. In order to understand and completely control its dynamic behavior during a state transition, which will ultimately impact the switching time, its accurate temporal modeling is essential. In spite of this, few works tackle the temporal aspects of LC between arbitrary states [30], [31], [32], [33], and all of them focus on the optical regime and not on RF. Moreover, given the challenge of achieving a proper phase shift range in mm-wave bands, multiresonant cells (i.e., including several resonant elements in a single-band cell) must be used [12], [34]. This makes modeling much more complex [35] since resonators create phase shifts that cannot be modeled with a medium constant, and they are also used to locally bias the LC. In [36], an accurate LC modeling at mm-wave frequencies was proposed for cells in which it is necessary to include resonant elements. Using that model, it was shown that inhomogeneity and anisotropy can be considered only in the longitudinal direction of the cell, and the minimum number of layers in which the media should be stratified to obtain a precise phase prediction was also found. However, that model only considers a static LC regime, that is, when enough time has passed after an external excitation so that molecules lie in a stationary state after rotating. In the nematic LC characteristic equation, this translates into neglecting time-dependent terms. Consequently, there is no previous research on accurately characterizing the dynamics of LC-based mm-wave devices to reduce switching times.

In this article, we accurately model for the first time the LC dynamics between transition states (Fréedericksz transition) in RF past the known approximations, in order to obtain a temporal design control capability of the LC, representing a contribution to the model beyond the one reported in [36]. First, we solve the LC dynamics equation applied to multiresonant cells, analyzing its convergence as a function of the number of layers. This is done to investigate whether it is possible to compress the LC inhomogeneous molecular orientation in a single layer of an effective permittivity tensor, computed with the average molecule tilt across the cavity, with the aim of enabling a much more efficient electromagnetic cavity evaluation. The validation of the proposed model is carried out experimentally through different state transitions. As another novelty of this work given its applicability, the proposed and validated modeling is used to introduce an efficient design procedure of the LC bias signal, similar to the overdrive technique used in optical panels, capable of diminishing the switching time (especially rise transitions) of planar multiresonant cells for phase control by a factor of 100X. Finally, both the model and the overdrive excitation technique are validated by comparing simulation and experimental data, obtained from reflective multiresonant cells fed by a plane wave (reflectarray, metasurface, or RIS), although the model is extendable to transmissive structures (transmitarrays) or other planar structures capable of controlling other parameters than a phase. In the article, we discuss the reconfigurability time improvement as a function of the used biasing signals, showing that the proposed method mitigates one of the most important challenges this technology must overcome to be widely used.

The model results are validated at the cell (pixel) level for two different frequencies (97 and 102 GHz), which in turn facilitates a tool for the analysis and synthesis of control signals at an arbitrary frequency and per each cell of the whole antenna, given that in a complete surface, a plane wave with a different incident angle will arrive to each pixel. Therefore, this tool allows for the synthesis of overdriving control signals without depending on experimental measurements for each cell and angle of incidence in the array.

The article is organized as follows. Section II introduces the dynamic modeling of LC multiresonant cells and discusses analytical solutions to motivate the use of overdriving to reduce transition times. In Section III, the dynamic LC differential equation is solved exactly by combining a finite-element method (COMSOL) and a full-wave electromagnetic analysis tool (CST), the phase convergence of the cell is analyzed and the model is validated. Then, in Section IV, the overdrive design tool is presented and experimentally tested, and Section V concludes.

II. DYNAMIC MODELING OF LC RESONANT CELLS

A. Permittivity Tensor Calculation

LC-based mm-wave devices leverage the tuning capability of this material, typically used as a substrate, to become dynamically reconfigurable. A typical LC cavity is shown in Fig. 1(a) and (b) with and without external excitation, respectively, where \( z = 0 \) and \( z = d \) planes are assumed to be indefinite electrodes. In this case, the rod-like molecules only present inhomogeneity along \( z \) when biased. In the nematic state, due to the small degree of positional order of nematic LCs, a low-frequency (ac) electric field applied across the cavity will rotate its molecules. This, together with the LC anisotropy (i.e., large orientational order), allows the permittivity to be varied, as shown in the following equation:

\[
\overline{\varepsilon}(\mathbf{\tau}, t) = \varepsilon_{r,\|} \mathbf{I} + \Delta \varepsilon \overline{N}(\mathbf{\tau}, t)
\]  

(1)

where \( \mathbf{I} \) is the \( 3 \times 3 \) identity matrix and \( \overline{N}(\mathbf{\tau}, t) = \hat{n}(\mathbf{\tau}, t) \otimes \hat{n}(\mathbf{\tau}, t) \), with \( \hat{n}(\mathbf{\tau}, t) \) being the macroscopic vector that defines the local orientation of the LC molecules at a certain point and time. This way, if an external electric field changes \( \overline{N} \), the macroscopic permittivity will be tuned. Given that the substrate under use is both inhomogeneous and anisotropic, its dielectric permittivity has to be expressed as a tensor \( \overline{\varepsilon} \). The dielectric anisotropy of the material is defined as \( \Delta \varepsilon_r = \varepsilon_{r,\|} - \varepsilon_{r,\perp} \), with \( \varepsilon_{r,\|} \) and \( \varepsilon_{r,\perp} \) being the parallel and
perpendicular dielectric constants with respect to \( \hat{n} \), which, respectively, relate the parallel and perpendicular components of the RF electric field to the electric displacement field. A concurrent problem in LC-based mm-wave designs is that the birefringence of LC cells has been typically underestimated and modeled with a scalar permittivity value, ranging the birefringence of LC cells has been typically underestimated of the RF electric field to the electric displacement field. respectively, relate the parallel and perpendicular components perpendicular dielectric constants with respect to \( \hat{n} \), instead of using its tensor form. This oversimplifies the problem by transforming it into an isotropic scenario, as by working with only the scalar permittivity the results are geometry-dependent and do not generalize, being insufficient for accurate modeling.

Both in reflectarray antennas and RIS, this dielectric anisotropy is used to perform a pixel-wise phase shift across an impinging electromagnetic wave. By applying a precomputed bias voltage to each cell, the reflection coefficient phase is locally modified, thus obtaining a desired global phase distribution at the output, which will dictate the direction of the reflected wave. As shown in Fig. 1(c) and (d), a unit cell of such reflectarray antennas consists of a set of electrodes (typically dipoles, connected to the same potential within the cell) printed below a superstrate (e.g., quartz), which will act as a top plate of the LC cavity; the LC layer itself; a bottom conductive plate; and a substrate to support the structure. When carefully designed, the role of the dipoles is to produce an appropriate resonance in the reflection coefficient in RF, which will ultimately create a phase shift depending on the biasing. However, besides their role in RF, the dipoles also have a function in ac, since they are typically used to polarize the LC with the low-frequency electric field. This makes the tensorial permittivity to actually be inhomogeneous also in the transverse directions \((x \text{ and } y)\), although in [36] it was shown in the static case how its effects in the reflected phase are negligible when compared to the inhomogeneity and anisotropy effects in the longitudinal direction. In this article, it will be shown how these effects also have little impact when modeling LC dynamics. Notwithstanding, in [37] and [35], a more rigorous LC modeling is introduced for complex structures in which these effects are not negligible.

It is worth noting that in literature, there exist three general strategies to perform 2-D addressing of the cells, in order to apply the proper voltage (and, therefore, to obtain the proper phase) to each antenna pixel: direct, active, and passive addressing [1]. In the cases of active or passive addressing, the sequential row sweep implies the need of synthesizing voltage sequences which must be properly computed, requiring a tool to analyze and synthesize control signals, like the one introduced in this article. In the direct addressing case, the proposed model and tool are especially useful to reduce transition times between states, enabling overdrive techniques.

The complex task of synthesizing control sequences could alternatively be done through measurement data instead of simulations. However, as long as sufficiently accurate models are used, the latter greatly simplifies the process given that the LC dynamic effects depend on the cell position within the array (different incidence angle), the dimensions of the resonators in each cell (cells could have different dimensions in each pixel), the operating frequency, and the LC properties.

**B. Dynamic Director Calculation**

Assuming that the applied ac electric field is homogeneous across the cell, which is feasible if the effects of transverse inhomogeneity are negligible, the dynamic behavior of the LC under such external excitation is described by the Ericksen–Leslie equation [1], [38], [39]

\[
\left(k_{11}\cos^2\theta + k_{33}\sin^2\theta\right)\frac{\partial^2\theta}{\partial z^2} + \left(k_{33} - k_{11}\right)\cdot \sin\theta \cdot \cos\theta \left(\frac{\partial \theta}{\partial z}\right)^2 \\
+ \left(\alpha_2\sin^2\theta - \alpha_3\cos^2\theta\right)\frac{\partial \theta}{\partial t} + \varepsilon_0 E^2 \Delta \varepsilon_e \cdot \sin\theta \cdot \cos\theta = \gamma_1 \frac{\partial \theta}{\partial t} + I \frac{\partial^2 \theta}{\partial t^2}
\]

where \( k_{11} \) and \( k_{33} \) are the splay and bend elastic constants, \( \alpha_2 \) is the Leslie viscosity coefficient, \( v \) is the flow velocity, \( E = V_d/d \) is the applied quasi-static electric field, \( \Delta \varepsilon_e \) is the low-frequency dielectric anisotropy, \( \theta \) is the tilt angle of the director, \( \gamma_1 \) is the rotational viscosity, and \( I \) represents the inertia. Two modifications can be safely made to the previous equation. First, the inertia term is typically neglected as it has a very small weight [40]. Second, the Leslie coefficients terms can be disregarded, as they also play a minor role and obtaining them requires experimental measurements [1], [41]. Their impact will be seen later on in relation to backflow effects. Therefore, the previous equation reduces to [30], [42]

\[
\left(k_{11}\cos^2\theta + k_{33}\sin^2\theta\right)\frac{\partial^2\theta}{\partial z^2} + \left(k_{33} - k_{11}\right) \\
\cdot \sin\theta \cdot \cos\theta \left(\frac{\partial \theta}{\partial z}\right)^2 + \varepsilon_0 E^2 \Delta \varepsilon_e \cdot \sin\theta \cdot \cos\theta = \gamma_1 \frac{\partial \theta}{\partial t}
\]

which allows the time-varying director to be found.

In order to solve (3), boundary conditions for \( \theta(z=0) \) and \( \theta(z=d) \) must be applied. In the ideal case, \( \theta(z=0) = \theta(z=d) = \theta_p = 0 \) (zero pre-tilt), which makes (3) stable from a certain

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**Fig. 1.** (a) LC cavity with an applied electric field. (b) LC cavity without excitation. (c) Layered view of the reflectarray unit cell. (d) Top-view of the reflectarray unit cell. Dimensions (mm): \( D_1 = 0.171, D_2 = 0.096, D_3 = 0.042, L_{x1} = 0.707, L_{x2} = 0.748, L_{x3} = 0.792, L_{x1} = 0.2, L_{x2} = 0.211, L_{x3} = 0.2, P_L = 1.145, P_R = 1.093, h_Q = 0.55, \) and \( h_{LC} = 0.075. \)
threshold voltage $V_{th}$. Then, the LC molecules will not start reorienting until this threshold voltage is reached. Specifically, $V_{th}$ can be computed as

$$V_{th} = \pi \sqrt{\frac{k_{11}}{\Delta \varepsilon_\varphi}}.$$  \hspace{1cm} (4)

In a real implementation of an LC cell, the innermost surface of the two conductive plates contains a rubbed polyimide orienting layer, which forces the pretilt boundary condition $\theta_0 \neq 0$ at $z = 0$ and $z = d$. This ensures that the molecules are correctly oriented also in the absence of excitation, as can be seen in Fig. 1(b). Under these conditions, $V_{th}$ is not a strict value anymore, as molecules are able to rotate even below this threshold. However, it can still be used as a reference to identify a voltage point in which the LC starts reacting more energetically, since below it the molecular orientation is weak.

Equation (3) entails the dynamic behavior of the LC under an excitation, but since it is too complex to be solved analytically, certain approximations are typically made in order to obtain approximate analytical solutions. Specifically, it is usually assumed that $k_{11} = k_{33}$ and that the LC is excited with a low-voltage source. This allows modeling the $\theta(z)$ curve with a sinusoidal function, so that $\sin(\theta) \sim \hat{\theta}$, which greatly simplifies the previous expression, resulting in the following equation:

$$k_{11} \frac{\partial^2 \theta}{\partial z^2} + \varepsilon_0 E^2 \Delta \varepsilon_\varphi \theta = \gamma_1 \frac{\partial \hat{\theta}}{\partial t}. \hspace{1cm} (5)$$

Then, the solution for the tilt angle along $z$ takes, in time, an exponential form with the following decay and rise time constants:

$$\tau_d = \gamma_1 \frac{d^2}{k_{11} \pi^2}, \hspace{1cm} (6)$$

$$\tau_r = \sqrt{\frac{\gamma_1}{\gamma_2}} \left( 1 - \frac{\gamma_1}{\gamma_2} \right). \hspace{1cm} (7)$$

However, these approximations oversimplify the dynamics problem as: 1) they assume a pretilt angle equal to zero, which is not realistic [31]; 2) they are only valid for small voltage excitation where the tilt can be approximated with a sine, which is a rough estimation; and 3) they assume that the driving voltage is little above $V_{th}$, while we will later show that voltages much greater than that are needed in order to accelerate the LC response. Although more elaborated expressions have been introduced in [42] to include pretilt effects, small angle approximations and single elastic constants ($k = k_{11} = k_{33}$ or $k = (k_{11} + k_{33})/2$) are still assumed. In [36], the static voltage dependence of LC is studied and accurately predicted but the dynamics are not tackled. In [9], the LC temporal behavior is experimentally measured for different commercially available materials in 4 $\mu$m thick cells, but a model is not provided.

Moreover, in optics, the phase change that occurs from this tilt dynamics can be well modeled, and the optical intensity change can be well predicted, since for such a short wavelength, the LC is simply a medium in which several $\pi$-times phase changes happen [31]. However, in mm-wave devices, extra resonant elements are needed to enlarge the phase range up to a few $\pi$-times, which makes the relationship between the tilt angle dynamics and phase changes much more complex to model. When including resonant elements such as printed dipoles, the electric field in the cavity contains significant components in all directions and anisotropy cannot be overlooked. That is, since the phase change is generated through printed metallizations in the superstrate, the cavity cannot be modeled anymore with a medium constant. Furthermore, in optics, the cavities are typically much narrower ($\sim 10 \mu$m) than in microwaves ($\sim 100 \mu$m), being such thick cavities quite unexplored and not modeled. Therefore, it is necessary to solve (3) for resonant cells without any of these limitations, so that an appropriate model is achieved considering the number of layers and the inhomogeneity to consider and to be validated with measurement data.

III. MODEL RESULTS AND EXPERIMENTAL VALIDATION

In order to accurately model the tilt angle dynamics of the LC when an excitation change occurs, we computationally solve (3) along $z$ and $t$ using the finite-element method in COMSOL Multiphysics [43]. This avoids several error sources as we specifically consider the pretilt effects and a more complete set of elastic constants, obtaining more precise data for the $\theta(z)$ curves at any timestamp and LC driving voltage. Moreover, this allows to model any kind of excitation beyond step-like functions, although if the excitation signal has a frequency high enough so that its period is much smaller than the relaxation time of the LC, it can be substituted by its root mean square (rms) value in (3).

Fig. 2 shows the molecules tilt angle as a function of $z$ for different timestamps in three different excitation scenarios, in a 75 $\mu$m thick cavity filled with GT3-23001 LC. It can be observed how large voltage excitations make transitions faster and much more homogeneous tilts. By using the proposed tool, Fig. 3 shows the error on the computed rise time (10%-90%) when the sine approximation and (6) and (7) are used with respect to the real solution of (3) for the same cavity. As expected, it is necessary to model the cell rigorously especially in the high-voltage regime, given that errors larger than 10% could be made in predicting the LC temporal behavior, which in turn induces large errors in the cell RF reflected phase as a function of time.

Once the different tilt angles along $z$ are obtained for each timestamp of a certain transition, and therefore $\hat{h}(z, t)$ is known, it is necessary to compute the permittivity tensors in accordance with the formulation of Section II-A. After the permittivity model has been calculated using COMSOL, this is used in an electromagnetic simulator (CST Studio [44]) with the aim of obtaining the electrical parameters of the periodical reflective cell in RF.

As sketched in Fig. 4, in order to model the LC inhomogeneity along $z$, two different strategies have been used and compared, similar to [36]. On the one hand, a stratified media has been considered, deploying different substrate layers within the LC. In this way, we consider the inhomogeneity along $z$ by partitioning the LC in $N$ uniform layers in which the average tilt angle is assumed. With a large number of
Fig. 2. Tilt angle dynamics in a 75-μm-thick cavity filled with GT3-23001 LC. (a) Step transition from 0 to 15 V. (b) Step transition from 0 to 150 V. (c) Transition from 150 to 10 V after 19 ms.

Fig. 3. 10%-90% rise time approximation error compared to the solver solution in a 75-μm thick cavity. $T_{\text{a}}$ refers to the approximated time from the closed expressions and $T_s$ refers to the simulated time from (3). It can be observed how the closed expressions fail for large voltages, as the sinusoidal approximation becomes invalid, as well as the Vth effect.

Fig. 4. Stratified and averaged LC cavity dynamic modeling strategies. In the stratified strategy, $\varepsilon_{r}(\theta, z, t)$ is computed with (1) and considering as $\theta_i$ the average tilt within the layer $i$. In the averaged strategy, $\varepsilon_{r, a v g}(\theta_{a v g}, z, t)$ is computed considering as $\theta_i$ the average tilt across the entire cavity.

In order to validate the simulated dynamic results, the transient phase curves at a certain frequency are compared against experimental data, captured from a reflectarray antenna.

is to find a tradeoff between accuracy and efficiency given that a multilayer electromagnetic analysis is very costly. Note that this is more precise than directly averaging the permittivity across z. This introduces a certain error to the computation, but greatly increases the efficiency of the simulation. Specifically, the latter method will become more accurate with extreme bias voltages, as the average and the local tilt values are almost the same across all $z$, and the difference with the stratified method will be negligible. This can be noticed in the top curves of Fig. 2, where the 150 V excitation makes almost all molecules along $z$ to be rotated 90° at $T = 35$ ms, in contrast with the 15 V excitation at $T = 4$ s. Therefore, in medium-voltage excitations, the stratified procedure will work slightly better but its complexity will increase abruptly. Fig. 5 compares the convergence of such stratified models by computing phase transitions in a 1-, 3-, 5-, and 20-layered unit cell, showing that the single-layer method is really precise, especially at large voltage excitations, as opposed to the analytical approximations. As will be seen later in the article, these high-voltage excitations are of special interest for the overdrive technique to reduce reconfigurability times. The error made in the homogeneous case with respect to the stratified model is found to be reduced (around 20° in the worst case) and admissible, given that the corresponding degradation of the radiation pattern for such phase deviation is negligible [45], [46]. Moreover, it can be appreciated how for increasing voltages, the difference between both methods vanishes (20° and 0.5° differences in 5- and 150 V excitation, respectively). The error is similar to that found in [36] for statics, but it is generalized here for dynamics. Therefore, single-layer modeling is carried out for the following experiments with the aim of increasing computation efficiency at a negligible accuracy loss, especially at high voltages. However, the stratified approach could be followed for perfectionist modeling at a higher computational cost. For midrange problems, increasing the number of layers until the accuracy converges is a reasonable procedure.
whose unit cell is shown in Fig. 1(c), containing an LC cavity filled with GT3-23001 from Merck \[47\] \( k_{33} = 34.5 \text{pN}; k_{11} = 24 \text{pN}; \gamma_1 = 746 \text{mPas}; \varepsilon_{r\parallel} = 3.27; \varepsilon_{r\perp} = 2.47; \Delta \varepsilon_q = 4.6 \) sandwiched below a Quartz superstrate \( \varepsilon_r = 3.78, \tan\delta = 0.002 \). The complete antenna consists of 60 \( \times \) 60 identical cells [see Fig. 6(a)], and its phase response is shown in Fig. 7 for extreme excitations (OFF state corresponds to \( V = 0 \) and ON state corresponds to \( V \gg V_{th} \)) in the stationary regime.

To experimentally acquire the dynamic cell phase curves at each timestamp for a specified frequency, incidence angle, and bias signal, the setup shown in Fig. 6(b) and (c) has been implemented. An arbitrary waveform generator (Keysight 33611A), programed to output different bias signals, drives the LC of the reflectarray antenna through a \( \times 15 \) V multiplier.

In order to ensure a specular reflection, all unit cells of the antenna are short-circuited so that the LC is excited equally along the entire array. The waveform generator sends a SYNC signal to a vector network analyzer (VNA) to guarantee a timely capture of the transition. The VNA has been previously calibrated with a metallic plane reference and equipped with a pair of horn antennas and captures the evolution of the transmission scattering parameters at 97 and 102 GHz when the bias signal sequence starts. These frequencies were selected since they show the maximum phase range within the band of operation of the 360\(^\circ\) cell, thus allowing the detection of the maximum phase errors. Both the experiments and the electromagnetic simulations have been carried out considering an impinging angle of 30\(^\circ\) with respect to the normal of the reflectarray plane \( (\phi_i = 0^\circ \text{ and } \theta_i = 30^\circ) \).

Fig. 8(b) compares simulations and measurements of the transient reflected field phase at 102 GHz as a function of time for different voltage rise transitions starting from idle, verifying that the tool can predict relatively close to the actual cell behavior. The applied 1-kHz square signal allows us to assume an amplitude equal to its rms value in (3). The model has been validated with relaxation measurements as well. Fig. 8(c) shows simulation and measurement data of the reflected field phase evolution at 102 GHz for different decay transitions parting from varying voltages. The corresponding biasing signals are shown in Fig. 8(a).

As can be seen, the temporal model of the LC transitions matches the experimental data both in rise and decay time, as well as in the phase range. It can be noticed how, as expected, while the rise transitions are highly dependent on the applied voltage, the decay transitions are quite similar.
regardless of the driving amplitude at $T = 0$. Small discrepancies ($< 30^\circ$) between the expected and measured phase ranges in the permanent regime can be explained by the phase curve in Fig. 7, where the phase difference between both states slightly differs. It should be mentioned that this range of error becomes negligible when confirming a full radiation pattern, as it is equivalent to a 3-bit phase quantization, which generally suffices to synthesize a collimated beam and only deteriorates gain by 0.2 dB and SLL by 0.8 dB [45], [48]. Errors in the transient regime (up to $200^\circ$ in the worst case of $V_1 = 8$ V) can be associated with different sources, including the 1-layer assumption and especially the pretilt angle estimation and LC RF characterization. This error could be minimized by choosing a denser layer stratification and assuming a lower computational efficiency, considering their tradeoff. Additionally, the different error sources could be compensated in the model by performing, a posteriori, an effective parameter tuning for each voltage curve using measurement data.

**IV. Biasing Synthesis Techniques**

The dynamic modeling of LC multiresonant cells, obtained and experimentally validated in Section III, enables the development of bias voltage design techniques through simulations, which allow an improvement in the antenna reconfigurability times. These methods can be used to reduce both the relaxation times (underdrive) and the rising times (overdrive) although, as will be seen next, the main improvement occurs in the rising transitions.

Specifically, by leveraging an accurate temporal control of the LC, a timely driving of the LC cells can be used to accelerate the transition times between phase states. That is, by overdriving it in the rise transitions, the LC orientation time can be accelerated when the electric field is increased (i.e., rotating the molecules toward parallel to $z$). This is achieved by using, during a short period of time, a larger voltage than the nominal biasing voltage (i.e., the voltage in which the cell presents the desired phase shift in the permanent regime, after the molecules stopped rotating). This can be seen in Fig. 9, where the overdrive LC driving signal amplitude is 150 V until the 10 V objective reflection coefficient phase is achieved, instant in which we switch the excitation to the nominal 10 V signal amplitude. Similarly, by underdriving it (sometimes referred to as undershoot), the LC orientation time can be accelerated when the electric field is decreased (i.e., rotating the molecules toward perpendicular to $z$). In this case, the LC is briefly driven at a lower voltage than the nominal one. Additionally, by using dual-frequency LC, the overdrive technique can be used to accelerate both transitions. The overdrive technique has been used in optic devices in the past [49], but by using approximations instead of accurate profiling, and not in the mm-wave regime where the cell thickness and modeling become problematic.
In the case of aperture antennas where the objective parameter is the pixel phase, the design procedure of the LC overdriving signal for quickly achieving the desired phase of an array cell, defined by its dimensions and incidence angle, is the following.

1) Identify the nominal voltage that achieves the desired phase shift in a stationary state.
2) Compute $\theta(z, t)$ for the rise transition toward the nominal voltage, by solving (3).
3) Find the phase-time curve of such transition by solving the structure electromagnetically, for each timestamp, after finding $\theta(z, t)$ from (1).
4) Repeat steps 2 and 3 for the rise transition toward the maximum voltage.
5) Pick, from the rise transition toward the maximum voltage, the timestamp in which the instantaneous phase matches the converged phase of the nominal transition.

Then, the driving signal consists of modifying the amplitude of the nominal biasing signal to the maximum voltage between $t = 0$ and the obtained timestamp. Regarding the underdriving signal design, the procedure is dual by using a drop transition toward a zero voltage. Given that implementing these strategies properly requires very precise knowledge of the LC dynamics in the cells and given that it is unfeasible to obtain such curves for each cell and incidence angle, it is necessary an accurate but more computationally costly. Even though this information through simulations.

In order to validate such a technique, different temporal driving signals have been computed so as to reduce the switching times for different state transitions, and experimental measures have been obtained using those excitations. In Fig. 10, a comparison between simulated and measured data for both overdrive and nominal excitations is shown for a 0–10 V transition. As can be seen, the overdrive technique applied to the reflectarray antenna allows to accelerate the rise time by a factor of 100X. In Fig. 11, measurements and simulations for both overdrive and underdrive techniques are compared against a normal operation for different phase transitions at two representative frequencies in the band of design, and the corresponding bias signals are shown. As can be observed, the overdrive strategy allows for a much quicker phase drop than the normal operation, reducing by several orders of magnitude the switching times. Although the underdrive technique also shows some time reduction [see Fig. 11(d)], its effect is not so pronounced, as the decay transition is less dependent on the excitation. Moreover, since the rise transitions are completely dependent on the driving amplitude, the voltage can theoretically be further increased to reduce the rising times (in practice, we will be restricted by equipment and the limited cavity impedance creating a short-circuit), but it cannot be underdriven beyond 0 V since it is the absolute magnitude of $E$ what makes LC molecules to rotate. Notwithstanding, the decay times can be further reduced by choosing a less viscous LC, or by employing dual-frequency LC, which can in turn benefit from this overdrive technique to decrease relaxation times. Additionally, both excitation and relaxation times may be drastically decremented by properly combining the overdrive techniques and the previously mentioned polymerizable materials, although future work on its characterization is required. It should be mentioned that even though the voltage is increased significantly during these transitions, the overall power consumption is minimum, as the LC cell hardly consumes any current.

An interesting phenomenon that occurs in some of the captured phase transitions is a significant rebound of the phase right after the objective phase is initially achieved in the overdrive excitation, as shown in Fig. 10 and the middle row of Fig. 11. This bounce is the manifestation of both the bias signal commutation [which causes the molecular reorientation of Fig. 2(c)] and the backflow effect [42], [55], [56], [57], which appears as a consequence of working in the high-voltage regime in thick cells and that our model did not completely capture. This is a well-known phenomenon that, if one has access to the LC Leslie coefficients, either through manufacturer data or experimental estimation [41], [58], could be included in the problem to make the model more accurate but more computationally costly. Even though this effect deteriorates the experimental measurements as the phase oscillates slightly (<65° in Fig. 10) until reaching the final value, we can still approach the objective phase state much faster than under a nominal excitation, being the instantaneous phase during such transient effect ±20% deviated only.

Overall, the predicted and measured reflectarray cells transitioned a maximum of 250X and an average of 100X faster between phase shift states when using overdrive techniques, when compared to using nominal excitations. On the other hand, by completely removing the biasing voltage temporarily, the underdrive excitations shortened on average a 2X time factor to achieve 90% of the objective phase, when compared to the nominal excitations. To put this into perspective, Table II compares different works on electrical beam-steering phase shift LC metasurfaces and unit cells, and their performance including transition times. Additionally, a comparison with other reconfigurable metasurface technologies is included.
Fig. 11. Phase transition between states using overdrive/underdrive and nominal excitations. The top row shows simulations and the middle row shows measurements of (a) 0–10 V at 97 GHz, using a 150 V overdrive for 19 ms; (b) 0–15 V at 97 GHz, using a 150 V overdrive for 21 ms; (c) 0–15 V at 102 GHz, using a 75 V overdrive for 90 ms; (d) 15–5 V at 97 GHz, using a 0 V underdrive for 2.5 s. The bottom row shows the applied overdrive/underdrive bias signal.

V. Conclusion

LC-based reconfigurable metasurfaces are promising candidates for developing electrically large aperture antennas supporting the future generation of communications, given their easiness of manufacturing, low cost, and wide operating frequency ranges. However, switching times between phase states must be reduced before they can be widely used in real-time applications. In this work, a dynamical model of LC transitions for different excitations beyond the known approximations is presented and validated in order to achieve temporal control of the unit cell phase, useful for both reflective and transmissive multiresonant cells. Further analysis of the LC stratified model is also provided by considering a different number of simulated layers, concluding that a reduced number of layers \((N = 20)\) is needed in the worst case, although using an effective tensor \((N = 1)\) will be enough to achieve reasonable accuracy most of the times and useful to perform efficient electromagnetic simulations. Even though the effect of the different LC driving excitations on the phase change can be carried out through both measurements and simulations, a generalization in frequency, incident angle, cell designs, and LC materials could be cumbersome to do by means of measures. Instead, a simulation tool like the one introduced in this work allows for a fast and accurate estimation of control signals to introduce the temporal parameter in the design space of electrically large antennas. In turn, this allowed us to design and validate an overdriving technique capable of drastically reducing transition times by one or two orders of magnitude in a simple way. In the rising case, reductions are of factor 100, while in the relaxation case, improvements are less drastic.

| Work | Technology | Freq. (GHz) | Losses | PR | Ton | Toff | Pol. | Complete antenna parameters |
|------|------------|-------------|--------|----|-----|------|-----|-----------------------------|
| [50] | PIN        | 7.45        | 12dB   | 180° | <1ms | <1ms | DL  | G: 21dB, SA: ±40°, 2D, BW: 0.33 (3dB) |
| [51] | Varactor   | 11.3/14.7   | 2/3dB  | 300° | <1ms | <1ms | C   | G: 14/16.6dB, SA: ±24°, 2D, BW: 0.85/0.63 (3dB) |
| [52] | Varactor   | 23.5        | 3dB    | 320° | <1ms | <1ms | SL  | SA: ±60°, 1D                  |
| [53] | VO₂        | 32          | 1dB    | 300° | 12ms | 2s   | SL  |                             |
| [54] | MEMS       | 11.2        | 0.5dB  | 180° | <1ms | <1ms | DL  |                             |
| [13] | LC         | 24.1        | 4dB    | 360° | 5°   | 10s  | SL  | G: 20.2dB, SA: ±45°, 2D, BW: 4 (3dB) |
| [15] | LC         | 78          | 12dB   | 270° | 5°   | 10s  | SL  | G: 25.1dB, SA: ±7°, 1D, BW: 3 (1dB) |
| [12]**| LC         | 100         | 6dB    | 360° | 5s   | 10s  | SL  | G: 19.4dB, SA: ±5°, 1D, BW: 6 (3dB) |

* Estimated considering technology. ** Same cell design and LC material employed to facilitate the temporal comparison.

PR = Phase range; DL = Dual linear; SL = Single linear; C = Circular; G = Gain; SA = Scan angle; BW = Gain bandwidth.
However, this strategy can be used together with others to enhance the whole LC dynamic behavior and obtain reduced antenna scanning times.

REFERENCES

[1] D. Yang and S.-T. Wu, “Fundamentals of liquid crystal devices,” in Wiley Set. Display Technol., 2nd ed. New York, NY, USA: Wiley, 2014, pp. 1–570.
[2] O. Buchnev, N. Podoliak, K. Kaltenecker, M. Walther, and V. A. Fedotov, “Metasurface-based optical liquid crystal cell as an ultrathin spatial phase modulator for THz applications,” ACS Photon., vol. 7, no. 11, pp. 3199–3206, Nov. 2020.
[3] M. Wittke, C. Fritzsche, and D. Schroth, “Employing liquid-crystal-based smart antennas for satellite and terrestrial communication,” Inf. Display, vol. 37, no. 1, pp. 17–22, 2021.
[4] A. C. Polycarpou, M. A. Christou, and N. C. Papanicolaou, “Tunable patch antenna printed on a biased nematic liquid crystal cell,” IEEE Trans. Antennas Propag., vol. 62, no. 10, pp. 4980–4987, Oct. 2014.
[5] N. Martin, P. Laurent, C. Person, P. Gelin, and F. Huret, “Patch antenna adjustable in frequency using liquid crystal,” in Proc. 33rd Eur. Microw. Conf., vol. 2, Oct. 2003, pp. 699–702.
[6] D. Wang, E. Polat, H. Tesmer, R. Jakoby, and H. Maune, “A compact and fast fast 1 × 4 continuously steerable endfire phased-array antenna based on liquid crystal,” IEEE Antennas Wireless Propag. Lett., vol. 20, no. 10, pp. 1859–1862, Oct. 2021.
[7] E. Martini et al., “Reconfigurable antenna based on liquid crystals for continuous beam scanning with a single control,” in Proc. IEEE Int. Symp. Antennas Propag. USNC-URSI Radio Sci. Meeting, Jul. 2019, pp. 449–450.
[8] A. Moessinger, C. Fritzsche, S. Bildik, and R. Jakoby, “Compact tunable Ka-band phase shifter based on liquid crystals,” in IEEE MTT-S Int. Microw. Symp. Dig., May 2010, pp. 1020–1023.
[9] D. Wang et al., “Fast and miniaturized phase shifter with excellent figure of merit based on liquid crystal and nanowire-filled membrane technologies,” IEEE J. Microw., vol. 2, no. 1, pp. 174–184, Jan. 2022.
[10] B. S.-Y. Ung et al., “Towards a rapid terahertz liquid crystal phase shifter: Terahertz in-plane and terahertz out-plane (TIP-TOP) switching,” IEEE Trans. Terahertz Sci. Technol., vol. 8, no. 2, pp. 209–214, Mar. 2018.
[11] E. Polat et al., “Reconfigurable millimeter-wave components based on liquid crystal technology for smart applications,” Crystals, vol. 10, no. 5, p. 346, Apr. 2020.
[12] G. Perez-Palomino et al., “Design and demonstration of an electronically scanned reflectarray antenna at 100 GHz using multiresistors based on liquid crystals,” IEEE Trans. Antennas Propag., vol. 63, no. 8, pp. 3722–3727, Aug. 2015.
[13] X. Li et al., “Broadband electronically scanned reflectarray antenna with liquid crystals,” IEEE Antennas Wireless Propag. Lett., vol. 20, no. 3, pp. 396–400, Mar. 2021.
[14] J.-X. Li, T. Jin, D. Erni, F.-Y. Meng, Q. Wu, and W.-N. Li, “Design and numerical demonstration of a 2D millimeter-wave beam-scanning reflectarray based on liquid crystals and a static driving technique,” J. Phys. D, Appl. Phys., vol. 52, no. 27, May 2019, Art. no. 275103.
[15] S. Bildik, S. Dieter, C. Fritzsche, W. Menzel, and R. Jakoby, “Reconfigurable folded reflectarray antenna based upon liquid crystal technology,” IEEE Trans. Antennas Propag., vol. 63, no. 1, pp. 122–132, Jan. 2015.
[16] S. V. Hum and J. Perrussseau-Carrier, “Reconfigurable reflectarrays and array layouts for dynamic antenna beam control: A review,” IEEE Trans. Antennas Propag., vol. 62, no. 1, pp. 183–198, Jan. 2014.
[17] E. Basar, M. Di Renzo, J. De Rosny, M. Debbah, M. Alouini, and R. Zhang, “Wireless communications through reconfigurable intelligent surfaces,” IEEE Access, vol. 7, pp. 116753–116773, 2019.
[18] B. Vasic, G. Ilic, R. Beccherelli, and D. C. Zografopoulos, “Tunable beam steering at terahertz frequencies using reconfigurable metasurfaces coupled with liquid crystals,” IEEE J. Sel. Topics Quantum Electron., vol. 26, no. 5, pp. 1–9, Sep. 2020.
[19] J. Wu et al., “Liquid crystal programmable metasurface for terahertz beam steering,” Appl. Phys. Lett., vol. 116, no. 13, Mar. 2020, Art. no. 131104.
[20] V. F. Fusco, “Mechanical beam scanning reflectarray,” IEEE Trans. Antennas Propag., vol. 53, no. 11, pp. 3841–3848, Nov. 2005.
[21] M. E. Trampler, R. E. Lovato, and X. Gong, “Dual-resonance continuous-beam-scanning X-band reflectarray antenna,” IEEE Trans. Antennas Propag., vol. 68, no. 8, pp. 6080–6087, Aug. 2020.
[47] Merck KGaA. Accessed: Mar. 5, 2022. [Online]. Available: https://www.merckgroup.com

[48] G. P. Palomino, “Contribution to the analysis and design of reflectarray antennas for reconfigurable beam applications at frequencies above 100 GHz using liquid crystal technology,” Ph.D. thesis, 2016.

[49] H. Okumura and H. Fujiwara, “A new low-image-lag drive method for large-size LCTVs,” J. Soc. Inf. Display, vol. 1, no. 3, pp. 335–339, 1993.

[50] N. Zhang et al., “A dual-polarized reconfigurable reflectarray antenna based on dual-channel programmable metasurface,” IEEE Trans. Antennas Propag., early access, Apr. 14, 2022, doi: 10.1109/TAP.2022.3165872.

[51] E. Baladi, M. Y. Xu, N. Faria, and S. V. Hum, “Dual-band circularly polarized fully reconfigurable reflectarray antenna for satellite applications in the Ku-band,” IEEE Trans. Antennas Propag., vol. 69, no. 12, pp. 8387–8396, Dec. 2021.

[52] D. Rotshild and A. Abramovich, “Realization and validation of continuous tunable metasurface for high resolution beam steering reflector at K-band frequency,” Int. J. RF Microw. Comput.-Aided Eng., vol. 31, no. 4, 2021, Art. no. e22559.

[53] R. Matos and N. Pala, “VO₂-based ultra-reconfigurable intelligent reflective surface for 5G applications,” Sci. Rep., vol. 12, no. 1, p. 4497, Dec. 2022.

[54] T. Debovovic and J. Perruisseau-Carrier, “Low loss MEMS-reconfigurable 1-bit reflectarray cell with dual-linear polarization,” IEEE Trans. Antennas Propag., vol. 62, no. 10, pp. 5055–5060, Oct. 2014.

[55] S. Wu and C. Wu, “High-speed liquid-crystal modulators using transient nematic effect,” J. Appl. Phys., vol. 65, no. 2, pp. 527–532, 1989.

[56] M. Grinfeld, M. Langer, and N. J. Mottram, “Nematic viscosity estimation using director kickback dynamics,” Liquid Crystals, vol. 38, no. 8, pp. 981–987, Aug. 2011.

[57] D. W. Berreman, “Liquid-crystal twist cell dynamics with backflow,” J. Appl. Phys., vol. 46, no. 9, pp. 3746–3751, 1975.

[58] Y.-D. Zhang et al., “Backflow effect enabling fast response and low driving voltage of electrophotorefractive E-ink dispersion by liquid crystal additives,” Sci. Rep., vol. 9, no. 1, p. 13981, Dec. 2019.

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