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Beam Scanning by Liquid-Crystal Biasing in a Modified SIW Structure

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***Abstract*—A fixed-frequency beam-scanning 1D antenna based on Liquid Crystals (LCs) is designed for application in 2D scanning with lateral alignment. The 2D array environment imposes full decoupling of adjacent 1D antennas, which often conflicts with the LC requirement of DC biasing: the proposed design accommodates both. The LC medium is placed inside a Substrate Integrated Waveguide (SIW) modified to work as a Groove Gap Waveguide, with radiating slots etched on the upper broad wall, that radiates as a Leaky-Wave Antenna (LWA). This allows effective application of the DC bias voltage needed for tuning the LCs. At the same time, the RF field remains laterally confined, enabling the possibility to lay several antennas in parallel and achieve 2D beam scanning. The design is validated by simulation employing the actual properties of a commercial LC medium.**

***Index Terms*—Beam scanning, Leaky-Wave Antenna (LWA), Liquid Crystals (LCs), Groove Gap Waveguide (GGW).**

I. Introduction

In recent years, Liquid Crystals (LCs) have been proposed and studied to implement electronically tunable beam-scanning antennas [1], [2]. In particular, they have been often employed in the context of Leaky-Wave Antennas (LWAs), thus benefiting from the simple feeding mechanism and the small form factor typical of these architectures [3]–[5].

In this paper, we address an LC-based 1D scanning antenna based on the leaky-wave paradigm with two joint specific goals: a) efficiently allowing the coexistence of DC bias of the LCs (actually AC at about 1 kHz) and of the RF wave guiding and radiation; and b) allowing 2D scanning via alignment of the present 1D scanning antenna block to form a 2D array. This latter goal requires to have isolation (or large decoupling) between neighboring 1D blocks to allow for independent feeding in an array environment, as it naturally happens for waveguide arrays (e.g. slotted waveguides).

A viable solution to the DC-RF coexistence requirement is the structure presented in [4], which consists of modulated slots in a metal plane and employs parallel-plate waveguide (PPW) guidance. However, that design cannot be directly extended to the 2D scanning presently targeted, as described above. The presently proposed structure satisfies instead the two mentioned functional requirements.

II. Antenna Structure and Design

We firstly note that an obvious general constraint for LC beam steering is to maximize field concentration in the LC, to maximise the effect of its variation of permittivity as a function of the applied DC electric field; along with the need for a DC biasing, this forces the structure to be as thin as possible.

The structure of the proposed antenna is shown in Fig. 1. It consists of a Substrate Integrated Waveguide (SIW) modified to work as a Groove Gap Waveguide (GGW) [6] with (transverse) slots etched in the top wall for radiation; the SIW is filled with a thin layer of LCs embedded in a thin dielectric substrate, as shown in Fig. 1c. Tuning the electric permittivity of the LCs allows to steer the radiation angle by changing the propagation constant of the traveling wave. Two separate electrodes are needed to DC-bias the LCs, which requires the closed-wall cross section of the hosting waveguide to be modified; this is done by employing the GGW technology (see Fig. 1b).

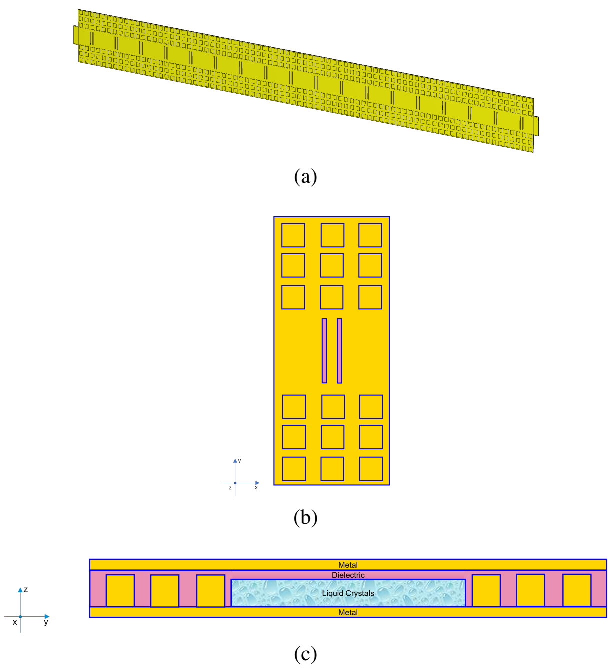


Fig. 1. Structure of the proposed antenna. (a) Front view of the whole antenna. (b) Constitutive unit cell. (c) View of the waveguide cross section.

The modified waveguide is filled with a 0.1-mm layer of LCs embedded in a RO3010 substrate ($\varepsilon_r = 11.2$, $\tan\delta = 0.0021$), for a total thickness of 0.13 mm. The LC mixture considered in this design is the licriOn$^{\text{TM}}$ GT7-29001 from Merck KGaA; its relative permittivity goes from 2.46 to 3.53, while $\tan\delta$ is in the range [0.0064; 0.0116] [7]. The width of the waveguide is set in order to ensure that only the HE$_{11}$ mode (of the closed waveguide) is above cutoff.

According to the leaky-wave paradigm, the periodic etching of transverse slots in the top wall of the waveguide allows for the radiation of the fast $n = -1$ Floquet harmonic. The period is chosen to be around $\lambda_0/2$ at the working frequency of 30 GHz, as to avoid spurious radiation from other harmonics.

One of the main drawbacks of using LCs is represented by the high material losses; therefore, highly radiating elements are needed to obtain an acceptable antenna efficiency. The slot length is set to be close to the resonant one, thus strongly coupling the slots to the traveling wave. Moreover, since beam scanning through broadside is desired, each unit cell contains two transverse slots of slightly different width, placed at a distance such as to suppress the open stopband [8].

The design process is based on the optimization of the unit cell shown in Fig. 1b. The antenna is designed to radiate near broadside when the electric permittivity of LCs is around 3, i.e. in the middle of the variation range. After an initial dimensioning of the waveguide, a Bloch analysis is performed to retrieve the dispersion diagram of the structure, i.e. the propagation constant β and leakage constant α of the traveling wave as functions of frequency [9]. Slot length, widths and relative distance are then optimized in order to suppress the natural increase in the leakage constant curve around broadside, thus effectively eliminating the open-stopband issue [8].

As mentioned before, the correct biasing of the LCs requires two separate planes, as allowed by the GGW (see Fig. 1b). This operation allows a DC bias of the LCs that obviously would not be possible with a standard waveguide with closed cross-section.

III. Results

A. 1D Scanning Antenna

The antenna shown in Fig. 1a, consisting of 18 unit cells, is simulated with a full-wave commercial solver [10].

The total length of the antenna is equal to 93.6 mm. The radiation pattern for three different values of the electric permittivity of LCs ($\varepsilon_{rLC} = 2.5, 3, 3.5$) at the working frequency of 30 GHz is shown in Fig. 2. Radiation angles and maximum directivity are reported in Table I.

The total steering range achieved with the designed antenna is equal to 58°.

The electric field in the cross section of the modified waveguide is shown in Fig. 3. It can be seen that the field remains confined inside the central section of the waveguide.

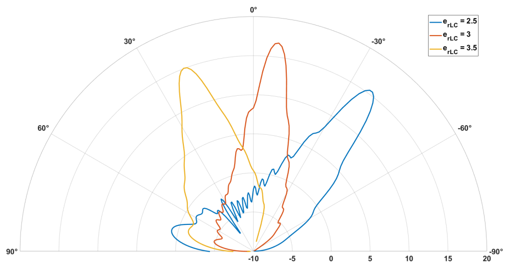


Fig. 2. Far-field directivity in the $\phi = 0°$ plane for different values of the LCs' permittivity.

TABLE I

Simulated Performance of the 1D Scanning Antenna

ε_{rLC}	θ_{rad} [deg]	Directivity [dBi]
2.5	-37	15.2
3	-7	16.8
3.5	21	15

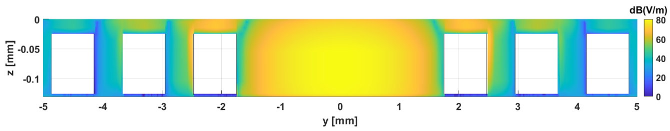


Fig. 3. Electric field in the cross section of the antenna.

B. 2D Array

As mentioned before, the field confinement ensured by the proposed modified waveguide allows to place several antennas in parallel. Fig. 4 shows an array of 3 blocks.

Since the central parts of the top broad walls of the modified waveguides can be all electrically separated from each other, the 3 LC tanks can be biased with different voltages. However, as a first test of the correct behaviour of the array, the radiating elements are excited in phase and the LC tanks are all biased with the same quasi-DC signal. What we expect is a reduction of the beam width in the transverse direction, caused by the array factor, with respect to the case of a single 1D scanning antenna.

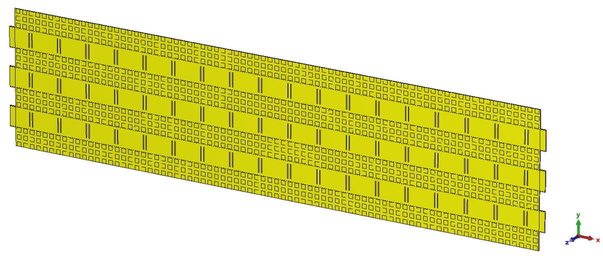
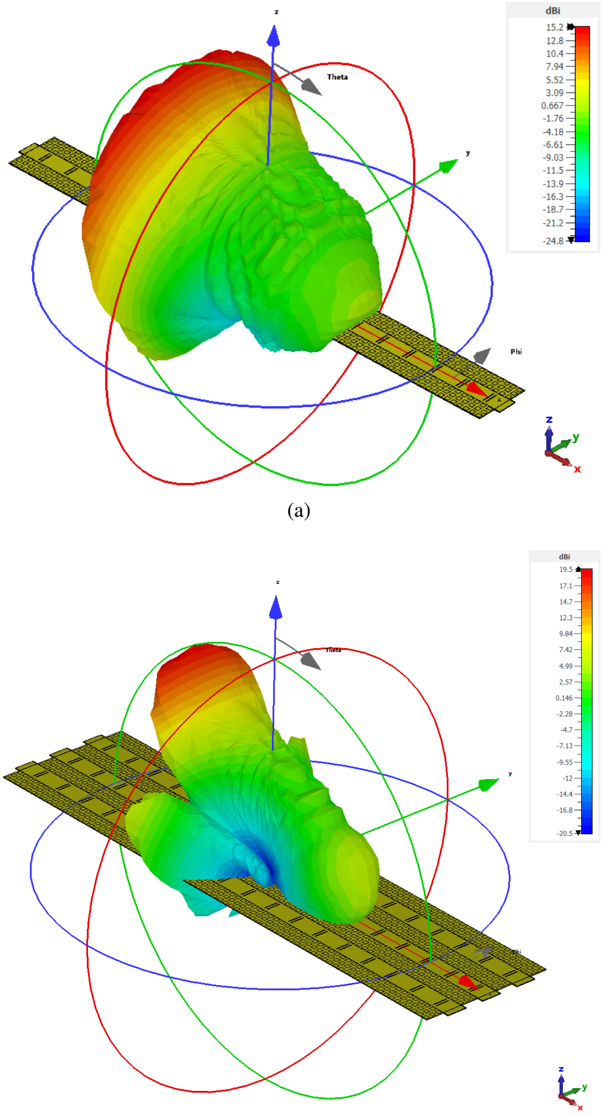


Fig. 4. Perspective view of a 2D array of three 1D scanning antennas.

Fig. 5 shows the simulated 3D far-field patterns for the single antenna and the 3-element array, for the same LC biasing

($\varepsilon_{rLC} = 2.5$). While the radiation angle is $\theta_{rad} = -37°$ in the $\phi = 0°$ plane for both the configurations, a significant reduction in the beam width in the transverse direction is observed, as expected. An accurate array synthesis technique can be used to properly exploit the degrees of freedom given by the independent biasing of the LC tanks and achieve 2D beam scanning.



(a)

(b)

Fig. 5. 3D far-field pattern for (a) one single antenna and (b) a 3-element array, for the same LC biasing.

IV. Conclusions

This work presents a beam-scanning antenna based on a modified slotted waveguide filled with Liquid Crystals. The structure is designed to comply with the physical constraint of DC biasing the LCs. Other relevant design issues are dealt with by appropriately designing the constitutive unit cell; this allows to avoid the open-stopband of the leaky-wave radiation and compensate for the high LC losses. An overall steering range of 58° is obtained.

The proposed 1D scanning antenna can be easily arranged in a 2D scanning array, thanks to the field confinement inside the modified waveguides and the possibility to bias the LCs in each antenna with a different voltage signal. The individual 1D antenna and a representative array are simulated, employing the actual properties of a commercial LC medium and accounting for all material losses. Realization and measurement of a prototype are currently under way.

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