

Impact of Addressing Techniques on Liquid Crystal-Based mm-Wave Reflectarrays

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Abstract—In this paper, different addressing techniques for driving 2D reflectarrays based on Liquid Crystal are analyzed, considering the practical advantages and disadvantages of each of them. Their specific performance implications in mm-wave devices, as well as the main challenges and differences with respect to optical devices, are discussed and analyzed for the first time, and practical implementation guidelines are reported.

I. INTRODUCTION

Reflective phase-shifting surfaces based on Liquid Crystals (LC), such as reflectarray antennas (RA), are structures capable of spatially tuning the phase shift of an impinging wave by means of local permittivity changes through a pixel-wise voltage biasing. Depending on their application, the cells can be passively, actively or directly addressed, as shown in Fig. 1. Although these biasing techniques were developed for optics, where their impact is known [1]–[3], in RF cells this has important and unique implications that have not been considered before. For instance, when working at mm-wave bands, there is the need of placing resonators to obtain enough phase shift and usually the LC cavity is much thicker, which completely changes the scenario. Other implementation aspects, such as crosstalk, also affect differently. A slight inter-pixel coupling can alter the cell operation and reduce the voltage selection ratio (SR), or dynamic range, defined as the relation between the maximum and minimum cell biasing voltage, $SR = V_{ON}^{rms}/V_{OFF}^{rms}$, that can be synthesized by different addressing techniques. Usually, the SR is not infinite, which implies that the LC molecules are not completely switched on or off, diminishing the phase range which is already scarce as compared to optic devices. In this paper, we describe the different 2D addressing strategies, discuss their specific effects on mm-wave devices and analyze their achievable phase range in different reflective unit cells.

II. ADDRESSING TECHNIQUES

A. Passive Addressing

In a passive addressing scheme (Fig. 1a), only $N_r + N_c$ connections are needed to drive an $N_r \times N_c$ array, as each row of the surface matrix is sequentially selected and the whole surface is periodically swept. When a specific row is activated, the ij pixel voltage is $V_{LC,ij}(t) = V_R^i(t) - V_C^j(t)$. The signals V_R^i and V_C^j are tailored so that even though the entire row is active, only the desired cells are addressed. This way, both

when switched ON and OFF, $V_{LC,ij}$ is non-zero. This strategy leverages the fact that the LC is indeed affected by the RMS value of the cell voltage V_{LC} , together with the slow relaxation times of LCs, to apply sequential refreshes to the cells.

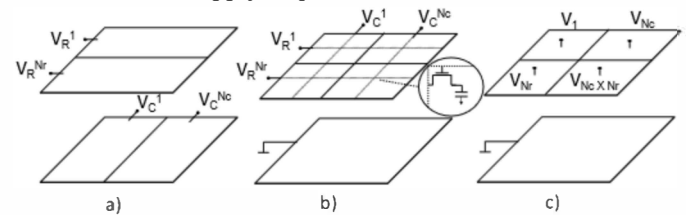


Fig. 1. a) Passive Addressing. b) Active Addressing. c) Direct Addressing.

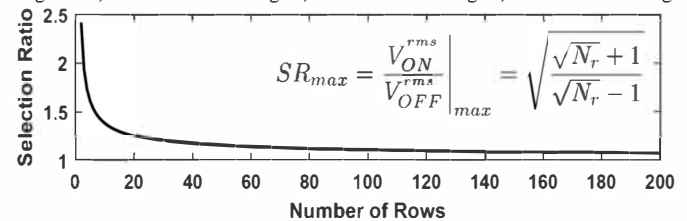


Fig. 2. Maximum selection ratio as a function of N_r in passive addressing.

Notwithstanding, the main drawback of the passive addressing technique is the reduced selection ratio, provided that pixels are never truly switched OFF [4]. Since the SR increases with N_r , large arrays will present a deficient contrast and the applicability reduces. This is seen in Fig. 2, where the SR gets asymptotically close to 1 (null phase range). Another limitation of this addressing scheme is that increasing matrix sizes will make the refreshing rate to diminish, and the driving voltage to increase to the point that crosstalk effects in neighbour pixels can worsen significantly. Overall, although the passive addressing scheme is quite simple to implement, the SR and crosstalk limitations make of this strategy to be impractical for large array implementations.

B. Active Addressing

In an active addressing scheme (Fig. 1b), the introduction of active elements in the array provides a certain pixel independence, which results in enlarged SR and reduced crosstalk at the cost of an increased manufacturing complexity [5]. As in the passive case, the number of required driving connections is $N_r + N_c$, and the row signals are used to sequentially select them. However, in this case, by placing thin-film transistors (TFT) attached to a capacitor, the applied voltage in V_C^j is directly the desired driving voltage, which will be held between refreshes. Both row and column signals are applied to the same electrode plane of the cavity, contrary to a passive

This work was supported by "la Caixa" Foundation (ID 100010434). The fellowship code is LCF/BQ/DR21/11880029.

The work was also supported by the Spanish Ministry of Science and Innovation (ENHANCE-5G PID2020-114172RB-C22/AEI/10.13039/501100011033).

scheme, and the other plane is grounded. When a pulse is applied to V_R^i , all the TFTs of row i activate at once, and the column information is stored in each capacitor. All in all, even though SR is greatly improved with respect to passive addressing, it is not infinite since in practice the isolation is not perfect (i.e. there exists a leakage current that can slowly discharge the capacitor) and parasitic effects take relevance. Similarly, crosstalk is greatly minimized but not completely negligible. Moreover, these advantages come at the cost of increasing the manufacturing complexity.

C. Direct Addressing

In a direct addressing scheme (Fig. 1c), each pixel is independently biased to the objective voltage, which requires a total of $N_r \times N_c$ individual pixel signals. This strategy can be prohibitive for large arrays, as the number of connections becomes unbearable. The main advantage of direct addressing lies on its theoretically infinite SR, being the only technique capable of truly providing it. Each cell is always individually fed by the correct RMS voltage, and consequently, a true zero voltage can be achieved in the OFF states. Overall, this scheme is the most attractive one in terms of performance, given the signal degradation avoidance and the achievable SR. However, the complexity lies on the increased circuitry, which limits its application to simple devices with a small number of pixels.

III. ADDRESSING EFFECTS ON LC REFLECTARRAYS

In RF phase-tuning metasurfaces such as reflectarrays, the achievable phase range is the most important parameter. In terms of phase range, while 360° is usually desired, relaxing this to structures of at least 180° (1-bit) allows to generate decent radiation patterns at the cost of reducing the gain and increasing the sidelobe levels. After the unit cell design and the LC properties, the addressing has a significant impact on the phase range by means of the SR. In photonic devices, the consequences of a reduced SR are noticeable but not as limiting as in RF, since the small wavelength allows for phase shifts in the order of several 2π times. However, in RF the structures naturally have a significantly smaller phase range, so if SR further reduces it the eventual range could even be of no use ($< 180^\circ$). Therefore, a large SR is essential in RF planar devices. Fig. 3 shows how by designing unit cells with steeper curves, smaller SR can be tolerated, allowing addressing techniques with small SR that tend to be simpler (e.g. passive addressing). As can be seen, the direct addressing allows for the maximum phase range and the active one slightly reduces it, while the passive clearly deteriorates it.

Regarding technological issues, the ground plane segmentation could theoretically distort the electric field in the cavity and therefore deteriorate the phase shifting. However, this is required for both planes in passive addressing and for one plane in direct and active addressings. Fortunately, if properly taken under consideration in the design, these effects should not impact beyond a slight deterioration in the smoothness of the phase [6]. Another technological limitation is related to the physical access to pixels, which in direct addressing requires to place potential electrically large via holes in the substrates,

limiting the operating frequency of the metasurface. An alternative is to place addressing lines through the plane in order to reach each pixel from the sides, which in turn limits the array size. A further consideration is the manufacturing complexity of actively addressed arrays, which is greatly developed in optic displays but not in RF devices. The introduction of retention circuits in each cell is a well established process in the former case, where millions of pixels coexist with more stringent requirements than in mm-wave. However, adapting them to RF requires new manufacturing chains, mainly due to size differences. Therefore, in terms of the manufacturing maturity and immediate availability only, passive addressing is the most convenient strategy for large arrays.

Finally, given the SR limitations in RF, as well as the radically different way phase shifts are obtained as compared to photonics, an accurate dynamic LC characterization becomes relevant in the different addressing techniques, especially in passive and active addressing arrays with N_r large. Amplitudes and timings of the biasing signals must be properly chosen considering the LC dynamics under such cells, so that the RMS is effective and the phase behaves as expected between refreshes. Therefore, a dynamic knowledge of the LC is needed, which is well studied in optics and in thin cells but not in thick cells or in mm-wave.

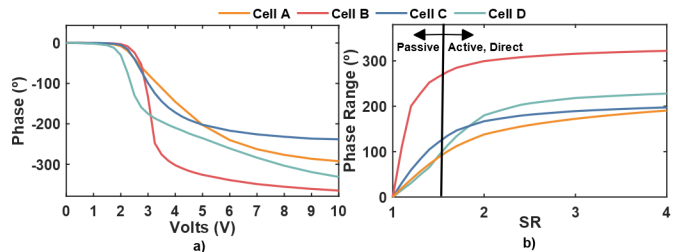


Fig. 3. a) Phase-Volts b) Phase range-SR curve in different RA cell designs.

IV. CONCLUSION

After analysing the RF implications of passive, active and direct addressing in LC-based reflectarray surfaces, it is shown how for small devices the three techniques show good performance, although the passive one is the simplest. For medium-sized arrays, direct addressing provides the best performance results at a limited complexity cost, while for large array implementations the active addressing scheme should be chosen for a reasonable trade-off between SR and complexity. However, the cell design and its achievable phase range have great impact on the optimal addressing technique.

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