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Tuneable Polarisation Agnostic Reflectarray Element at mmWave Using Polymer Dispersed Liquid Crystal

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***Abstract*—A reflectarray element operating at 73 GHz is designed using polymer dispersed liquid crystal (PDLC) to allow tuning of the reflected phase. Liquid crystals allow low-loss tuning at mmWave frequencies, but add complexity to the fabrication process. PDLCs trap pockets of liquid crystal in polymer, simplifying fabrication at the cost of reduced birefringence in permittivity. This paper proposes and simulates a polarisation agnostic element design achieving 200 degrees phase change with only 2.1 dB magnitude variation using PDLCs by using a slotted, rotationally symmetrical unit cell with two closely spaced resonances.**

***Index Terms*—Reflectarray, metasurface, polymer dispersed liquid crystal, mmWave**

I. INTRODUCTION

Reconfigurable reflectarrays have been proposed for producing the directive beams required to overcome high pathloss at mmWave frequencies [1]. Elements produce different phase shifts when illuminated by a plane wave, allowing a planar surface to mimic curved reflectors. Tuning the phase shifts of the individual elements allows the reflecting pattern to be reconfigured.

Liquid Crystals (LCs) are an increasingly investigated method for tuning reflectarrays at these frequencies due to introducing less loss than semiconductor devices [2]. In response to an electric field, the crystal structure realigns and changes the material's relative permittivity ϵ_r. Previous work has produced LC tuned reflectarrays which operate in only one polarisation, but with scanning across both E and H planes [3]. This achieved over 360^o phase change at 37.5 GHz, with losses varying from 0.7dB to 2.1dB over the tuning range. Others have produced elements for circular polarisation, including achieving 177^o phase change with 7.5dB losses at 100 GHz [4]. Recently a one-bit tuneable reflectarray was designed which can address each element in the array individually, and operates equally in two polarisations over a range of incident angles [5]. The work achieved 189^o phase shift at 108 GHz with negligible amplitude change between the two states, and only 1.4dB loss. All these approaches have complex fabrication process, requiring grooved rubbing layers to align the LC in their rest state, and either etched regions of quartz or inserted spacers to contain the LC and prevent leakage.

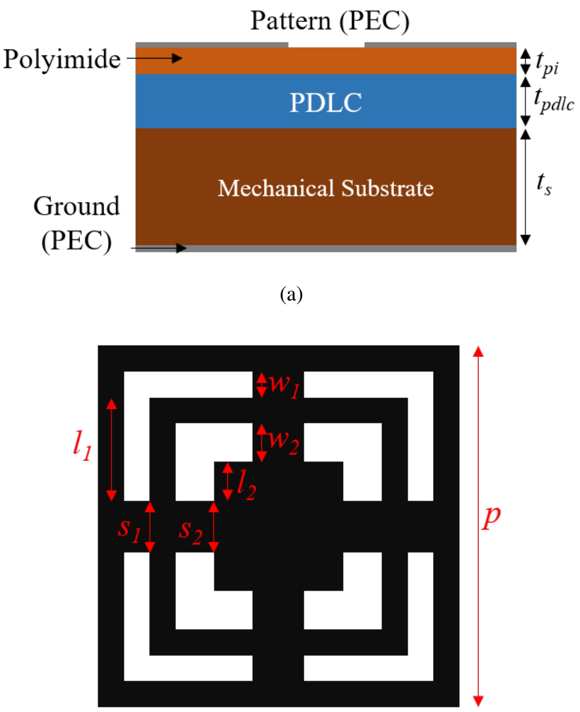
Polymer Dispersed Liquid Crystals (PDLCs) offer a solution. LCs are mixed with a polymer, such as polyethelene, resulting in a polymer with droplets of LC suspended within it [6]. These have been found to improve the physical resilience of tuneable materials, while also decreasing their tuning times [7]. PDLCs are also easily printable onto most surfaces, improving fabrication [8], [9]. This comes at the disadvantage of reduced tuning of ϵ_r. They are established in optical fields and have been used for tuning mmWave phase shifters [7], and reconfigurable antennas in the THz region [10].

This work presents and simulates the first reflectarray element using PDLC to achieve reconfigurability. The resulting element is simpler to fabricate than conventional LC tuned designs. In order to compensate for the reduced birefringence of PDLCs compared with LCs, a new resonant element is designed using two slots with similar resonant frequencies to increase the rate of change of phase. The slots are also repeated in a rotated pattern to maintain performance across different incident polarisations. The element is designed to operate at 73 GHz.

II. REFLECTARRAY ELEMENT DESIGN

The vertical structure of the designed element is shown in Fig. 1a. First, a dielectric substrate is used to provide mechanical stability, and has a ground plane on one side. On the other side the layer of PDLC is deposited. This is held in place by a thin layer of polyimide, which stops the LC leaking [7]. Note that this does not need to be mechanically rubbed, as the polymer in the PDLC encourages the rest-state orientation of the LC droplets when no bias is applied. The conducting resonant pattern is then fabricated directly onto the polyimide, which could be achieved with techniques such as aerosol jet printing [11]. The bias across the PDLC is achieved by applying one voltage on the ground plane and another on the resonant pattern.

The PDLC chosen for this investigation is a mixture of BL011 nematic LC, manufactured by Merck, and NOA-65, an acryl urethane-based photosetting polymer manufactured by Norand. This combination was measured to have $\epsilon'_{\parallel} = 2.5$ when no voltage is applied and $\epsilon'_{\perp} = 2.9$ with voltage applied, which is significantly reduced from the 2.3 to 3.3 tuning range of the LC alone as measured by the manufacturer [7]. Note that the polymer has a relative permittivity of $\epsilon_r = 1.8$. The loss in the PDLC was modelled as a loss tangent $\delta = 0.01$, and is assumed to be deposited evenly across the substrate in a $t_{pdlc} = 40\mu$m thick layer.



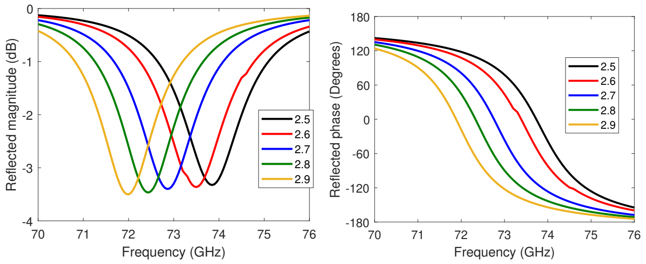
(a)

(b)

Fig. 1. Unit cell design. (a) Layered structure, (b) Resonant element.

TABLE I
UNIT CELL RESONANT ELEMENT DIMENSIONS

Name	Dimension (mm)
p	1.70
l_1	0.685
l_2	0.36
w_1	0.12
w_2	0.30
s_1	0.05
s_2	0.05



(a)

(b)

Fig. 2. Element unit cell simulation with varying PDLC ϵ_r. (a) Magnitude, (b) Phase.

Rogers RT5880 was chosen for the mechanical substrate, due to its low relative permittivity of 2.2, which minimises the effect of the substrate on the element performance, and low loss tangent of $\delta = 0.0009$. The lowest thickness available was selected at $t_s = 0.127$mm. The polyimide is modelled as having $\epsilon_r = 3.5$ and loss tangent $\delta = 0.027$, and has thickness $t_{pi} = 5\mu$m. Finally, both the ground plane and surface pattern are modelled as infinitely thin sheets of perfect electrical conductor (PEC).

The novel unit cell resonant element design is shown in Fig. 1b. The basic structure is two L-shaped slots of different dimensions, one towards the outer corner of the unit cell and one towards the inside. These are sized to have similar circumferences, and so similar resonances, so creating a steeper phase gradient than a single resonance would. This means more phase change can be achieved for a given amount of tuning, helping compensate for the reduced birefringence of PDLCs compared with conventional LCs. These two slots are then repeated in each corner of the unit cell in order to maintain its rotational symmetry, so the element behaves identically for all polarisations. Note that the dimensions, given in Table I, produce a minimum feature size of 25μm, within the tolerances of aerosol jet printing [11].

III. SIMULATION AND DISCUSSION

The element was simulated using Floquet mode boundaries in CST microwave studio (Fig. 2). The reflection loss at resonance is fairly constant, changing from 3.3dB to 3.5dB as the element is tuned. The resonant point tunes from 73.9 GHz where $\epsilon_r = 2.5$ to 72.0 GHz where $\epsilon_r = 2.9$, a ratio of 2.6%. This is a small amount of tuning, as expected due to the limited birefringence of the PDLC. Despite this, up to 200^o phase change is achievable at 73 GHz.

This is clearer in Fig. 3, which shows that in a one-bit system tuning directly between $\epsilon_r = 2.5$ and $\epsilon_r = 2.9$, there is over 180^o phase change achieved over a 1 GHz bandwidth centred on 73 GHz. This can be considered the element's operating region. At the centre frequency, there is only 0.1dB magnitude variation, though it increases to ±1.5dB at the extremes of the operating region.

The element's performance in a continuous tuning mode is shown in Fig. 4. At the 73 GHz centre frequency, 200^o phase change is achieved over the range of permittivity tuning available. Note the phase is not saturated at either end of the range of ϵ_r, suggesting the element is capable of more tuning if PDLCs with increased birefringence were developed. The magnitude variation is 2.1dB with a maximum loss of 3.4dB, comparable with other continuously tuning LC-based reflectarray elements [2].

A. A Note on Biasing

As simulated above, both the element pattern and the ground plane are continuous across the whole infinite surface. This means that the same bias voltage will be applied across the whole PDLC layer, and so the phase change will be uniform from the surface. To allow variation in the reflected phase to produce reconfigurable beamforming, either the ground plane or the surface pattern must be divided into sections, and the other used as the uniform reference voltage. Most techniques use a continuous ground plane, but this complicates connection to the control circuitry, usually solved through line addressing

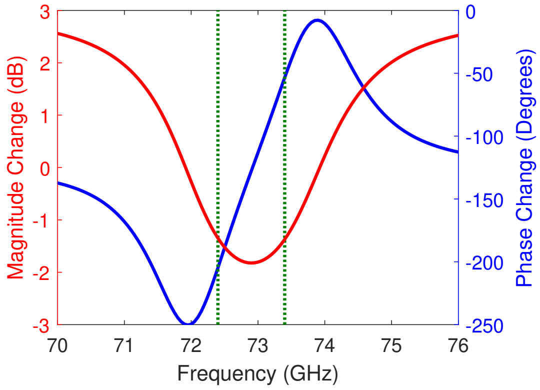


Fig. 3. Variation in magnitude and phase against frequency between PDLC tuning states $\epsilon_r = 2.5$ and $\epsilon_r = 2.9$. Green dotted lines show the operating region.

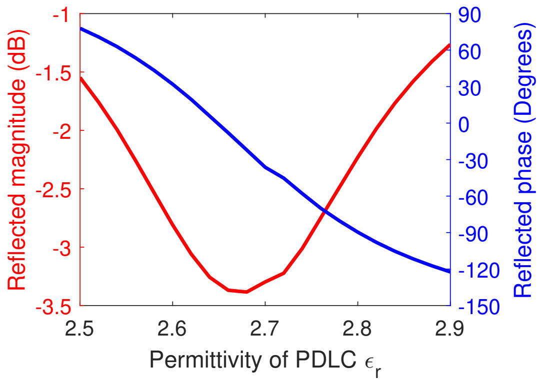


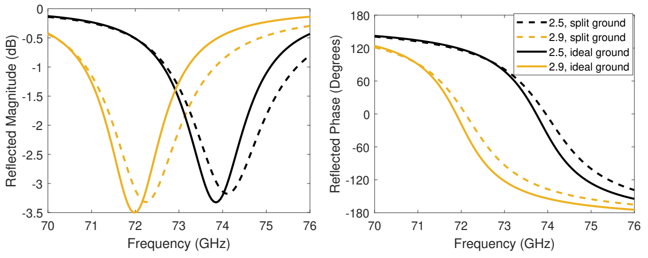
Fig. 4. Variation in magnitude and phase against varying PDLC relative permittivity ϵ_r at 73 GHz.

the elements rather than having control over scanning in both azimuth and elevation [2].

An alternative approach is to divide the ground plane into sections, and to use the selement surface as the uniform reference voltage. Whether elements are required to be controlled individually or in groups depends on the application. The most stringent scenario, where every unit cell is addressed individually, is investigated here to check worst-case performance. To minimise performance loss while ensuring manufacturability is maintained, the apertures fabricated in the ground plane will be 5μm in width, a reasonable minimum feature size for current printing techniques [11]. As such, the unit cell is resimulated with the ground plane stopping 0.0025mm short of the unit cell period (Fig. 5).

This shows a slight shift in resonant frequency, and an increase in minimum reflection magnitude to -3.3dB. More importantly, the maximum phase change has reduced to 188^o. As such, the potential operating bandwidth is reduced to 500 MHz from 1 GHz, now centred on 73.2 GHz. This is still comparable to some earlier work, while reducing fabrication complexity [4]. Note also that transmission through the element was found to remain below -11dB for all frequencies.

It may be possible to reduce the effects of a split ground plane by iterating the design process, but this is left to future work. Alternatively, they be ameliorated by using RF chokes between the unit cells, or placing a continuous ground plane behind what is now a control layer. Both of these come at the cost of increasing complexity, but retain full reconfigurability of the reflectarray.



(a) (b)

Fig. 5. Element unit cell simulation with varying PDLC ϵ_r, with an ideal ground plane (solid lines) or a ground plane split to allow individual element addressing (dashed lines). (a) Magnitude, (b) Phase.

IV. CONCLUSION

A PDLC tuned reflectarray element for operation at mmWave frequencies has been design and simulated. Using PDLCs rather than conventional LCs decreases the complexity of the reflectarray fabrication process. The element can achieve up to 200^o phase change with any incident polarisation, or over 180^o over a 1 GHz bandwidth centred at 73 GHz. A maximum of 2dB magnitude variation occurs over the complete tuning range, or in 1-bit operation only 0.1dB variation is observed between the states. Future work will integrate the element into a reflectarray and will fabricate and test the resulting device.

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