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Dielectric Embedded Bandpass FSS
Linear to Circular Polarisation Transformers

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Abstract—This paper describes a major advance in the design of bandpass anisotropic frequency selective surfaces (FSS) which are engineered to convert linearly polarized (LP) waves into circularly polarized (CP) signals at normal incidence. The thin metal structure operates in transmission mode and is composed of an array of cross slots with unequal arm lengths in the vertical and horizontal directions. We show that a polarisation converter formed by sandwiching the FSS between two flat PTFE substrates can be designed to give a 3dB axial ratio (AR) bandwidth that is significantly larger than the maximum value previously reported for freestanding topologies. The influence of the two supporting dielectric layers on the passband amplitude shaping and phase responses for TE and TM waves is investigated for various dielectric slab thicknesses. Numerical optimisation is then used to exploit this additional design parameter to create a polarization transformer that exhibits a 3dB AR bandwidth of about 8% at a center working frequency of 10.33 GHz. Spectral transmission measurements in the 8–12 GHz band will be presented at the conference.

Index Terms—frequency selective surfaces, polarisation converters, circularly polarised waves

I. INTRODUCTION

Periodic arrays composed of single perforated thin metal screens exhibit spectral responses with a center resonant frequency and passband shape that is mainly controlled by the geometry and size of the slots contained in the individual unit cells [1], [2]. A significant reduction in the separation ratio between transmission and reflection channels is obtained when identical screens are cascaded [3], [4]. For many filter applications it is desirable to nest two different slots in each unit cell to independently control the spectral transmittances in the TE and TM planes [5], [6]. The key technology challenge for filter design is to ensure that the FSS exhibits very low signal loss throughout the transmission and reflection bands and therefore the frequency dependent phase behavior of these structures is not normally studied. However, in [7] the authors have investigated the amplitude and phase responses of three different anisotropic slot FSS geometries, and by engineering the structure to produce a phase difference of 90° between the equal amplitude vertically and horizontally polarised exit waves, the ability to create a simple LP to CP polarization converter was demonstrated. One of the desirable features of this arrangement is that it provides a means for self-filtering of unwanted signals by rejecting energy outside the narrow operating frequency range defined by the bandpass response [8]. In [7] an AR fractional bandwidth of 2.4% was reported for a single screen perforated with either cross slots or nested split rings. However more recently the geometry of the former topology has been optimized to obtain a fractional bandwidth of 5.0% [9]. This was achieved by increasing the slot width and decreasing the metal plate thickness. In [10] an equivalent circuit was employed to model the unit cell geometry and explain the performance improvement by providing physical insight into the electromagnetic behavior of the FSS array.

Previous published results for this class of LP to CP polarization converter only reported investigations for structures composed of free standing perforated screens [7], [11]. However, in this paper we show that a significant increase in the 3dB AR bandwidth is obtained when the periodic array is sandwiched between two PTFE slabs (εr = 2.1) which are equal in thickness. The influence of bonded microwave laminates on the passband shape of a linear slot FSS was first reported in [12]. Building on this work we have studied the impact of dielectric loading on both the amplitude and the phase of signals transmitted through a cross slot FSS that was designed to resonate at a center frequency of around 10 GHz. The results show that a significant AR bandwidth improvement is obtained by carefully selecting the dimensions of the two slots in conjunction with the thickness of the PTFE slabs. The design methodology requires tailoring of the spectral transmission to obtain a low Q amplitude response in conjunction with a weak phase variation with frequency in the TE and TM planes. The paper concludes by presenting the optimised spectral transmission responses, and axial ratio performance obtained from a dielectric embedded FSS polarisation transformer which was designed to work at a center frequency of 10.33 GHz. The proposed manufacturing route based on the use of an ink-jet printer to pattern the 140 µm thick periodic screen is discussed.
II. PRINCIPLE OF OPERATION

A perfect CP wave is generated by a radiating source that simultaneously transmits two orthogonally orientated LP signals that are equal in amplitude and exhibit a phase difference of 90°. Formal definitions for this mode of propagation, the metrics used to calculate the polarisation purity and the wave handedness convention are given in [13]. A slant 45° signal incident on the surface of the FSS polariser screen can be decomposed into vertical (TE) and horizontal (TM) polarised waves which are equal in amplitude and phase. Resonance in conjunction with maximum signal transmission occurs when the slot length is approximately half the wavelength at resonance. FSS polarisation transformers can be designed to exhibit an in-plane anisotropic impedance when the length of the two arms of a cross slot arrangement are selected to be unequal. For one polarization the resonance occurs at a frequency slightly above $f_0$, the center working frequency of the LP to CP converter, and for the orthogonal field vector it is shifted to a slightly lower frequency. A capacitive path is created when the slots are increased in length in one direction and an inductive path is encountered in the orthogonal plane when the slot size is decreased by the same amount in the other direction. A perforated FSS screen can therefore be engineered to create a phase lag of 45° for one component of the incident LP waves and advance the other in phase by 45°, thus satisfying the criteria for CP wave propagation.

III. INFLUENCE OF DIELECTRIC ON WAVE TRANSMISSION

CST Microwave Studio [14] software was employed to model the transmission response of a perforated conductive surface printed on a 140 µm thick dielectric substrate with permittivity 2.95 and $\tan\delta = 0.025$ corresponding to the Novelle-IJ substrate used for ink-jet printing [15]. The infinite array is composed of unit cells with equal length cross slots. At normal incidence the spectral transmission of the coupled slots is identical in the TE and TM planes [10], therefore the electromagnetic responses were simulated for only one direction of the incident E field over the frequency range 8-12 GHz. Fig. 1 depicts a schematic of the unit cell geometry which has structural dimensions: $dx=dy=14$ mm, $w=2.7$ mm, $lx=ly=10.35$ mm. To determine the influence of slab thickness on wave transmission the periodic array was embedded between two PTFE slabs ($\varepsilon_r = 2.1$) of equal thickness $t$. Fig. 2a shows that when $t$ is varied from 1 mm to 7 mm in 2 mm increments, a small shift in the resonant frequency from 9.94 GHz to 11.16 GHz occurs but this can easily be removed by adjusting the length of the slot elements. A more significant outcome from this work is the predicted change in the shape and Q-factor of the amplitude responses of the dielectric embedded FSS. A slab thickness of 5 mm exhibits the lowest Q-factor of 2.3 whereas the structure with a 1 mm thick PTFE layer placed on opposite sides of the FSS yields the largest Q-factor, 3.8. Fig. 2b shows the corresponding phase change with frequency for
each arrangement studied. The gradient of each phase curve is proportional to the corresponding Q-factor, and as such the most linear phase curve with the smallest variation with frequency is observed for the structure with \( t=5\text{mm} \), which corresponds to an electrical thickness of about \( \lambda/2 \).

IV. FSS POLARISER DESIGN AND PERFORMANCE

In [9] the authors presented a set of design guidelines based on a suitable choice of physical dimensions which may be employed to maximize the 3dB AR bandwidth of transmission mode LP to CP polarization converters. Optimum performance is obtained when the arrangement exhibits relatively flat amplitude plots and a gentle phase gradient in the TE and TM plane. This is required to reduce the amplitude difference between the two field vectors which is zero only at the center operation frequency of the polariser, and the variation from 90° phase difference which is observed at the same frequency. These spectral responses are produced by freestanding FSS structures composed of close packed unit cells with wide slots formed in a very thin metal plate [9], [10]. Fig. 2 shows that an additional degree of freedom is obtained when the periodic array is embedded in a dielectric medium. This provides a means for further reducing the amplitude roll-off and phase gradient, thus increasing the 3dB AR bandwidth to a value beyond what is currently possible for this class of polarisation converter.

Numerical modelling has been used to obtain the optimum performance of a dielectric embedded FSS polariser by simulating the transmission coefficients for structures with PTFE slab thicknesses in the range, \( t = 1 - 10 \text{mm} \). In the CST model the slot array was formed on a 140 \( \mu \text{m} \) thick substrate with electrical parameters (\( \varepsilon_r = 2.95, \tan \delta =0.025 \)) corresponding to the Novelle-IJ substrate [15] which was used to fabricate the FSS. The unit cell periodicity and slot widths were fixed at \( d_y = dx = 14 \text{mm} \) and \( w = 2.7 \text{mm} \) throughout. The surface thickness, \( z \), was assumed to be zero to closely emulate the physical characteristics of the conductive ink used to pattern the array. Throughout the study the vertical and horizontal slot lengths \( l_y \) and \( l_x \) were varied in order to maintain a center operating frequency of 10.33 GHz.

For brevity Fig 3 only illustrates the predicted transmission amplitude and phase responses for TE and TM waves and the corresponding axial ratios for LP to CP polarisers with slab thicknesses of \( t = 1 \text{mm}, 5 \text{mm}, \text{and } 10 \text{mm} \). Fig 3(a) shows that the thickest structure exhibits the sharpest amplitude roll off rate, associated with the largest Q-factor values of 7.6/4.2 for the TE/TM wave components respectively. In contrast the smallest Q-factor values of 4.2/0.9 are obtained for the 5mm thick dielectric clad structure. The gradient of the phase plots are inversely proportional to the phase quadrature fractional bandwidth (PQFB) which is obtained over the frequency range where the phase difference between the TE and TM spectral responses are within ±5° of the value required for perfect excitation of CP waves i.e. \( \Delta \theta = 90^\circ \). The smallest PQFB of

![Fig. 3](image-url)
6.3% was found for a slab thickness of 10 mm whereas values of 14.8% and 15.4% are predicted for polarisation transformers constructed with the $t = 1$ mm, and $5$ mm respectively. Fig 3(b) shows that the phase responses in the TE and TM planes are more linear and the structure better impedance matched when the polarizer is constructed with 5 mm thick dielectric slabs. This observation is consistent with the results depicted in Fig. 2. Fig 3(c) depicts the AR between 9.5 -11 GHz for all the three polarization transformers. These exhibit predicted 3dB AR bandwidths of 4.0% (1 mm), 7.9% (5 mm) and 2.1% (10 mm). Despite the similar PQFB values obtained for the 1 mm and 5 mm thick structures, the bandwidth performance of the latter is almost twice as large. This is attributed to the lower Q value of the amplitude responses, which as observed in Fig 3(a), reduces the amplitude difference between the TE and TM waves above and below 10.33 GHz, the center operating frequency of the polarisation converter. Therefore, the amplitude and phase requirements for CP wave propagation outlined in section II are better satisfied by this arrangement.

V. MANUFACTURE

The FSS with the optimised unit cell dimensions of $dx=dy=14$ mm, $w=2.7$ mm, $l_y=13.91$ mm and $l_x=8.51$ mm has been manufactured using ink-jet printing for rapid prototyping. An Epson Stylus C88+ printer was used to print Metalon [16] silver nano-particle ink onto a 140 µm thick Novelle IJ-220 substrate ($\varepsilon_r=2.95$) [15], [9]. The surface was then cured in an oven for 20 minutes set at 90°C. Fig. 4 shows a photograph of the patterned FSS and a side view schematic of the polariser which will be clad with 5 mm thick PTFE slabs [17]. Measurements are ongoing and will be presented at the conference.

VI. CONCLUSIONS

In this paper we have used numerical simulations to investigate the spectral transmission of FSS based polarisation converters, composed of a periodic slot array which is sandwiched between two identical PTFE slabs. A large improvement in the obtainable 3dB AR bandwidth was made, increasing this figure of merit from 5.0% reported in [10] for a freestanding LP to CP converter, to almost 8% for the structure reported in this paper. Moreover, this arrangement is better suited for practical applications, because a robust structure is created by encasing the thin FSS screen in rigid dielectric material.

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REFERENCES


