Introduction: The integration of a linear polarised (LP) source and a standalone polarisation converter is an attractive option for generating circular polarised (CP) waves. Placing the planar structure above the aperture of an LP antenna allows the design of the antenna to be decoupled from the challenges of creating CP propagation [1]. In the literature, several different arrangements have been reported, which employ anisotropic frequency-selective surfaces (FSSs) working in either reflection or transmission mode [1–6]. Transmission type LP to CP polarisation converters based on thin freestanding metal screens perforated with asymmetrical-shaped slots [6] are desirable for applications where the bandwidth requirements are not onerous and it is necessary to provide strong ‘out of band’ filtering capability [7, 8]. However, these architectures exhibit axial ratio (AR) bandwidths (BWs) that are often very narrow due to the resonant behaviour of the elements of the periodic structure; moreover, the insertion loss is typically around 3 dB. A significant increase in the transmission efficiency (> 90%) can be achieved by cascading two or more identical screens, but this has little impact on the bandwidth [6]. The first published study of a single freestanding screen composed of asymmetrical cross-slots reported a 3 dB AR BW of only 2.4% [6]. However, by optimising the physical dimensions of the unit cells, the authors have shown that this can be increased to a value of about 5.0% [9]. A further increase in the BW can be achieved by bonding the perforated sheet centrally between identical dielectric slabs [10]; however, this solution is bulky and costly to manufacture. The purpose of this letter is to present an alternative means to obtain a major increase in the AR BW of single-layer anisotropic FSS without incurring the inherent drawbacks of architectures based on the use of dielectric material. This is achieved by decomposing the unequal length arms of a centre-connected cross-slot into orthogonally orientated unequal length rectangular apertures, which are repeated to fill the unit cells. The additional design flexibility afforded by this topology is exploited to flatten the passband responses by reducing the amplitude roll-off rate and phase change above and below the resonant frequency in the Transverse Electric (TE) and Transverse Magnetic (TM) planes, respectively. This is shown to produce an 84% increase in the 3 dB AR BW, compared to the freestanding cross-slot polarisation transformer reported in [9].

Principle of Operation: At resonance, screens perforated with metal straight slots of length \( \sim \lambda/2 \) are impedance matched to free space (377 \( \Omega \)), and therefore impinging waves exit the FSS with very low loss. A slant 45° wave incident on the screens shown in Figure 1 can be resolved into electric vectors with equal amplitude and phase in the vertical (TE) and horizontal (TM) directions. The generation of CP is achieved by adjusting the dimensions of the slots in each unit cell so that one component of the incident wave is exposed to a capacitive (longer than resonance slot) and the other to an inductive (shorter than resonance slot) reactance. In one case, the in-plane anisotropic impedance presented to the waves produces a 45° phase advance, and for the other wave orientation, a 45° delay occurs at the crossover frequency where the amplitude of the two transmitted waves is equal and approximately 3 dB below the peak value at resonance for the TE and TM signals.

Design and Simulated Performance: CST Microwave Studio was employed to optimise the design and obtain the physical dimensions of the two-unit cell topologies that were investigated, (i) a cross-slot decomposed into two independent perpendicular-oriented rectangular-shaped apertures, which are the basic building block of (ii) the optimum solution, a design based on the use of multi-element rectangular slots. The FSS screens were simulated using a single 3D unit cell with the apertures formed on the surface of a 140 \( \mu \)m thick metalised polyethylene terephthalate (PET) sheet \((\varepsilon_r = 2.95, \tan \delta = 0.025)\) to model the material that was used to construct the experimental structures. Figure 1 illustrates the geometry of the two topologies. The main physical dimensions are summarised in Table 1 in addition to those for the current state-of-the-art cross-slot structure [9], which is used as a baseline to compare the BW improvement. The electric field distributions for TE and TM wave incidences for the 11-element structure are presented in Figures 2(a) and (b), respectively. The single-layer perforated screens were designed to work at normal incidence at a centre frequency of 10.0 GHz. The optimum
performance was obtained by adjusting the geometry, and in the second case, it was obtained by the number of equally spaced slots in the unit cell of the FSS array. The objective was to flatten the amplitude response plots below the resonant frequency of the shorter horizontal (TE) slots and above resonance for the longer vertical (TM) slots. This ensures that the amplitude difference between the two field vectors and the variation from phase quadrature is minimised outside the centre (crossover) working frequency. The computed spectral transmission plots are illustrated in Figure 3 for normal incidence where the two-slot unit cell arrangements are shown to exhibit variations between 9 and 11 GHz of about 1.7 dB/GHz and 11.9°/GHz (TE) and 1.7 dB/GHz and 11.0°/GHz (TM). The computed change in the responses of the strongly coupled multi-slot design is 0.8 dB/GHz and 5.1°/GHz (TE) and 1.5 dB/GHz and 10.3°/GHz (TM). The significant reduction in the phase and amplitude gradient for the TE wave component is a consequence of the slowly varying intrinsic impedance, which is presented by the large array of closely packed horizontal slots. The difference between the spectral transmission of the TM wave components is much smaller; therefore, the increase in the AR BW can mainly be attributed to the spectral behaviour of the TE waves. The simulated phase and amplitude roll-off rates for the individual TE and TM modes are very similar on either side of the crossover frequency for both structures; therefore, the AR response plots depicted in Figure 4 are shown to be symmetrical about the minimum AR values. The simulated performance of the optimum freestanding cross-slot polariser arrangement [9] is also plotted for comparison. This LP to CP polarisation convertor yields a 3 dB AR BW of 5.0% [9], but by exploiting the design flexibility afforded by physically decoupling the two slots and carefully positioning these in the unit cell, a value of 6.3% is achieved. A further and much more significant improvement is obtained for the 11-element topology. In this case, filling the physical space available in the unit cells to weaken the resonant response produces a BW of 9.2%.

Fabrication and Experimental Results: The design methodology used to create the multi-slot LP to CP polarisation convertor was verified by comparing the computed results with the experimental behaviour of single-layer screens composed of the two-unit cell geometries shown in Figures 1(b), and (c). Fast prototyping was made by inkjet printing the slot arrays on the surface of 140 μm thick A4 size Novole IJ-220 PET sheets [11] using a Epsilon Stylus C88+ desktop printer and Metalon JS BS25HV [12] nano-silver ink. The manufacture was completed by placing the patterned sheets in an oven to cure at a temperature of 90°C for 20 min and then bonding these to a flat 10 mm thick Rohacell foam sheet with an aluminium tape rim. The amplitude and phase responses for vertically and horizontally polarised waves were measured in an anechoic chamber over the frequency range 8–12 GHz, and the data was post-processed using the equations given in [13] to obtain the AR. In the test set-up shown in Figure 5, the FSS was illuminated at normal incidence by a SUNOL dual-ridge horn rotated about its propagating axis to provide a slant 45° signal. An identical receive horn was mounted onto an NSI 2000 planar nearfield scanner, which allowed for automated alignment and rotation of the horn from 0 to 90° in order to record the amplitude and phase of the TE and TM waves. The two antennas were connected to an Agilent PNA 8631A vector network analyser and positioned 60 cm from the surface of the FSS, which were inserted in the centre of a 91 × 91 cm screen covered with radar-absorbent material. Careful alignment of both structures was achieved using an SC-LO3
Fig. 5 Photographs of the experimental arrangement and the manufactured surface. (a) Photograph of the transmission response measurement set-up with an arrow pointing to the FSS under test, (b) photograph showing four unit cells of the manufactured multi-slot polarisation converter

laser. Although the plane wave normal incidence and an infinite size periodic structure are assumed in the CST model, for this test set-up, there is a measured amplitude and phase variation of about ± 1 dB and 80°, respectively, across the surface of the polarisation convertor [14]. Nevertheless, a very good correlation between the simulated and measured results are shown in Figure 3 for the amplitude and phase responses of the structure with unit cells composed of two dipole slot elements. The post-processed 3 dB AR BW is also in very good agreement, and the values plotted in Figure 4 are 6.3% and 5.7%, respectively. Although both AR minima are centred at approximately 10 GHz, the measured differential phase between the TE and TM waves at this frequency is 84.1°, and not 90.4° as computed; therefore, the minimum AR value is about 0.9 dB larger. Figure 4 shows that good agreement is also obtained for the multi-slot unit cell arrangement, but for this case, a 500 MHz downwards shift is observed in the measured TM mode resonance, and this yields an amplitude crossover point and AR minima at 9.5 GHz as illustrated in Figure 4. The computed and measured 3 dB AR BW values are 9.2% and 12.7%, respectively, thus providing experimental evidence of the significant increase in the BW, compared to the cross-slot design [9], which is also plotted in Figure 4. The mismatch from simulation can be partially attributed to the non-ideal experimental arrangement, which makes it difficult to ensure perfect alignment between transmitting and receiving horns required of such a measurement. An additional factor is that the dimensional tolerances required of the 11-element printed structures, particularly the vertical (TM) slots, is at the limit of the printer’s capabilities.

**Conclusion:** By exploiting the design flexibility afforded through the use of offset perpendicular slots, we have created a more advanced unit cell topology that enables the TE and TM mode spectral transmission to be more precisely tailored, and thereby achieve the desired responses for a broader band operation than cross-slot topologies. This design strategy is used to achieve a 3 dB AR BW that is 84% larger than the structure reported in [9]. Moreover, because the unit cells are more compact and the real estate better utilised, the reduction in the polarisation purity of the CP waves and the shift in the AR minimum [10] is less significant for operation at oblique incidence. Future work will seek to reduce the insertion loss of these resonant structures by cascading the screens as reported in [6].

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**References**

1. Hosseini, M., Hum S.: A circuit driven design methodology for a circular polarizer based on modified Jerusalem cross grids. *IEEE Trans. Antennas Propag.* **65**, 5322–5331 (2017)

2. Mahdi, F., Armaki S.: Design of metasurface polarization converter for near-field application; stacked conical horn antenna for circular polarizat. *Int. J. RF Microwave Comput. Aided Eng.* **29**(7), 21712 (2019)

3. Peng, F., et al.: Design of a wideband planar linear-circular polarization converter with centrosymmetric dual-loop elements. *Prog. Electromagn. Res.* **74**, 83–92 (2018)

4. Naseri, P., et al.: Dual-band dual-linear-to-circular polarization converter in transmission mode application to K/Ka-band satellite communications. *IEEE Trans. Antennas Propag.* **66**(12), 7128–7137 (2018)

5. Fei, P., et al.: A single-layer circular polarizer based on hybrid meander line and loop configuration. *IEEE Trans. Antennas Propag.* **63**(10), 4609–4614 (2015)

6. Euler, M., et al.: Comparison of FSS based linear to circular polarization converter geometries. *IET Microwaves Antennas Propag.* **4**(11), 1764–1772 (2010)

7. Farzami, F., et al.: Reconfigurable linear/circular polarization rectangular waveguide Filtenna. *IEEE Trans. Antennas Propag.* **66**(1), 9–15 (2018)

8. Barbuto, M., et al.: A combined bandpass filter and polarization transformer for horn antennas. *IEEE Antennas Wirel. Propag. Lett.* **12**, 1065–1068 (2013).

9. Clendinning, S., et al.: Bandwidth optimization of linear to circular polarization converters based on slot FSS. *Microwave Opt. Technol. Lett.* **61**(5), 1200–1207 (2019)

10. Clendinning, S., et al.: Dielectric embedded bandpass FSS linear to circular polarisation transformers. In: 13th European Conference on Antennas and Propagation (EuCAP 2019), Krakow, Poland (2019)

11. Novacentrix. NoveleUJ-220, 2212. www.novacentrix.com (2020) Accessed 22 Nov 2020

12. Novacentrix. Metalon JS-B25HV. www.novacentrix.com/products/metalon-conductive-inks (2011) Accessed 22 Nov 2020

13. Toh, B.Y., Cahill, R., Fusco, V.: Understanding and measuring circular polarization. *IEEE Trans. Educ.* **46**(3), 313–318 (2003)

14. Clendinning, S., et al.: Influence of dielectric layers on performance of transmission mode frequency selective surface based linear to circular polarization transformers. *Microwave Opt. Technol. Lett.* **62**(4), 1815–1823 (2020)