Coupled Split-Ring Resonator Circular Polarization Selective Surface

Wenxing Tang, Member IEEE, George Goussetis, Senior Member, IEEE, Nelson J. G. Fonseca, Senior Member, IEEE, Herve Legay, Elena Sáenz, Member IEEE, Peter de Maagt, Fellow, IEEE

Abstract—A novel class of circular polarization selective surfaces (CPSSs) consisting of a pair of planar split-ring resonator arrays is proposed. A significant advantage of the proposed structure over existing designs is its manufacturing simplicity compatible with standard printed technology processes. Its operating principle is reviewed alongside that of the Pierrot cell and in light of the linear polarization reflection and transmission characteristics of CPSSs. Guidelines for the initial design of the proposed CPSS concept are thus derived. Further design considerations and trade-offs are also discussed. The validity of the concept is confirmed by means of a design example entailing a right-hand circular polarization selective surface (RHCPSs) at 20 GHz. Full-wave simulation results and experimental testing on a fabricated prototype are presented and agree well with the theoretical predictions.

Index Terms—Circular polarization selective surface (CPSS), split-ring resonator (SRR), Pierrot cell, frequency selective surface (FSS), multibeam antennas.

I. INTRODUCTION

A

n ideal Circular Polarization Selective Surface (CPSS) is a surface that fully reflects one sense of circularly polarized electromagnetic wave and fully transmits the orthogonal one [1]. CPSSs are the equivalent in circular polarization (CP) of wire grids in linear polarization (LP). CPSSs can therefore be employed as building blocks for free-space CP diplexers, such as CP filters, converters, etc. [2, 3]. They can also be used to mitigate the beam-squint effect in offset reflector antennas, in a similar way that gridded sub-reflectors are sometimes used to mitigate the cross-polarization induced by offset geometries with relatively short focal lengths [4, 5].

Fig. 1. Layout of the proposed RHCPSs. (a) 3-D view. (b) Top layer with unit cell.

One of the first CPSS was proposed by Pierrot [6]. The Pierrot cell consists of two metallic arms, each of length 3λ/8, perpendicularly arranged on two planes parallel to the wavefront of an incoming plane wave and separated by λ/4, where λ is the wavelength at the center operating frequency. A metallic segment orthogonal to these planes connects the two arms, so that the Pierrot cell can be manufactured with a single wire of total length λ [7]. Assuming a normally incident CP plane wave, the λ/4 separation ensures that the currents induced on the two orthogonal arms by the rotating incident electric field add in-phase or out-of-phase depending on the handedness of the incident polarization. When the currents induced on the two arms add in-phase, the resulting resonance fully reflects the incoming wave in the same CP sense. For incidence in the orthogonal CP, very low (ideally zero) currents are excited on the unit cell and the array is practically transparent.

Several CPSSs have been developed and measured based on the operating principle of the Pierrot cell [2, 7]-[11]. Tilston [8] proposed a CPSS structure using two wires joined by orthogonal conductive segments embedded in a substrate with permittivity value such that these conductive segments operate as half-wavelength transmission lines having a quarter-wave physical length in free space. This arrangement allows the current induced on the two arms to add in- or out-of-phase depending on the handedness of the illuminating CP waves, thus achieving an operation similar to that of the Pierrot cell. More recently, and in order to overcome the manufacturing complexity associated with the required metallized via of the Pierrot cell, an implementation that exploits a folded flexible
substrate was presented in [11]. Still, some of these designs used manufacturing techniques that were rudimentary and implementations based on a “3D” elementary cell will require specific manufacturing and assembly processes, potentially difficult to extend to large or non-planar surfaces.

In this respect, multilayer planar CPSSs, compatible with standard printed technology processes, are considered advantageous for future applications, and received specific attention in recent years. Some designs and experimental investigations are reported in [12]-[16]. The approach in [12-13] exploits circular to linear polarization conversion surfaces cascaded with a LP selective surface (i.e. a wire grid) and a reciprocal LP-CP converter. Meander-line polarizers were employed in [14] as a means of increasing the bandwidth, which means resulted in a 7-layer CPSS implementation and a 9-layer CPSS using bisected split rings has been presented in [15].

More recently, a 5-layer CPSS was developed [16] based on multilayer meander lines rotated in proportion to the distance between different layers. These multilayer CPSSs exploit non-resonant operation and as a result deliver wider bandwidth in comparison with the resonant type of CPSSs. The increased number of layers still results in a relatively complex manufacturing and assembly process, with potential alignment issues. Insertion losses may also become a limitation, requiring specific attention to the choice of materials and bonding processes. A concept with only 3 layers is proposed in [17] in which the orthogonal conductive segment of the Pierrot cell is replaced by an L-shape coupling pattern. However transmission losses of 2.4 dB are reported, of which 0.9 dB are due to losses in the substrates and glue layers.

A novel 2-layer CPSS design based on coupled split-ring resonator arrays has been proposed [18] as shown in Fig. 1. It is noted that this is the minimum number of layers for a multilayer CPSS at normal incidence [19]. In some similarity to the Pierrot cell operating principle, the proposed structure delivers CPSS response exploiting the coupling between two resonant arrays, which in isolation would only interact with either one of the two orthogonal LP incident waves. Unlike the Pierrot cell or the approach proposed in [17], here the coupling does not require any additional geometrical feature and relies on the electromagnetic near fields generated by the two arrays. In this paper, full detailed theoretical analysis of the proposed coupled split-ring resonator CPSS is discussed and a design example is presented with experimental validation.

II. THEORETICAL CONSIDERATIONS

In order to better understand the operation of the proposed structure, we first decompose the response of an ideal CPSS into LP reflection and transmission coefficients. A discussion on the operation of the Pierrot cell is also provided to highlight some similarities with the proposed approach. Subsequently, and in light of this analysis, we introduce the proposed structure and discuss the underlying operation. Based on that discussion, design guidelines and performance trade-offs are derived.

A. CPSS condition from LP reflection and transmission

We assume a planar CPSS normal to the z-axis. The incoming and transmitted waves propagate along the negative z-direction while the reflected wave propagates along the positive z-direction. Assuming the usual time-harmonic convention $e^{j\omega t}$, then LP and CP polarized wave components are related according to equation (1) [20]:

$$\begin{bmatrix} E_x \nabla_i \nabla_t \nabla_s \nabla_y \nabla_z \nabla_{xy} \nabla_{yz} \nabla_{zx} \nabla_{yx} \nabla_{xz} \nabla_{zy} \nabla_{yz} \nabla_{xz} \nabla_{xy} \end{bmatrix} = \begin{bmatrix} 1 & -j & \frac{1}{\sqrt{2}} & 1 \\ j & 1 & \frac{1}{\sqrt{2}} & 1 \\ 1 & j & \frac{1}{\sqrt{2}} & 1 \\ 1 & j & \frac{1}{\sqrt{2}} & 1 \\ 1 & j & \frac{1}{\sqrt{2}} & 1 \\ 1 & j & \frac{1}{\sqrt{2}} & 1 \\ 1 & j & \frac{1}{\sqrt{2}} & 1 \\ 1 & j & \frac{1}{\sqrt{2}} & 1 \\ 1 & j & \frac{1}{\sqrt{2}} & 1 \\ 1 & j & \frac{1}{\sqrt{2}} & 1 \\ 1 & j & \frac{1}{\sqrt{2}} & 1 \\ 1 & j & \frac{1}{\sqrt{2}} & 1 \\ 1 & j & \frac{1}{\sqrt{2}} & 1 \\ 1 & j & \frac{1}{\sqrt{2}} & 1 \end{bmatrix} \begin{bmatrix} E_x \nabla_i \nabla_t \nabla_s \nabla_y \nabla_z \nabla_{xy} \nabla_{yz} \nabla_{zx} \nabla_{yx} \nabla_{xz} \nabla_{zy} \nabla_{yz} \nabla_{xz} \nabla_{xy} \end{bmatrix}$$

where $E$ is the electric field and the superscripts $i$, $t$ and $r$ designate the incident, transmitted and reflected waves, respectively. The subscripts $x$ and $y$ denote the x- and y-polarized LP electric field, while the subscripts $R$ and $L$ represent Right-Hand Circularly Polarized (RHCP) and Left-Hand Circularly Polarized (LHCP) waves, respectively. The transmission coefficients, which are defined in terms of the total (scattered plus incident) field [14, 21], and reflection coefficients for LP and CP excitation respectively are given in (2)-(3):

$$\begin{bmatrix} E_{x,R} \nabla_i \nabla_t \nabla_s \nabla_y \nabla_z \nabla_{xy} \nabla_{yz} \nabla_{zx} \nabla_{yx} \nabla_{xz} \nabla_{zy} \nabla_{yz} \nabla_{xz} \nabla_{xy} \end{bmatrix} = \begin{bmatrix} t_{xx,RR} & t_{xy,RL} \\ t_{yx,LR} & t_{yy,LL} \end{bmatrix} \begin{bmatrix} E_i \nabla_i \nabla_t \nabla_s \nabla_y \nabla_z \nabla_{xy} \nabla_{yz} \nabla_{zx} \nabla_{yx} \nabla_{xz} \nabla_{zy} \nabla_{yz} \nabla_{xz} \nabla_{xy} \end{bmatrix}$$

$$\begin{bmatrix} E_{y,R} \nabla_i \nabla_t \nabla_s \nabla_y \nabla_z \nabla_{xy} \nabla_{yz} \nabla_{zx} \nabla_{yx} \nabla_{xz} \nabla_{zy} \nabla_{yz} \nabla_{xz} \nabla_{xy} \end{bmatrix} = \begin{bmatrix} t_{xx,RR} & t_{xy,RL} \\ t_{yx,LR} & t_{yy,LL} \end{bmatrix} \begin{bmatrix} E_i \nabla_i \nabla_t \nabla_s \nabla_y \nabla_z \nabla_{xy} \nabla_{yz} \nabla_{zx} \nabla_{yx} \nabla_{xz} \nabla_{zy} \nabla_{yz} \nabla_{xz} \nabla_{xy} \end{bmatrix}$$

where variables $t$ ($r$) denote the transmission (reflection) coefficient respectively. Subscripts $xx$ (RR) and $yy$ (LL) designate the co-polar coefficients for x-polarized (RHCP) and y-polarized (LHCP) incident waves respectively while subscripts $xy$ (RL) and $yx$ (LR) designate the cross-polar coefficients following a similar nomenclature. Substituting (1) into (2) and (3) and upon using simple algebraic manipulations we can obtain the following two equations for the transmission and reflection of CP waves based on the corresponding LP coefficients:

$$\begin{bmatrix} E_{x,R} \nabla_i \nabla_t \nabla_s \nabla_y \nabla_z \nabla_{xy} \nabla_{yz} \nabla_{zx} \nabla_{yx} \nabla_{xz} \nabla_{zy} \nabla_{yz} \nabla_{xz} \nabla_{xy} \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ j & 1 \\ 1 & j \end{bmatrix} \begin{bmatrix} E_{x,L} \nabla_i \nabla_t \nabla_s \nabla_y \nabla_z \nabla_{xy} \nabla_{yz} \nabla_{zx} \nabla_{yx} \nabla_{xz} \nabla_{zy} \nabla_{yz} \nabla_{xz} \nabla_{xy} \end{bmatrix}$$

An ideal CPSS fully reflects one sense of CP and fully transmits the other sense of CP. Here and without loss of generality we consider the case of a reciprocal symmetrical RHCPS [1] that fully reflects incoming RHCP in the same sense while being transparent to incoming LHCP. From (4) and (5) it is evident that when the equations (6)-(9) simultaneously apply, a reciprocal symmetrical RHCPS [1] is obtained.
Equations (6)-(9) are approximately valid in the case of a practical Pierrot cell CPSS and it is therefore instructive to discuss the operating principle of the Pierrot cell in light of these equations.

From (7) and (9), it can be concluded that all co-polar and cross-polar transmission and reflection coefficients have magnitude equal to 0.5. In other words, (7) and (9) pose the requirement for half the incident power of an LP incident wave to scatter (i.e. reflect or transmit) in the orthogonal polarization. If two orthogonal LP arrays are employed for the implementation of the CPSS (such as the two orthogonal arm arrays on either side of a Pierrot surface), the strong cross-polarized scattering necessitates a strong mechanism transferring energy between them. In the Pierrot cell this transfer of energy between the two orthogonal arms occurs by virtue of the metallic segment connecting them. Assuming LP incidence with electric field parallel to one arm, the current from this primarily excited arm will, by virtue of the metallic segment, flow continuously into the orthogonal arm thus leading to scattering in the orthogonal polarization. At resonance, the current flowing in the two orthogonal arms will be of equal magnitude and therefore half of the incident power will be scattered in the orthogonal polarization. Coupled resonator theory further suggests that when two resonators with the same resonant frequency (synchronously tuned) are coupled, the combined system no longer resonates at that frequency but instead is characterized by a split in an even and an odd mode [22]-[23].

Equation (6) further suggests that the two orthogonal co-polarization transmission coefficients are in-phase, i.e. \( \varphi(t_{xx}) = \varphi(t_{yy}) \). In a Pierrot cell this can be understood considering the nature of the interaction between the incident LP and the primarily excited dipole array; at resonance a dipole array would excite currents that will radiate out-of-phase with the incident wave and symmetrically in the two semi-infinite spaces on both sides of the array. In an isolated dipole array this would cause zero transmission since in the forward half-space the incident radiation would exactly cancel out the fields scattered by the array. Consequently, all incoming energy would be reflected. This is indeed the typical stopband response of a capacitive dipole FSS array [24]. As discussed above, in the Pierrot cell half of the incoming energy is scattered in the orthogonal polarization and therefore the power radiated by the primarily excited arm cancels out only half the power in the incident plane wave. This mechanism indicates that the co-polarized transmission for both orthogonal LP components (i.e. \( t_{xx} \) and \( t_{yy} \)) is in phase with the incident wave when reference is taken with respect to the plane of the primary scattered array and in any case \( \varphi(t_{xx}) = \varphi(t_{yy}) \), provided the same reference plane is used.

Equations (6) and (8) further indicate a \( 90^\circ \) phase difference between co- and cross-polarized reflection and transmission coefficients. In a Pierrot cell the \( 90^\circ \) lead/lag phase between co- and cross-polarized scattering are attributed to the \( \lambda/4 \) separation between the two orthogonal arm arrays; since the cross-polarized radiation occurs from arms orthogonal to the primarily excited ones, this separation indicates that at resonance a \( \pm 90^\circ \) relative phase shift occurs between the co-polarized scattering (occurring from the primarily excited arm) and the cross-polarized scattering. Similar considerations apply for the \( 180^\circ \) difference requirement between the two co-polar reflection coefficients, i.e. \( \varphi(t_{xx}) = \varphi(t_{yy}) \pm \pi \), where now the quarter wavelength distance is travelled twice for waves reflecting at the bottom split-ring \( r_{yy} \) compared to those reflecting at the top split-ring \( r_{xx} \).

### B. Proposed CPSS and its operation

The unit cell geometry of the proposed CPSS is depicted in Fig. 1. It consists of two identical split-ring resonator planar arrays in two parallel layers. For a RHCPSS the bottom split-ring is rotated clockwise by \( 90^\circ \) with respect to the top split-ring, while for a LHCPSS, the bottom split-ring is rotated counter-clockwise by \( 90^\circ \). For simplicity we assume that vacuum fills the remaining space. The electric length of the split-ring (outer edge) is approximately \( \lambda_0/2 \), where \( \lambda_0 \) is the electric wavelength in free space at the target frequency here assumed to be 10 GHz. This initial value does not consider capacitive loading from the gap, \( s \), in Fig. 1, which anyway is required to be small (see also discussion below). The separation \( (h) \) between the two split-ring arrays is initially assumed to be \( \lambda_0/4 \).

![Fig. 2. Simulated transmission magnitude of a single split-ring under LP x-component and y-component illumination, respectively. (r=3.0 mm, w=1.6 mm, s=0.4 mm, D=26 mm)](image)

The scattering from each isolated array of split-rings resembles that produced by isolated array of dipoles of the corresponding polarization. This is illustrated in Fig. 2, where the transmission response of the two split-ring arrays in isolation is shown upon illumination by an x-polarized or a y-polarized plane wave, respectively. Dimensions are provided in the caption. The array unit cell depicted as inset in Fig. 2 (top array in Fig. 1) resonates only with x-polarized waves while it is transparent to incident y-polarized waves. The opposite applies for the array rotated clockwise \( 90^\circ \) with respect to the top array (bottom array in Fig. 1). By arranging
the two arrays in proximity as shown in Fig. 1, the electromagnetic near-fields in the array that is primarily excited by an incident LP wave provide a mechanism for energy coupling to the other array. In particular, and neglecting the capacitive effect of the gap, the first resonant mode of the split ring element is associated with currents flowing around a loop along the split ring following a half wavelength pattern with zero magnitude at the two open ends. Such a current loop gives rise to a strong magnetic near-field in the direction normal to the array plane [25]. The magnetic near-field is a shared feature of the two rings and provides a mechanism for strong coupling between the two arrays; the energy exchange occurring between the primarily excited and rotated array elements gives rise to strong cross-polarized scattering. At resonance, the current density of the top split-ring is approximately the same as the bottom split-ring one. Top split-ring radiates a $x$-polarized scattered field and bottom split-ring radiates a $y$-polarized scattered field. Moreover, the $\lambda_0/4$ separation between the two arrays imposes phase characteristics similar to those of the Pierrot cell discussed above. It is noted that an increased capacitive effect at the gap reduces the magnetic near-fields at resonance, hence justifying a $\lambda_0/2$ length for the split ring as an initial value and a reasonably large value for the gap, $s$.

![Fig. 3. Simulated co- and cross-polarized transmission for the coupled split-ring array of Fig. 1 under LP excitation for varying separation, $h$. (a) Magnitude response. (b) Phase response normalized to $t_{yx}$. Dimensions: $r=3.0$ mm, $w=1.6$ mm, $s=0.4$ mm, $D=26$ mm.](image)

Next, the above is illustrated by means of full-wave EM simulations using CST Microwave Studio [26]. Fig. 3a (red line) shows the LP co- and cross-polarized transmission response of the coupled split-ring arrays of Fig. 1. Two resonant peaks can be observed at 9.75 GHz and 10 GHz respectively, where it is shown that the co- and cross-polarized transmission magnitudes are equal to 0.5 as required by equation (7).

![Fig. 4. Current distribution and magnetic field distribution of the coupled split-ring arrays of Fig. 3 under LP excitation for $h=7.5$ mm. (a) even mode current distribution and (b) magnetic field distribution at 9.75 GHz. (c) odd-mode current distribution and (d) magnetic field distribution at 10 GHz. (Red arrows indicate current flow directions and magnetic field distributions are displayed by cutting in XZ plane through the middle of the two split-ring arrays)](image)

The current flow excited on the two array elements at these frequencies is shown in Fig. 4, which indicates currents of approximately equal magnitude in- and out-of-phase, respectively. Red arrows indicate current flow directions...
which are defined by the winding direction about the axis of
the split-ring when viewing the split-ring from above. In
agreement with the usual phenomena observed during
magnetically coupled resonators [22, 27], these current
distributions indicate the excitation of an even and an odd
mode, respectively. To change the handedness of the proposed
CPSS, the bottom split-ring can be rotated by 180°, bringing
the gap of the bottom split ring in a diametrically opposite
point. Full wave analysis shows that in this case the currents
maintain the relative directions of the currents in the top and
bottom arrays (clockwise and counter-clockwise respectively)
resulting in an opposite handedness for the overall CPSS
structure.

According to the coupled resonator theory [22, 27], the
even and odd modes are more widely separated for more
strongly coupled resonators. This is confirmed by the other
curves in Fig. 3a, which show the effect of varying the
separation between the two arrays. As shown, for more closely
placed arrays (smaller h) the frequency split between the even
and odd resonance is wider whereas the two peaks tend to
merge for a half-wavelength separation (h = 15 mm). Similar
plots are presented for the LP co- and cross-polarized reflection responses in Fig. 5a, where analogous conclusions
can be derived. Significantly, Figures 3a and 5a demonstrate
that the magnitude conditions of equations (7) and (9) are
approximately achieved in the proposed structure by virtue of
the strong magnetic coupling between the two split ring
resonator arrays.

In order to achieve the RHCPSS operation, the phase
conditions described in (6) and (8) should also be satisfied.
The transmission and reflection phase variations as a function
of the separation h are given in Fig. 3b and Fig. 5b
respectively. It is noted that in both figures all the phases are
normalized to the cross-polarized coefficient, \( \varphi(t_{yx}) \) and
\( \varphi(t_{xy}) \) respectively. Since the magnitude conditions are not
satisfied for the weak coupling associated with larger
separation distances h, the response for h = 15 mm is excluded
for clarity. It can be seen that when h = 7.5 mm, the phase
conditions of equations (6) and (8) are approximately satisfied
at 10 GHz as highlighted. Thus, a RHCPSS can be obtained at
the odd mode resonance of the structure. At that frequency the
separation h = 7.5 mm corresponds exactly to \( \lambda/4 \) and
therefore the arguments of section II.A for the Pierrot cell also
apply here. As also shown, for other values of h the phase
conditions are not met. It is noticed that the reflection phases
not being exactly equal to the ±90° that are required by
equation (8) is attributed to the non-ideal performance of the
proposed RHCPSS.

For the case of h = 7.5 mm, the response of the structure in
terms of CP reflection and transmission coefficients are
plotted in Fig. 6. Perfect electric conductors are considered so
the contribution from ohmic dissipation is neglected. The even
and odd modes of Fig. 3 and 5 are here also indicated by two
peaks.

![Reflection Magnitude](image1)

![Phase normalized to \( \varphi \)](image2)

Fig. 5. Simulated co- and cross-polarized reflection for the coupled split-ring
array of Fig. 1 under LP excitation for varying separation, h. (a) Magnitude
response. (b) Phase response normalized to \( \varphi \), since \( \varphi(t_{yx})=\varphi(t_{xy}) \) both
curves are omitted. Dimensions: \( r=3.0 \) mm, \( w=1.6 \) mm, \( s=0.4 \) mm, \( D=26 \) mm.

![Transmission coefficient (dB)](image3)

![Reflection coefficient (dB)](image4)

Fig. 6. Simulated S-parameter and AR of the coupled split-ring structure of
Fig. 1 under LHCP or RHCP illumination. (a) Transmission response. (b)
Reflection response. Dimensions: \( r=3.0 \) mm, \( w=1.6 \) mm, \( s=0.4 \) mm, \( h=7.5 \) mm, \( D=26 \) mm.
As shown, an incoming LHCP is transmitted through the structure with minimum attenuation at 10 GHz (transmission coefficient of -0.21 dB and reflection coefficient of -14.05 dB) and axial ratio of 0.55 dB (Fig.6a). Incoming RHCP is highly reflected (transmission coefficient of -35 dB and reflection coefficient of -0.01 dB) with axial ratio of 0.64 dB (Fig. 6b). As also anticipated from the discussion above, these figures indicate that the structure operates to a good approximation as a RHCPSS at 10 GHz. It is noticed that the power balance has been checked and found to satisfy the conservation of power with an accuracy better than 0.03% for the structure with $h=3, 4.5, 7.5$ and 15 mm.

C. Design considerations

The discussion of the previous section implies a methodology for the initial design of the proposed CPSS structure. Additional optimization can then be performed in order to account for some approximations made as well as design trade-offs that are applicable. For example, the $\lambda_0/4$ separation is not necessarily optimal even in the assumption of free-standing periodic arrays in vacuum since the phase associated with the scattering at each array and their mutual coupling have to be considered in order to provide a true 90° separation between the two arrays. More significantly, the design presented above leads to a very small bandwidth and in this respect it is instructive to investigate further the performance characteristics and design trade-offs.

In the above design, the unit cell edge length is close to one wavelength at the operating frequency. Such large unit cell dimensions which can lead to grating lobes for oblique angles of incidence and to narrowband responses, is typical for a periodic array (such as a frequency selective surface)[28]. This is due to the reduced mutual coupling between elements of the same array, which is known to lead to higher external Q-factors [29] and stronger near-fields excitation [25, 30]. In this respect, the large periodicity employed in the previous example enhances the coupling between the two arrays in return for a more narrowband response; it is noted from Fig. 3 and Fig. 5 that a stronger coupling between the two arrays is associated with a larger split of even and odd mode resonances, which according to Fig. 6, improves the transmission coefficient of the transmitted LHCP wave in this example.

Alternatively, it is possible to reduce the periodicity of the constituent arrays as a means to broaden the bandwidth [2]. This however will lead to weaker currents excited on the resonant arrays [28]. Since the dominant coupling mechanism between the two arrays is the varying magnetic flux through the rings of one layer produced by the currents in the rings of the other layer, reduced periodicity will lead to reduced coupling between the two arrays. This is illustrated in Fig. 7, which depicts the CP transmission from the structure considered in Fig. 6 when all geometrical parameters are fixed except the array periodicity, $D$. As shown, the bandwidths of the two resonances become broader for smaller array periodicity, however the frequency split between even and odd mode resonances reduces, which situation indicates a weaker coupling between the two arrays [22]. Therefore the transmission selectivity (and therefore AR) deteriorates for more densely packed arrays. It is noted that weaker coupling between the two arrays can be partly compensated by placing the two arrays in closer proximity (i.e. reducing separation, $h$). According to previous discussions this will have an impact on the phase response, thus indicating the role of numerical techniques in the final optimization of the design.

In summary, the discussions in this section provide a design methodology for the proposed CPSS. In particular, the initial electric length of the split-ring element is chosen at $\lambda_0/2$ at centre frequency. The gap, $s$, is chosen to be wide such that capacitive effects are weak while the width, $w$, is chosen relatively wide to minimize ohmic losses. The periodicity of the unit cell for the two arrays can be determined depending on the required bandwidth of the CPSS. The separation between the top and bottom split-ring can be chosen as $\lambda_0/4$ initially, and can then be optimized for the final design. The operating frequency will be shifted as the coupling between the two arrays is introduced. In order to maintain the operating frequency, the gap and the width of split-ring can be adjusted as these parameters have an insignificant effect on the coupling.

III. DESIGN EXAMPLE

A. Design A

In this section, the design procedure outlined above is illustrated by means of a RHCPSS design centered at 20.2 GHz. The arrangement of Fig. 1 is employed. A foam layer with $\varepsilon_r = 1.07$, $\tan\delta = 0.0011$ and thickness 2.0 mm is considered for the spacer. The metallic arrays are printed on dielectric laminates of thickness 0.13 mm with $\varepsilon_r = 2.5$, $\tan\delta = 0.0019$ and are bonded to both sides of the spacer. The dielectric stack is schematically depicted in Fig. 8. The conducting elements are assumed to be made of copper of thickness 17 $\mu$m and lie on the outer side of the dielectric stack.

Fig. 7. Effects of periodicity ($D$) on the simulated transmission coefficient of the RHCPSS considered in Fig. 6 under CP wave excitation. Dimensions: $r=3.0$ mm, $w=1.6$ mm, $s=0.4$ mm, $h=7.5$ mm.

![Stack for the proposed RHCPSS (Design A and Design B).](image_url)
Following the design approach outlined above and some numerical optimization, the design parameters with reference to Fig. 1 are (in mm): \( r = 1.9, w = 1.3, s = 1.0, h = 2.26, D = 9.0 \). The co-polar transmission \( t_{LL,RR} \) and reflection \( r_{LL,RR} \) coefficients for incoming left- and right-handed CP waves at normal incidence as predicted by full-wave EM simulations are depicted in Fig. 9 (dashed lines), where the corresponding AR is also shown. As shown, incoming LHCP is transmitted with transmission coefficient of -1.18 dB and AR of 1.50 dB. An incoming RHCP is reflected with a reflection coefficient of -0.3 dB and AR of 0.86 dB. The fractional bandwidth (FBW) at -10.0 dB transmission coefficient level of RHCP is 2.1%.

The angular performance of the CPSS in the \( yz \)-plane up to \( 30^\circ \) incidence is shown in Fig. 10(a-d). As shown, the response remains reasonably good up to an incidence angle of \( 15^\circ \). The angular sensitivity in the performance of the proposed CPSS is attributed to the required phase separation and strong magnetic field coupling between the top and bottom split-rings which are sensitive to oblique incidence. A comparison of the angular performance between the proposed CPSS and Pierrot cell is given in Fig. 10. It can be seen that the variation of the transmission coefficient and that of the reflection coefficient for the proposed CPSS are smaller than those for the Pierrot cell when the incident angle increases from \( 0^\circ \) to \( 30^\circ \) (see Fig. 10a and Fig. 10e). This may indicate that the Pierrot cell with its longitudinal quarter-wavelength conducting segment is more angular sensitive than the SRR with its strong magnetic near-field coupling between the top and bottom rings. It should be noted that the comparison is approximate as the bandwidth of the two designs is different.

![Fig. 9](image_url)

**Fig. 9.** Simulated S-parameter and AR of Design A and Design B under LHCP and RHCP incident waves. (a) Transmission response. (b) Reflection response.

**B. Modified Design (Design B)**

As discussed in section II, enhancing the coupling between the top and bottom arrays enables improving the transmission coefficient of the transmitted LHCP. One technique that allows this without compromising the bandwidth exploits an array where successive elements are rotated by \( 180^\circ \), as shown in Fig. 11b, which in the remaining of this paper is referred to as Design B.

Such an arrangement forces resonant currents in adjacent elements to flow in opposite directions and therefore the
corresponding magnetic near-fields to interact effectively \[25\], thus leading to stronger coupling between the two arrays.

The comparison of current and magnetic field distributions of Design A and Design B are given in Fig.12 and Fig.13, respectively. It can be seen that with the adjacent rotation arrangement of the CPSS (Design B), field interaction between the adjacent rings can be introduced as highlighted in Fig.12b, and due to the interaction of the field, the coupled energy reduce the total energy of the resonant mode (odd mode), results in a frequency shift up. While for the even mode, due to the interaction of the field as highlighted in Fig.13b, the coupled energy enhance the total energy of the resonant mode (even mode), results in a frequency shift down. This is demonstrated in Fig. 9, where a wider separation between the odd and even mode resonances of Design B is observed, indicating the stronger coupling between the two arrays. Notice that there is no such magnetic field interaction between the adjacent rings for Design A as highlighted in Fig.12d and Fig. 13d, respectively.

In terms of the CPSS performance, the wider frequency separation between the two resonant modes improves the transmission coefficient of the transmitted LHCP with minimal compromise on the bandwidth. It is noticed that apart from mirroring every other unit cell, Design B shares the same stack and array dimensions as Design A.

As shown in Fig. 9 (solid lines), the transmission coefficient of transmitted LHCP is improved to -0.51 dB with AR of 1.50 dB. An incoming RHCP is reflected with a reflection coefficient of -0.32 dB and AR of 1.01 dB. The fractional bandwidth (FBW) at -10.0 dB transmission coefficient level of RHCP is 2 %. It is acknowledged that this configuration doubles the unit cell dimensions and therefore becomes liable to grating lobes. However our full-wave electromagnetic simulations have indicated that the excitation of higher-order propagating Floquet space harmonics, which would give rise to grating lobes, is negligible for normally incident waves. Although in principle the large dimension of the unit cell suggests that the structure is liable to grating lobes even at normal incidence, in practice full-wave simulations show that negligible power is directed to grating lobes for angles of incidence less than 5°. Power balance has been checked and found to satisfy the conservation of power with an accuracy better than 0.03% for Design A and Design B.

IV. EXPERIMENTAL VALIDATION

In order to validate the proposed RHCPSS, a prototype based on Design B has been fabricated and tested. The design parameters of Design B with reference to Fig. 1 and Fig. 11b are (in mm): \(r = 1.9, w = 1.3, s = 1.0, h = 2.26, D = 9.0\). It is noted that the periodicity of Design B is 18.0 mm (2D). The two arrays were etched by standard photolithographic
techniques on Taconic laminates [31] with \( \varepsilon_r = 2.5, \tan\delta = 0.0019 \) and a thickness of 0.13 mm. A Rohacell sheet 31HF [32] (\( \varepsilon_r = 1.07, \tan\delta = 0.0011 \)) of thickness 2 mm was used as a spacer. Four holes were used to align the two arrays while adhesive spray 90 from 3M was employed for bonding the two arrays onto two sides of the Rohacell sheet. The thickness associated with the adhesive layer has an insignificant impact on the performance [33] and has been neglected in the simulation. The total size of the RHCPSS is 305 x 305 mm² (approximately 20λ x 20λ at 20 GHz) with 16 x 16 unit cells. A photograph of the fabricated prototype is shown in Fig. 14.

![Fig. 14. Fabricated proposed RHCPSS.](image)

The measurement of the manufactured prototype was performed using the Microwave Material RF Characterization Free Space Test Facility available at the European Space Research and Technology Centre (ESA/ESTEC), shown in Fig. 15. This free-space quasi-optical system, operating from 8 GHz up to 110 GHz, enables high-purity LP operation (cross-polarization discrimination better than 50 dB) by using wire-grid polarizers in front of the transmit (Tx) and receive (Rx) blocks. Each feed block is composed of a corrugated horn and an offset reflector antenna, producing a plane wave with a beam waist diameter of about 5 wavelengths, thus minimizing interference from the sample holder as well as other surrounding and supporting items. The two LP horn antennas are connected to a vector network analyzer (VNA) and placed on both sides of the RHCPSS.

![Fig. 15. Photograph of the microwave material characterization free space test facility used for the characterization of the CPSS, describing the different components, i.e. horns, grids, reflectors, sample holder and CPSS.](image)

The complex transmission coefficient between the two horn antennas is measured and then normalized with respect to an identical measurement without the sample. The Tx horn can be rotated to evaluate both the co- and cross-polarization components in transmission. In reflection, only the Tx horn is used and the measured complex reflection coefficient is normalized with respect to an identical measurement with a metallic plate in place of the prototype under test. Due to the presence of the grid polarizer, only reflection in the same polarization as the transmitted one can be measured at normal incidence, but this is deemed sufficient at this stage to validate the proposed new CPSS concept. A full characterization of a CPSS would require to upgrade the test facility to operate in dual-circular polarizations. This was not possible within the scope of this activity.

Fig. 16 compares the simulated and measured transmission coefficient and AR under CP excitation. Equation (4) in conjunction with the measured LP components was used to obtain the CP response. The measured centre operating frequency is slightly shifted to 20 GHz corresponding to about 3% error. This can be attributed to tolerances associated with the permittivities of the dielectric layers and mechanical dimensions. As shown, the measured transmission coefficient of the transmitted LHCP and RHCP are -0.6 dB and -22.0 dB, respectively. The measured transmission AR is 1.0 dB.

![Fig. 16. Measured and simulated transmission performance of the RHCPSS under CP incident waves.](image)

The measured reflection results in comparison with simulated ones are plotted in Fig. 17. Again, reasonably good agreement between measured and simulated results can be seen besides the slight operating frequency shift. It is noticed that only reflected co-polarization components were measured due to the current practical difficulties in measuring reflected cross-polarization components at normal incidence. Nevertheless, the measured results presented indicate that the reflection coefficient and AR of the RHCPSS are expected to match the simulated ones in Fig. 9b (solid lines) under CP excitation.

V. CONCLUSION

A novel class of CPSS employing coupled split-ring
resonator arrays has been proposed. It operates with only two planar layers and no vias, hence leading to simpler fabrication process. The operating principle has been discussed and design guidelines have been derived. Based on the design conditions, a design procedure has been developed. A design example of the proposed CPSS has been demonstrated and measurements on a fabricated prototype agree well with the simulated results. The proposed CPSS provides the CP equivalent of a gridded reflector, often used on board satellites in a dual-reflector configuration to provide two independent beams from a same antenna aperture. Such a use of the CPSS would require a shaped surface, which is easier to achieve with the proposed dual-layer design in combination with technologies and processes already employed in the manufacturing of shaped reflectarrays. The performances obtained so far are encouraging, but improvements are needed before considering the use of CPSS in a space mission. Future work will include investigations on ways to enhance the bandwidth of the proposed design without compromising its simplicity and overall performance.


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**REFERENCES**


