Manipulation of circular polarised electromagnetic waves by artificial periodic structures (Invited Paper)

Manipulation of circular polarised electromagnetic waves by artificial periodic structures

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December 8, 2015
Circularly polarised wave

RHCP wave

The hand is defined from the point of view of the source

\[ |E_x| = |E_y| \]

\[ \varphi_y - \varphi_x = \pm \frac{\pi}{2} \]

LHCP wave
• Spectral selectivity: CP frequency selective surfaces
• Beam forming: Conical beam generation with rotational phase shift
• Polarisation selectivity: circularly polarised selective surface (CPSS)
Motivation

- Frequency selective surfaces (FSS) remain a key component of satellite antenna feeding sub-systems.
- They provide low-loss filtering and beam-splitting capacity that allows using single antenna for multi-band operation.
- FSS is dual-polarisation or even circular polarisation (CP) properties.
- Properties of the dielectric stack utilised to support printed FSS structure becomes crucial for successful design.
<table>
<thead>
<tr>
<th></th>
<th>Ku-band</th>
<th>Ka-band</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Frequencies (GHz)</strong></td>
<td>11.7-12.75</td>
<td>17.3-20.2</td>
</tr>
<tr>
<td><strong>Losses (dB)</strong></td>
<td>Reflected &lt;0.25dB</td>
<td>Transmitted &lt;0.25dB</td>
</tr>
<tr>
<td><strong>Rejection (dB)</strong></td>
<td>30 dB</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Axial Ratio (dB)</strong></td>
<td>0.25</td>
<td>0.25</td>
</tr>
</tbody>
</table>

45 degree angle of incidence!
\[ \Gamma_i = -\frac{1}{1 + 2Z_c/Z_0} \]

\[ \Gamma_c^{TE} = \Gamma_c^{TM} \]
Ku-band Reflection

Ka-band Transmission

Axial Ratio Reflection

Axial Ratio Transmission
Material stack inside the structure
Full-wave simulation of the FSS with different stack configurations.
There is a notable difference between the measured results and simulation of the material stack.
\[ \varepsilon_r = \begin{pmatrix} 1.02 & 0 & 0 \\ 0 & 1.05 & 0 \\ 0 & 0 & 1.05 \end{pmatrix} \]

\[ \tan \delta = \begin{pmatrix} 0.007 & 0 & 0 \\ 0 & 0.012 & 0 \\ 0 & 0 & 0.007 \end{pmatrix} \]
Measured results:

- FSS
- Meas T
- Meas R
- Sim T
- Sim R
- Meas A
- Sim A

Frequency (GHz)
Magnitude (dB)
Axial ratio (dB)
Conical beam applications

- Conical beam antennas have omnidirectional radiation pattern in azimuth and a notch in the normal direction
- “Exotic” applications:
  - Data transfer by free-space modes with non-zero orbital angular momentum
  - Vortex coronography, where object is in the “shadow” of much brighter one
Conical beam generation

- Helicoidal dish
- Spiral phase plate
- Sectorial spiral reflector
Generation of helical beam: (a) amplitude of incident Gaussian beam, (b) spiral phase plate, (c) amplitude of resultant Laguerre-Gaussian beam.
Rotational phase shift

\[ \mathbf{E}_R = \left( \begin{array}{cc} \cos \theta_r & -\sin \theta_r \\ \sin \theta_r & \cos \theta_r \end{array} \right) \left( \begin{array}{cc} \Gamma_{x'} & 0 \\ 0 & \Gamma_{y'} \end{array} \right) \left( \begin{array}{cc} \cos \theta_r & \sin \theta_r \\ -\sin \theta_r & \cos \theta_r \end{array} \right) \mathbf{E}_i \]

\[ \Gamma_{x'} = -\Gamma_{y'} \]

Half-wave plate condition

\[ \mathbf{E}_i = \frac{1}{2} \left( \begin{array}{c} 1 \\ \pm j \end{array} \right) e^{-j k z} \]

CP excitation

\[ \mathbf{E}_R = \Gamma_{x'} e^{\pm j 2 \theta_r} \frac{1}{2} \left( \begin{array}{c} 1 \\ \pm j \end{array} \right) e^{j k z} \]

Unit cell of the reflecting FSS
LP analysis of reflecting FSS

<table>
<thead>
<tr>
<th>$R_1, \text{mm}$</th>
<th>$R_2, \text{mm}$</th>
<th>$R_3, \text{mm}$</th>
<th>$R_4, \text{mm}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.7</td>
<td>5.9</td>
<td>6.8</td>
<td>8</td>
</tr>
<tr>
<td>$\alpha_1, \text{deg}$</td>
<td>$\alpha_2, \text{deg}$</td>
<td>$h, \text{mm}$</td>
<td>$d, \text{mm}$</td>
</tr>
<tr>
<td>21</td>
<td>95</td>
<td>7.5</td>
<td>19</td>
</tr>
</tbody>
</table>
CP analysis of reflecting FSS

\[
E_R = \Gamma_{x'} e^{\pm j 2 \theta_r} \frac{1}{2} \left( 1 \mp j \right) e^{j k z}
\]

\[
\begin{align*}
|\Gamma| & = \begin{cases} 0 & \text{Out} \\ 1 & \text{In} \end{cases} \\
\angle \Gamma & = \begin{cases} 0 & \text{Out} \\ 90^\circ & \text{In} \end{cases}
\end{align*}
\]
Array factor of a finite array with given phase distribution.

\[ AF_{\theta,\varphi} = \sum_{m} \sum_{n} A_{mn} e^{-j(k x_m \sin \theta \cos \varphi + k y_n \sin \theta \sin \varphi + \psi(x_m, y_n))} \]

\[ \psi(x, y) = \begin{cases} 
\tan^{-1} \frac{y}{x}, & x > 0, y > 0 \\
\tan^{-1} \frac{y}{x} + \pi, & x < 0 \\
\tan^{-1} \frac{y}{x} + 2\pi, & x > 0, y \leq 0 
\end{cases} \]

Predicted array factor of the 10x10 array with spiral phase distribution (a) amplitude, (b) phase.
Simulated 3D bi-static RCS of the 10x10 slit ring reflectarray with spiral phase distribution.
The reflector has been milled from a 1mm thick aluminum with solid aluminum ground plane. The 7.5mm separation is maintained with plastic screws.
The setup consists of illuminating dual-polarized horn and rotating fixture with reflector and receiving Fermi antenna.
Fermi antenna and its radiation pattern in E- and H-plane

Rotating fixture with the reflector and Fermi antenna

Fermi antenna foam fixture
Comparison of simulated and measured radiation patterns (normalised) when excited by a normally incident x-polarized plane wave at 10.4 GHz.

(a) $E_\theta$ for $\varphi=0$ and $-90<\theta<90$  

(b) $E_\theta$ for $\varphi=90$ and $-90<\theta<90$
Comparison of simulated and measured radiation patterns (normalised) in plane $\varphi=0$ when excited by a normally incident CP-polarized plane wave at 10.4 GHz.
Transmit-array

Unit cell

Measurement setup
Measured radiation pattern

Magnitude

Phase

(a) RHCP, (b) LHCP excitation
Reciprocal symmetrical right-hand circular polarisation selective surface: (a) – reflection, (b) – transmission.
General case: LP and CP Jones matrices

\[ T_{lin}^f = \begin{pmatrix} S^{21}_{xx} & S^{21}_{xy} \\ S^{21}_{yx} & S^{21}_{yy} \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \]

\[ T_{circ}^f = \frac{1}{2} \begin{pmatrix} A + D - j(B - C) & A - D + j(B + C) \\ A - D - j(B + C) & A + D + j(B - C) \end{pmatrix} \]

RHCPSS: LP and CP Jones matrices

\[ T_{circ}^f = \begin{pmatrix} 0 & 0 \\ 0 & S_{LCP,LCP}^{21} \end{pmatrix} \quad A = D = jB, B = -C \]
Single SRR model

Co-polar

Cross-polar
SRRs magnetic coupling

Twisted SRR
Unit cell

Coupling inductance

\[ L_m = k_h L_3 \]
Equivalent circuit of 90 degree TSSR
RO 4003C h3=0.5mm
Rohacell foam h2=5mm
RO 4003C, h1=0.5mm