

Theory and Design of Polarization Converters Made of Mushroom-like Electromagnetic Band Gap Materials

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Abstract: Polarization converters play an important role in antennas and radar. Electromagnetic band gap materials enable manufacture of polarization converters which are : low cost, low profile, light weight and have large bandwidth. In this paper mushroom-like electromagnetic band gap materials are considered for polarization converters. The theory is reviewed. A simple design procedure is developed. A simple procedure for improving the design is proposed. Three design converters are designed to convert (1) linear polarization to linear perpendicular, (2) linear polarization to linear parallel and (3) linear polarization to circular.

Keywords: Electromagnetic Band Gap Materials, Polarization Converters, Mushroom – like EBG, Cassegrain Antennas, Dual Polarized Antennas, Circularly Polarized Reflector Antennas.

Introduction

Polarization converters play an important role in antennas and radar. In Cassegrain antennas polarization converters help avoid blocking due to subreflectors, [1]. They also help simplify the structure of dual-polarized satellite communication antennas, [2]. In circularly polarized parabolic reflector antennas, polarization converters simplify the structure of the feeding system of the antenna, [3,4]. Polarization converters enhance the radar cross section of trihedral corner reflectors used for civil maritime radars, [5]. Also polarization converters are essential for the calibration of polarimetry radar,[6,7]. In this paper the theory of polarization converters made of mushroom-like electromagnetic band gap (EBG) materials is reviewed. A simple design procedure for the design of these converters is developed. Three polarization converters are designed for three different applications. A simple procedure for improving the design is proposed. The results are checked using HFSS. Conclusions and references come at the end of the paper.

Theory

The geometry of mushroom-like EBG is shown in Fig.(1). The structure can be modeled as a parallel resonant circuit with components L and C as shown in Fig.(2), [8,9].

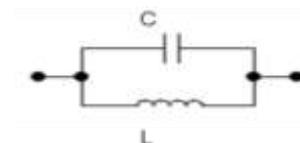
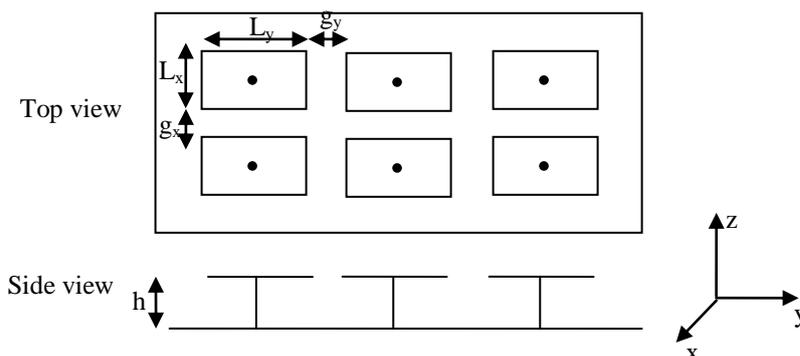


Figure 1. The geometry of mushroom-like EBG

Figure 2. A parallel resonant circuit

There are two resonant circuits. One for each component of the incident electric field. The parallel resonant circuit for the electric field in x-dimension has components L and C_x. The parallel resonant circuit for the electric field in the y-direction has components L and C_y. The components L, C_x and C_y are related to the dimensions of the EBG material as follows :

$$L = \mu h \dots\dots\dots(1)$$

$$C = \frac{l\epsilon_0(1 + \epsilon_r)}{\pi} \cosh^{-1}\left(\frac{l + g}{g}\right) \dots\dots\dots(2)$$

If you put $l = l_x$ and $g = g_x$ in Eq. (2) we get C_x. C_y can be obtained from (2) by putting $l = l_y$ and $g = g_y$. The surface impedances (Z_x and Z_y) of the x- and y- components of the electric field are given by Eqn.(3) by replacing C_x and C_y for C respectively.

$$Z = \frac{j\omega L}{1 - \omega^2 LC} \dots\dots\dots(3)$$

The reflection coefficients (R_x and R_y) for the x- and y- components of the electric field are given by Eqn.(4) by putting Z_x and Z_y instead of Z :

$$R = (Z - \eta) / (Z + \eta) \dots\dots\dots(4)$$

Where η is the intrinsic impedance of free space. The reflection phases (phase angles of the reflection coefficients) for the x- and y- components of the electric field are given by:

$$\Theta_x = \text{Im}\{ \ln R_x \} \dots\dots\dots(5)$$

$$\Theta_y = \text{Im}\{ \ln R_y \} \dots\dots\dots(6)$$

The reflection phase difference $\psi = \theta_y - \theta_x$ is the parameter that causes polarization conversion. The conditions on ψ to transform polarization is derived below for three different cases.

A. Linear-to Linear Perpendicular Polarization Conversion

The incident wave is:

$$\vec{E}^i = e^{jkz} \vec{a}_x + e^{jkz} a_1 \vec{a}_y$$

$$\vec{E}^i = [\vec{a}_x + a_1 \vec{a}_y] e^{jkz}$$

The reflected wave is :

$$\vec{E}^r = e^{-jkz} e^{j\theta_x} \vec{a}_x + e^{-jkz} a_1 e^{j\theta_y} \vec{a}_y$$

$$\vec{E}^r = [\vec{a}_x + a_1 e^{j(\theta_y - \theta_x)} \vec{a}_y] e^{j\theta_x} e^{-jkz}$$

The condition for E_i and E_r to be perpendicular is:

$$[\vec{a}_x + a_1 \vec{a}_y] \cdot [\vec{a}_x + a_1 e^{j(\theta_y - \theta_x)} \vec{a}_y] = 0$$

$$\text{or } 1 + a_1^2 e^{j(\theta_y - \theta_x)} = 0$$

$$a_1^2 e^{j(\theta_y - \theta_x)} = -1$$

This can be decomposed into two equations:

$$a_1^2 \cos(\theta_y - \theta_x) + ja_1^2 \sin(\theta_y - \theta_x) = -1$$

$$a_1^2 \cos(\theta_y - \theta_x) = -1 \dots\dots\dots(7)$$

$$a_1^2 \sin(\theta_y - \theta_x) = 0 \dots\dots\dots(8)$$

From eqn.(8) : $\theta_y - \theta_x = 0$ or $\theta_y - \theta_x = \pi$.

The solution $\theta_y - \theta_x = 0$, does not satisfy (7), because it gives $(a_1)^2 = -1$, while $(a_1)^2$ must be positive number. The other solution, $\theta_y - \theta_x = \pi$, satisfies eqn(7) provided $a_1 = \pm 1$.

Then the condition to transform linear polarization to another linear polarization but perpendicular to the incident field is that

$$a_1 = \pm 1, \quad \theta_y - \theta_x = \pi \quad (9)$$

B. Linear-to Linear Parallel Polarization Conversion

Unit vectors in the direction of the incident and reflected electric fields are given respectively by:

$$\bar{a}_i = \frac{\bar{a}_x + a_1 \bar{a}_y}{\sqrt{1 + a_1^2}} \quad \bar{a}_r = \frac{\bar{a}_x + a_1 e^{j(\theta_y - \theta_x)} \bar{a}_y}{\sqrt{1 + a_1^2}}$$

The condition for a_i and a_r to be paralleled is that:

$$\bar{a}_i \cdot \bar{a}_r = 1$$

$$\frac{\bar{a}_x + a_1 \bar{a}_y}{\sqrt{1 + a_1^2}} \cdot \frac{\bar{a}_x + a_1 e^{j(\theta_y - \theta_x)} \bar{a}_y}{\sqrt{1 + a_1^2}} = 1$$

Or

$$1 + a_1^2 e^{j(\theta_y - \theta_x)} = 1 + a_1^2$$

$$e^{j(\theta_y - \theta_x)} = 1, \text{ thus}$$

$$\theta_y - \theta_x = 0$$

Thus the required condition is that:

$$\theta_y - \theta_x = 0$$

$$a_1 : \text{arbitrary}$$

C. Linear-to Circular Polarization Conversion

Incident electric field is linearly polarized:

$$\bar{E}^i = e^{jkz} \bar{a}_x + a_1 e^{jkz} \bar{a}_y$$

The reflected field is

$$\bar{E}^r = e^{-jkz} e^{j\theta_x} \bar{a}_x + e^{-jkz} a_1 e^{j\theta_y} \bar{a}_y$$

$$\bar{E}^r = \left[\bar{a}_x + a_1 e^{j(\theta_y - \theta_x)} \bar{a}_y \right] e^{j\theta_x} e^{-jkz}$$

The condition that the reflected field be circularly polarized is that $a_1 = 1, \quad \theta_y - \theta_x = \pi/2$.

DESIGN

The data available for the design are : polarization of the incident wave, operating frequency (f_{op}), bandwidth (bw), and the required polarization. The first step is to find the angle ψ from the polarization of the incident and reflected waves. The second step is to find the resonance frequencies of the two parallel resonant circuits. The resonant frequencies are taken to be the lower edge (f_L) and the upper edge (f_U) of the bandwidth. Thus, we have

$$f_L = \frac{1}{2\pi\sqrt{LC_y}} = f_{op}(1-bw/2) \dots\dots\dots (10)$$

$$f_u = \frac{1}{2\pi\sqrt{LC_x}} = f_{op} (1+bw/2) \dots\dots\dots(11)$$

$$\Psi = \text{Im}\{\ln R_y\} - \text{Im}\{\ln R_x\} \dots\dots\dots(12)$$

Solving these equations give L, C_x , and C_y . Using these values ,solve Eqs.(1) and (2) above and get the dimensions of the EBG structure: l_x , g_x , l_y , g_y , and h. To simplify the solution choose the substrate material. Thus ϵ is known. Take $g_x = 0.1 l_x$, and $g_y = 0.1 l_y$ which is a reasonable practical assumption.

RESULTS

Three polarization converters were designed. The first converts linear polarization to linear perpendicular. The operating frequency, bandwidth and dimensions of the converter are: $f_{op} = 3$ GHz, $bw = 15\%$, $\epsilon_r = 2.2$, $\psi = \pi$, $h = 2.4$ mm, $l_x = 29$ mm, $g_x = 2.9$ mm, $l_y = 39$ mm , $g_y = 3.9$ mm. The reflection phase difference computed using HFSS and the required one are shown in Fig.(3). There is a big difference between the two because of the inherent approximations in the LC model of the EBG surface.

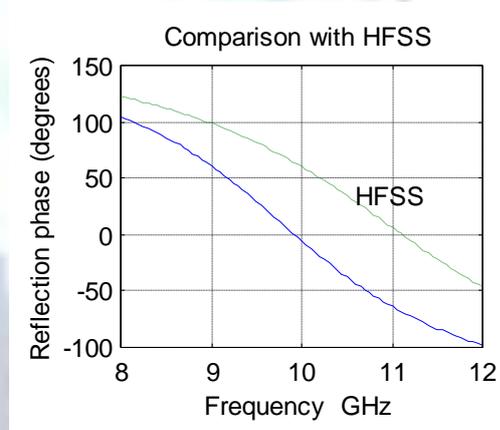
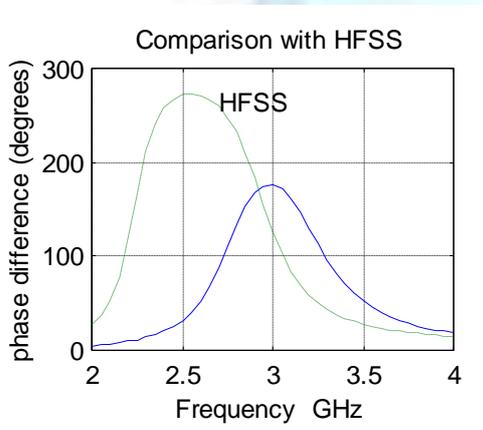


Figure 3. Reflection phase difference for polarization converter to convert linear polarization to linear perpendicular

Figure 4. Reflection phase difference to keep the polarization of the incident wave without change

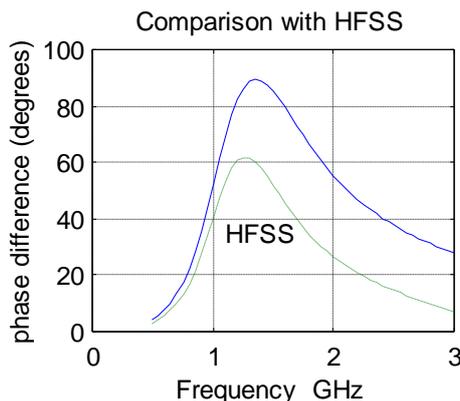


Figure 5. Polarization converter to convert linear polarization into circular

The second converter reflects the incident wave with no change of polarization. It keeps the polarization of the incident wave without any change. The parameters of the converter are: $f_{op} = 10$ GHz, $bw = 30\%$, $\psi = 0$, $\epsilon_r = 2.2$, $h = 1.6$ mm, $l = 4.6$ mm, $g = 0.46$ mm. The patch is square. The reflection phase difference is shown in Fig.(4).

The third polarization converter converts linear polarization to circular. The parameters are : $f_{op} = 1.296$ GHz, $bw = 30\%$, $\epsilon_r = 2.2$, $\psi = \pi/2$, $h = 27.72$ mm, $l_x = 11.76$ mm, $g_x = 1.176$ mm, $l_y = 21.54$ mm, $g_y = 2.154$ mm. The reflection phase difference is shown in Fig. (5).

As mentioned above there is a noticeable difference between the required and computed reflection phase difference. However it is possible to reduce this difference by changing the dimensions of the patch. A parametric study was conducted to find out which dimensions to be changed and in what value. Figure (6) below shows the effect of changing the x- dimension of the patch upon reflection phase difference. Increasing the x-dimension, decreases the reflection phase and reduces the frequency at which the peak value occurs. The gaps between patches (g_x and g_y) were changed simultaneously, and all other parameters were kept constant. The reflection phase difference was computed . The result is shown in Fig.(7). Increasing the gap width decreases the reflection phase slightly and increases the frequency at which peak value occurs. The effect of changing patch y-dimension is shown in Fig.(8). Increasing the y-dimension, increases the reflection phase and decreases the frequency at which peak value occurs. Figure (9) shows the effect of changing substrate thickness. Increasing substrate thickness slightly decreases reflection phase and decreases the frequency at peak values. Finally changing the substrate material (ϵ_r) affects reflection phase as shown in Fig. (10). Increasing dielectric constant slightly increases reflection phase and decreases the frequency at peak value.

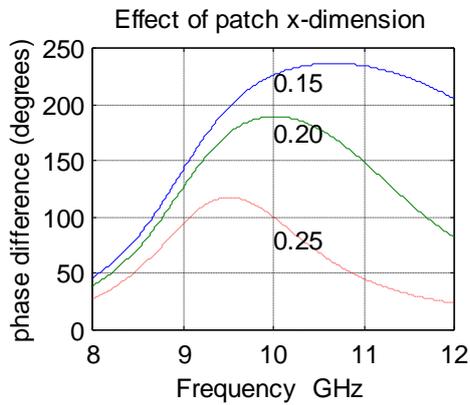


Figure 6. Effect of changing x- dimension

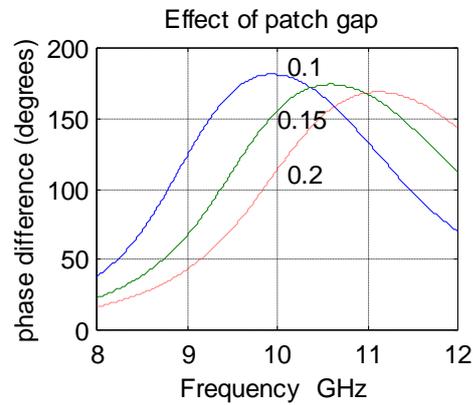


Figure 7. Effect of changing gap between patches

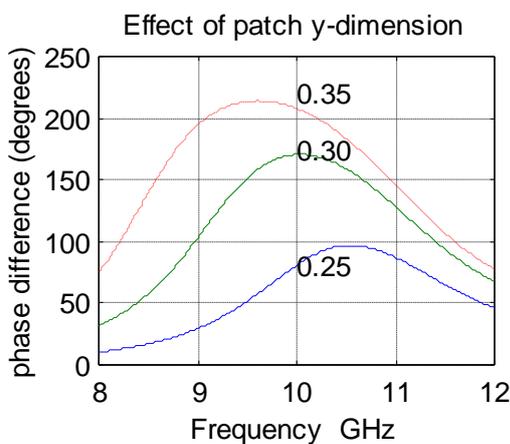


Figure 8. Effect of patch y-dimension

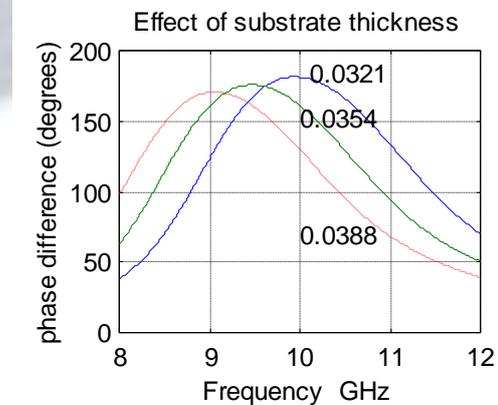


Figure 9. Effect of substrate thickness

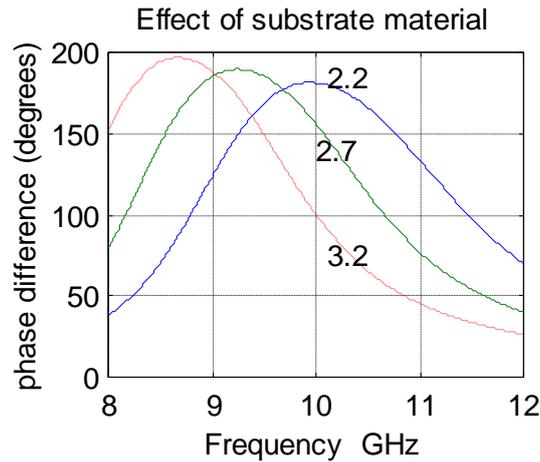


Figure 10. Effect of substrate material ϵ_r

Guided by the parametric study, the dimensions l_x and l_y were changed for the three design cases mentioned above. For the first case (linear to linear perpendicular), l_x and l_y were changed to be 26.5 mm and 31 mm respectively. The reflection phase was computed, the result is shown in Fig.(11) below. Very good agreement with the required reflection phase can be observed.

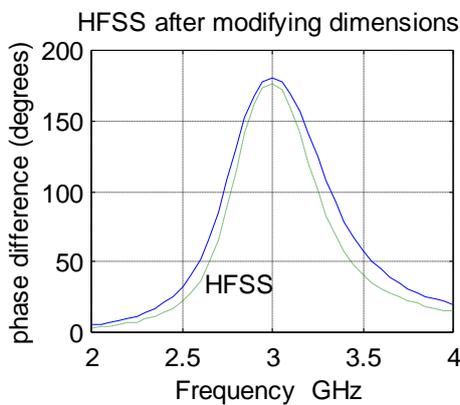


Figure 11. Reflection phase after modifying dimensions for linear-to-linear perpendicular conversion

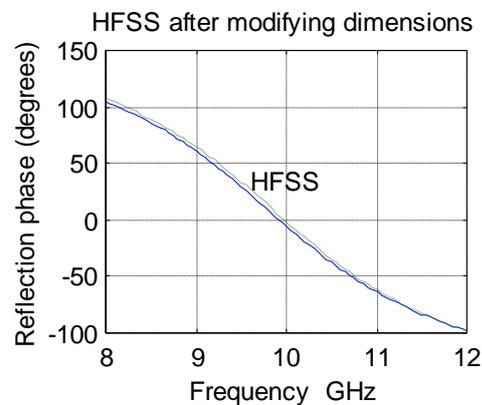


Figure 12. Reflection phase after modifying dimensions for linear-to-linear parallel conversion

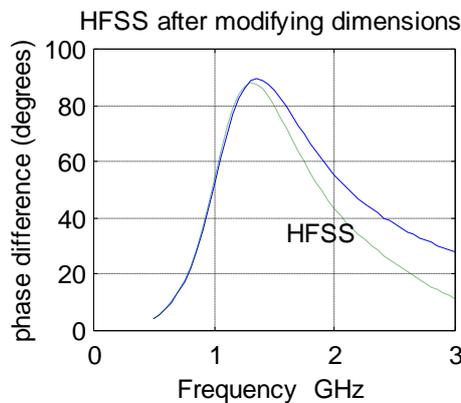


Figure 13. Reflection phase after modifying dimensions for linear-to-circular conversion

The case of linear – to – linear parallel conversion is shown in Fig. (12). The patch dimension was changed to be $l = 5.4 \text{ mm}$. All other dimensions were kept constant. The agreement between computed and required is excellent.

The third case (linear to circular polarization) is shown in Fig. (13). The x- and y-dimensions of the patch were changed to be 9 and 22 mm respectively. Good agreement between required and computed reflection phase can be observed.

Conclusions

A simple design technique is developed. The technique is used to design polarization converters. Three polarization converters were designed for three different applications. The first converter transforms linearly polarized incident wave to a linearly polarized wave with the electric field normal to the incident. This converter is used in Cassegrain antennas to avoid blockage from subreflector. The second converter reflects two incident linearly polarized waves with electric fields normal to each other, such that the polarization does not change after reflection. This is used in dual polarized satellite communications antennas. The third converter transforms a linearly polarized wave to a circularly polarized wave. This is used to simplify the feed structure of circularly polarized parabolic reflector antennas.

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