Refinement of circular-polarization based on multilayer film structure

LI Bin, LEE Kuei-jen, CHOU Hsi-tseng, HUANG Shan-guo, GU Wan-yi

Key Laboratory of Optical Communications and Lightwave Technologies, Beijing University of Posts and Telecommunications, Beijing 100876, China

Abstract

Circular-polarization discrimination appears in many antennas’ applications. A compensation approach based on multilayer film structure is proposed to improve the axial ratio of the magnitude of the two perpendicular modes of the lump ports. The goal is to widen the beamwidth of radiation that has an axial ratio less than 3 dB and thus reducing the complexity at the receiver. A transfer matrix method was developed to represent the multilayer film and characterize its performance. Simulation using high frequency structure simulator shows that a crossed dipole, as an example, can achieve a beamwidth of more than 30° at the frequency of 12.45 GHz after compensation. Finally, conclusions and future work about this compensation method are presented.

Keywords crossed dipole, multilayer, compensation, beamwidth

1 Introduction

With the rapid development of wireless communications, dipoles are widely applied in short-distance wireless environments, such as Bluetooth, HomeRF, GPS, etc. Of the various kinds of dipoles, crossed dipole can generate a circular polarization (CP) required by services. Although a perfect CP can be obtained in the direction the antenna points to, the polarization discrimination against transverse electric (TE) and transverse magnetic (TM) modes grows as the incident angle increases [1–2]. That is, higher measurement accuracy is required, thus increasing the cost of equipment.

To improve the efficiency of antennas and maintain the polarization discrimination against them at a low level in a wide range, a compensation method is introduced using multilayer film structure to broaden the 3 dB TE/TM ratio region.

The concepts of multilayer film were first put forward by Yablonovitch E and John S [3]. Multilayer film structure generally refers to periodically structured dielectric materials that can be recognized as a compensation structure. If the structures show periodicity in the range of light wavelength, there will be strong interferences affecting the light propagation in these materials. Multilayer film structures have wide applications, such as laser applications, glass fibers, photonic crystals, and pigments. Also, they can be used in the newly emerging areas of integrated optics and sensing [4].

This article is organized as follows. In Sect. 2, the theory of multilayer film is reviewed, including the transfer matrix method used in the compensation approach. Sect. 3 presents the simulation environment in high frequency structure simulator (HFSS) 9.0. Following that, two criteria are proposed to evaluate the performance of compensation. Sect. 4 shows the simulation results and analysis. Sect. 5 presents the conclusions.

2 Theory of transfer matrix

For multilayer film structure, the amendment of Maxwell equation can be expressed as follows:

\[
\frac{\partial^2 E}{\partial x^2} + \frac{\varepsilon(x)}{c^2} \omega^2 E = 0
\]  

(1)

A representative structure of the multilayer film structure is illustrated in Fig. 1. Note that only two layers are shown in the figure. Compared with its lateral displacement, the width of the incident beam is assumed large considering multiple reflections that contribute significantly to the resultant reflected and transmitted beams. Several approaches can be used in the optical film computations. The analytical resolution is rather complex while calculating the electromagnetic field layer-by-layer within the multilayer films. The authors introduce a transfer matrix method that can provide great flexibility in designing interference coatings with almost any specified frequency-dependent reflectance or transmittance.
characteristics.

The electric and magnetic field of the incident wave must obey the boundary condition restrictions. That is, the tangential components of the resultant \( E \)-field and \( B \)-field are continuous across the interface; their magnitudes on either side are equal.

Under the restriction of the boundary condition [5], the relation of the electric and magnetic fields between the adjacent layers of the films is obtained:

\[
\begin{bmatrix}
E_k \\
B_k
\end{bmatrix} = 
\begin{bmatrix}
\cos \xi_k & i\sin \xi_k \\
\gamma_k & 
\end{bmatrix}
\begin{bmatrix}
E_{k+1} \\
B_{k+1}
\end{bmatrix}
\]

(2)

where \( \xi_k = (2\pi / \lambda) n_k d_k \cos \theta_k \), \( 1 \leq k \leq N \); \( \gamma_k = n_k / \cos \theta_k \) for \( p \)-polarization, and \( \gamma_k = n_k \cos \theta_k \) for \( s \)-polarization, in which \( \theta_k \) is the incident angle of the \( k \)th layer.

\[
\begin{bmatrix}
E_k \\
B_k
\end{bmatrix} = Z
\begin{bmatrix}
E_k \\
B_k
\end{bmatrix}
\]

(3)

where \( Z \) is the compound matrix.

Generally, the \( Z \)-matrix is depicted as follows:

\[
Z = \begin{bmatrix}
z_{11} & z_{12} \\
z_{21} & z_{22}
\end{bmatrix}
\]

(4)

The reflection and transmission coefficients are defined as:

\[
r = \frac{E_t}{E_0} \quad \text{and} \quad t = \frac{E'_t}{E_0}
\]

(5)

By substituting the expression of \( t, r, \) and \( Z \) into Eq. (3), the total transmission and reflection coefficients can be solved as follows:

\[
E_t = \frac{2\gamma_0}{\gamma_0 + \gamma_1} \frac{z_{21} + \gamma_0 z_{22}}{z_{11} + \gamma_0 z_{12}}
\]

(6)

\[
r = \frac{E_t}{E_0} = \frac{2\gamma_0}{\gamma_0 + \gamma_1} \frac{z_{21} + \gamma_0 z_{22}}{z_{11} + \gamma_0 z_{12}}
\]

(7)

The transfer-matrix elements and Eqs. (6) and (7) makes possible the evaluation of the reflection and transmission properties of single or multilayer film represented by the transfer matrix.

3 Simulation environment

In this project, we introduce includes three scenarios: the crossed-dipole antenna without any compensation, the crossed-dipole antenna with parallel films compensation, and the crossed-dipole antenna with 30° rotated compensation. The flowchart of the design is illustrated in Fig. 2 presents the flow chart of our designs. The authors first drew the compensation model in HFSS, and then optimized the argument of the structure with transfer matrix method for a satisfactory result.

![Fig. 2 Flowchart of the design](image)

The specific procedure is as follows. First, the authors designed a cross-dipole model in HFSS, as shown in Fig. 3. As can be seen in the center of the reflector antenna, the length of the cross-dipole is 3.6 mm, the inner width is 0.3 mm, and the outer width is 0.8 mm. The inner width and outer width are referred to as the corresponding width of the cross-dipole edge near and far from the feed, respectively. A 72 mm diameter and 18 mm height paraboloid reflector was used.

![Fig. 3 Structure of the cross-dipole](image)
been shown in the geometrical optics that if a beam of parallel rays is incident upon a reflector whose geometrical shape is a paraboloid, the radiation will converge at the focal point of the paraboloid. Hence, the cross-dipole was placed on the focal point of the paraboloid so that an enhanced parallel beam can be obtained.

![Fig. 4 Multilayer film structure polarization compensation for antennas](image)

The authors used a glass substrate \(n_s = 1.52\) on the top of the multilayer film and incidence from the air \(n_0 = 1\), and the relative permittivities of the 4 layers below the substrate are 1.44, 1.172, 1.44, 1.172, respectively, but the relative permeability of all the layers is 1. The thickness of each layer is a quarter of the effective wavelength. All the films are assumed to be both homogeneous and isotropic.

To evaluate the performance of the compensation approach, the authors introduced a 3 dB region as criterion. If the remote signal receiver can easily recognize the signals sent by the transmitter, then the axial ratio must satisfy the following constriction:

\[
20 \log_{10} R_{TE/TM} < 3 \text{ dB}
\]

where \(R_{TE/TM}\) denotes the ratio of electric field intensity of TE and TM modes. The minimal angle of transmission that cannot meet the requirement of Eq. (8) is recorded as \(\theta_{\text{min}}\); likewise, the maximal angle of transmission is recorded as \(\theta_{\text{max}}\), the 3 dB region is defined as the degree of the angle that ranges from \(\theta_{\text{min}}\) to \(\theta_{\text{max}}\). Angles that fall in the above-mentioned range are defined as the beamwidth of angle.

For antennas, the accepted power is a measure of the incident power reduced by the mismatch loss at the port plane. Gain is often related to directivity by the radiation efficiency of the antenna. The following equation is used to calculate the gain in HFSS:

\[
G = 10 \log_{10} \left( \frac{4\pi U}{\text{real} \int_A (E \times H^*) \, ds} \right) \quad \text{(dB)}
\]

Here, \(U\) is the radiation intensity in watts per steradian in the direction specified; real denotes the real part of a complex number; \(A\) is the union of all port boundaries in the model; \(E\) is the radiated electric field; \(H^*\) is the conjugation of \(H\); \(ds\) is the local port-boundary unit normal directed into the 3D HFSS model. Generally, a higher gain can be expected in a specified direction.

### 4 Experimental result

Fig. 5 gives the total gain of the cross-dipole at the frequency of 12.45 GHz. It can be seen from this figure whether the simulation model of the cross-dipole is effective.

![Fig. 5 Total gain of the cross-dipole antenna](image)

Simulation results of the beamwidth are shown in Fig. 6. The three curves denote different conditions, that is, dipole without lens (indicated by ‘NC’), dipole with a lens but does not rotate (indicated by ‘R0C’), and dipole with a lens of 30° lean (indicated by ‘R30C’). From the result, it can be seen that under the third condition, the widest 3 dB region can be obtained by adjusting the excitation of the cross-dipole. The abscissa represents the axial ratio of the magnitude of the two perpendicular modes of the lump ports. When adjusting the magnitude ratio to about 4:3, the maximal 3 dB region of 38° is obtained. In both the cases of no lens being used and the case of no rotating lens, the maximal 3 dB region can be reached at ratio of 1:1. This proves that the parallel lens do not change the axial ratio and the 3 dB region. Although the average 3 dB region of lens 30 is not broader than the other two, the maximal region can be obtained. This is very useful in applications of satellite communications because the magnitude ratio of the two perpendicular modes can be easily modified in cross-dipole antenna [8].

![Fig. 6 Beamwidth of angle with different magnitude ratio](image)

The far-field of the rectangular plot is shown in Figs. 7–9.
The beamwidth can be obtained in each scenario. In Fig. 9, it is asymmetrical with the axial \( \theta = 0^\circ \) due to the 30° rotation of the multilayer film. When the excited magnitude is 0.75, there is a peak value at 10° but still in the acceptable range. As the input axial ratio grows, the beamwidth decreases again as a result of ray distortion.

![Fig. 7 Far-field of rectangular plot without lens](image)

![Fig. 8 Far-field of rectangular plot with parallel lens](image)

![Fig. 9 Far-field of rectangular plot with 30° rotated lens (ratio = 1:0.75)](image)

Fig. 10 shows the far-field gain of 3D polar plot in all the three cases. The black color denotes higher gain in dB; the white color denotes a lower gain. The gain is calculated from the input signal at the port.

![Fig. 10 Far-field of the 3D polar plot with 30° rotated (ratio = 1:0.75)](image)

5 Conclusions

In this article, we study on the polarization compensation methods using multilayer film structure. The transfer matrix method is developed to calculate the multilayer film structure quickly. The results show that the circular polarization discrimination can be significantly amended, and the rotated structure under different excited magnitude ratio can flexibly adjust the expected 3 dB beamwidth and the far field gain. We find that the TE/TM ratio pattern is not symmetrical, thus a new multilayer film structures of symmetrical structure is expected to obtain better performance. Any intelligent controlling algorithms to be embedded in the antenna will improve the efficiency of operation, but the tradeoff between the performance and the cost should be considered.

Acknowledgements

This work was supported by the Hi-Tech Research and Development Program of China (2006AA01Z246), the National Natural Science Foundation of China (60702005).

References


(Editor: ZHANG Ying)