Analysis of a Horizontally Polarized Antenna with Omni-Directivity in Horizontal Plane Using the Theory of Characteristic Modes

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***Abstract*-In this paper we propose a horizontally polarized antenna with omni-directivity in horizontal plane. Ripple coefficient of the radiation pattern in horizontal plane improve to ±0.1 dB. The theory of characteristic modes is used to analyze why the omni-directivity property of the proposed antenna increased comparing with that before optimization.**

I. Introduction

Recent years, orthogonally polarized composite antennas are proposed for wireless communications because of their excellent characteristics to increase channel capacity and keep compact antenna size. However, a horizontally polarized antenna with dipole-like omni-directivity is not easy to realize. [1][2] presented notch array antennas as horizontally polarized antenna for practical applications. As an important index to evaluate circular degree, ripple coefficient of radiation patterns in horizontal plane of the antennas proposed in [1] are ±1~2.5 dB. It indicates more than 40% energy weaken at somewhere in the horizontal plane. In [2], increased quantity of notch cause the ripple coefficient reduced to about ±0.65~0.8 dB.

To seek for other approaches except adding array element to improve directivity property, we use the theory of characteristic modes which is one of the best methods to help us penetratingly understand antenna operating principles. This paper is devoted to apply the theory of characteristic modes to provide an in-depth physical insight into the behavior of notch array antenna and subsequently improve its directivity property. In this paper, the proposed antennas are simulated by FEKO based on method of moment (MoM).

II. Brief Review of The Theory of Characteristic Modes

The theory of characteristic modes was first developed by Garbacz [3] and was later refined by Harrington and Mautz [4], [5] in 1971. Characteristic modes are current modes numerically obtained for discretionarily shaped conducting bodies, and provide a physical explanation of the radiation phenomena taking place on the antenna. The characteristic modes can be obtained from the following particular weighted eigenvalue equation:

$$X(J_n) = \lambda_n R(J_n), \qquad (1)$$

where the λ_n are the eigenvalues which are real, the J_n are the eigencurrents. $R(x)$ and $X(x)$ are the real and imaginary parts of the impedance operator. A mode is at resonance when its eigenvalue $|\lambda_n| = 0$, and is inferred that the smaller the magnitude of the eigenvalue, the more efficiently the mode radiates when it is excited. Besides, there is another more visualized representation of the eigenvalues, which is based on the use of characteristic angles and is defined as:

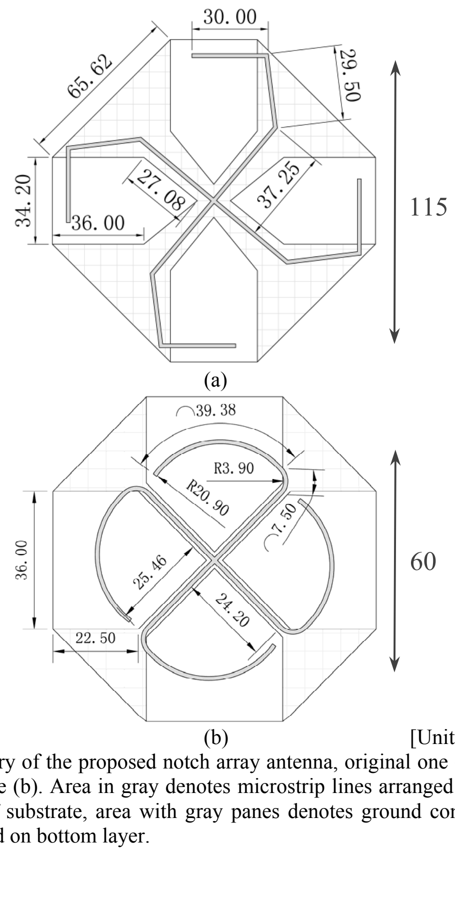
$$\alpha_n = 180° - tan^{-1}(\lambda_n). \qquad (2)$$

The characteristic angles physically characterizes the phase difference between the characteristic current J_n and the associated characteristic field E_n. Hence, a mode is at resonance when its characteristic angle is or close to 180°. Additionally, when the characteristic angle is near 90° or 270°, the mode is thought mainly storing energy. In addition, it should be noticed that characteristic modes are independent of any kind of excitation but only depend on the shape and size of the conducting object.

III. Analysis of Proposed Antennas

In order to obtain horizontally polarized radiation and omni-directivity in horizontal plane, a notch array antenna with four array elements is originally proposed at 1.5 GHz and its geometry is shown in Fig. 1(a). There are four notches cut out from the bottom conductor layer, and four microstrip lines feed them, respectively, on the upper layer. A power divider is constructed and fed from the center. The relative dielectric coefficient of dielectric-layer ε = 2.6, while the thickness of the substrate is 0.8 mm. Horizontally polarized waves with semi-omni-directivity in horizontal plane (the plane of antennas' surface) radiated by each notch element, compose an dipole-like omni-directional composite radiation pattern as expected.

In order to further investigate the operating principle of this antenna, we use the theory of characteristic modes to analyze the antenna. Fig. 2 shows current schematics on top layer associated with characteristic current modes J_1~J_4. The



(a)

(b) [Unit: mm]

Fig. 1 Geometry of the proposed notch array antenna, original one (a) and final one (b). Area in gray denotes microstrip lines arranged on top layer of substrate, area with gray panes denotes ground conductor arranged on bottom layer.

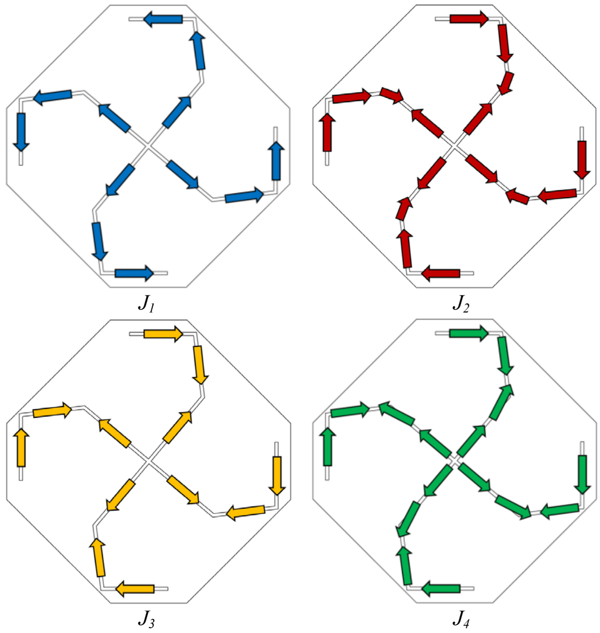


Fig. 2 Current schematics on top layer associated with characteristic current modes J_1~J_4.

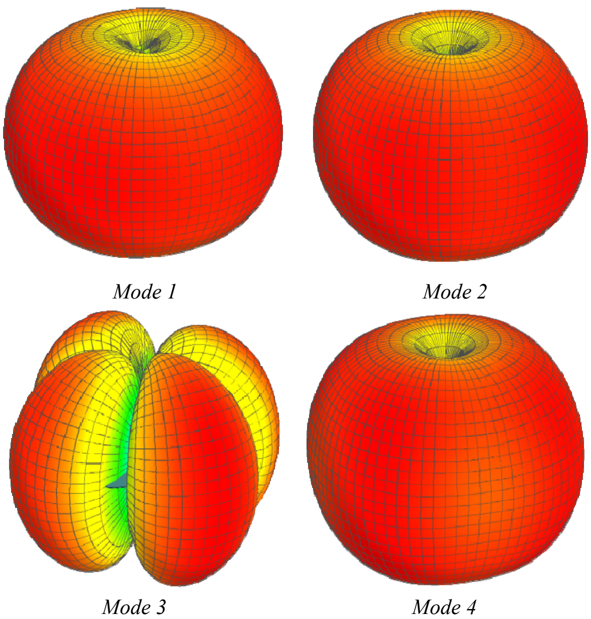


Fig. 3 Normalized radiation patterns of the originally proposed antenna associated with *Mode 1*~*Mode 4* at their resonant frequencies.

length of each branch of microstrip lines is 96.8 mm, that approximately equals $\frac{1}{2}\lambda_{g[0.96\,\mathrm{GHz}]}$, $(\frac{1}{4}+\frac{1}{2})\lambda_{g[1.44\,\mathrm{GHz}]}$ and $\lambda_{g[1.92\,\mathrm{GHz}]}$. This length causes about 1 standing wave in *mode 1*, 1.5 standing wave in *mode 2* and *mode 3*, 2 standing waves in *mode 4*, respectively. Fig. 3 shows normalized radiation patterns of *mode 1* ~ *mode 4*. It can be verified that J_1, J_2 and J_4 contribute to exciting the notches located on bottom layer for the omni-directional radiation pattern is thought composed by semi-omni-directional patterns radiated by the four notches. J_3 contributes to exciting the tail-end of microstrip lines to make them operating as monopoles. Due to the in-phase current on the opposite tail-end of microstrip lines and the approximate half-wave distance between them, double 8-shaped radiation patterns are orthogonally formed and can be confirmed in Fig. 3. It should be noticed that J_1~J_4 are not the all current modes occurring at concerned frequency spectrum, but the modes possible to be

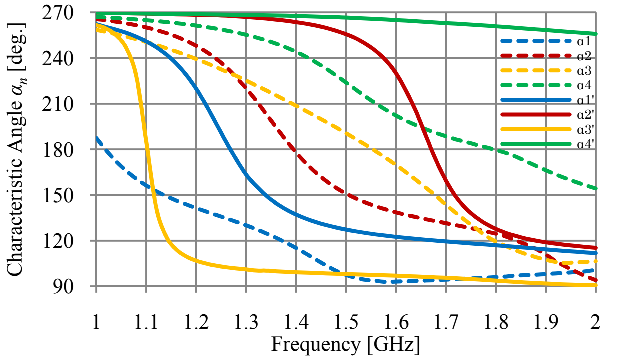


Fig. 4 Variation with frequency of the characteristic angles associated with current modes of the originally proposed antenna (dotted line) and the finally proposed antenna (solid line).

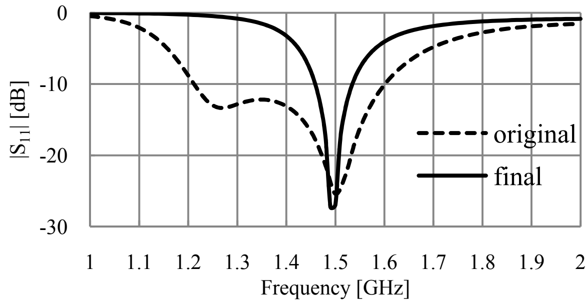


Fig. 5 $|S_{11}|$ characteristics of the originally proposed antenna (dotted line) and the finally proposed antenna (solid line).

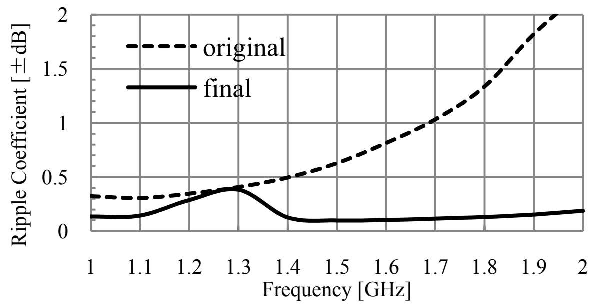


Fig. 6 Ripple coefficient characteristics of the originally proposed antenna (dotted line) and the finally proposed antenna (solid line).

excited by the central feeding. Discussion about other current modes impossible to be excited is ignored in this paper.

Dotted lines in Fig. 4 present the variation with frequency of the characteristic angles α_1~α_4 associated with current modes J_1~J_4 of the proposed antenna. It is found the characteristic *mode 1*, *mode 2*, *mode 3* and *mode 4* are in resonant state at 1.02 GHz, 1.4 GHz, 1.55 GHz and 1.8 GHz, respectively.

Dotted line in Fig. 5 shows input characteristics $|S_{11}|$ of the originally proposed antenna. Dotted line in Fig. 6 presents the ripple coefficient characteristics. In the range of bandwidth 1.2 ~ 1.6 GHz, the ripple coefficient varies in ±0.35 ~ 0.8 dB and increases along with operating frequency. By observing and comparing the curves of $|S_{11}|$ and characteristic angles, we may affirm that the double resonances of the antenna are generated by the cooperating of J_1, J_2 and J_2, J_4. As one of the most direct reason, radiation pattern of the actually excited antenna performed as that of *mode 1*, *mode 2* and *mode 4*. Additionally, it is considered that J_3 is not adequately excited by the actual feeding, since the actual current distribution and radiation pattern do not perform as that associated with *mode 3*. However, we believe that the existence of *mode 3* which radiates orthogonally double 8-

shaped patterns within antenna's operating spectrum does have effect on actual radiation characteristics so that the ripple coefficient rapidly rises when the frequency is above 1.4 GHz.

In order to improve the ripple coefficient characteristic, an optimized notch array antenna is proposed and its geometry is shown in Fig. 1(b). The entire area reduces by 43 % of the original one. Shape of notches becomes a little shorter and wider. Microstrip lines are 26 % shorter and their tail-ends are designed to circular-arc.

Solid lines in Fig.4 present the variation with frequency of the characteristic angles $\alpha_1 \sim \alpha_4$ associated with current modes $J_1 \sim J_4$ of the finally proposed antenna. It can be found that resonant frequency of *mode 1* and *mode 2* rises to 1.27 GHz and 1.68 GHz, respectively, due to the shortening of microstrip lines. Resonant frequency of *mode 4* rises over 2 GHz. What merits special attention is that *mode 3* resonates at 1.1 GHz, which is outside the range between the resonant frequencies of *mode 1*, *mode 2* and *mode 4*, and outside the actual operating band 1.46 GHz ~ 1.54 GHz which can be confirmed by $|S_{11}|$ curve shown in Fig. 5 by solid line. Profit from this change, ripple coefficient reduced to ±0.1 dB in the concerned operating band, shown by solid line of Fig. 6. The variation of *mode 3*'s resonant frequency is thought due to the lengthening of microstrip lines' tail-ends which operate as monopoles. Besides, slopes of the curves near 180° exhibit bigger. This variation indicates narrower bandwidth of the antenna. The actual resonance at 1.5 GHz is regarded as the cooperating of J_1 and J_2. However, existence of *mode 3*'s resonance does not make the antenna resonating at 1.1 GHz. But its influence to antenna can be verified by ripple coefficient curve. We find the values become much lower except the spectrum around 1.2 ~ 1.3 GHz. The peak-like variation at that band is considered as a cooperating of J_1 and J_3. However, the influence by *mode 3* is not very remarkable because the distance between the opposite tail-end of microstrip lines is only quarter wave that the directive gain of 8-shaped patterns decreases relatively.

IV. Conclusions

A horizontally polarized notch array antenna is proposed in this paper. We used the theory of characteristic modes to analyze the potential current modes of the antenna so that factors affect radiation pattern's ripple coefficient can be found out. In this case, we can confirm the wherefore as the existence of *mode 3*, in which the tail-end of microstrip lines operate as monopoles to make the radiation pattern unsmooth. To solve the problem, we optimized and proposed another design in smaller size. The redesign of antenna's structure especially the microstrip lines makes *mode 3* resonate at lower frequency that is outside antenna's operating band. Profit from this change, the ripple coefficient reduced to ±0.1 dB in operating band.

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