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Cavity model analysis of 30°–60°–90° triangular microstrip antenna

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ABSTRACT

Modal analysis of probe fed 30°–60°–90° triangular microstrip antenna (TMA) is presented using cavity model for TM^z mode. Probe excitation is modeled here in three simple ways. A comparative study among these three types of feed modeling is given in a systematic way, hitherto unreported. Input impedance, quality factor, radiation patterns, efficiency, gain are discussed for first five modes. Closed form expressions for calculating the far-field radiation patterns are given here for the first time. New broadside modes are identified and excited successfully, hitherto unreported. Theoretical results are in good agreement with measured data and/or data obtained using 3D EM simulator. It is found that all first five modes show a peak in broadside direction. The results should be useful for practical design of 30°–60°–90° TMA.

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1. Introduction

Microstrip antennas (MA) are widely used as an efficient radiators because of light weight, low profile, compactness in size, low cost, ease of fabrication, conformability, flexibility in shapes and integration with solid-state devices. However, majority of studies have been proposed and concentrated on rectangular, circular, elliptical, circular ring and equilateral triangular shaped antennas [1–3]. In contrast, 30°–60°–90° Triangular MA (TMA) did not get much attention compared to equilateral TMA [4–6]. The study of 30°–60°–90° TMA is very important for designing compact antenna with respect to conventional regular shaped MAs. At fundamental mode of operation around 2.6 GHz, the rectangular, circular, semi-circular, annular ring and equilateral triangular MAs take almost 3.6, 3.2, 1.6, 2.5 and 2 times area compared to 30°–60°–90° TMA respectively where all antennas have been excited using coaxial-probe [7, Table 2.13]. Therefore, the study of 30°–60°–90° TMA is very important to design compact antenna. Further, study of 30°–60°–90° TMA is very important compared to above mentioned MAs from far-field radiation point of view. It is found that the first five modes of 30°–60°–90° TMA shows a peak in the broadside direction as discussed in this paper and has not been reported so far.

Reflection of plane waves (i.e. geometrical optics) [8] has been used by Kuester et al. to predict the resonant frequency and quality factors of 45°–45°–90°, 60°–60°–60° and 30°–60°–90° TMAs in 1983 for few modes. Similar approach can also be found in [9] where the resonant frequency of above mentioned antennas have been compared with magnetic wall model for fundamental mode only. But the magnetic wall model has not been explained explicitly in [9]. Similar approach (i.e. geometrical optics) has also been adopted to find input impedance of 30°–60°–90° TMA for fundamental TM_{10} mode only in 1989 [10]. Contour integration has been utilized to find the input impedance. In [11], resonant frequency has been predicted from the eigenvalue of 30°–60°–90° triangular waveguide with metallic walls and verified MoM based commercial software IE3D. No experimental validation has been performed for 30°–60°–90° TMA. Recently, cavity model analysis of probe fed 30°–60°–90° TMA has been reported for TM_{10} mode [12]. Current has been modeled as uniform one dimensional ribbon to predict the input impedance and the far-field radiation patterns therein. Cavity model analysis has not been reported on 30°–60°–90° TMA for arbitrary TM_{mn} modes so far. In this work, the characteristics of 30°–60°–90° TMA is presented using modal analysis for the first time.

Further, literature survey shows that current has been modeled either as one dimensional uniform ribbon [6] or as two dimensional strip [13] to analyze the microstrip antennas using cavity model. There is no comparative study between one and two dimensional feed modeling on input impedance, far-field radiation patterns, gain, radiation *Q*-factor etc. for a particular mode as per our knowledge goes.

Commercially available numerical EM simulators can predict the input impedance, far-field radiation patterns etc. but take a long time to simulate one antenna structure. IE3D and HFSS EM

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simulator take (approx.) 2–3 min and 5–6 min respectively to simulate one 30°–60°–90° TMA in personal computer having Core 2 Duo processor and 3GB RAM whereas the analytical solution is able to solve the same problem within few seconds. Further, the analytical results may be efficiently utilized in the full-wave MoM analysis of an antenna or cavity or waveguide to choose the proper entire domain basis function [5,14]. Also, the theoretical analysis gives a proper insight into the mechanism of antenna generation. Therefore, the analytical investigation on 30°–60°–90° TMA is very important.

In this paper, modal analysis on probe fed 30°–60°–90° TMA is performed for TM^z_{mn} mode. Feed is modeled here in three different ways for theoretical investigation: (I) one dimensional uniform ribbon along $\hat{x}$ direction, (II) one dimensional uniform ribbon along $\hat{y}$ direction and (III) two dimensional rectangular shaped sheet. A comparative study among these three types of feed modeling with respect to input impedance, far-field radiation patterns, gain, radiation *Q*-factor etc. for a particular mode are given here for the first time. Far-field radiation patterns are predicted using conventional magnetic wall model. Closed form expressions are given here to predict the far-field radiation patterns for various TM^z_{mn} modes, hitherto unreported. Input impedance, quality factor, radiated power, efficiency, gain etc. are also discussed for first five modes. Theoretical results are compared with experimental data to show the accuracy of our theory. The effect of substrate thickness on bandwidth (BW) is also discussed here. A comparative study on BW between conventional 30°–60°–90° TMA and two-layered 30°–60°–90° TMA is also presented here for the first time.

After this theoretical investigation, several fruitful properties (except compactness) are observed as given below:

- 30°–60°–90° TMA shows more number of broadside radiating modes compared to equilateral TMA. All first five modes of 30°–60°–90° TMA are broadside radiating mode whereas equilateral TMA [6] and rectangular MA [15] both have three broadside modes respectively among the first five modes.
- 30°–60°–90° TMA can efficiently be utilized to design penta-band antenna. This attractive feature separates the 30°–60°–90° TMA from other conventional microstrip antennas.
- 30°–60°–90° TMA shows very high *Q*-factor compared to equilateral TMA. Therefore, the 30°–60°–90° triangular geometry can be utilized as an energy storage device.
- Due to high *Q*-factor, 30°–60°–90° TMA shows narrow bandwidth. This property will be very useful for designing narrow band filter using resonators of such structure.
- 30°–60°–90° TMA can efficiently be utilized to design multiband antenna without any extra circuitry.

Further, the analysis on 30°–60°–90° TMA can easily be extended to design 30°–60°–90° triangular shaped cavity resonator, filter, circulator, dielectric resonator antenna etc.

2. Theoretical analysis

Fig. 1 shows the geometry of antenna where the TMA of base (AB) length *a* is placed on thin substrate with relative permittivity ε_r and thickness *h*. Coax-probe is located at (x_o, y_o). The antenna is placed on *x*-*y* surface. The analysis of a microstrip antenna using cavity model is well documented in [2,3], but the relevant equations are also given here for reference purpose.

2.1. Eigenfunction and eigenvalue

To predict the eigenfunction of 30°–60°–90° TMA for TM^z mode, the concept of duality is applied as found for equilateral triangular

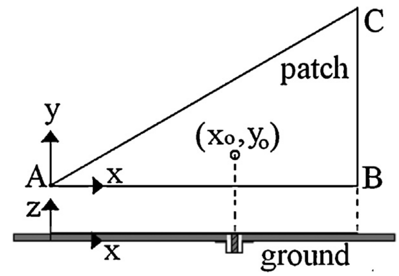

Fig. 1. Antenna configuration.

resonator in [16,17]. The eigenfunction (ψ) for TE^z mode with electric boundary condition i.e. Neumann boundary condition ($\psi = 0$) will be equivalent to the eigenfunction for TM^z mode with magnetic boundary condition i.e. Dirichlet boundary condition ($d\psi/dn) = 0$. This is mathematically derivable using [18,19] for rectangular geometry. Hence, the eigenfunction of 30°–60°–90° triangular resonator having perfect magnetic conductors (PMC) for TM^z mode can be found by duality from TE^z mode of 30°–60°–90° triangular waveguide with perfect electric conductors (PEC) and given by [20,21]:

$$\psi_{mn}(x, y) = \cos\frac{\pi l x}{a}\cos\left(\frac{\pi(m-n)}{\sqrt{3}a}y\right) + \cos\frac{\pi m x}{a}\cos\left(\frac{\pi(n-l)}{\sqrt{3}a}y\right) + \cos\frac{\pi n x}{a}\cos\left(\frac{\pi(l-m)}{\sqrt{3}a}y\right) \quad (1)$$

where *m*, *n*, *l* are mode indices such that

$$l + m + n = 0 \quad (2)$$

Hence, the internal field for TM^Z mode due to probe excitation ($\vec{J}$) is given by:

$$E_z = j\omega\mu\sum_{m=0}^{\infty}\sum_{n=0}^{\infty}\frac{A_{mn}}{(k^2 - k^2_{mn})}\psi_{mn}(x, y) \quad (3)$$

where

$$A_{mn} = \frac{\langle J\psi_{mn}\rangle}{\langle\psi_{mn}\psi_{mn}\rangle} \quad (4)$$

$$k_{mn} = \frac{2\pi}{\sqrt{3}a}(m^2 + mn + n^2)^{1/2} \quad (5)$$

Here, all notations are carrying their usual meaning. The resonant frequency can be found using

$$fr_{mnl} = \frac{k_{mn}c}{2\pi(\varepsilon_r)^{1/2}} \quad (6)$$

where *c* is the velocity of light in free space and ε_r is relative permittivity of substrate. To account the effect of fringing, one can consider effect side length (a_e) as given below [17]:

$$a_e = a + 0.25 \times \frac{h}{(\varepsilon_r)^{1/2}} \quad (7)$$

The concept of effective permittivity is not considered here as found in case of circular and equilateral triangular microstrip antennas [3,6].

2.2. Feed Model

In this work, feed ($\vec{J}$) is modeled in three different ways: (I) uniform current ribbon of effective width w_x along $\hat{x}$ direction ($\vec{J}_x$) [6], (II) uniform current ribbon of effective width w_y along $\hat{y}$

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