An Analytical Approach for Testing the Air gap Tuning Effect on an Equitriangular Microstrip Antenna's Radiation

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ABSTRACT: *Using a combined approach, the effect of air gap tuning on the resonant frequency and radiation field of an equitriangular microstrip antenna is presented in this paper. An equilateral triangular patch is implemented on an isotropic dielectric with an air gap inserted under this one in order to estimate the influence of an air gap on radiation antenna's characteristics. The problem is analysed in spectral domain using the moment method and an electric field integral equation combined with a mathematical approach. However, the dyadic Green's functions corresponding to the proposed structure are developed and the Fourier transform of basis current components are calculated mathematically using "the reference element" method. A numerical result shows that the change in resonant frequency, bandwidth and radiation field of the antenna is due primarily to a small disturbance of the air gap thickness and consequently substrate's equivalent permittivity.*

Keywords: Equitriangular Microstrip Antenna, MoM, Resonant Frequency, Radiation Field Control

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1. Introduction

Antennas designers have found that the most sensitive parameter in microstrip antenna performance estimation is the dielectric constant of the substrate material. However, there are many substrate materials on the market with dielectric constants ranging from 17 . 1 to about 25 and loss tangents from 0001 . 0 to 004 . 0 [1]. Generally the value of permittivity is unchangeable, it depends on dielectric's nature only, but in some cases as microwaves domain, we need to change it without changing the media or modifying the structure. A simple method which is easy to implement consists to insert an air gap in the substrate between the dielectric and the ground plane of the patch antenna. This model was applied to an equitriangular patch antenna with coaxial feed and relatively thin substrate. The choice of the equitriangular shape here is not arbitrary. It is known that there are only a handful of investigations on the triangular patches with or without air gap[2-6].

However, a summary of work established on the equitriangular patch antenna were reported by the reference [7].

In the present work, the proposed structure is modelled and analysed using an analytical rigorous approach based on spectral-domain method of moments combined with the reference element method [8], [9]. Air gap tuning effects were tested and compared versus resonant frequencies in order to analyse its influence on band width and radiation characteristics of the antenna. Results shows a considerable improvement achieved over the previous theories within very small percentage errors for almost all cases.

This paper is divided into three essential parts: the formulation and implementation of the equation problem is given by explaining all necessary formulas for the characterization of the structure. Then the simulation results using a program developed in FORTRAN will be given and interpreted, and we conclude with a general conclusion.

2. Probmlem Formulation

The proposed structure is configured on Figure 1; A patch of side length a , neglected thin and perfect electric conductor was implemented on an isotropic dielectric with relative permittivity ε_r. An adjustable air gap (with constitutive parameters ε_0 and μ_0) and thickness d_g was inserted between the ground plane and the dielectric. We suggest the layers as an infinite isotropic dielectric with thin thicknesses to avoid some interferences, and the metallic ground plane etched under the substrate have negligibly thin and perfect conductor. The analysis is lead by Galerkin's moment method in the spectral domain using boundary conditions [10] to derive an electric current.

It is preferable to express the unknown patch current in terms of an appropriate basis functions formed by a set of transverse magnetic modes of the triangular cavity with magnetic side walls and electric top and bottom walls. However an appropriate basis current system was chosen [4], from which we have calculated analytically the Fourier Transform of current components by applied a mathematical method [9], to overcome the complexity of the geometry. Numerical results were obtained by programming the calculating steps without the use of specific simulation software. Starting from Maxwell's equations in Fourier-transform and assuming that the propagation is in the Z direction, in each layer i the wave equation in on spectral domain is defined by the following equation:

$$\frac{\partial^2 \tilde{E}_i}{\partial z^2} + K_z^2 \tilde{E}_i = E^{ext} \qquad (1)$$

Where K_z , K_i, K_x, K_y are propagation constants

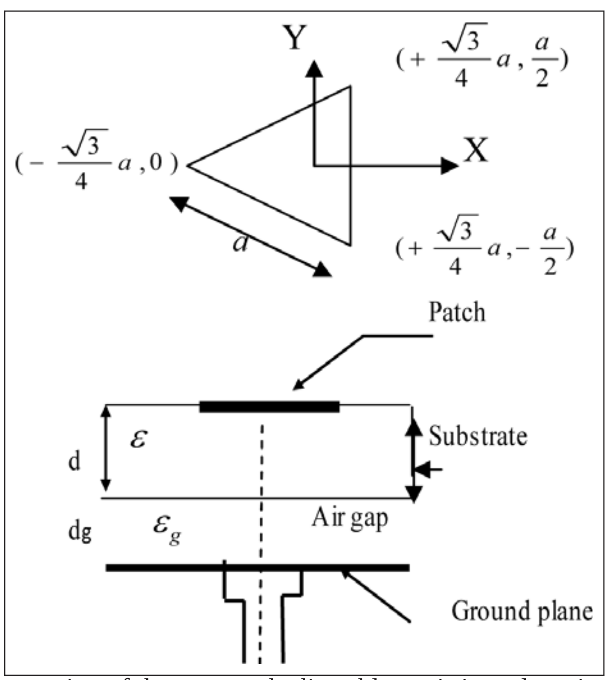


Figure 1. Cross section of the proposed adjustable equitriangular microstrip antennas

At spectral domain in the representation TE-TM electric field is represented on matrix form and in terms of longitudinal components as

$$\bar{E}^e(K_s,z)=\begin{bmatrix}\tilde{E}^e(K_s,z)\\ \tilde{E}^h(K_s,z)\end{bmatrix}=\bar{g}_i\,(K_s)\begin{bmatrix}\dfrac{j}{K_s}\quad\dfrac{\partial\tilde{E}_z(K_s,z)}{\partial z}\\ \dfrac{\omega\mu_0}{K_s}\quad\tilde{H}_z(K_s,z)\end{bmatrix} \tag{2}$$

$\tilde{E}_z$ and $\tilde{H}_z$ are respectively electric and magnetic fields in the direction Z.

$$\bar{g}_i\,(K_s)=\begin{bmatrix}\dfrac{\omega\varepsilon}{Kz} & 0\\ 0 & \dfrac{Kz}{\omega\mu}\end{bmatrix} \tag{3}$$

Considering the wave propagating media as a single layer, the problem will be easy to solve. After substitutions we can find the expressions of both electric and magnetic field in each media as:

$$\begin{cases}E^+=E^-Cos\,(K_Z d_i)-jg^{-1}H^-sin\,(K_Z d_i)\\ H^+=H^-Cos\,(K_Z d_i)-jgE^-\,sin\,(K_Z d_i)\end{cases} \tag{4}$$

Matrix form of system (4) is represented as following:

$$\begin{bmatrix}E_i(K_s,Z_i^+)\\ H_i(K_s,Z_i^+)\end{bmatrix}=\bar{T}_i\begin{bmatrix}E_i(K_s,Z_i^-)\\ H_i(K_s,Z_i^-)\end{bmatrix} \tag{5}$$

$\bar{T}_i$ is the Green's matrix representation of i^{th} layer in TE-TM representation.

Exact diagonal Green dyadic function can be now deduced for two layers by generalizing the formula as:

$$G=\begin{bmatrix}G_{11} & G_{12}\\ G_{12} & G_{22}\end{bmatrix} \tag{6}$$

$$G_{11}=\frac{K_x^2}{K_x^2+K_y^2}\frac{D_m}{T_m}+\frac{K_y^2K_0^2}{K_x^2+K_y^2}\frac{D_e}{T_e} \tag{7}$$

$$G_{22}=\frac{K_y^2}{K_x^2+K_y^2}\frac{D_m}{T_m}+\frac{K_x^2K_0^2}{K_x^2+K_y^2}\frac{D_e}{T_e} \tag{8}$$

$$G_{12}=G_{21}=\frac{K_xK_y}{K_x^2+K_y^2}\frac{D_m}{T_m}+\frac{K_xK_y}{K_x^2+K_y^2}\frac{D_e}{T_e} \tag{9}$$

Terms D_m, T_m, D_e, T_e for the proposed structure were calculated analytically. The following expressions were deduced [11]:

$$D_m=K_{z0}K_{z1}\varepsilon_r\,sin\,(K_{z0}d_g)\,cos\,(K_{z1}d_1)+K_{z0}K_{z1}\varepsilon_0\,cos\,(K_{z0}d_g)\,sin\,(K_{z1}d) \tag{10}$$

$$T_m=j\omega\varepsilon_0^2\,cos\,(K_{z0}d_g)\,(\varepsilon_rK_{z0}cos(K_{z1}d)+jK_{z1}sin(K_{z1}d))-\omega\varepsilon_r\varepsilon_0K_{z0}cos(K_{z0}d_g)\,(cos(K_{z1}d)+j\varepsilon_r\frac{K_{z0}}{K_{z1}}sin(K_{z1}d)) \tag{11}$$

$$D_e=K_0^2K_{z0}\,sin\,(K_{z0}d_g)\,cos\,(K_{z1}d)+K_0^2K_{z1}\,sin\,(K_{z1}d)\,cos(K_{z0}d_g) \tag{12}$$

$$T_e = j\omega\varepsilon_0 K_{z0} \cos(K_{z0} d_g)(K_{z1} \cos(K_{z1} d) + jK_{z0} \sin(K_{z1} d)) - \omega\varepsilon_0 K_{z1} \sin(K_{z0} d_g)(K_{z0} \cos(K_{z1} d) + jK_{z1} \sin(K_{z1} d)) \quad (13)$$

Equivalent permittivity's expression was deduced from the generalized equation given by [12]:

For two layer's substrate $\varepsilon_{equi} = \dfrac{(d+d_g)\,\varepsilon_r\varepsilon_g}{d\varepsilon_g + d_g\varepsilon_r}$ (14)

Basis functions selected in this study were proposed by W. Chen, k. F. Lee and J. S. Dahele [4]:

$$j_x(m,n) = \sqrt{3}[l \sin(\frac{2\pi lx}{\sqrt{3}a}) \cos(\frac{2\pi(m-n)y}{3a}) + m \sin(\frac{2\pi mx}{\sqrt{3}a}) \cos(\frac{2\pi(n-1)y}{3a}) + n \sin(\frac{2\pi mx}{\sqrt{3}a}) \cos(\frac{2\pi(l-m)y}{3a})] \quad (15)$$

$$j_y(m,n) = (m-n)\cos(\frac{2\pi lx}{\sqrt{3}a}) \sin(\frac{2\pi(m-n)y}{3a}) + (n-1)\cos(\frac{2\pi mx}{\sqrt{3}a}) \sin(\frac{2\pi(n-1)y}{3a}) + (l-m)\cos(\frac{2\pi nx}{\sqrt{3}a}) \sin(\frac{2\pi(l-m)y}{3a})] \quad (16)$$

l, *m* and *n* are numbers which design propagation modes. However, calculus of the two dimensional Fourier transform current components on the triangular patch were developed, the following results were deduced:

$$\begin{cases} \tilde{J}_x = I_{1x} + I_{2x} + I_{3x} \\ \tilde{J}_y = I_{1y} + I_{2y} + I_{3y} \end{cases} \quad (17)$$

With

$$\begin{cases} I_{1x} = \frac{\sqrt{3}l}{4i}(I_{11x} + I_{12x} - I_{13x} - I_{14x}) \\ I_{2x} = \frac{\sqrt{3}m}{4i}(I_{21x} + I_{22x} - I_{23x} - I_{24x}) \\ I_{3x} = \frac{\sqrt{3}n}{4i}(I_{31x} + I_{32x} - I_{33x} - I_{34x}) \end{cases} \quad (18)$$

$$\begin{cases} I_{1y} = \frac{\sqrt{3}l}{4i}(I_{11y} + I_{12y} - I_{13y} - I_{14y}) \\ I_{2y} = \frac{\sqrt{3}m}{4i}(I_{21y} + I_{22y} - I_{23y} - I_{24y}) \\ I_{3y} = \frac{\sqrt{3}n}{4i}(I_{31y} + I_{32y} - I_{33y} - I_{34y}) \end{cases} \quad (19)$$

Terms I_{vwx} *and* I_{vwy} are given as:

$$I_{vwx} = I_{vwy} = U_{vw}[\sin c(aK_y + Y_{vw}) - \frac{i\cos a(K_y + Y_{vw})}{aK_y + Y_{vw}} + \frac{i}{aK_y + Y_{vw}}]$$

$$[\sin c(\frac{\sqrt{3}}{2}aK_x + \frac{a}{2}K_y + X_{vw}) - \frac{i\cos(\frac{\sqrt{3}}{2}aK_x + \frac{a}{2}K_y + X_{vw})}{\frac{\sqrt{3}}{2}aK_x + \frac{a}{2}K_y + X_{vw}} + \frac{i}{\frac{\sqrt{3}}{2}aK_x + \frac{a}{2}K_y + X_{vw}}] \quad (20)$$

The electric field integral equation must be deduced by applying the boundary conditions requiring that the current distribution vanish on the triangular patch yields:

$$\bar{A} = \begin{bmatrix} (\bar{A}_1)_{N*N} & (\bar{A}_2)_{N*M} \\ (\bar{A}_3)_{M*N} & (\bar{A}_4)_{M*M} \end{bmatrix} \begin{bmatrix} B_1 \\ \hline B_2 \end{bmatrix} \tag{21}$$

Finally the complex resonant frequency $f = f_r + if_i$ result from the resolution of equation

$$det\,(A_{ij}) = 0 \tag{22}$$

Far-zone electric field at point $P\,(i, \theta, \varnothing)$ is given by [5]:

$$E_\theta = -j\omega\zeta_0 (F_x \cos\theta \cos\phi + F_y \cos\theta \sin\phi) \tag{23}$$

$$E_\phi = -j\omega\zeta_0 (-F_x \sin\phi + F_y \cos\phi) \tag{24}$$

where

$$\zeta_0 = 1/120\pi$$

3. Numerical Results

Although the proposed approach can give results for several resonant modes according to different parameters of the antenna, only analysis of the complex resonant frequency real part are presented in this paper for fundamental and the four first modes, focusing on the behaviour of air gap tuning versus the frequency, bandwidth and the far zone field.

In table1, air gap height is varried between 0 to 1 mm. Resonant frequencies corresponding to different gap widths for the five first modes of an adjustable equitriangular patch antenna with two layers are presented in table 1. Hence, it can be remarked that the insertion of gap has significant influence on frequency when using cavity model method or our approach. As a consequence, relatively close agreement between our results and those of C.S.Gurel [6] is achieved.

	Results of [6] using cavity model fr (GHz) for			Results using our approach fr (GHz) for :		
Mode	*dg* = 0 (mm)	*dg* = 0.5 (mm)	*dg* = 1 (mm)	dg = 0 (mm)	dg = 0.5 (mm)	dg = 1 (mm)
TM_{10}	1.278	1.436	1.509	1.3053	1.4225	1.5280
TM_{11}	2.224	2.486	2.613	2.2794	2.5147	2.6035
TM_{20}	2.556	2.871	3.018	2.6350	3.0212	3.2375
TM_{21}	3.398	3.798	3.992	3.4797	3.9936	4.2653
TM_{30}	3.834	4.307	4.526	3.9436	4.5251	4.8463

Table 1. Theoretical resonant frequencies of two layered equitriangular microstrip antenna for $\varepsilon_r = 2.32$, $a = 10$cm, $d = 0.159$cm.

In Figure 2. Three different dielectric materials were tested ($\varepsilon_r = 2.32$, $\varepsilon_r = 3$, $\varepsilon_r = 6.4$ and $\varepsilon_r = 10.5$). Our results are similar to those from reference [6] and confirm that the resonance frequency increases by enlarging the air gap.

The effect of an air gap inserted between the ground plane and an isotropic substrate with relative permittivity $\varepsilon_r = 2.32$ on radiation pattern of an equitriangular microstrip antenna with size ($d = 1.8mm$, $w = 4cm$) is illustrated in figure3. (a and b). The diagram given in dB shows a decrease of the opening radiation at - 3dB when increasing in the thickness of the air gap in the plane E. We also note that radiation pattern in E plane passes through a minimum at $\theta = 0\,°$ in contrast to the case of single-layer antenna [11], the beam width is very narrow in this direction, but s' turns out intense in the lateral direction at $\theta = -10\,°$ and $\theta = 10\,°$ and extends from -60 ° to + 60 ° at –3 dB. On the other side, H plane radiation pattern's is insensitive to variations of the gap thicknesses. It may be noted also that the maximum field is located in the plane E.

The effect of air gap on the bandwidth of an equitriangular antenna with dimensions ($d = 0.508mm$, $w = 15.5mm$) with an isotropic dielectric of permittivity $\varepsilon_r = 2.2$ is also considered and studied. The figure (4) shows a comparison between our results and the measurements made by Siddiqui and Guha [14].

From the curves, results are very similar and indicate that there is a proportional relationship between the bandwidth and air gap's thickness.

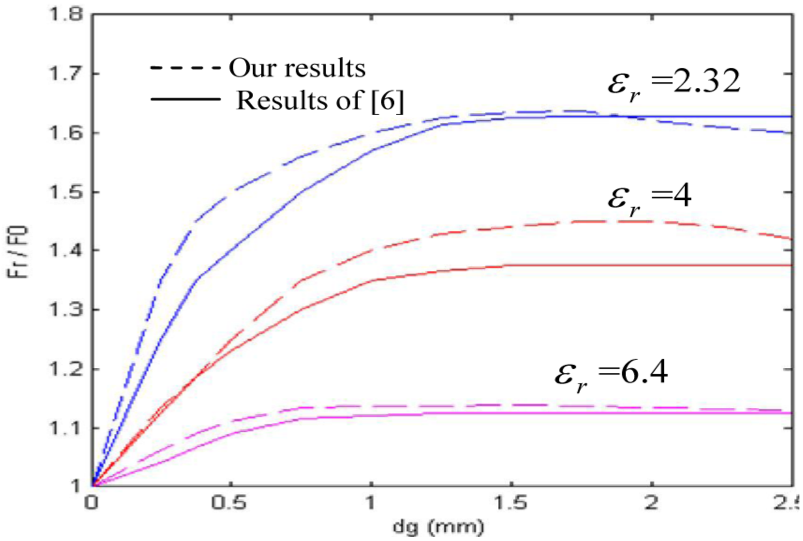
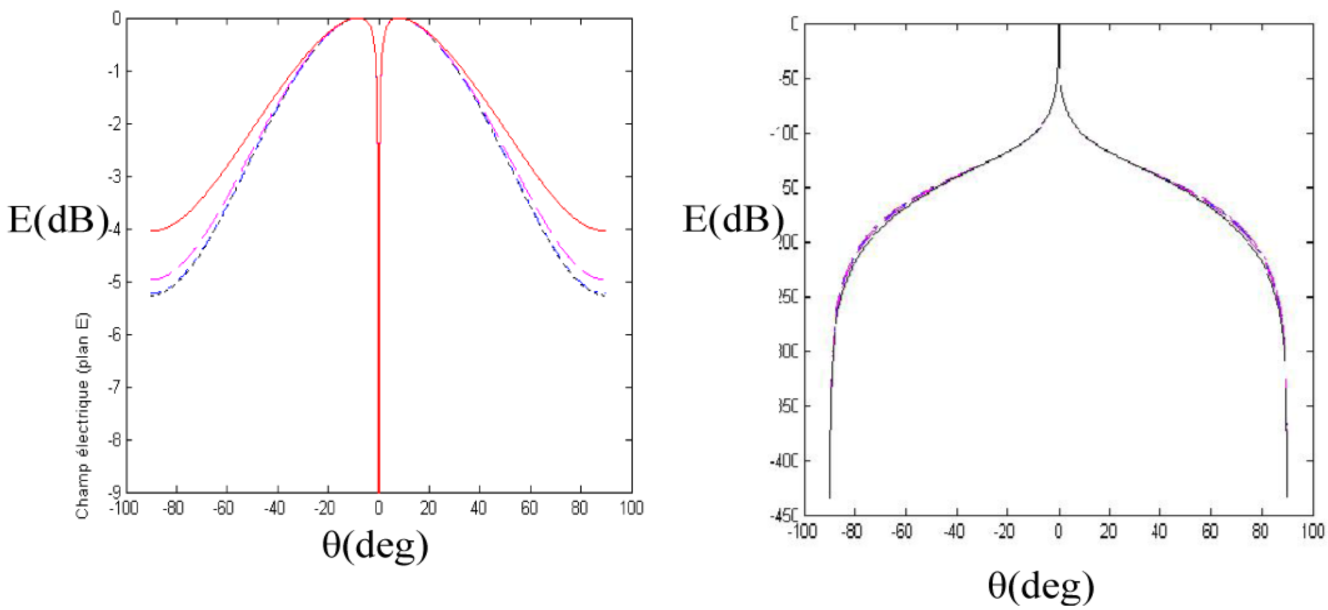


Figure 2. Resonance frequency variation versus air gap normalized thickness of an equitriangular patch antenna for TM_{10} mode, $d = 1.8mm$, $w = 4cm$.



(a) (b)

Figure 3. Radiation pattern around the resonance according to θ, of two-layer's equitriangular antenna for TM_{10} mode, ε_r = 2.32 versus air gap

dg = 0mm, dg = 0.25mm, dg = 0.5mm, dg = 1mm, (a) E plane ($\varphi = 0°$) ; (b) H plane ($\varphi = 90°$)

Conclusion

In this paper, a general and compact approach for analysing bilayered dielectric used for manufacture a tunable equitriangular microstrip antenna is presented. Spectral-domain integral equation with the Galerkin moment method solution together with the

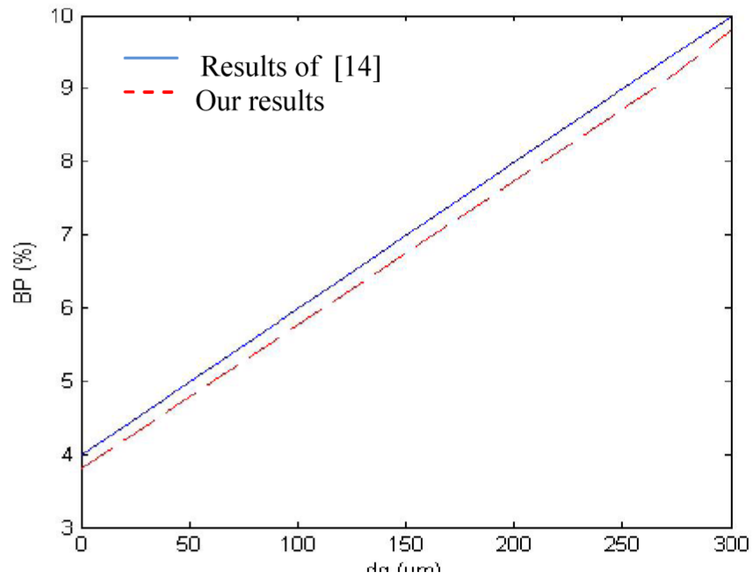


Figure 4. Variation of bandwidth depending on the air gap's thickness for the fondamental mode TM_{10} of a bilayer equitriangular microstrip antenna

reference element method have been used to solve the problem for the resonant frequency bandwidth and radiation pattern of the proposed antenna. An exact spectral domain Green's functions of the tunable equitriangular structure and moment method (MoM) were used to reduce the integral equation into a matrix equation. Fast numerical convergence was obtained using the proposed sinusoidal basis functions to expand the current on the patch. The accuracy of this method was checked by performing a set of results. Very good agreements compared with the literature, were obtained. The obtained results show that the insertion of an air gap has a significant effect on those resonant frequency, bandwidth and E-plane radiation pattern, resulting in a narrower -3dB beamwidth when the thickness of air gap increased. It is also concluded that this rigorous combined approach can be conveniently used for numerical solutions of several equitriangular patch antenna structures.

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