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ANALYSIS OF ERG MATERIAL LOADED BROAD BAND ELLIPTICAL PATCH

KANHAIYA ROY

Research Scholar, University Deptt. of Physics, L.N.M.U., Darbhanga

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Undoubtedly, Electromagnetic band gap material inspired theoretical ideas can offer new points of view in the "traditional" small antenna design. Also, many of the theoretical works are already backed up with prototypes experimentally verifying the proposed ideas. However, to push the proposed broad band antennas in commercial applications (*e.g.* in mobile phones), it is necessary to properly demonstrate the practical benefits of EBG material based antenna when compared with "traditional" reference antennas for the same application. Unfortunately, at the time being, solid comparative demonstrations can hardly be found in the literature.

INTRODUCTION

In recent years, EBG materials have attracted much attention because of their special electromagnetic properties and potential applications in microwave, infrared and optical frequencies. Because microstrip patch antennas are small lightweight, and low cost they have found widespread applications in satellite and wireless mobile communication systems [1, 2]. Conventional microstrip patch antennas can be easily miniaturized by increasing the electric permittivity (ε_r) although, in this way, the fractional bandwidth is dramatically decreased [3]. For this reason the use of EBG materials as artificial antenna substrates is studied as an alternative method to efficiently miniaturize patch antennas, according not only the electric permittivity (ε_r) but also magnctic permeability (μ_r). In addition, a compact fractional bandwidth formulation proposed in [4] is applied to compute the maximum achievable bandwidth of patch antennas for both homogeneous and dispersive EBG material substrates.

The patch antennas are widely used for their low profile and cost, combined with easy design and technology. In order to squeeze the transverse dimension of patch antenna, typically high permittivity dielectrics, such as ceramic-oxide materials [4, 5], are employed as host substrate. However, their employment raises some intrinsic problems, such as difficulty in impedance matching, or the excitation of surface waves that could lower the radiation efficiency and deteriorate the radiation pattern [5]. To date, many alternative techniques have been proposed, such as the use of magnetodielectric subtrates and metasurfaces, which have the advantage of improving the impedance bandwidth properties [6, 7]. Volakis and his group also proposed the use of textured engineered materials [8] and magnetic photonic crystals [9, 10] as another promising venue to achieve patch antenna miniaturization. With today's rapid progress in artificial surface and material technology, more degrees of freedom are available for antenna miniaturization without heavily sacrificing impedance matching, gain bandwidth, efficiency and front-to-back ratio. Of particular interest, artificially engineered EBG materials are composed of electrically small inclusions that may tailor the material's effective permittivity and permeability with positive, near zero. or negative values. Applications of double negative (DNG) or single negative (SNG) EBG materials have been extensively studied in the miniaturization of subwavelength cavities [11], waveguides, scatterers and antennas [12], in which a filling ratio factor, rather than the total volume, determines then resonance frequency. At the interface between materials with oppositely signed permittivity and/or permeability, a local compact plasmonic resonance may arise, squeezing the dimensions of resonant components, in principle arbitrarily [13].

Compared to other techniques to shrink the patch size, the advantage of the inhomogeneous metamaterial filling resides in the arbitrary choice of the resonance frequency, as long as negative effective permeability is achievable at that frequency. Although this technique indeed represents a promising solution to squeeze the resonant dimensions of patch antennas, the circular geometry presents some drawbacks, mainly represented by the limited modes of operation with significant efficiency and by the non-uniform excitation of the dominant mode around the patch, which is reflected in a lower-than-optimal value of aperture efficiency and ultimately gain.

In this paper we explore the possibility of using n elliptical EBG material patch, in order to improve the aperture efficiency and at the same-time, increase the degrees of freedom and improve the gain performance of this electrically small radiator. It is shown that indeed, more degrees of freedom will be available in the design as the eccentricity and the feed position will play a major role in the overall radiation properties. Moreover we show how, despite its sub-wavelength dimension, an elliptical resonant patch may support two orthogonal modes, of which the odd one supports a magnetic current aperture effectively larger than the one of a circular patch with same area, leading to an overall increase in gain and aperture efficiency.

THEORETICAL MODEL :

An elliptical patch antenna partially filled by a concentric elliptical EBG material core substrate, surrounded by air, with permittivity so and permeability μ_0 is shown in Fig. 1.

The antenna is loaded by a grounded in homogeneous substrate with thickness d, which is composed a regular double-positive (DPS) dielectric shell with permittivity ε_2 and permeability μ_2 and a EBG material core with permittivity $\varepsilon_1(\omega)$ and permeability $\mu_1(\omega)$ in general dispersive with frequency, which may assume negative real parts. The substrate is effectively constituted by two confocal elliptical cylinders. The semi-major and semi-minor axes of the EBG material core are denoted by *al* and *bi* respectively, and a_2 and b_2 define the surrounding DPS shell whose outer boundary coincides with the patch perimeter.

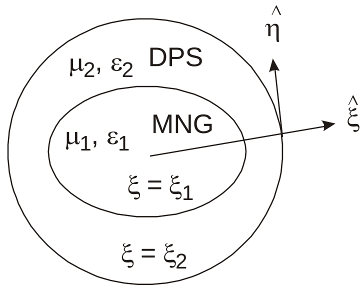

Fig. 1 : Concentric elliptical EBG material

The geometry is embedded in a suitable elliptical reference system, with coordinates ξ and η, related to the Cartesian coordinates by:

$$x = F \cos h\, \xi \cos \eta$$

$$y = F \sin h\, \xi \sin \eta \qquad ...(1)$$

where the semi-focal length. It follows that the eccentricity e of the metallic patch: $e = [1 - (b_2/a_2)^2]^{1/2} = 1/\cosh \xi_2$ $(0 \le e < 1)$. When e approaches zero, the limit of a circular patch is obtained. Whereas when e approaches unity, a very narrow and thin elliptical shape is obtained. We also define a filling ratio $\Gamma = [(\cos h\, \xi_1 \sin h\, \xi_1)/(\cos h\, \xi_2 \sin h\, \xi_2)]$ as the volume of the EBG material core divided by the overall volume underneath the patch $(0 < \Gamma < 1)$.

Assuming that the thickness of the dielectric substrate is much smaller than the wavelength, a standard cavity model [14, 15] applied to approximately calculate the patch resonant frequencies, closing the metallic patch with a magnetic wall at $\xi = \xi_2$. It is clear that this approximation neglects the radiation loss at the edges of the patch, which effectively produce the antenna radiation, but this model may all approximate the relevant resonant features of the structure. In such cavity, Maxwell's equations reduce to the allowing set of equations in elliptical coordinates:

$$\frac{1}{F^2(\cosh^2 \xi - \cos^2 \eta)}\left(\frac{\partial^2 E_z}{\partial \xi^2} + \frac{\partial^2 E_z}{\partial \eta^2}\right) + k^2 E_z = 0$$

$$H_z = j\frac{1}{\omega\mu F(\cosh^2 \xi - \cos^2 \eta)^{1/2}}\frac{\partial E_z}{\partial \eta}$$

$$H_\eta = -j\frac{1}{\omega\mu F(\cosh^2 \xi - \cos^2 \eta)^{1/2}}\frac{\partial E_z}{\partial \eta}$$

$$H_z = 0 \qquad E_\xi = 0 \qquad E_\eta = 0 \qquad ...(2)$$

The corresponding elliptical wave equation solution is available in various books [16] and the field distribution in the two regions of the cavity may be expanded in terms of elliptical wave functions as:

$$E_z^{(MNG)} = \sum_{n=0}^{n=\infty} c_{en}^1 M_{en}^{(1)}(q_1,\xi)\, G_{en}(q_1,\eta) + \sum_{n=1}^{n=\infty} c_{en}^1\, M_{en}^{(1)}(q_1,\xi)\, S_{en}(q_1,\eta)$$

$$E_z^{(DPS)} = \sum_{n=0}^{n=\infty}\left[c_{en}^1 M_{en}^{(1)}(q_2,\xi) + c_{en}^2 M_{en}^{(2)}(q_2,\xi)\right]\times G_{en}(q_2,\eta)$$

$$+\sum_{n=1}^{n=\infty}\left[c_{en}^1 M_{en}^{(1)}(q_2,\xi) + c_{en}^3 M_{en}^{(2)}(q_2,\xi)\right]\times S_{en}(q_2,\eta) \qquad ...(3)$$

where q_i = $(k_iF/2)^2$ is the radial wave number, k_i = $\omega\sqrt{\varepsilon_i\mu_i}\,, M_{en}^{(i)}$ and $M_{en}^{(i)}$ are the even and odd radial Mathieu function of the with kind, respectively [17], and n is the order of the angular Mathieu functions C_{en} (q_2, η) (even) and S_{en} (q_2, η) (odd), which determine the azimuthal variation along η [17].

In the most general dynamic case there is no closed-form dispersion relation for the modes supported by this cavity in the case of inhomogeneous filling ($\xi_1 < \xi_2$), since the angular Mathieu functions are not orthogonal for different values of q_1 # q_2. This implies that the boundary conditions at the interface $\xi = \xi_1$ may be matched only by the entire summations in [3] in the general case, making the analytical solution difficulty obtainable. The only possibility that the angular field variations may match separately at this interface for each angular order n is that the two filling materials are iso-refractive, *i.e.*, $k_1 = k_2$. However, since we are interested here in squeezing the resonant dimensions of the Cavity, we can safely assume that in such sub-wavelength scenario the two materials have indeed similar angular wave numbers $q_1 \sim q_2$? 1, even when $k_1 \neq k_2$, since F is very small. In this case, the problem is equivalent to the one of an; elliptical cavity filled by isorefractive materials, for which the dispersion relation may be expressed, after some algebra, in terms of the n-th order radial Mathieu functions [18-19]. For the n-th order even and odd mode the dispersion relation reads in this case. Assuming that the dielectric shell and the FRG material case are sub-wavelength.

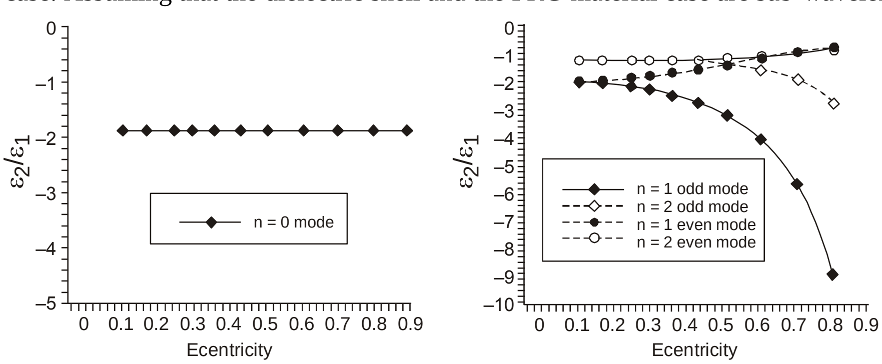

Fig. : 2(a) and (b) dependencies of $\varepsilon_1/\varepsilon_2$ and μ_1/μ_2 on the eccentricity of elliptical patch

In the case of a subwavelength rectangular patch, we have shown [19] how the azimuthally-symmetric mode is not expected to radiate efficiently, since the opposite sides of the patch radiate with opposite phases, canceling out by interference most of the radiated energy when their distance is small. Only the since variation in the circular patch was proven to efficiently radiate in the extreme subwavelength limit [14]. Similarly, it is relevant to study in the elliptical cavity model the radiation properties for the different supported modes, in order to deduce which modes may efficiently radiate for electrically small size.

In Fig. 3 the corresponding E_z distributions along the edge of the elliptical patch as a function of η, normalizes to the same maximum value of H_n, which implies same amplitude of the feeding current underneath the patch in a realistic scenario.

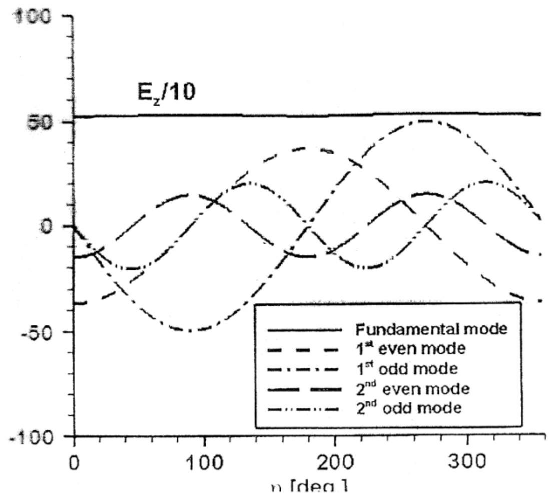

Fig. 3 : E_z Distributions along the edge of the elliptical patch

It is clear that the electric field variation for n = 0 is almost uniform, and its phase is constant passing from one side to the other of the patch. For the n=1 even and odd modes, however, the electric field flips sign, respectively at

$$\eta = 0 \text{ and } \eta = \pi \text{ and at } \eta = \eta/2 \text{ and } \eta = 3\pi/2.$$

These are the radiating areas of the patch, over which the effective magnetic currents K= $K=\hat{n}\times E\,|_{\xi=\xi_2}$ indeed radiate in phase, implying good radiation efficiency, even for extreme sub-wavelength size of the patch. For n=2 and higher-order modes, however, opposite sides of the patch have in-phase tangential electric field with weaker amplitudes, implying much poorer radiation performance. As a result, analogous to the circular patch, the EBG material sub-wavelength elliptical patch should be operated at the n = 1 resonance, in either the odd or even mode of operation. In particular, as highlighted above, the electric field amplitude for the odd mode is stronger, and due to the coarser distribution of the n coordinate along the active region of the perimeter for the odd mode, it ensures much larger aperture efficiency.

This is consistent with the electric field and tangential magnetic field distribution in Figs. 3 and 4 and the above discussion. For any $n \neq 1$, similar to the circular geometry [14], very poor radiation efficiency is achieved, even though the associated sub-wavelength resonance may be well supported by a properly loaded patch.

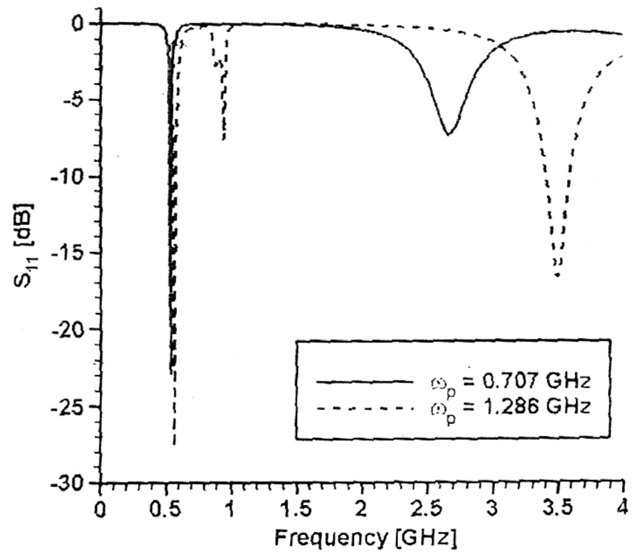

Fig. : 4 Electric field and tangential magnetic field distribution

EBG MATERIAL LOSS ANALYSIS

It is seen that the model assumed in our full-wave simulations is limited by the assumption of a homogeneous electromagnetic bandgap material substrate and of small absorption. On the other hand, the relatively novel field of EBG material antennas has often struggled for the presence of a significant often not expected from simulations, level of loss in the experimental realization of EBG materials sample, which has in practice limited the use of EBG material in antenna applications.

Although a recipe for evaluating the expected total level of loss in the EBG material substrate practical realization is not readily available, to complete this discussion on the antenna feasibility, we analyze in the following the influence of EBG material loss on its overall performance, by varying the damping coefficient ω_r, of the Drude magnetic material load. In particular, we vary ω_r, in the design of Fig. 4 from a very small value (10^{-6} MHz) to a huge value (1 GHz). Correspondingly, the imaginary part of magnetic permeability increases from 10^{-6} to 1.92. It is reasonable to expect that any practical realization of the EBG material core would have an effective magnetic permeability lying in this range.

It is seen that, as expected higher loss implies a larger bandwidth and lower Q-factor of the antenna resonance, which is still present even for large loss tangents. The corresponding far-field pattern, although unchanged in shape, is affected in terms of total radiated power.

The Fig. 5 reports the maximum of far field electric distribution versus frequency with damping coefficient of Drude magnetic material of ω_e = 500 MHz (dash – dot line), and ω_r = 1000 MHz (dash-dot-dot line).

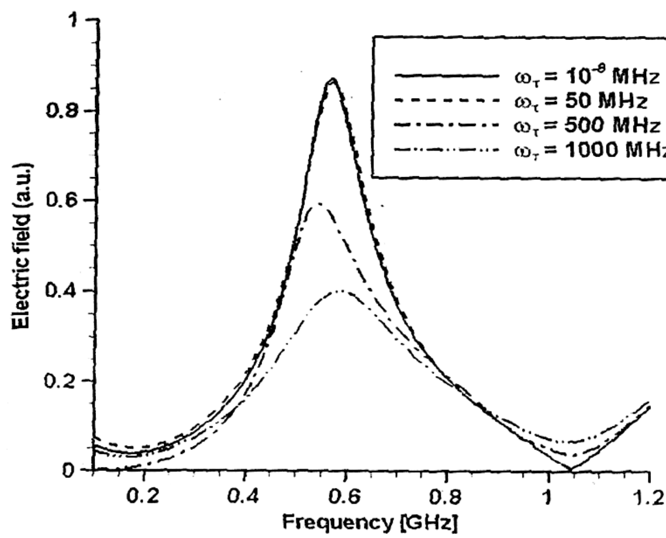

Fig. 5 : Maximum of far field electric distribution versus frequency

This shows that for higher losses the magnitude of the maximum electric field is indeed sensibly deteriorated. Still, a clear resonance and relatively strong peak may be obtained for moderately large losses, consistent with practical realizations of magnetic EBG materials at radio-frequencies.

CONCLUSION :

A theoretical and numerical analysis of elliptical patch antennas partially loaded with magnetic EBG material have been studied in this chapter. Firstly it has been formulated a general theory for inhomogeneously loaded sub wavelength elliptical patch antennas, deriving a closed form solutions for the modes supported by this geometry in the long wavelength unit. The elliptical patch provides a better aperture efficiency and gain and possibility to further reduce the physical patch area without reducing the radiated power. The fundamental advantages have been firstly analytically derived using a cavity model and then validated and confirmed numerically with full wave simulation, including the presence of a realistic feed, finite size of the ground plane, dispersion and loss of the involved EBG materials.

REFERENCES

1. R. Garg, *et al, Microstrip Antenna Design Handbook*. Norwood, M.A: Artech House (1995).
2. 2.J.R. James, *et al., Microstrip Antenna Theory and Design London*, U.K: Peter Peregrinus (1981).
3. C.A. Balanis, *Antenna Theory: Analysis and design*, 2nd ed, New York: Wiley (1997).
4. A.D. Yaghjian, S.R. Best, "Impedance, band width, and a for antennas," IEEE Trans Antennas Propag., vol. **53**, no. 4, p 1298-1324, April (2005).
5. J.S Colborn and Y. Rahmat-samii, "Patch antennas on externally performed light dielectric constant substrates", *IEEE Trans. Antennas Propag*., Vol. **47**, no. 12, pp 17851794 (1999).

6. P.M.T. Jkonen, *et al*, "On rotificial magnetodielectric loading for improving the impendence bandwidth properties of microstrip antennas," *IEEE Trans Antennas Propag*., vol **54**, pp 1654-1662 (2006).
7. H. Mosallai and K. Sarobandi, "Antenna miniaturization and bandwidth enhancement using a reactive impendence substrate," *IEEE Trans. Antennas Propag*, vol **52**, no. 9, pp 1558- 1567 (2004).
8. D. Psychoudakis, et al., Design method for aperture coupled micropstrip patch antennas on textured dielectric-substrates," *IEEE Trans Antennas Propag*, vol. **52**. no 10, pp. 2763-2766 (2004).
9. J.L. Volokis, *et al.*, "Miniaturization methods for narrowband and ultra-wideband antennas," in Proc. *IEEE Int Horbshop on Antennas Technology*: Small Antennas & Novel Metomatuiab, pp 119-121 (2005).
10. G. Mumcu, *et al.*, "Superctriective miniature antennas embedded with magnetic photonic crystals," presented at the *JEEE APS USNC/URSI Int Symp, Washington, DC* (2005).
11. N. Engheto, "An Idea for thin sub-wavelength cavity resonator using metamaterials with negative permittivity and permeability, *JEEE Antennas Wireless Propag*. Left, vol. No. 1, pp. (2002).
12. A. Alu, *et al.*, "Sub-wavelength planar leaky wave components with metamaterial bilayers," *IEEE Trans Antennas Propag*. Vol **55**, no. 3, pt. 2. pp. 882–891 (2007).
13. A. Alu and N Enghta, "Poiring an apsilon- negative slab with a negative slab: Ananalous tunneling and transparency." *IEEE Trans Antennas Propag, special issue on metamaterials*, vol **51** no 10, pp 2558-2570 (2003).
14. K.R. Carrer and J.W. Mink, "Microstrip antenna technology." *JEEE Trans. Antennas Propag,* Vol Ap. 23, no. 1, pp. 2-24 (1981).
15. W.F. Richard, *et al.*, "An improved theory of microstrip antennas with applications" *IEEE Trans Antennas Propag.* Vol. Ap. 29, no. 1, pp 34-46 (1981).
16. P. Moon and D.E. Spencer, Field Theory hand book Berlin: *Springer Verlag editions* (1963).
17. Chapter 23, matches functions, "*In handbook of mathematical functions with formulas graphs, and mathematical Tables* M. Abramowitz and DA Stegun, Eds New York: Dover, PP 358-364, 9th printing (1972).
18. L.J. Chu, "Physical Limitations of Omnidirectional antennas," *J. Appl. Phys,* vol. **19**, pp. 583-591 (1938).
19. A. Alu, F Bilotti, *et al.*, "Sub-wavelength, compact, resonant patch antennas loaded with matamaterials," *IEEE Trans. Antennas Propag*, vol. **55**, no. 1, pp 13-25 (2007).

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