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The Marvels of Electromagnetic Band Gap (EBG) Structures

Y. Rahmat-Samii
Electrical Engineering Department
University of California at Los Angeles
Los Angeles, CA, 90095-1594, U. S. A.
rahmat@ee.ucla.edu

1. INTRODUCTION

Artists and scientists alike have been fascinated by the existence of periodic structures in nature. When these structures interact with electromagnetic waves many unique features result. Observables are characteristics such as frequency stop-bands, pass-bands, and band-gaps. Various terminology have been used to classify these structures depending on the domain of the applications in filter designs, gratings, frequency selective surfaces (FSS), photonic crystals and band-gaps (PBG), etc. We prefer to classify them under the broad terminology of "Electromagnetic Band-gaps (EBG)". Recently, many researchers have adopted this terminology. Broadly speaking, EBG structures are 3-D periodic objects that prevent the propagation of the electromagnetic waves in a specified band of frequency for ***all*** angles of arrival and for ***all*** polarization states of electromagnetic waves. In practice, however, it is very difficult to obtain such complete band-gap structures and partial band-gaps are achieved. Filters typically cover the scalar situation and single angle of arrival. FSS typically cover limited angles of arrival and respond differently to polarization states. PBG typically cover in-plane angles of arrival and also sensitive to polarization states. Surveying the literature, one finds that FSS terminology has been widely used in the microwave community while PBG terminology has been widely applied in the optical community.

This overview paper presents a powerful computational engine utilizing Finite Difference Time Domain (FDTD) technique integrated with novel extrapolating algorithms to illustrate the marvels of EBG structures. The paper addresses structures such as (a) FSS structures, (b) PBG crystals, (c) smart surfaces for communication antenna applications, (d) surfaces with perfectly magnetic conducting properties (PMC), (e) creation of materials with negative permittivity and negative permeability, (f) surfaces with reduced edge diffraction effects and (g) reduction of mutual coupling among array antenna elements. Some representative applications of these structures are highlighted. In the last several years, there have been numerous published conference papers and journal articles dealing with the characterizations and applications of EBG structures. This paper is based on some of the results published by the author and his co-workers in the cited references. The reader is encouraged to perform detailed literature search to learn more about this area.

2. UCLA-FDTD CHARACTERIZATION OF EBG STRUCTURES

To perform an in-depth assessment of the performance characteristics of the complex EBG structures the FDTD technique with Periodic Boundary Condition/Perfectly Matched Layer (PBC/PML) is developed by modifying previously developed and well tested FDTD code without periodic boundary conditions, Jensen and Rahmat-Samii [1]. The split-field approach detailed in the book by Taflove [2], is incorporated to discretize the Floquet transformed Maxwell's equations, Mosallaei and Rahmat-

Samii [3]. The broadband analysis capabilities of the FDTD technique provide great computational efficiency and accuracy when one requires determining the frequency response of complex structures. Extrapolation schemes such as Prony method (Mosallaei and Rahmat-Samii [4]) and Auto Regressive Moving Average (ARMA) method (Yang and Rahmat-Samii [5]) are also incorporated to increase the efficiency of the computational technique. The key components of this powerful computational engine are briefed in Fig. 1.

The developed FDTD/Prony/ARMA technique has been effectively applied to the characterization of a variety of complex periodic EBG structures illustrated in Fig. 2. Representative examples are discussed to highlight unique features of the results and application areas.

2. ULTRA BROADBAND MULTI-LAYERED TRIPOD FSS

This section focuses on the performance evaluation of the electromagnetic band-gap multi-layered tripod FSS (Barlevy and Rahmat-Samii [6]) with ultra wideband characteristics. Fig. 3(a) shows the geometry of a single layer tripod FSS. The FDTD/Prony technique is applied to analyze the structure, and the results for the normal incidence (E_z) reflected power is presented in Fig. 3(b). This structure exhibits resonance behavior around $f_0 = 145\,GHz$.

The resonance and bandwidth frequency of this structure can be controlled using a 2-layer tripod FSS, as depicted in Fig. 4(a). The second layer is rotated 180° with respect to the first layer, and is shifted along the z-axis in such a way that all three legs of each tripod overlap a leg of a tripod in the first layer. The overlap region creates a capacitor, which is used to tune the frequency for 100% reflection. The reflected power of the normal incident plane wave is presented in Fig. 4(b) showing that for the 2-layer tripod the resonance frequency is shifted down.

To further broaden the 100% reflection bandwidth, a 4-layer tripod FSS is introduced in Fig. 5(a). This is a rather complex structure composed of two sets of the FSS shown in Fig. 4(a). The geometry allows two degrees of freedom, d and D. The capacitance governed by the small distance d controls the lower edge of the rejection band, where the large inter-capacitor spacing D controls the upper edge of the band. The reflected power for both the normal and 30° oblique incidence ($\theta^i = 90^\circ, \phi^i = 150^\circ$) for TE ($E_z$) and TM ($H_z$) polarization cases are presented in Fig. 5(b). One notices that by increasing the bandwidth of the 100% reflection, an EBG structure utilizing the multiple coupled tripod arrays is designed. For the angles near to the grazing, the TM waves are almost normal to surface of tripods and the FSS cannot reject them. Incorporating interconnecting vias between tripods helps to reject the normal components. This design approaches a complete band-gap structure as demonstrated by Barlevy and Rahmat-Samii [6].

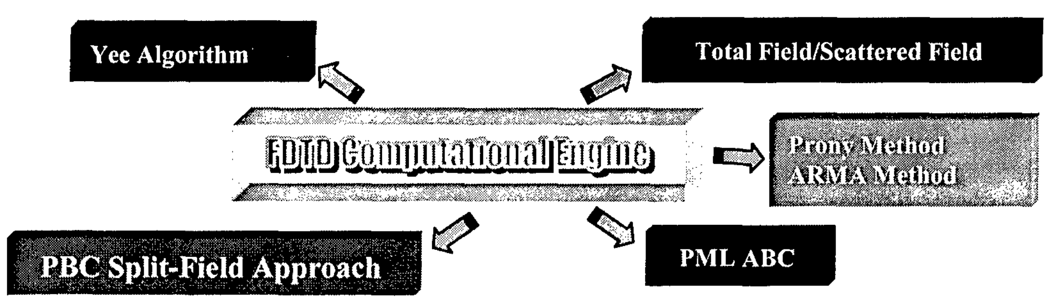


Fig. 1: Schematic of the UCLA-FDTD/Prony/ARMA computational technique.

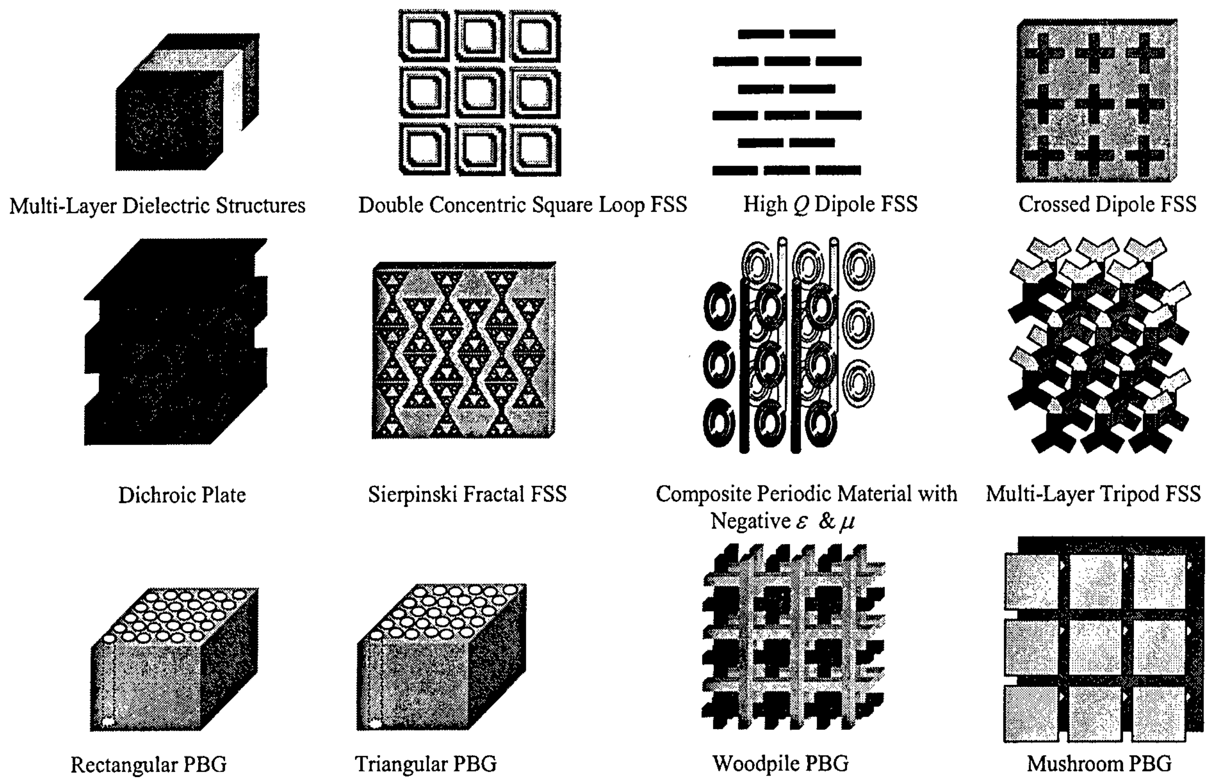


Fig. 2: Different classes of complex EBG structures characterized by the FDTD/Prony/ARMA technique.

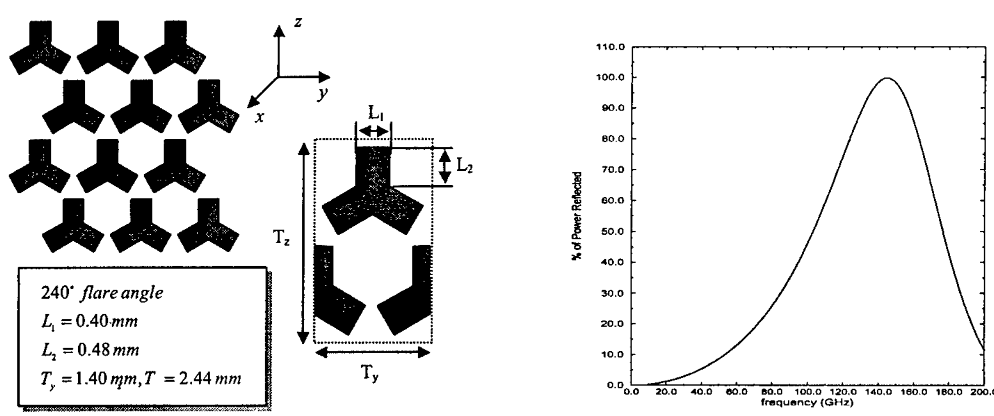


Fig. 3: 1-Layer tripod FSS, (a) Periodic structure, (b) Normal incident reflected power.

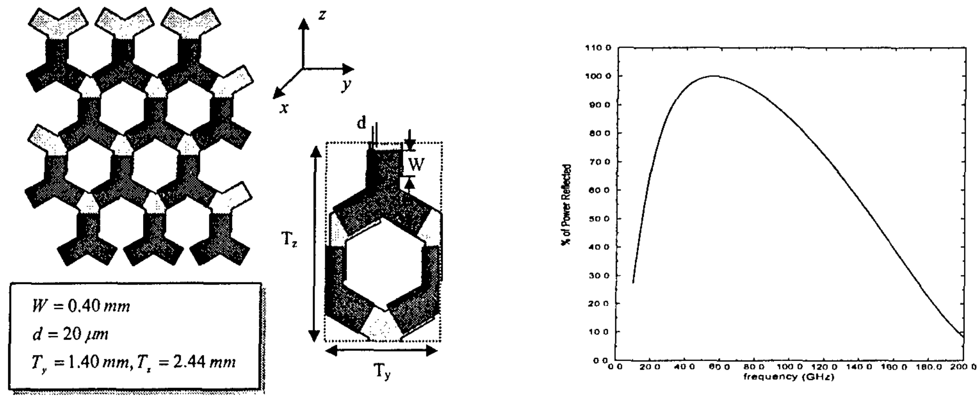


Fig. 4: 2-Layer tripod FSS, (a) Periodic structure, (b) Normal incident reflected power.

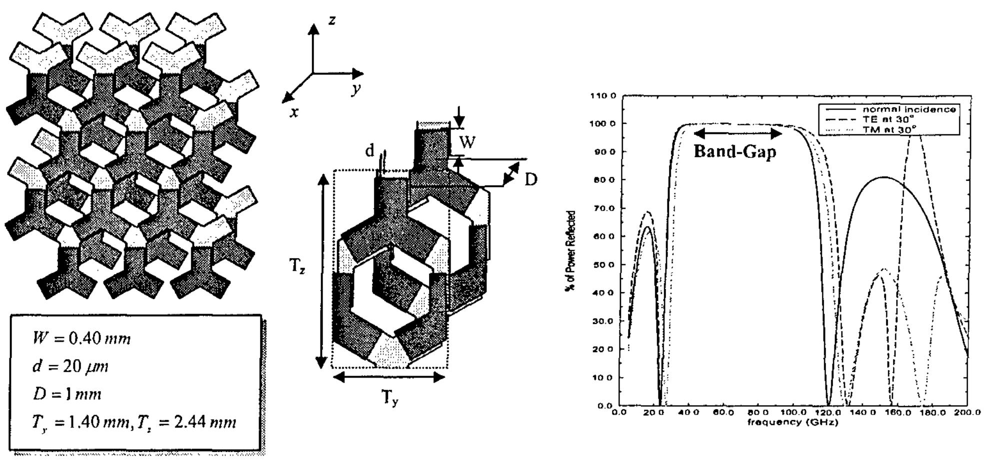


Fig.5: 4-Layer tripod FSS, (a) Periodic structure, (b) Normal and oblique (TE/TM) incidence reflected power.

3. PBG CRYSTALS FOR OPTICAL APPLICATIONS

This section addresses utilization of EBG structures in optical regime and classifies them as the photonic band-gap (PBG) crystals (Coccioli et al. [7]). The UCLA-FDTD technique is applied to obtain the reflection coefficient of the plane wave incident on various PBG structures. The plane wave approach has some distinct advantageous compared to the dispersion diagram method as listed below:

- Presenting phase and polarization information of the scattered fields,
- Obtaining reflection and transmission coefficients outside the band-gap regime,
- Ease of implementation.

For a 5-layer 2-D rectangular PBG structure of air holes in the dielectric material and for both normal and oblique incidence plane waves, Fig. 6 shows the reflection coefficients. There is a complete band-gap region for the *z*-polarized (TE) waves for the normalized frequencies $0.21 \le a/\lambda_0 \le 0.28$. The region of the band-gap frequency band has an excellent agreement with the data presented in

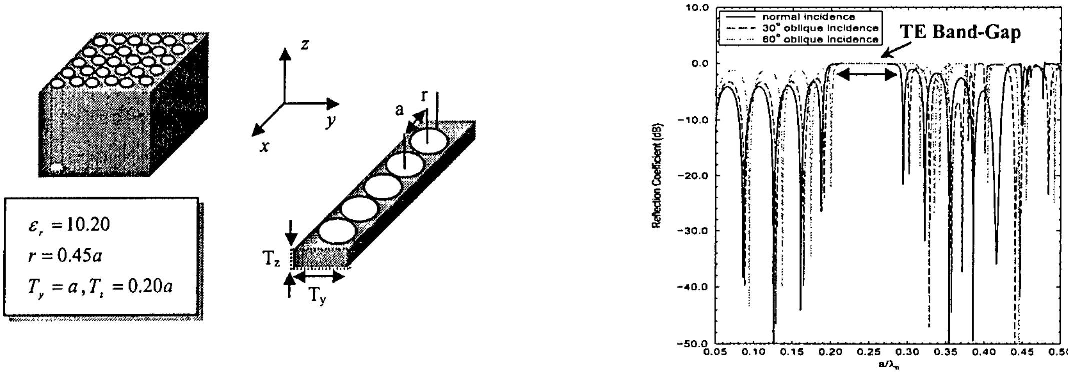


Fig.6: 5-Layer rectangular PBG, (a) Periodic structure, (b) Normal and oblique incidence reflection coefficient.

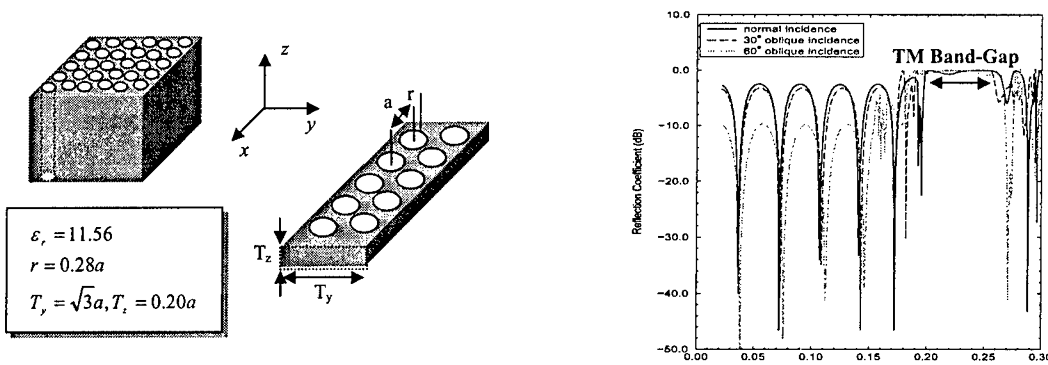


Fig.7: 5-Layer triangular PBG, (a) Periodic structure, (b) Normal and oblique incidence reflection coefficient.

Joannopoulos et al [8] based on the dispersion diagram. The PBG structure can be also created to generate a TM band-gap region using a triangular array of holes (5-layer) in the dielectric material, as shown in Fig. 7. The electric field is polarized in the plane normal to the axis of holes. One observes that there is a TM band-gap region in the normalized frequency range $0.20 \le a/\lambda_0 \le 0.25$. Ho et al [9] proposed a novel PBG structure that has the potential of generating a complete band-gap region for all angles of incidence and for all polarizations (an ideal EBG structure). The geometry of a 2-layer woodpile PBG is depicted in Fig. 8(a). The symmetric arrangement of the structure forbids propagation in almost all the wave vector directions. Fig. 8(b) presents the reflection coefficient for the normal, 30° oblique/TE, and arbitrary incident wave $\theta^i = 40^\circ, \phi^i = 150^\circ$ with 45° polarization angle (between the electric field and reference direction $\hat{\mathbf{k}}^i \times \hat{\mathbf{z}}$). As observed, the structure is able to generate an almost complete band-gap region. The reflected phase on the surface of the structure for 30° oblique wave in obtained in Fig. 8(c). It is interesting to note that within the band gap region the phase has an almost linear frequency variation. This means that the woodpile can be represented as a Perfect Electric Conductor (PEC) where the location of the PEC is variable instead to be fix at the front surface of PBG.

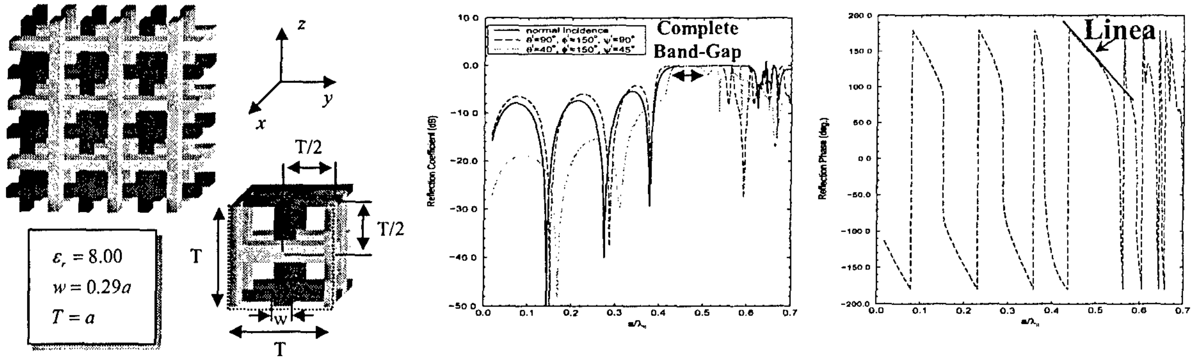


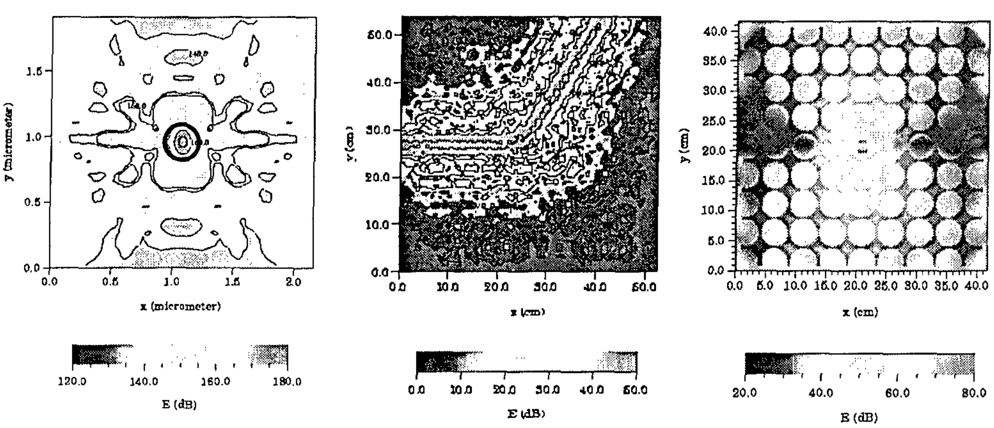
Fig.8: 2-Layer woodpile PBG, (a) Periodic structure, (b) Normal and oblique incidence reflection coefficient, (c) Reflection phase for the 30° /TE incidence wave.

4. VARIOUS APPLICATIONS OF EBG

One may wonder how some of those novel characteristics of EBG structures can be used in engineering designs. This section discusses utilization of the EBG structures into some potential applications such as nanocavities, waveguides, and patch antennas, as shown in Fig. 9. Some practical antenna examples using EBG structures have also been fabricated and tested.

4.1 High Q nanocavities. To create a high Q cavity for distributed laser applications a finite thickness 2-D PBG structure is used to localize the electromagnetic waves inside a defect region in three directions. The confinement is based on the PBG gap/total internal reflections properties of the structure. The defect-excited mode (inside the gap region) becomes localized in the transverse plane utilizing the PBG crystal. In the vertical direction, the dielectric contrast between the impurity and outside air region produces the total internal reflections trapping the waves in this direction (Coccioli et al. [7]).

4.2 Guiding the light in sharp bends. Another useful application of the PBG is for guiding the light in sharp bends. This is achieved by an array of the PBG holes removed in the guiding direction as shown in Fig. 9(b). In the frequency range within the gap-region, light is confined through the channel, and cannot be scattered through the PBG. This is even the case at tight corners. It has been shown that by appropriate shaping of the bend one can reduce scattering of



(a) (b) (c)

Fig.9: Potential applications of the PBG structures in (a) High Q nanocavities, (b) Guiding the EM waves in sharp bends, and (c) Miniaturized microstrip patch antennas.

the light waves at sharp corners.

4.3 Miniaturized microstrip patch antennas. Miniaturized patch antennas can be constructed using the EBG as the substrate surrounding the patch as shown in Fig. 9(c). This results into suppression of the surface waves. Although, in general, this EBG structure *cannot* generate a complete surface wave band-gap, it still has the capability of suppressing surface waves, and improving the radiation performance of the patch antenna (Colburn and Rahmat-Samii [10]).

4.4 Low profile CP curl antenna design. The curl antenna was originally proposed as a simple radiator to generate circular polarized electromagnetic waves. This antenna concept does not function efficiently when it is placed close to a finite PEC ground plane due to the reverse image. Therefore, the mushroom EBG surface, which shows an in-phase reflection feature inside its band gap, provides a good alternate to the PEC ground plane to build a low profile structure as well as the circular polarization (Yang and Rahmat-Samii [11]).

Fig. 10(a) shows a photo of a curl antenna designed by the UCLA-FDTD computational tools. The height of the antenna is only 3 mm, which is about 0.07 λ at 7 GHz. Compared to a curl on the PEC ground plane, the curl on the EBG ground plane has a much better input match as shown in Fig. 10(b). The axial ratio of the antenna is also measured and plotted in Fig. 10(c). A good axial ratio of 0.9 dB is achieved at 7.18 GHz.

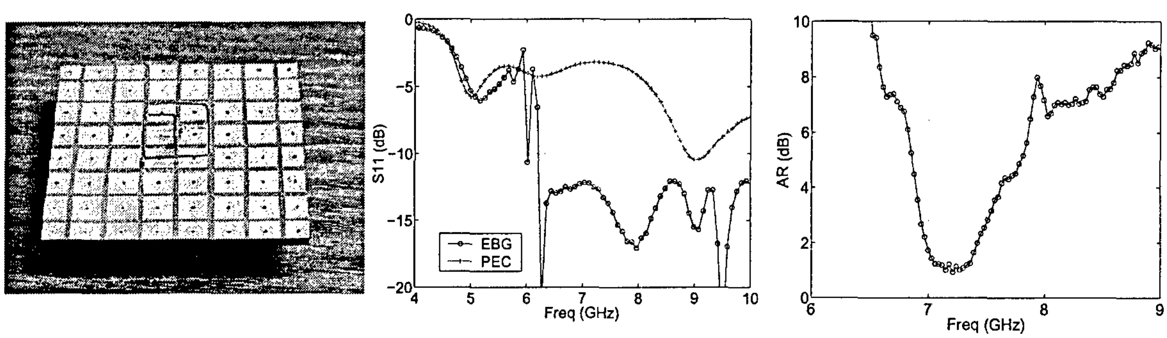
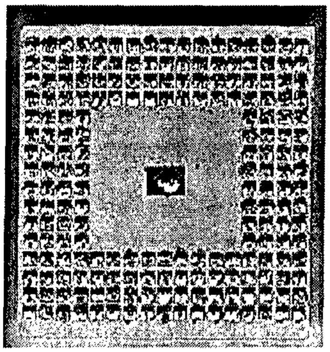


Fig. 10: A low profile circularly polarized curl antenna on a finite mushroom EBG surface: (a) a photo of the design, (b) return loss of the curl on the EBG compared to that of a curl on a PEC surface, and (c) axial ratio (AR) of the curl antenna.

4.5 Microstrip antenna element within an EBG for enhanced performance. Applications of microstrip antennas on high dielectric constant substrates are of growing interest due to their compact size and conformability with monolithic microwave integrated circuit (MMIC). However, there are some drawbacks with the utilization of high dielectric constant substrates such as a narrow bandwidth and pronounced surface waves. The bandwidth can be recovered using a thick substrate; however, this excites severe surface waves, which will decrease the antenna efficiency, degrade the antenna pattern and increase the mutual coupling. Because the mushroom EBG structure exhibits a surface-wave suppression feature, it is applied to the patch antenna and array to improve their performance.

Fig. 11(a) shows a photo of a microstrip antenna surrounded by four rows of EBG patches and Fig. 11(b) presents the E plane radiation pattern of the antenna compared to other conventional microstrip antenna designs (Yang and Rahmat-Samii [12]). It is observed that the radiation



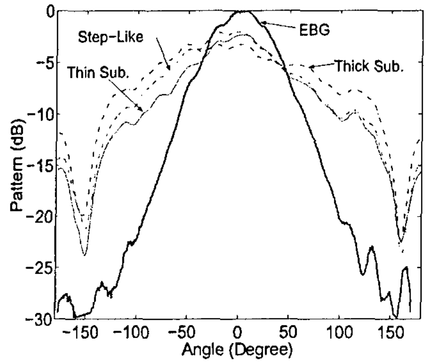
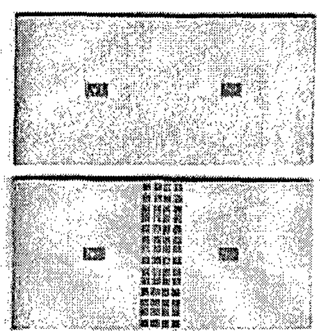


Fig. 11: Enhanced performance microstrip antenna with EBG around: (a) a photo of the design and (b) measured radiation patterns of various microstrip antenna designs. It is noticed that the microstrip antenna with EBG around has the highest gain and lowest back lobe.

performance of the antenna with EBG around is the best: its front radiation is the highest that is about 3 dB higher than the thick case while its back lobe is the lowest which is more than 15 dB lower than other cases.

4.6 Microstrip antenna array with EBG in between for reduced mutual coupling. Above experiments have demonstrated that the EBG structure can suppress surface waves successfully so that the performance of an antenna element is significantly improved. This approach has also been extended to array applications (Yang and Rahmat-Samii [13]). Two pairs of microstrip antenna arrays were fabricated on Roger RT/Duroid 6010 substrates. Fig. 12(a) shows a photograph of the fabricated antenna arrays with and without EBG in between. The antenna size and EBG parameters are carefully designed by the UCLA-FDTD tools. The measured results are plotted in Fig. 12(b). It is noticed that both antennas resonate at 5.86 GHz with impedance matches better than -10 dB. For the antennas without the EBG structure, the mutual coupling at 5.86 GHz is -16.8 dB. As a comparison, the mutual coupling of the antennas with the EBG in between is only -24.6 dB. About 8 dB reduction of mutual coupling is achieved at the resonant frequency. From this experimental demonstration, it can be concluded that the EBG structure can be



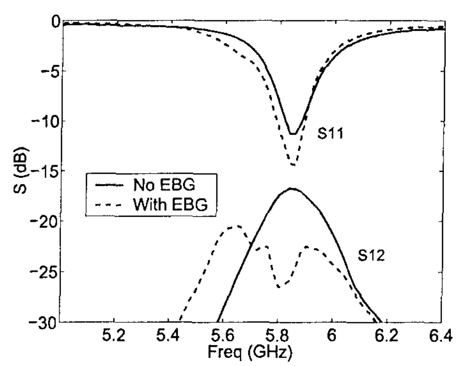


Fig. 12: Microstrip antenna array with reduced mutual coupling: (a) photos of microstrip antenna arrays with and without EBG in between and (b) measured return loss and mutual coupling results of the arrays. It is observed that the mutual coupling is greatly reduced when the EBG is inserted between patch elements.

utilized to reduce the mutual coupling between elements of antenna arrays.

5. CONCLUSIONS

This invited plenary session paper provides an overview of research activities at author's laboratory at UCLA in the area of EBG structures. As such, it is based on some of the results published by the author and his co-workers in the cited references. Computational tools of FDTD/Prony/AMRA are discussed. Ample representative examples are provided to highlight the marvels of EBG structures for both microwave and optical applications. Characterizations of EBG structures and related meta-materials are interesting research frontiers with potential electromagnetic engineering system applications.

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Yahya Rahmat-Samii is a Professor and the Chairman of the Electrical Engineering Department at the University of California, Los Angeles (UCLA). He was a Senior Research Scientist at NASA's Jet Propulsion Laboratory, California Institute of Technology before joining UCLA in 1989. He was a Guest Professor at the Technical University of Denmark (TUD) in the summer of 1986. He has also been a consultant to many aerospace companies. He received the M.S. and Ph.D. degrees in Electrical Engineering from the University of Illinois, Urbana-Champaign.

Dr. Rahmat-Samii was the elected 1995 President and 1994 Vice-President of IEEE Antennas and Propagation Society. He was appointed an IEEE Antennas and Propagation Society Distinguished Lecturer and presented lectures internationally. Dr. Rahmat-Samii was elected as a Fellow of IEEE in 1985, and a Fellow of IAE in 1986. He was also a member of the Strategic Planning and Review Committee (SPARC) of IEEE. He was the IEEE AP-S Los Angeles Chapter Chairman (1987-1989) and his chapter won the best chapter awards in two consecutive years. He has been the plenary and millennium session speaker at many national and international symposia. He was one of the directors and Vice President of the Antennas Measurement Techniques Association (AMTA) for three years. He has been editor and guest editor of many technical journals and book publication entities. He has also served as Chairman and Co-Chairman of several national and international symposia. Dr. Rahmat-Samii was also a member of UCLA's Graduate council for a period of three years.

Prof. Rahmat-Samii has authored and co-authored over 500 technical journal articles and conference papers and has written seventeen book chapters. He is the co-author of two books entitled, *Electromagnetic Optimization by Genetic Algorithms, and Impedance Boundary Conditions in Electromagnetics* published in 1999 and 1995, respectively. He is also the holder of several patents. He has had pioneering research contributions in diverse areas of electromagnetics, antennas, measurement and diagnostics techniques, numerical and asymptotic methods, satellite and personal communications, human/antenna interactions, frequency selective surfaces, electromagnetic band gap structures and the applications of the genetic algorithms, etc., (visit http://www.antlab.ee.ucla.edu). On several occasions, Prof. Rahmat-Samii's work has made the cover of many magazines and has been featured on several TV News casts.

For his contributions, Dr. Rahmat-Samii has received numerous NASA and JPL Certificates of Recognition. In 1984, Prof. Rahmat-Samii received the coveted Henry Booker Award of URSI from the International Union of Radio Science which is given triennially to the most outstanding young radio scientist in North America. Since 1987, he has been designated every three years as one of the Academy of Science's Research Council Representatives to the URSI General Assemblies held in various parts of the world. In 1992 and 1995, he was the recipient of the Best Application Paper Prize Award (Wheeler Award) for papers published in the 1991 and 1993 IEEE AP-S Transactions. In 1993, 94 and 95, three of his Ph.D. students were named the Most Outstanding Ph.D. Students at UCLA's School of Engineering and Applied Science. Seven others received various Student Paper Awards at the 1993-2002 IEEE AP-S/URSI Symposiums. Dr. Rahmat-Samii is a member of Commissions A, B, J and K of USNC/URSI, AMTA, Sigma Xi, Eta Kappa Nu and the Electromagnetics Academy. He is listed in Who's Who in America, Who's Who in Frontiers of Science and Technology and Who's Who in Engineering. In 1999, he was the recipient of the University of Illinois ECE Distinguished Alumni Award. In 2000, Prof. Rahmat-Samii was the recipient of IEEE Third Millennium Medal and AMTA Distinguished Achievement Award. In 2001, Rahmat-Samii was the recipient of the Honorary Doctorate in physics from the University of Santiago de Compostela, Spain. In 2001, he was elected as the Foreign Member of the Royal Academy of Belgium for Science and the Arts.