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Electromagnetic Band Gap Structures Incorporated In Antenna Array: A Review

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***Abstract*— Patch antennas or antenna arrays finds wide range of applications in today's wireless communication systems. It is also required to integrate many wireless system applications in one unit. Antennas need to be placed on same substrate very close to each other. This leads to interference. Electromagnetic Band Gap structures are used to reduce these interferences. This paper deals with EBG structures, their types, their behavior in enhancing the performance of patch antennas. It is found that EBG can reduce surface wave radiation and mutual coupling, which are main factors affecting the antenna gain, radiation pattern, bandwidth and beam width.**

***Index Terms*—Antenna Gain, Mutual coupling, Radiation Efficiency, Reflection, Surface waves.**

I. INTRODUCTION

Printed antenna and arrays suffer from relatively high level of mutual coupling between individual elements due to surface waves [1]. This becomes progressively worse with increasing frequency, dielectric constant, and substrate thickness. While mutual coupling can be reduced by increasing the inter element spacing, this results in undesirable grating lobes. The major problem associated with planar antennas originates in the guiding of plane waves by a plane interface between two different media: conductor-dielectrics or dielectrics-dielectrics. The electromagnetic energy trapped between the interfaces, and forming into surface waves, is substantial: an elementary dipole, placed on a uniform substrate with no losses and represented by the relative dielectric constant ε, radiates $\varepsilon^{3/2}$ times more power into the substrate than into the air; a second problem is that the electromagnetic waves radiated into substrate and reaching the dielectric-air interface at angles greater than θ_c = sin-1 $\varepsilon^{-1/2}$ are totally reflected. The power transferred into the surface waves does not contribute to the main radiation of the antenna, but it is scattered off the edges of the finite ground plane and leads to deep nulls and ripples in radiation patterns, increased back radiation, gain deterioration, lower polarization purity, etc. In general, the higher the permittivity of dielectrics and thicker the substrate, the stronger is the influence of the surface waves. Mutual coupling, surface wave influence and problem of reflection can also be reduced by incorporating electromagnetic band gap (EBG) structures in between array elements.

II. EBG GEOMETRIES AND TYPES

A. *mushroom type or planar?*

EBG structures used in microwave and electronic engineering are mainly 2D periodic structures. These 2D geometries can be broadly classified into two categories: Textured (Mushroom or thumbtack) type and Uniplanar (or patterned) structures. The most widely used type of EBGs are metallo-dielectric structures, consisting of periodic array of patches, connected (mushroom type) or not (planar type) to the ground plane (Fig. 1). [9]

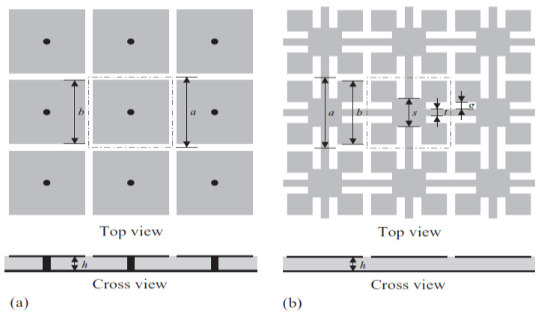

Fig. (1) Electromagnetic band gap structures (a) Mushroom type (b) Unplanned type [18]

The mushroom and planar EBG differs in many aspects and which to choose always depends upon application. For successful implementation in practice, also particular care should be paid to their correct design and computer modeling. Undoubtedly planar EBG structures are preferred over 3-D EBGs due to their simplicity and ease of fabrication. Planar EBGs with band gaps at the lower GHz frequency range are needed so that they can be used between array elements to reduce mutual coupling. The prerequisites for transverse magnetic (TM) and transverse electric (TE) surface wave propagation on a general impedance surface whose properties can be described with a single parameter, the surface impedance *Zs*. The surface is positioned in the *y-z* plane as shown in Fig. 2.

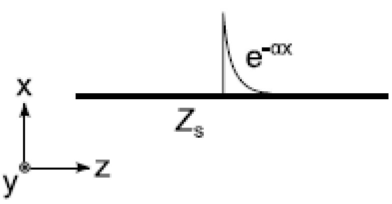

Fig (2) Surface Wave Propagation [9]

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A surface wave propagates in the +*z* direction with the fields decaying exponentially with decay constant α in the +*x* direction. For TM surface waves, the *x* and *z* components of the magnetic field intensity and the *y* component of the electric field intensity are equal to zero, $H_x = H_z = E_y = 0$. The surface wave impedance can be expressed as the ratio of the electric field over the magnetic field at the surface. Considering that the essential difference between mushroom and planar EBGs (Fig. 1) is the presence or absence of shorting vias which represent a shunt inductance in the equivalent network model shown below.

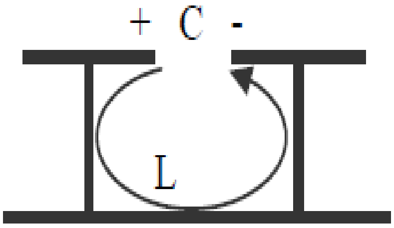

Fig (3) Equivalent Network Model [5]

The following conclusion can be made: the mushroom EBG can suppress surface waves of both polarization (both permittivity and permeability can be negative), whereas the planar one can suppress TE waves only (permeability can be negative). However, even the mushroom EBG cannot suppress TM and TE surface waves at the same time. A novel uni-planar electromagnetic Band Gap (EBG) structure incorporated with inter-digital capacitor and meandered line inductor (ML-ID-EBG) is presented in [5], this novel structure significantly enlarges the fringe capacitance to reduce sized cells, as well as increases the equivalent inductance to widen the relative bandwidth. Based on the above stated, surface waves can be successfully suppressed by EBGs, if the antenna(exciting surface waves

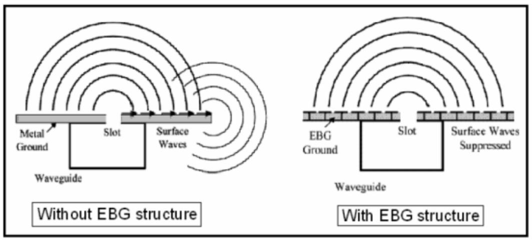

Fig (4) Suppression of Surface Waves [14]

of both polarization) works under the first substrate TE surface wave cutoff frequency (i.e. the slab guides TM_0 mode only), or a mushroom-type EBG is used. If these conditions are not satisfied, the suppression of surface waves is impossible and there is only a minor (if any) improvement in radiation properties of an antenna surrounded by EBG cells[14]. For example, the well-known uniplanar compact electromagnetic band-gap (UC-EBG) structure will never work in combination with an antenna that excites both TM and TE surface waves, because of the absence of vias.

Uniplanar or patterned EBG structures can be realized as a grid/meshed plane, 2D stepped impedance structure, interconnected slotted patches, metal patches connected by meander lines or other parasitic sections. Some of the geometries used for developing planar patterned and mushroom EBG structures have been shown in Figure 5.

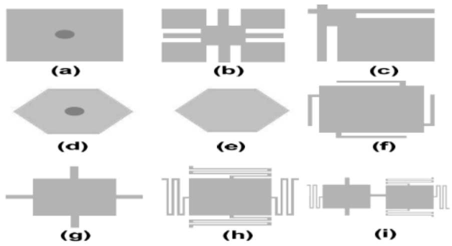

Fig (5) EBG geometries [14]

B. Analysis methods

To analyze unique features of EBG structures, various methods have been implemented. These methods can be put into three categories: (1) lumped element method, (2) periodic transmission line method, and (3) full wave numerical methods [18]. Owing to the fast development in computational electromagnetic, various numerical methods have been applied in the full wave simulations of EBG structures. Both the frequency domain methods such as the MoM and FEM and the time domain methods like FDTD [2,9] have been utilized by different research groups to characterize EBG structures. One advantage of the full wave numerical methods is the versatility and accuracy in analyzing different EBG geometries. Another important advantage is the capability to derive various EBG characteristics, such as the surface impedance, reflection phase, dispersion curve, and band gaps. Determination of the stop bands and the degree of isolation obtained in the forbidden bands of EBG structures in filtering and noise suppression applications are the two most important measures of their efficiency. These characteristics can be ascertained from the dispersion diagram and scattering parameter (s-parameter) plots. The dispersion characteristic is the plot of propagation constant of every mode versus frequency, commonly known as $k - \beta$ diagram in waveguides. To obtain such plots, eigen values of the electromagnetic problem should be found. The most commonly used procedure to obtain these attributes is by utilizing commercial electromagnetic (EM) field solvers. These tools are very accurate in predicting the EBG characteristics, but they often require a lot of time to converge on the eigen values especially when a large number of modes are investigated. Hence, any modification to the layout for the purpose of design optimization results in hours of simulation time. It has to be noted that the design or optimization process is simplified, since the only information required is the dispersion diagram of the EBG unit cell or the reflection phase behavior. This reduces the computational effort, since there is no need to optimize the entire geometry.

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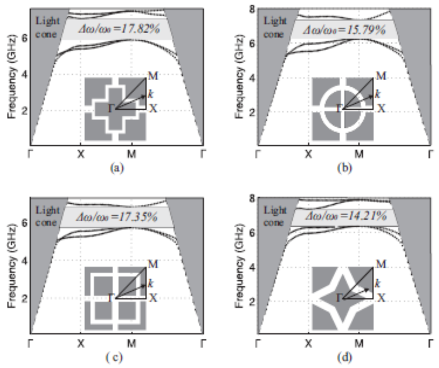

Fig.(6) Dispersion Diagram For Various Uniplanar EBG Structures [15]

III. EBG DESIGN TECHNIQUES

Electromagnetic properties of an EBG structure are determined by its physical dimensions. For a mushroom-like EBG structure shown in Fig.1(a), there are four main parameters affecting its performance, namely, patch width *W*, gap width *g*, substrate thickness *h*, and substrate permittivity ε_r. In this section, the effects of these parameters are investigated one by one in order to obtain some engineering guidelines for EBG surface designs. Note that the vias' radius *r* has a trivial effect because it is very thin compared to the operating wavelength. Patch width plays an important role in determining the resonant frequency. Wider patch width leads to a larger capacitance *C*. Thus, the frequency reduces and the bandwidth becomes narrow. The gap width *g* controls the coupling between EBG patch units. When the gap width is increased, the resonant frequency increases. Meanwhile, the slope of the curve becomes flat near the resonance, which indicates a wide bandwidth. According to the lumped LC model, increasing the gap width will decrease the value of the capacitance *C*. Thus, both the resonant frequency and the bandwidth increases. When the substrate thickness is increased, the equivalent inductance *L* increases. Thus, the frequency reduces but the bandwidth increases. Similar to the mushroom-like EBG surface, the operational mechanism of the uniplanar EBG surface can be explained by the lumped LC model. The capacitance *C* also comes from the edge coupling between adjacent patches. Instead of using vertical vias to provide an inductance *L*, a thin microstrip line on the same layer of the patches is used to connect them together. Thus, this structure is named as a "uni-planar" EBG. To increase the inductance value, the microstrip line needs to be inset into the patch. The main parameters of the metallic pattern design are labeled in Fig. 1(b).

IV. SOME USEFUL RESULTS

C. Reduction of mutual coupling

The mutual coupling of microstrip antennas is parametrically investigated, including both the E and H coupling directions, different substrate thickness, and various dielectric constants. It is observed that the E-plane coupled microstrip antenna array on a thick and high permittivity substrate has a strong mutual coupling due to the pronounced surface waves.

Therefore, an EBG structure is inserted between array elements to reduce the mutual coupling. A mushroom-like EBG structure is analyzed using the finite-difference time-domain (FDTD) method in[6]. Its band-gap feature of surface-wave suppression is demonstrated by exhibiting the near field distributions of the electromagnetic waves. Its band-gap features are revealed in two ways: the suppression of surface-wave propagation, and the in-phase reflection coefficient. The feature of surface-wave suppression helps to improve antenna's performance such as increasing the antenna gain and reducing back radiation. Meanwhile, the in-phase reflection feature leads to low profile antenna designs.

However, most researchers only study the EBG effects on a single microstrip antenna element. The mutual coupling of microstrip antennas is parametrically investigated, including both the E- and H-coupling directions, different substrate thickness, and various dielectric constants. In both coupling directions, increasing the substrate thickness will increase the mutual coupling. However, the effect of the dielectric constant on mutual coupling is different at various coupling directions. It is found that for the E-plane coupled cases the mutual coupling is stronger on a high permittivity substrate than that on a low permittivity substrate. In contrast, for the H-plane coupled cases the mutual coupling is weaker on a high permittivity substrate than that on a low permittivity substrate. It is observed that increasing the substrate thickness still increases the mutual coupling, while increasing the permittivity decreases it. This difference is due to surface waves propagating along the E-plane direction[6]. To reduce the strong mutual coupling of the E-plane coupled microstrip antennas on a thick and high permittivity substrate, the mushroom-like EBG structure is inserted between antenna elements. When the EBG parameters are properly designed, the pronounced surface waves are suppressed, resulting in a low mutual coupling. The difference of field levels is seen inside and outside frequency band. This is due to the existence of the EBG structure, which suppresses the propagation of surface waves so that the field level in the EBG case is much lower than in the conventional case. However, the EBG structure cannot successfully suppress surface waves outside its frequency band gap. From this it can be concluded that as expected, the surface-wave suppression effect exists only inside the band gap of the EBG structure. The antennas on a low permittivity substrate have a larger patch size and their fringing fields couple to each other, resulting in a strong mutual coupling. However, for the antennas on a high permittivity substrate, there is less coupling between their fringing fields due to its small patch size. The surface waves which contribute to the strong mutual coupling of the E-plane coupled case have less effect now because they do not propagate along the direction. It can be concluded from the

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above discussion that the mutual coupling behaviors of microstrip antennas are determined by both the directional surface waves and antenna size. It is found that the E-plane coupled microstrip antennas on a thick and high permittivity substrate exhibit very strong mutual coupling due to the pronounced surface waves.

Since the EBG structure has already demonstrated its ability to suppress surface waves, four columns of EBG patches are inserted between the antennas to reduce the mutual coupling fig. 8(a), The mutual coupling results are shown in Fig. 8(b).

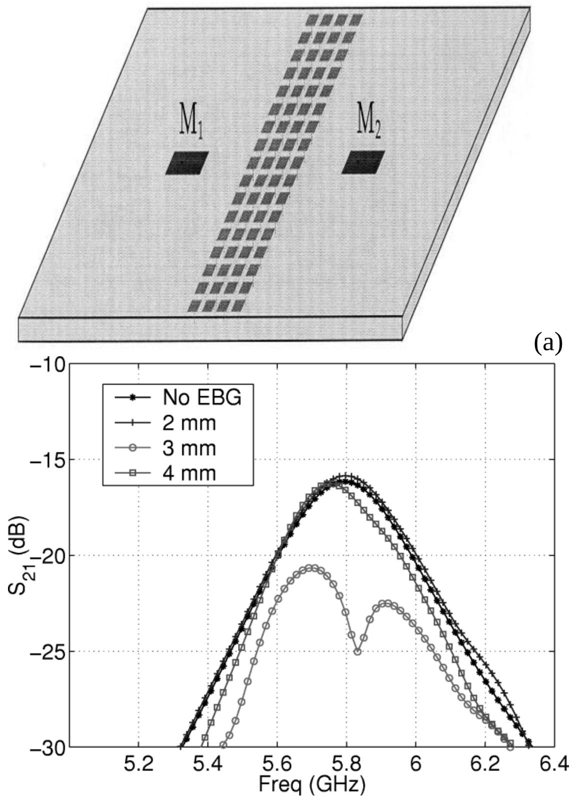

Fig (7) Antenna with EBG Patches (A) And Mutual Coupling Results (B) [6]

Without the EBG structure, the antennas show a strong mutual coupling of 16.15 dB. If the EBG structures are employed, the mutual Coupling level changes. When the 2mm EBG case is used, the mutual coupling is not reduced and a strong coupling of 15.85 dB is seen. For the 3mm EBG case, the resonant frequency 5.8 GHz falls inside the EBG band gap so that the surface waves are suppressed. As a result, the mutual coupling is greatly reduced: only 25.03dB at the resonant frequency. It is worthwhile to point out that the bandwidth of the EBG structure is much wider than the antenna bandwidth so that it can cover the operational band of the antenna. When the size of the mushroom-like patch is increased to 4 mm, its band gap decreases, and is now lower than the resonant frequency. Therefore, the mutual coupling is not improved and is still as strong as 16.27 dB. The design and analysis of planar circularly symmetric (PCS) electromagnetic band gap (EBG) structures for reducing the surface waves excited by printed antennas on dense dielectric substrates is analysed in [7]. The key advantage of the circularly symmetric geometries is that a surface wave generated by a source located at its center experiences the same band gap effect in all radial directions.

The PCS-EBGs are simple to manufacture since they do not present vertical via holes or pins, and can be designed starting from a two-dimensional (2-D) equivalent geometry with a one-dimensional (1-D) periodicity. The 2-D geometry yields a very good first order estimation of the overall performances of the relevant three-dimensional (3-D) geometry, while reducing the numerical effort. A new compact spiral mushroom EBG is proposed in [8]. It has reduction in size due to spiral inductive pattern which further affects the overall compactness of antenna and array. The mutual coupling reduction between two inverted-F antennas has been investigated when mushroom-type EBG structures are arranged between two inverted-F antennas at intervals of a half wavelength on a finite ground plane in[10]. A dual layer compact uniplanar EBG is proposed in [13].

D. Gain enhancement

The antenna must, for example, to have miniature dimensions, a wide band, a high gain, and a large directivity if the application requires it. All these criteria are impossible to obtain with classical antennas. Usually, we are required to choose between the bandwidth, the efficiency of radiation and the size of the antenna. The EBG structures were recently, the subject of many practical works which showed that these structures have interesting electromagnetic properties to improve the performances of the antennas. It is illustrated in [19] article that these structures, used as ground plane, make possible to miniaturize the total thickness of a printed antenna, to enlarge its bandwidth, and increase its gain. The reference antenna on classical ground plane works inside the band of frequencies [1.85GHz - 2.25GHz]. Besides its perfect symmetry, this antenna is characterized by a high directivity and a high gain. The main disadvantage, of this antenna, is a quarter wavelength thickness: h-tot = 20.75mm. The conceived EBG structures are employed as ground plane and the thickness of air-box was reduced, in both cases, at the value h-air = 0.78mm. In the fig. , we give the geometry of antenna on the new EBG ground plane, and the results of simulations and measurements of the return losses S11.

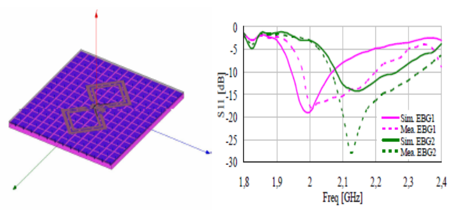

Fig (8)(a) Antenna geometry with EBG background (b) S11 [19]

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The EBG structure performs as the perfect magnetic surface for its in-phase reflection phase properties, which can be used as ground plane for a low profile wire antenna to get a good return loss. Within the surface-wave frequency band-gap, the EBG can block the propagation of the surface wave, which can make the antenna perform with high gain and low backward radiation. Moreover, surface wave suppression can also reduce mutual coupling between antennas.

The efficiency and radiation of an antenna can be significantly improved by both the in-phase reflection phase properties and the surface wave suppression features by integration of EBG structures. Table below gives the results of different EBG structures on gain and beam width of the antenna.

Table (1) Gain and beam width for different EBG structures

Ground plane	h-tot (mm)	Bandwidth (GHz)	Maximum gain (dB)				Beam width (°)			
			2.1GHz		2.2GHz		2.1GHz		2.2GHz	
			H	E	H	E	H	E	H	E
PEC	20.75	0.4	9.12		9.13		56	64	56	64
BIE1	4.70	0.225	8.19		5.95		36	76	48	90
BIE2	4.70	0.3	9.28		10.24		50	84	42	76

With the great interest in designing multi-band antennas in wireless communication devices, EBG structures with dual-band and compact size are promising. However, most of these structures must have different periods on two layers [8] or several EBG layers with different permittivity [9] to obtain dual band, which makes the size of these EBG structures non compact. So it becomes main challenge to realize the two bandwidths with one unit. In most works, the in-phase reflection phase of a normal plane wave is used to define the band gap region for EBG structures.

E. Enhancement of radiation characteristics

When two different types or shapes of radiating elements working at two different frequencies of operation are being integrated as one array formation, the possibilities of having a uniform and controlled radiation patterns are quite tricky to achieve. Other than the existence of mutual couplings among these patches [1,6], and the others acting as parasitic elements when not resonating, one of the contributing factors to this drawback is that, the lower band radiating elements also demonstrate higher (harmonics) resonant frequencies and if it happens to resonate at the intended second band of frequency of operation at a different phase, this will probably degrades the antennas' radiation patterns. The configuration of the modeled antenna to be evaluated is as shown in Figure 9(a).

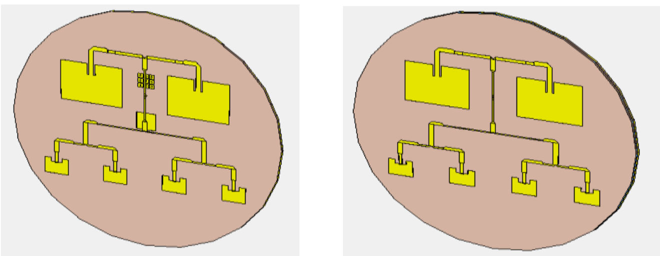

Fig (9) Corporate inset feed DbMSAA with and without EBG[17]

The figure shows a combined non-symmetry corporate inset feed DbMSAA operating at 2.4GHz and 5.8GHz. E Field at 5.8GHz and 2.4GHz patches resonate at the contiguous patches at different phases. This circumstance degrades the radiation patterns of the antenna, at both frequencies. In this work, the EBG structures were positioned in between the respective corporate feeding lines and ground plane, thus making them work as an Electromagnetic Band Rejecter (EBR) at this point. The EBR composition works by prohibiting the EM waves and currents of a certain targeted band of frequencies from propagating through them thus separates that section of transmission lines from the others, at the respective band of frequencies, only. The configuration of the proposed EBG structures is as shown in Figure 9(a). The design consists of a two layer substrates where the corporate transmission line feeds and its arrays of radiating patches were imprinted on the top section of the first layer. These EBG structures successfully rejected or filtered out the targeted band of frequencies and stops the waves and currents from propagating and flowing through, thus make them flows to the decided direction only.

Table(2) beamwidth variation with and without EBG

Antenna (f_r)	E Plane (HPBW) & Gain	H Plane(HPBW)& Gain
wo EBG (2.4GHz)	47.3 " , 4.7 dB	101.9" , 4.90 dB
w EBG (2.4GHz)	48.5" , 5.12 dB	115.6" , 5.12 dB
wo EBG (5.8GHz)	24.0" , 7.50 dB	25.5" , 7.50 dB
w EBG (5.8GHz)	17.0" , 9.35 dB	47.5" , 9.75 dB

F. Reduction of reflection

It is well known that the in-phase reflection phase properties and surface-wave suppressing feature are the unique characteristics of the electromagnetic band-gap (EBG) structure. The EBG structure performs as the perfect magnetic surface for its in-phase reflection phase properties, which can be used as ground plane for a low profile wire antenna to get a good return loss [1, 2]. Within the surface-wave frequency band-gap, the EBG can block the propagation of the surface wave, which can make the antenna perform with high gain and low backward radiation. Moreover, surface wave suppression can also reduce mutual coupling between antennas [6, 7]. The efficiency and radiation of an antenna can be significantly improved by both the in-phase reflection phase properties and the surface wave suppression features by integration of EBG structures. With the great interest in designing multi-band antennas in wireless communication devices, EBG structures with dual-band and compact are promising. However, most of these structures must have different periods on two layers [8] or several EBG layers with different permittivity [9] to obtain dual band, which makes the size of these EBG structures not be compact. So it becomes main challenge to realize the two bandwidths with one unit. In most works, the in-phase reflection phase of a normal plane wave is used to define the band gap region for EBG structures. In [11], one mushroom-like EBG unit with slots is utilized to realize the dual-band in-phase reflection phase properties. The dual-band in-phase reflection phase properties of this

EBG structure can be exploited to design dual-band inverted L antenna with low profile structure and good return loss characteristics.

V. IMPROVEMENT OF ISOLATION

A compact elongated mushroom electromagnetic band-gap (EM-EBG) structure, exploiting the thickness of the substrate to achieve higher isolation compared to the case of the conventional mushroom EBG (CM-EBG), has been proposed in [12] for the enhancement of the performances of patch antenna arrays. The compactness of the EM-EBG has been investigated and shown to be superior to that of the CM-EBG in practical cases. The superior reduction of mutual oupling of the EM-EBG has been demonstrated by full-wave and experimental results.

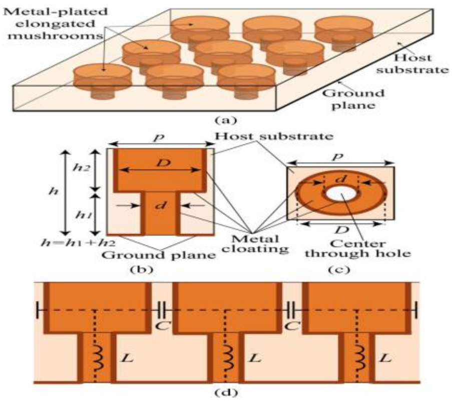

Fig.(10) Elongated mushroom EBG(EM-EBG)[12]

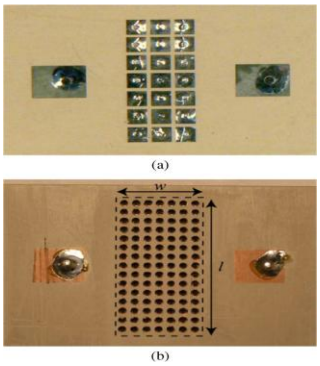

Fig.(11) antenna array with (a) CM-EBG (b) EM-EBG[12]

specifically side-lobe level (SLL) control and direction of arrival (DOA) estimation, have been presented. By exploiting the substrate thickness, the EM-EBG structure reduces the transverse dimensions of the EBG for a given number of cells or improves the isolation between antenna elements by fitting more cells between them for the same transverse dimensions. This benefit is critical in antenna arrays, where the maximal allowable distance between the antenna elements is set to half a free-space wavelength to avoid grating lobes.

VI. CONCLUSION

The antennas with EBG in comparison with their counterparts without EBG have smooth and almost symmetric radiation patterns, significantly better front-to-back ratio and lower cross-polarization level. High gain is possible on high thickness substrates with reduction in mutual coupling and surface wave radiations. Multi band antenna array can be constructed with minimum effect over radiation pattern using EBG structures.

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