Application of Electromagnetic Bandgap Structures for mutual coupling reduction in microstrip antenna arrays

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Abstract – Microstip antenna arrays became increasingly popular in modern antenna applications due to their simplicity, compact size, easiness of manufacturing of mass production. One of the biggest problems in antenna arrays of microstrip antennas is the strong mutual coupling between elements, due to the space and surface waves, that severely impacts the active impedances and antenna pattern. The present paper discusses an opportunity to mitigate this undesirable impact.

Keywords – **antenna array, microstrip patch antenna, electromagnetic band gap (EBG) structure, high impedance surface, mutual coupling, surface wave.**

I. INTRODUCTION

Microstrip antenna arrays are found in a vast majority of modern devices for telecommunications and echolocation. They are cherished for their small footprint, low cost, and ease of manufacturing. One of the most studied and well-documented building blocks for such arrays are the microstrip patch antennas. Such elements allow even novice RF engineers to achieve the desired radiation pattern, gain and phase scanning up to +/-50 degrees while meeting the ever so stricter design deadlines in the modern telecom business.

A basic microstrip patch element is easy to match and achieves high gain at the desired frequency of operation due to its resonant nature, but this also leads to a narrow frequency band. The planar shape of the element also leads to high levels of mutual coupling – something highly undesirable for a scanning antenna array. Patch arrays tend to exhibit steep shifting of the impedance and radiation pattern distortions when the beam is steered more than 30-40 degrees from boresight. These issues are due to unwanted transmission modes propagating inside the underlying substrate as well as surface waves propagating on the plane between adjacent patch elements. In such cases not all the electromagnetic energy will be radiated into the free space ahead of the antenna's aperture. Undesirable phenomena like increase of the number of sidelobes and their amplitude, increase of the back lobe radiation and decrease of the antenna gain can result from the surface waves, when they get dispersed from the antenna's edges. [1]

In recent years, High-Impedance Surfaces have started to appear on the antenna arrays used in high-performance telecommunication and radiolocation devices. One of their applications is mitigation of surface wave phenomena in planar antenna arrays. By surrounding every patch element with a bandgap structure, the amplitude of the undesirable propagation, and in turn coupling, can greatly be reduced. [2] This approach on its own can increase the antenna's realized gain. An alternative approach would be to manufacture the antenna using a low permittivity substrate when the design constraints allow this. Materials with higher permittivity enable planar patch arrays with smaller footprints at the cost of narrower bandwidth when compared to designs utilizing lower Er substrates. The design can regain bandwidth by utilizing a low permittivity substrate and increasing its thickness. This approach not only increases antenna gain over broader bandwidth, but also results in additional advantages like improved mechanical strength of the antenna. These improvements, however, come at the cost of increased price, weight, and most importantly undesirable increase of the surface waves. Here the electromagnetic bandgap can again be used to mitigate the surface waves. Such a design will result in a high-performance wideband antenna with significant back lobe and sidelobe level reduction, that will feature improvements in both realized gain and directivity. [1]

II. DESIGN OF THE PATCH ANTENNA AND EBG STRUCTURE

A. *Patch Antenna Design*

The evaluated antenna array design consists of circular probe-fed microstrip patch elements. This type of patch element has well-known characteristics and is broadly found in telecommunication and radar systems. It is cheap and easy to manufacture, the small element size allows for compact and lightweight designs and most importantly enables easy integration of antenna elements, placed on one side of the substrate, with active components like low-noise amplifiers or power amplifier stages, placed on the opposite site of the PCB substrate.

Microstrip patch antennas tend to exhibit very narrow impedance bandwidth, when optimized for high realized gain. Modern communication equipment operates in a wide frequency spectrum to meet the requirements of multiple wide-band concurrent communication channels. Technologies like RF-to-bits architectures allow for instantaneous bandwidth far exceeding what simple patch arrays can offer. The cost and mechanical rigidity of patch arrays has kept them a go-to solution for the telecoms, so many studies have been performed

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on how to increase the antenna's bandwidth without sacrificing realized gain or gain flatness. One of the most analyzed characteristics is the element-to-element mutual coupling in the array.

When antenna elements are placed in proximity to one-another, especially in the same plane, which is the case in a planar antenna array, their fields will interact strongly with each-other, and energy will be coupled between neighboring elements which in turn alters the antenna parameters. This phenomenon is called mutual coupling and it affects the input impedance and radiation pattern of the antenna element. The level of mutual coupling can be controlled by altering the element-to-element spacing, the lattice pattern of the array or the element's radiation pattern.

B. EBG Structure Design

Great care must be taken when designing radiating elements to be used in antenna arrays, especially planar ones. When the individual elements share a common reference plane, the surface currents in that plane are one of the sources of mutual coupling. For the fundamental mode of operation of a planar antenna array the surface waves are primarily excited in the E-plane and interfere in an undesirable way with the characteristics of the radiating elements. Element-to-element mutual coupling is caused by both radiated waves and surface waves. The second can dominate when the design utilizes high-permittivity substrates. Performance degradation due to mutual coupling is critical in microstrip patch element designs and to avoid it one needs to mitigate the surface wave phenomena.[3]

The intensity of undesirable surface waves can greatly be decreased by utilizing electromagnetic bandgap structures in the antenna array. Their frequency-selective characteristic results in decreased mutual coupling, increased realized gain and a more focused radiation pattern. For size-constrained designs, smaller footprint of the antenna elements can be achieved by utilizing high-permittivity substrates. In such cases proper placement of planar EBG structures in the array can negate the typical drawbacks of high Er designs, which are prone to high levels of surface wave excitation, reduced directivity, and increased levels of back-lobe radiation.[4]

For designs utilizing low Er substrates with larger thickness, mushroom-like electromagnetic band-gap structures can be used to provide the above-mentioned advantages. The resulting array will carry the added benefits of wider bandwidth and increased efficiency without significant increase in manufacturing costs.

For both high- and low-permittivity substrates, transverse magnetic mode (TM) surface wave propagation is supported by inductive surfaces. Transverse electric mode (TE) surface waves, on the other hand, require capacitive surfaces to propagate. To extinguish the propagation of surface waves in both modes, the surface of the dielectric material must simultaneously have high inductive and capacitive impedance. This can be achieved by implementing L-C resonators using lumped elements combined in planar textures with appropriate spacing in between them. The resulting band-stop filters prevent surface wave propagation by scattering them when a discontinuity occurs. The radiation interference attenuates the undesired modes and presents a high-impedance surface in the form of a band-gap structure operating over a finite frequency band.[5]

Electromagnetic band-gap structures (Figure 1) can be modeled using equivalent lumped-element schematics to simplify their analysis. A network of inductors and capacitors can be connected in a multi-stage L-C resonator, used to describe the frequency-selective properties of the EBG structure. The resulting frequency response can be assigned as surface impedance of the EBG structure. This approach gives a valid approximation if the period of the EBG structure's texture is significantly smaller than the surface wave's wavelength.[6]

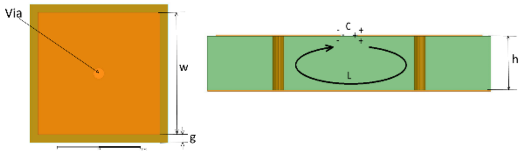

Figure 1 EBG top and cross-section view

The inductor results from the current flowing through the vias, and the capacitor due to the gap effect between the adjacent patches. For an EBG structure with patch width (W), gap width (g), substrate thickness (h) and dielectric constant ε_r, the values of the inductor and the capacitor are determined by the following formulas [7]:

$$L = \mu_0 h \tag{1}$$

$$C = \frac{W\varepsilon_0(1+\varepsilon_r)}{\pi}cosh^{-1}(\frac{2W+g}{g}), \tag{2}$$

where μ_0 is the permeability of free space and ε_0 is the permittivity of free space.

The frequency band gap is given as

$$\omega = \frac{1}{\sqrt{LC}} \tag{3}$$

$$BW = \frac{\Delta\omega}{\omega} = \frac{1}{\eta}\sqrt{\frac{L}{C}}, \tag{4}$$

where η is the free space impedance which is 120π.

III. SIMULATION MODELS AND RESULTS

To evaluate electromagnetic properties of the EBG structure, a unit cell model (Figure 2) is constructed in commercial full-wave EM simulation software High Frequency Structure Simulation (HFSS). In unit cell model the Master and Slave boundaries force a periodicity in the fields, modeling a single element as if it is in an infinite array environment. This is done by mapping the fields from Master boundary to the corresponding Slave boundary and the fields are identical to each other.

The upper face of the unit cell is terminated with Floquet port, which in HFSS is exclusively used for planar-periodic structures. When the Floquet port is defined, a set of modes known as Floquet modes represent the fields on the port boundary. The Floquet modes are plane waves with propagation direction set by the frequency, phasing, and geometry of the periodic structure.

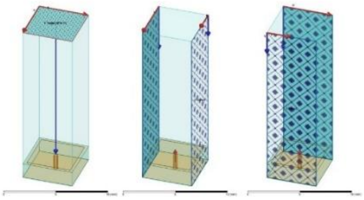

Figure 2 EBG 3D model with Floquet port and Master and Slave boundaries

The proposed EBG structure is designed at 10GHz. The model consists of a two-layered PCB with square metal patch with 4.4mm width on the top layer, connected through via with 0.4mm diameter to the ground plane on the bottom layer. The substrate used is RO4350B with 1.524mm thickness, 3.66 relative permittivity and 0.004 dielectric loss tangent.

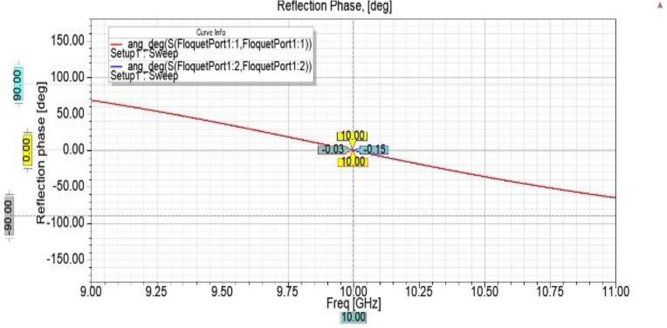

Figure 3 EBG Reflection phase

The phase shown in Figure 3 falls within ±90° when the magnitude of the surface impedance exceeds the impedance of free space.

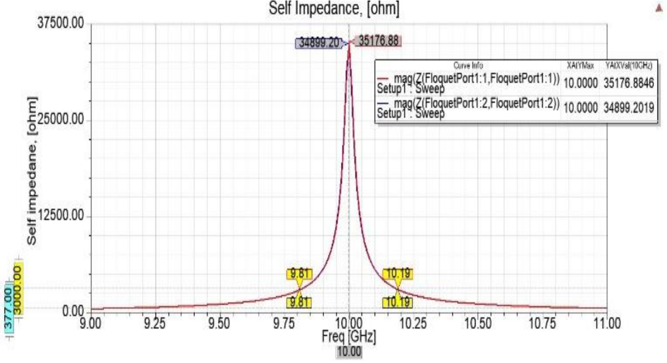

Figure 4 EBG Self impedance

As revealed in Figure 4, the EBG structure exhibits high impedance at resonance frequency. As a result, the surface waves are not supported at that frequency. Since EBG structures have been proved to suppress surface waves, it is integrated into patch antenna array in order to reduce the mutual coupling between neighboring elements.

Simulations are done with one to four columns of EBG elements placed between the antenna elements in E-plane configuration. In order to fit four columns of EBGs between the elements, the distance from element center to its neighboring element center is fixed at one wavelength for the resonance frequency. For comparison, an identical patch antenna without implemented EBG structure is modeled as a reference. Compared models are shown in Figure 5. In both cases, the input impedance is matched to 50 Ohms. The same approach is followed in H-plane configuration (Figure 8)

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Figure 5 3D model of two antenna elements in E-plane configuration with and without implemented EBG structure between them

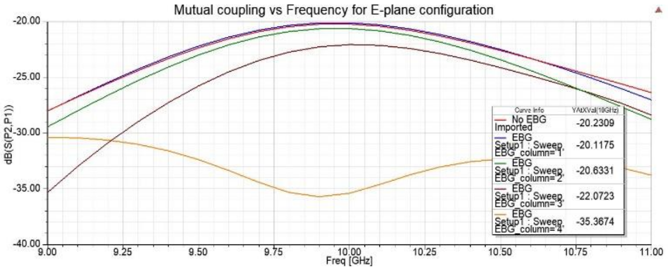
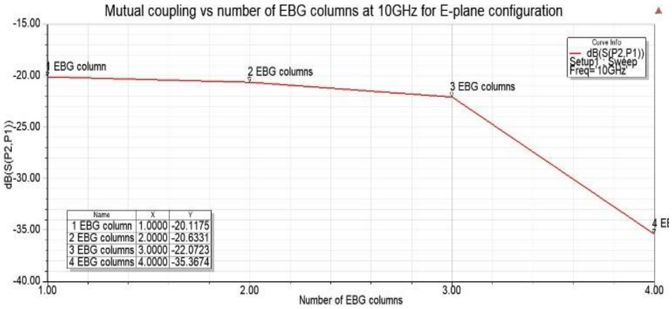


Figure 6 Mutual coupling in E-plane configuration without EBG and with one, two, three and four columns of EBG elements



Name	X	Y
1 EBG column	1.0000	-20.1175
2 EBG columns	2.0000	-20.6331
3 EBG columns	3.0000	-22.0723
4 EBG columns	4.0000	-35.3674

Figure 7 Mutual coupling at 10GHz in E-plane configuration with one, two, three and four columns of EBG elements

Figure 8 3D model of two antenna elements in H-plane configuration with and without implemented EBG structure between them

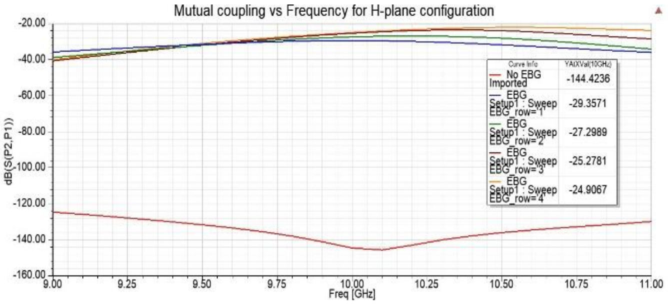
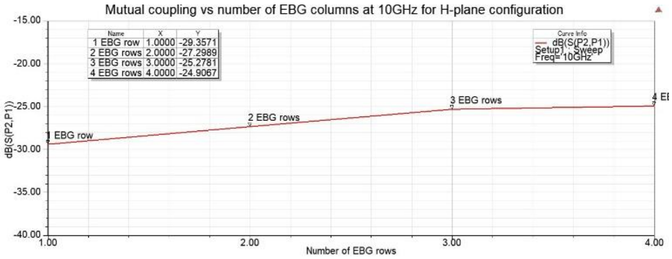


Figure 9 Mutual coupling in H-plane configuration without EBG and with one, two, three and four rows of EBG elements



Name	X	Y
1 EBG row	1.0000	-29.3571
2 EBG rows	2.0000	-27.2989
3 EBG rows	3.0000	-25.2781
4 EBG rows	4.0000	-24.9067

Figure 10 Mutual coupling at 10GHz in H-plane configuration with one, two, three and four rows of EBG elements

IV. CONCLUSION

The mutual coupling in antenna arrays is the main cause of undesired phenomena in array performance, like rapid change in the active impedances, pattern perturbation and in some occasion zeros or grating lobes in certain directions of radiation in a given scanning angle. This paper discus a novel approach to minimize the mutual coupling in a narrow frequency band, based on frequency bandgap structures. The approach is appropriate, since the radiating elements are also narrowband, therefore the EBG frequency performance is not a limiting factor in this particular case.

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