Microstrip Patch Antenna Array Mutual Coupling Reduction using Capacitive Loaded Miniaturized EBG

M.S.Mohamad Isa[1,2], R.J.Langley[2], S.Khamas[2] ,

A. Awang Md Isa[1], M.S.I.M. Zin[1], F.M. Johar[1], Z.Zakaria[1]

[1]*Faculty of Electronic and Computer Engineering, Universiti Teknikal Malaysia Melaka, Melaka, Malaysia*

[2]*Department of Electronics and Electrical Engineering, University of Sheffield, Sheffield S1, United Kingdom*

saari@utem.edu.my

***Abstract*— In this paper, a compact miniaturized EBG loaded with surface mounting capacitor has been developed. The dimension of the EBG patch with approximately λ/36 has been achieved with dimension highly dependent on the capacitor values. The integration of the capacitive loaded miniaturized EBG with a couple of microstrip patch antenna has reduced approximately 12dB mutual coupling within the elements at the antenna resonance frequency of 2.2GHz. The antenna E-plane gain has been improved for more than 2dB with 3dB reduction in side lobes when comparing the traditional array with the array integrated with EBG. The propagation characteristics and gain of the array have been analyzed using CST Microwave Studio (CST MWS). The measured results have shown good agreement with the simulated results. The miniaturized EBG will be very useful in minimizing the space within the array antenna especially for the MIMO application.**

***Index Terms*—Miniaturized EBG, Array antenna, Mutual Coupling Reduction, MIMO**

I. INTRODUCTION

Array antenna normally couple through two paths; the primary path arises from the free space radiation and the secondary path arises from the surface waves propagation within the array elements, which is strongly excited in the E-plane. The surface waves cause mutual coupling effects including low side lobe level antenna array and scan blindness for infinite, phased array with large scanning angle which degrade the performance of the array [1-3].

Various methods for reducing the effects of mutual coupling have been proposed in the literature. These methods including the optimizing of the antenna dimensions [4], adding shorting pins to cancel out the substrate capacitive polarization current [5], adding a dielectric layer [6] or a defected ground plane [7, 8], and the most popular techniques is to introduce an EBG structure within the elements [9-12].

Tunable EBG and AMC have been published in [13, 14] by making use of lumped capacitive and inductive elements. The design methodology for the miniature frequency selective surface (FSS) using lumped reactive components has been described in [14]. The capacitive and inductive elements have been utilized to achieve similar current loops as in the FSS band pass aperture. The design structure was fairly small with a unit cell period of approximately λ/36. The structure resonance frequency is mainly controlled by the value of the lumped components values that are normally associated with tolerance and losses, which might effects the tuning frequency and cost, as the components with a very low tolerance are expensive.

Microstrip antenna printed on a high dielectric constant substrate is attractive as it offers compactness and a low profile. However, drawbacks of this design, such as the narrow bandwidth and high excitation of surface wave need to be considered. The bandwidth can be improved using a thicker substrate, but this could excite severe surface waves. Based on the study reported in [15], a strong surface wave can be excited if the condition of $h > 0.3\lambda_0/2\pi\sqrt{\varepsilon_r}$ is satisfied. As a result, the mutual coupling increases and cause degradation in the gain and, in more severe cases, a blindness angle in a scanning array [16].

One approach to develop the miniaturized EBG structure has been suggested by embedding a miniaturized capacitive loaded EBG within the array element to shunt the surface wave current, hence reducing the mutual coupling effects. The continual research has been done based on the previous design methodology suggested by Liu in [14]. The FSS or EBG structure miniaturized technique has been improved by considering a new EBG structure that has been utilized using only the capacitor element without the inductor component. This approach minimizes the number of elements required and reduces the tolerance errors introduced by the electronic components. By introducing only a capacitor component in the structure, an electronically tunable FSS can be obtained by replacing the capacitor with DC biased varactor diodes as published in [17, 18]

To achieve an EBG with smaller dimensions, the element of inductance in the current loop circuit has been generated by inserting a connecting pin via into the structure. In order to minimize the fabrication and assembly costs, the capacitor values range can be selected from those available in market. Fine tuning of the EBG operating frequency can be implemented by slightly adjusting the EBG patch dimensions and the width of gap between the EBG patches. For the design compactness and easiness of the fabrication and assembly process, an EBG length and width range of 3mm ($\lambda_{2.2GHz}/45$) to 5mm ($\lambda_{2.2GHz}/27$) has been used. Additionally, a gap range of 0.5-1.0mm has been chosen between the patch for an operating frequency of 2.2GHz. However, the dimensions can be slightly increased for EBG to operate in a lower frequency, providing enough space between the array elements and the EBG structure.

Another advantage of this design is the capability of altering the surface characteristics by switching the pin vias in and out, which alternately turn the EBG structure to an artificial ground and control the propagation of surface waves, as described in [19-21]. The simple and various techniques for tuning the EBG wide operation frequency have shown the design flexibility for the proposed structure.

II. Capacitive Loaded Miniaturized EBG

An EBG structure that is based on the design methodology as describe in [14] has been designed as shown in Figure 1.The new design has been developed for miniaturizing the EBG overall period, *p,* by utilizing only the capacitive lumped elements. The EBG structure has been etched on a double sided FR4 substrate, where the bottom side of the conducting surface is used as the antenna and EBG structures ground plane. The FR4 substrate has a dielectric constant, $\mathcal{E}_r$, of 4.3 and a thickness, *t,* of 6.4mm.

The operation mechanism of the EBG structure can be modeled as an LC filter array with a parallel external lumped capacitance, C_L , equivalent circuit as shown in Figure 2. The element capacitor C is due to the effects of surface area and gap within the adjacent patches, whereas the inductance L results from the current flowing through the vias to ground plane. Referring to [9] , for the series of miniaturized EBG structures with patch width, *w* , length, *l* (where *l*=*w*) and gap width, *g,* which is etched on a substrate with a dielectric constant of $\mathcal{E}_r$ and a thickness of *t*. The capacitor and inductor values for the EBG patches, without the external lumped elements, can be written as [22]

$$C = \frac{w\,(1+\mathcal{E}_r)\mathcal{E}_0}{\pi} cosh^{-1}\left(\frac{2w+g}{g}\right) \tag{1}$$

$$L = \mu_0 t \tag{2}$$

where ε_0 and μ_0 are the free space permittivity and permeability constants respectively.

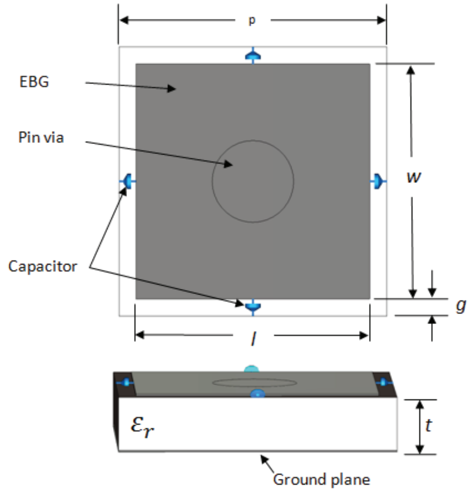


Figure 1: Unit cell for miniaturized EBG with capacitance

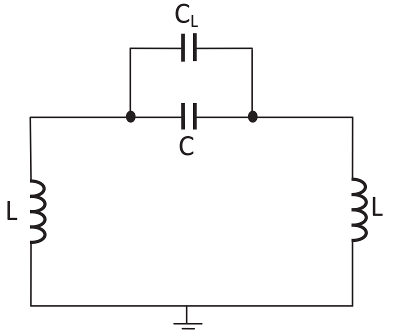


Figure 2: New equivalent circuit of capacitive loaded EBG.

From the EBG equivalent circuit diagram as shown in Figure 2, the equations for the band-gap resonance frequency and bandwidth can be expended as [9]

$$f_c = \frac{1}{2\pi\sqrt{LC_{tot}}} \tag{3}$$

$$BW = \frac{1}{\eta}\sqrt{\frac{L}{C_{tot}}} \tag{4}$$

 ISSN: 2180 - 1843 Vol. 4 No. 2 July - December 2012

where C_{tot} is the total capacitance in parallel which is the summation of C and C_L $(C+C_L)$ and η is the free space characteristics impedance which is defined as 120π

From Equations (3) and (4) it can be noticed that the EBG resonance frequency and bandwidth can be reduced by increasing the capacitance value. Additionally, the bandwidth can be increased by increasing the surface inductance value, which can be achieved by increasing the thickness of the substrate.

As illustrated in Figure 1, the miniaturized capacitive loaded EBG unit cell composed of a PEC metal plate with a connecting via at the middle. The capacitors are connected at each side of the EBG patch as a connection current path to the adjacent cell. To analyze the EBG with capacitance loaded performance, the dimensions of the cell have been varied. A unit cell with p =3.8mm, 7.6mm and 15mm has been simulated for comparison. The gap within the element has been set to 0.5mm for all the dimensions. For the 3.8mm and 7.6mm EBG unit cells, 0.5pF capacitors have been loaded. However, no capacitors have been used for the basic mushroom-like of 15mm EBG

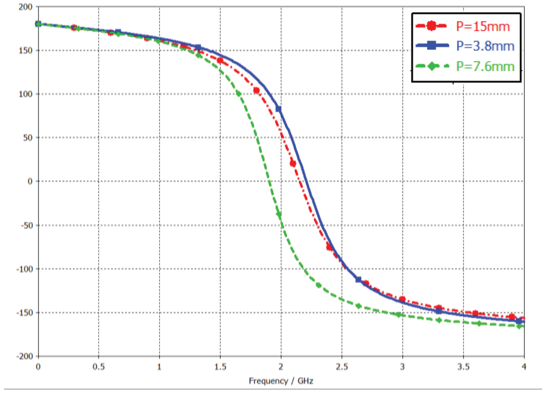


Figure 3: Reflection phase for a unit cell EBG.

Figure 3 shows that a resonance frequency of approximately 2.2 GHz has been achieved for the 15mm and 3.8mm EBG, which suggest a 75% reduction in the unit size. Doubling the miniature unit cell period has shown only ~14% shift in the resonance frequency and almost no reduction in bandwidth. Although the element sheet resistance increases with the increment of the cell periodicity, it is always very small with compared to the loaded lumped capacitance, hence resulting in a small reduction in the EBG operation frequency and the bandwidth of approximately 22% that has been achieved for all sizes.

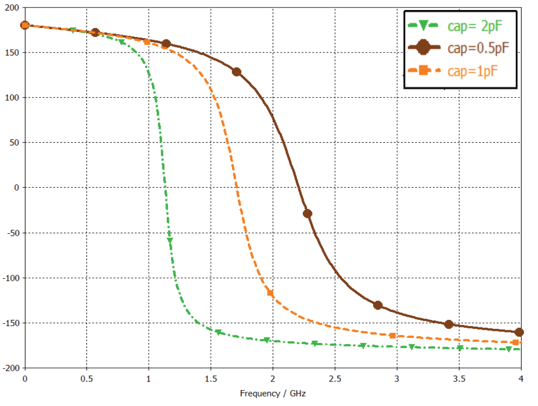


Figure 4: Reflection phase for unit cell with variable lumped capacitance value.

The characteristics of the EBG against the loaded capacitance value are shown in Figure 4. The unit cell period, p has been fixed at 3.8mm with a 0.5mm gap within the cells. The capacitance value has been set to 0.5pF, 1pF and 2pF. The EBG unit cell reflection phase results show that the resonance frequency has decreased by more than 20% when the capacitor value is doubled. As the chosen capacitance is large compared to the surface sheet capacitance, the bandwidth has been reduced from 0.55GHz to 0.32GHz, i.e. by approximately 42% when the capacitance value is doubled from 0.5pF to 1pF. The bandwidth is further reduced by 50% when the capacitor value is doubled from 1pF to 2pF. The simulated results show that the characteristics of the developed EBG structure are highly dependent on the loaded lumped capacitor value and marginally effected by the EBG dimensions.

The EBG structure has been scaled and optimized using a 50Ω microstrip transmission line as shown in Figure 5 to determine the best parameter for the EBG inserted with pin for it to have the band gap frequency which could cover the antenna operating frequency. For the analysis purposes, the antenna operating frequency has been selected as 2.2GHz.

Based on the impedance calculations in CST MWS, the width of the transmission line has been determined as 12.4mm for it to match with 50Ω impedance at 2.2GHz. The parameter is closely related with the FR4 substrate thickness and relative permittivity constant. Discrete ports have been connected at both edges of the microstrip line for calculating the surface mutual coupling across the EBG structure.

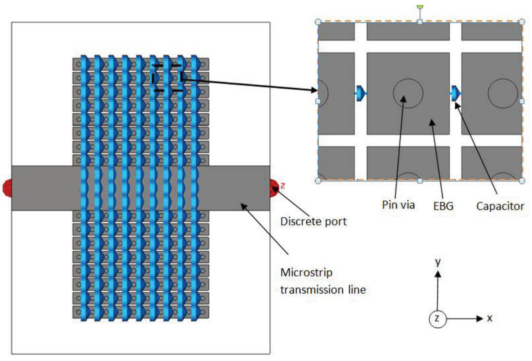


Figure 5: EBG structure with microstrip transmission line

Figure 6 shows the mutual coupling across the optimized EBG surface. The mutual coupling of the EBG without via has been included for comparison purposes. It has been noticed that switching the pin via in and out has alternately switch the EBG characteristics from suppressing to propagating the surface waves. The optimized dimensions of the EBG have been determined as: p=3.8mm; l=w=3.3mm; g=0.5mm and C_L=1pF. The structure substrate has been constructed using an FR4 material with a dielectric constant of ε_r =4.3 and a thickness of 6.4mm

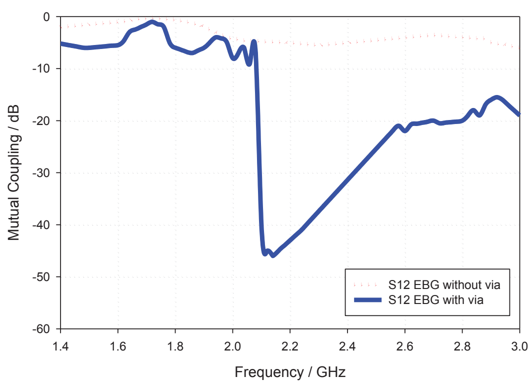


Figure 6: Surface mutual coupling for EBG structure

A. Two elements Microstrip Patch Array Antenna

Two patch antennas that are arranged in the E-plane as shown in Figure 7 have been simulated. Typically the space between adjacent array elements is chosen as $0.5 - 1.0\lambda_0$ at the antenna operation frequency. Based on [23, 24], for a thick and high-permittivity dielectric substrate, the E-plane configured microstrip exhibits a stronger mutual coupling with compared to the H-plane for elements separated by more than $0.5\lambda_0$. Hence, the analysis of mutual coupling reduction will be focused on the E-plane coupling.

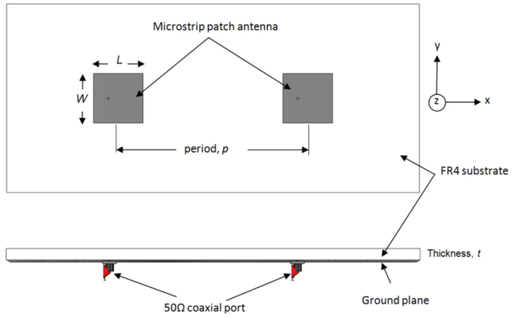


Figure 7: Microstrip patch array antenna with miniaturized EBG

An array of two square microstrip patch antennas, each with a width of *W* and a length of *L*, has been designed on a double sided FR4 substrate as shown in Figure 7. The array antenna has been etched on the top side of the substrate, whereas the bottom side has been utilized as the common ground plane for the array and later for the EBG structure. The substrate and ground plane length and width have been set to 218mm and 92mm, respectively

Both of the antenna patches have been fed using 50Ω coaxial probes as shown in Figure 7. The array elements have been arranged in-phase, such that the radiating edges are in line to each other. This kind of arrangement radiates power that is directed towards 0° when the phase gradient within the elements is set to 0°. Due to the transmitted and received signal characteristics, the broadside signal will suffer deep null at 0° if the phase gradient within the array has been set to 180°. Another possible array arrangement is to place the radiating edges to or in opposite directions to each other. These arrangements operate in reverse characteristics compared to the in-phase configuration. The transmitted signal from one element is 180° out of phase with that from the other element, thus a deep null will be observed with a 0° phase gradient within the elements. The array power radiation can be directed towards 0° when the phase gradient between the elements is set to 180°.

In this analysis, a microstrip patch array antenna with in-phase arrangement has been utilized. Simulated results for the E-plane coupled microstrip antennas are dispicted in Figure 9. The square patch has a size of 28.6mm, and resonated at a frequency of 2.2GHz, where a minimum$|S_{11}|$of -17dB has been achieved in conjunction with an impedance bandwidth of ~4.43%. Figure 9 also presents the mutual coupling for the array antenna which has been seperated $0.8\lambda_{2.2GHz}$ (109mm) between the antennas, where $\lambda_{2.2GHz}$ is the free space wavelength at the antenna resonance frequency of 2.2GHz. A mutual coupling of approximately -26 dB has been achieved.

B. Mutual Coupling Reduction using a Miniaturized Capacitive Loaded EBG

The miniaturized capacitive loaded EBG structure performance has been analyzed to assess its' capability in reducing the mutual coupling in a microstrip patch array. Four columns of the miniaturized EBG structure have been placed between the array elements that are separated by a period of 109mm as shown in Figure 8. The array and dielectric constant have been kept identical to those in the previous structure of an array without EBG. The lumped capacitor components have been connected along the E-plane configuration, and expected to suppress the surface wave propagation between the elements. This arrangement has been chosen since the surface waves effect the E-plane radiation power with a marginal effect on the H-plane radiation [5, 7].

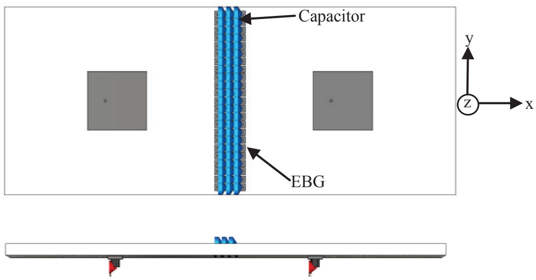


Figure 8: Microstrip patch array antenna with EBG

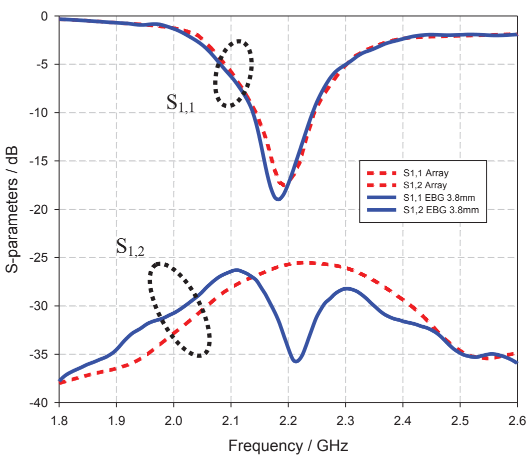
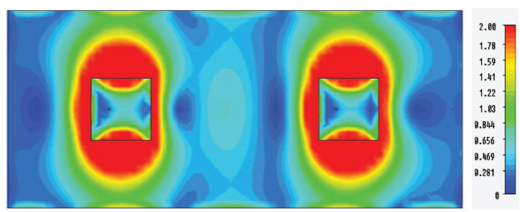


Figure 9: S-parameters for a patch array antenna

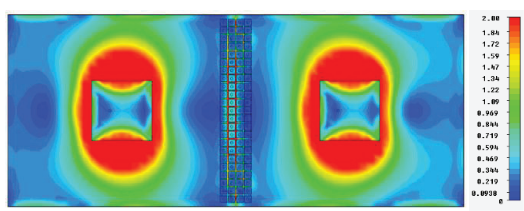
The simulated reflection coefficient for an array that is integrated with a miniaturized EBG is shown in Figure 9, where it can be noticed that the antenna resonates at approximately 2.2GHz. The existence of the EBG structure has a slight effect on the matching characteristics since the antenna still offers a good matching which indicates sufficient spacing within the EBG structure and the array elements.

The transmission coefficient result at 2.2GHz has been reduced from -26dB to -35dB when the EBG structure is utilized. These results show that the surface waves within the array elements have been suppressed remarkably when a miniaturized EBG is integrated within the elements.

Figure 10 illustrates the surface current density, where it can be noticed that the EBG structure reduces the current density between the elements. Figure 10(b) illustrates that the amplitude of the surface current between the array element and EBG structure is almost zero, but a much higher density can be observed at the middle of the latter. These results confirm the suppression of the surface current by the EBG structure, which dictates the reduction in mutual coupling and improvement in the isolation between the array elements.



(a)



(b)

Figure 10: Array surface current at the resonance frequency 2.2GHz.
(a) Patch Array (b) Array with a miniaturized EBG.

The radiation performance of the simulated and the results for the E-, and H-, plane radiation patterns are shown in Figures 11 and 12, respectively. The radiation pattern indicates that the power radiation for the array with EBG has exposed about 2dB increment in gain at 0°. The E-plane radiation pattern has approximately 3dB reduction in the radiation side lobes when EBG structure has been placed within the array element. These results illustrate that the integration of the EBG elements within the array has effectively suppressed the surface wave and improved the antenna radiation performance. The H-plane pattern shows a marginal difference between the patterns of an array with and without EBG. This is owing to the fact that almost no surface waves are excited in the H-plane even without EBG structure. Furthermore, the array is arranged in E-plane configuration, which has no definite effect on H-field radiation power.

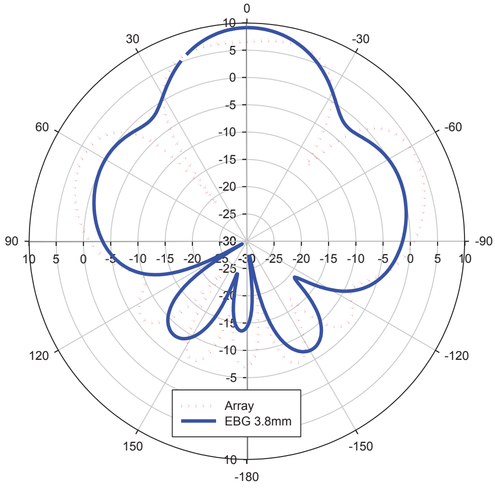


Figure 11: E-plane Radiation pattern for array antenna at 2.2GHz

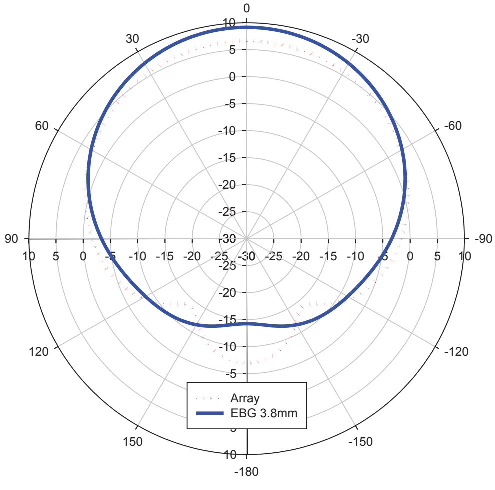


Figure 12: H-plane Radiation pattern for array antenna at 2.2GHz

C. Fabrication and Measurement

The prototypes of two elements array with and without a miniaturized EBG have been fabricated using double sided FR4 printed circuit board as shown in Figure 13 and 14. A finite ground of 218mm x 92mm has been chosen for both structures. The measured S-parameters are shown in Figure 15, which illustrates the performance of the array in term of the reflection coefficient and mutual coupling.

Figure.13: Front and back view of the two-element traditional microstrip path array

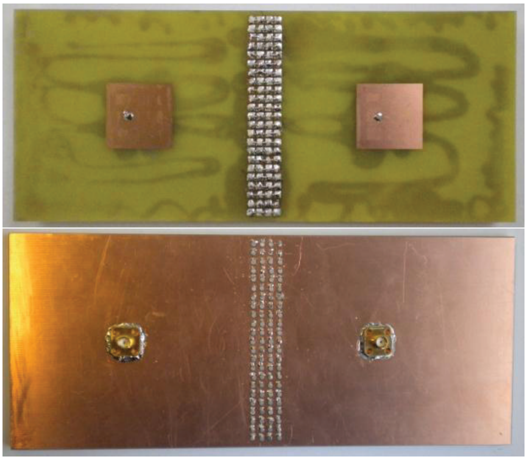


Figure 14: Front and back view of the two-element microstrip path array with miniaturized EBG

From Figure 15, it can be observed that the array elements, in both arrays, are matched at 2.2GHz with $|S_{11}|$ approximately -20dB. The antenna S_{11} is remain stable when integrated with EBG illustrates that the chosen gap between the radiating patches and the EBG structure is large enough. The operation bandwidths are approximately 4.45% for both array configurations. The measured mutual coupling between the elements at an operating frequency of 2.2GHz is reduced from -28dB to -40dB due to the integration of the miniaturized EBG into the array. A mutual coupling reduction of 12dB has been measured, which is better than the 9dB reduction which achieved in the simulation results. The comparison of the simulation results in Figure 9, and measurement results for both array configurations has shown very good agreement.

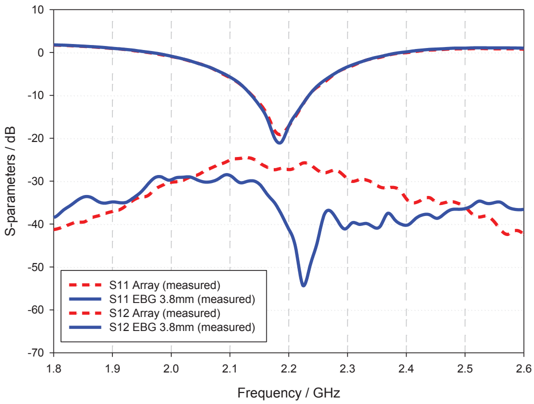


Figure 15: Measured S-parameters results of two-element arrays with and without miniaturized EBG

The E-plane radiation pattern has been measured as shown in Figure 16 and 17. The measured results indicate that the array with the EBG has approximately a 2dB increment in gain with compared to the array without EBG. Additionally, the results illustrate the side lobes reduction for the array with the miniaturized EBG compared to the traditional array. Good agreement has been achieved between the simulations and measurements on the evaluation of the EBG performance to improve the antenna radiation pattern. The result is also related to the effectiveness of the miniaturized EBG on suppressing the surface wave within the array elements.

For the array without EBG, the measured radiation pattern has illustrated no deep reduction at ±40° as observed from the simulated results. However this has no major impact on the overall performance, as the results are within the acceptable range and the main focus of this measurement is to analyze the performance of the miniaturized EBG. Reduction of radiation side lope for the array with EBG with compared to the traditional array illustrates the effectiveness of the miniaturized EBG to suppress the surface wave.

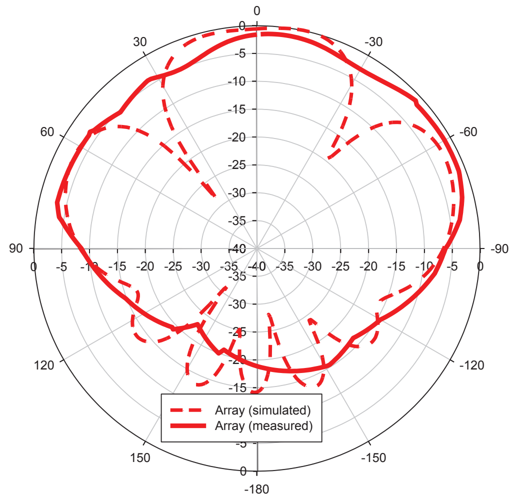


Figure 16: Comparison normalized E-plane Radiation pattern for array antenna at 2.2GHz. Array antenna without EBG (b) Array antenna with 3.8mm EBG

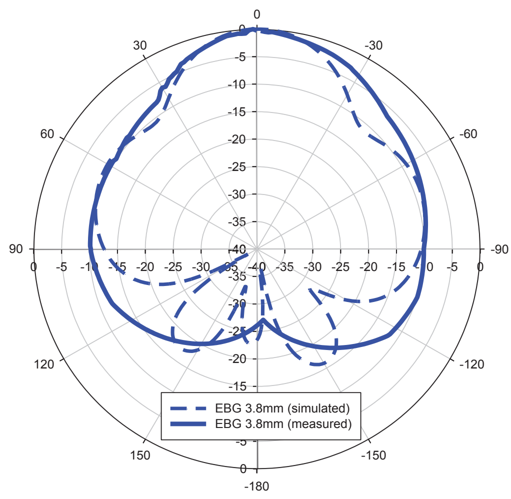


Figure 17: Comparison normalized E-plane Radiation pattern for array antenna at 2.2GHz. array with 3.8mm EBG

III. Conclusion

In this paper, a novel compact miniaturized capacitive loaded EBG with a period of 3.8mm (λ_0/36) has been developed and implemented in the design of a microstrip patch array to reduce the strong mutual coupling between the elements. The designed miniaturized EBG is approximately 75% smaller than the mushroom-like EBG, and with an approximately 22% operating bandwidth. The compact size of the EBG has been achieved by loading capacitive components within the EBG cells. The EBG operating frequency is mostly dependant on the loaded capacitor value and less influenced by the dimensions of the EBG elements.

The introduction of the miniaturized EBG structure between the array elements has demonstrated its capability of suppressing the surface waves. This was evident by the 12dB reduction of the mutual coupling at the resonance frequency. The incorporation of the miniaturized EBG in the array structure has improved the antenna E-plane gain by more than 2dB, with a 3dB reduction in the side-lobes without sacrificing the antenna compact size nor matching and bandwidth. A very good agreement has been achieved between measurement and simulations in all cases.

Acknowledgment

The authors would like to thank University of Sheffield for their facilities and the Malaysian government and Universiti Teknikal Malaysia Melaka (UTeM) for their financial support for this work in part under grant “Short term grant: PJP/2012/FKEKK(11C)/S01015“

References

[1] D. Pozar and D. Schaubert, "Analysis of an infinite array of rectangular microstrip patches with idealized probe feeds," *IEEE Transactions on Antennas and Propagation*, vol. 32, pp. 1101-1107, 1984.

[2] D. Pozar and D. Schaubert, "Scan blindness in infinite phased arrays of printed dipoles," *IEEE Transactions on Antennas and Propagation*, vol. 32, pp. 602-610, 1984.

[3] D. M. Pozar, "Scanning Characteristics of Infinite Arrays of Printed Antenna Subarrays," *IEEE Transactions on Antennas and Propagation*, vol. 40, pp. 666-674, 1992.

[4] M. A. Khayat, J. T. Williams, D. R. Jackson, and S. A. Long, "Mutual coupling between reduced surface-wave microstrip antennas," *IEEE Transactions on Antennas and Propagation*, vol. 48, pp. 1581-1593, 2000.

[5] M. M. Nikolic, A. R. Djordjevic, and A. Nehorai, "Microstrip antennas with suppressed radiation in horizontal directions and reduced coupling," *IEEE Transactions on Antennas and Propagation*, vol. 53, pp. 3469-3476, 2005.

[6] N. Alexopoulos and D. Jackson, "Fundamental superstrate (cover) effects on printed circuit antennas," *IEEE Transactions on Antennas and Propagation*, vol. 32, pp. 807-816, 1984.

[7] S. Xiao, M. C. Tang, Y. Y. Bai, S. Gao, and B. Z. Wang, "Mutual coupling suppression in microstrip array using defected ground structure," *IET Microwaves, Antennas & Propagation*, vol. 5, pp. 1488-1494, 2011.

[8] M. K. Mandal and S. Sanyal, "A Novel Defected Ground Structure for Planar Circuits," *IEEE Microwave and Wireless Components Letters*, vol. 16, pp. 93-95, 2006.

[9] D. Sievenpiper, Z. Lijun, R. F. J. Broas, N. G. A. A. N. G. Alexopolous, and E. A. Y. E. Yablonovitch, "High-impedance electromagnetic surfaces with a forbidden frequency band," *IEEE Transactions on Microwave Theory and Techniques*, vol. 47, pp. 2059-2074, 1999.

[10] Y. Ang and Z. Xuexia, "A Novel 2-D Electromagnetic Band-Gap Structure and its Application in Micro-strip Antenna Arrays," *3rd International Conference on Microwave and Millimeter Wave Technology Proceedings*, pp. 580-583, 2002.

[11] Y. Fan and Y. Rahmat-Samii, "Microstrip antennas integrated with electromagnetic band-gap (EBG) structures: a low mutual coupling design for array applications," *IEEE Transactions on Antennas and Propagation*, vol. 51, pp. 2936-2946, 2003.

[12] M. F. Abedin and M. Ali, "Reducing the Mutual-Coupling between the Elements of a Printed Dipole Array using Planar EBG Structures," *IEEE Antennas and Propagation Society International Symposium*, vol. 2A, pp. 598-601, 2005.

[13] H. Liu, K. L. Ford, and R. J. Langley, "Novel Planar Band Pass Lump-Loaded Frequency Selective Surface," *IEEE MTT-S International Microwave Workshop Series on Art of Miniaturizing RF and Microwave Passive Components*, pp. 87-89, 2008.

[14] L. Hui Lai, K. L. Ford, and R. J. Langley, "Design Methodology for a Miniaturized Frequency Selective Surface Using Lumped Reactive Components," *IEEE Transactions on Antennas and Propagation*, vol. 57, pp. 2732-2738, 2009.

[15] J. R. James and A. Henderson, "High-frequency Behaviour of Microstrip Open-circuit Terminations," *IEE Journal on Microwaves, Optics and Acoustics*, vol. 3, pp. 205-218, 1979.

[16] Z. Iluz, R. Shavit, and R. Bauer, "Microstrip antenna phased array with electromagnetic bandgap substrate," *IEEE Transactions on Antennas and Propagation*, vol. 52, pp. 1446-1453, 2004.

[17] B. Sanz-Izquierdo, E. A. Parker, J. B. Robertson, and J. C. Batchelor, "Tuning technique for active FSS arrays," *Electronics Letters*, vol. 45, pp. 1107-1109, 2009.

[18] C. Mias, "Varactor-tunable frequency selective surface with resistive-lumped-element biasing grids," *IEEE Microwave and Wireless Components Letters*, vol. 15, pp. 570-572, 2005.

[19] M. S. Mohamad Isa, R. J. Langley, S. Khamas, A. Awang Md Isa, M. S. I. M. Zin, F. M. Johar, and Z. Zakaria, "Antenna Beam Steering using Sectorized Square EBG," *Journal of Telecommunication, Electronic and Computer Engineering (JTEC)*, vol. 4 No 1, pp. 39-44, 2012.

[20] M. S. Mohamad Isa, R. J. Langley, and S. Khamas, "Antenna control using EBG," *Proceedings of the 5th European Conference on Antennas and Propagation (EUCAP)*, pp. 216-219, 2011.

[21] M. S. Mohamad Isa, R. J. Langley, and S. Khamas, "Antenna pattern diversity using EBG," *Loughborough Antennas and Propagation Conference (LAPC), 2010*, pp. 325-328.

[22] D. F. Sievenpiper, "High-Impedance Electromagnetic Surfaces," in *Electrical Engineering*, vol. PhD: University of California, Los Angeles, 1999.

[23] R. Jedlicka, M. Poe, and K. Carver, "Measured mutual coupling between microstrip antennas," *IEEE Transactions on Antennas and Propagation*, vol. 29, pp. 147-149, 1981.

[24] Y. Fan and Y. Rahmat-Samii, "Microstrip antennas integrated with electromagnetic band-gap (EBG) structures: a low mutual coupling design for array applications," *IEEE Transaction on Antennas and Propagation*, vol. 51, pp. 2936-2946,2003.