

CYLINDRICAL CAVITY EBG FOR SUB-6 GHZ MSA ARRAY

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Abstract

The utilization of metamaterials in electromagnetic band gap or EBG structure to improve the performance of a microstrip antenna (MSA) was investigated. A typical MSA array has a bandwidth of 5.2 GHz (1.42-6.62 GHz). This covers the frequency ranges supporting sub-6 GHz frequency bands applications such as cellular, ISM, WiMAX, Machine to Machine (M2M), and Internet of Things (IoT). Results determined that the cylindrical woodpile cavity EBG structure was appropriate for a beam shaped MSA array as the installation resonant circuit put on an antenna. The procedure for efficiency progression, especially gains and impedance matching, transferred the EM field radiating from an MSA array through the cylindrical woodpile cavity EBG and achieved a better overall MSA array performance. Average gains of all operating frequencies of the proposed antenna were improved by around 3.3 dB when compared to an MSA array without EBG. This concept was validated by both simulated and measured results. Good concurrence between the simulations and experimental results were achieved.

Keywords: Metamaterial, Electromagnetic Band Gap (EBG), microstrip antenna, Sub-6 GHz applications

Introduction

Improvement of antenna performance has become necessary to increase the efficiency of new services and networks, especially for the novel ranges of modern wireless communication systems, especially the sub-6 GHz frequency bands that have mushroomed with technological developments such as 5G sub-6 GHz cellular, wireless networking (Wi-Fi) using the 2.4 and 5.7 GHz ISM bands following the IEEE 802.11 standard, WiMAX following the IEEE 802.16 standard, M2M, and IoT devices. A microstrip antenna (MSA) is the preferred antenna for modern communication applications as

its simple structure, light weight, and compact low profile with adaptability for design and fabrication (Bahl and Bhartia, 1980; Bhartia *et al.*, 2000). Because the MSA is a resonant-type antenna, this has two main disadvantages as narrow impedance bandwidth and low gain due to its resonant nature. Consequently, the design of an MSA must respond to a wideband and high gain antenna. The slot structure is more suitable to achieve a wideband antenna because this structure is simple and easy to fabricate, with especially wide bandwidth performance. The coplanar waveguide (CPW) fed

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structure with slots, as reviewed by (Chen, 2003; Chaimool *et al.*, 2005; Tang *et al.*, 2007; Krishna *et al.*, 2009; William and Nakkeeran, 2009) is a good design for simulating a wide bandwidth antenna. This is formed of rectangular slots with a metal tuning stub fed by a CPW feed line. A CPW fed slot antenna was proposed by (Hongnara *et al.*, 2011), where the functional bandwidth was defined by the length of the stub. Advantages of the CPW fed slot antenna structure include its ease of integration and simplicity to match impedance and conduct bandwidth. Therefore, here, this antenna was selected for sub-6 GHz applications.

Many new technologies have recently appeared as modern antenna designs. One breakthrough is the advancement in metamaterials as artificial materials with acceptable electromagnetic properties not readily found in nature (Kshetrimayum, 2005). The utilization of metamaterials on an electromagnetic band gap (EBG) structure for antenna design comes to be a new research direction that appears to be attractive to antenna engineers (Yang and Rahmat-Samii, 2008). An EBG structure is capable to design a competent low profile antenna, get rid of the surface waves, and enhance the performance of the antenna by improving its directivity, gain, and radiation efficiency (Gonzalo *et al.*, 1999; Thevenot *et al.*, 1999; Yang and Rahmat-Samii, 2003). The EM properties of an EBG structure are defined and optimized by its physical dimensions (Weily *et al.*, 2005).

Theoretically, high gain antennas are achieved by utilizing a parabolic antenna or large antenna array; nevertheless, the curved surface of a parabolic antenna does not easily conform to mobile platforms where large antenna arrays are overabundant long and heavy. Moreover, high amounts of electromagnetic energy are lost inside the phasing lines of a feed network. Thus, the proper structure of a resonant EBG to improve antenna gain includes as an additional a resonant circuit placed in front of the antenna to exhibit band gap characteristics at the operating frequency. A cylindrical resonant cavity was found to be more suitable for a beam shaped CPW fed slot antenna. Gains of a 4×1 MSA array with a cylindrical woodpile cavity EBG improved by nearly 3 dB for all operating frequencies when compared to a 4×1 MSA array without EBG. Gains of a 4×1 MSA array with EBG structure were the same as gains achieved by an 8×1 MSA array. Therefore, here, we present the application of a cylindrical woodpile cavity EBG structure to achieve performance improvement in an MSA array for sub-6 GHz applications. This proposed concept offers the good points of decreasing the total length and feed loss of the MSA

array, while also increasing gain, with the easy installation of a low profile antenna.

Microstrip Antenna and EBG Configurations Design of Microstrip Antenna

A CPW fed structure with a tuning stub and a rectangular slot was applied to excite a wide bandwidth for the MSA. It was composed of a rectangular stub to match impedance by adjusting the gap between the tuning stub and the ground plane. To optimize operation in sub-6 GHz applications, a frequency range of 1.33-6.69 GHz was selected as the prototype for our proposed antenna. Operating frequencies of 1.8 GHz, 2.1 GHz, 2.45 GHz, 2.6 GHz, 3.5 GHz, 5.2 GHz, and 5.8 GHz were investigated in this paper, supporting WLAN, WiMAX, and mobile GSM technologies. Our proposed antenna, printed on an FR4 substrate ($\epsilon_r = 4.5$, $\tan\delta = 0.02$) was defined as a rectangular stub with dimensions of $W_T = 48$ mm, $L_T = 50$ mm, $W_A = 25$ mm, $L_B = 10$ mm, $W_L = 2$ mm, $L_F = 16.5$ mm, $L_{S2} = 9.8$ mm, $L_{S3} = 7.72$ mm, $a = 2.88$ mm, and $h = 1.6$ mm (Hongnara *et al.*,

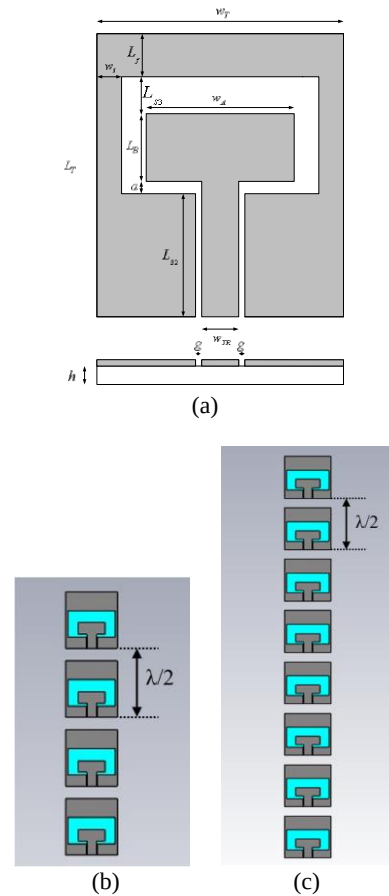


Figure 1. Shows the MSA: (a) Single MSA, (b) A 4×1 MSA array, (c) An 8×1 MSA array

2011) Figure 1(a). The antenna was fed by a 50 Ω CPW feed line with strip width (W_{TR}) of 9 mm and a distance gap (g) of 0.55 mm. Simulation of the impedance bandwidth of this proposed antenna was decided by the width and length of the tuning stub, while impedance matching depended on the location of the tuning stub in a rectangular slot. A waveguide port for CPW feeding was used for S-parameter computation to calculate pattern of E- and H-field, line impedance, and radiation.

To improve signal gain, the MSA was chosen as a 4×1 array with element spacing of $\lambda/2$ as shown in Figure 1(b). Effects of the variation of λ on the operating frequencies of 1.8 GHz, 2.1 GHz, 2.45 GHz, and 2.6 GHz were observed. A λ value at higher frequencies than 3.5 GHz caused the elements to overlap. Element spacing of the antenna array was applied to operate the impedance bandwidth and impedance matching of a 4×1 MSA array. The return loss or S_{11} changed when the element spacing was varied as shown in Figure 2. The bandwidth of a 4×1 MSA array with element spacing of $\lambda/2$, with λ of 2.6 GHz, can support sub-6 GHz applications; however, gains of all operating frequencies were lower than gains obtained from λ of 2.45 GHz. Therefore, an element spacing of $\lambda/2$, with λ of 2.45 GHz was chosen. In addition, an 8×1 MSA array was simulated to examine the gain characteristics and its configuration as illustrated in Figure 1(c). The simulation results suggested that gains of all operating frequencies increased on average by around 4.06 dB for the 4×1 MSA array, and by 6.89 dB for the 8×1 MSA array as shown in Table 1.

Design of Cylindrical Woodpile Cavity EBG

Theoretically, a high gain antenna requires a large antenna array; however, large antenna arrays increase the weight and size of the structure, while high electromagnetic energy is attenuated inside the feed line. Our investigations determined that the signal gain of the woodpile EBG structure was improved when adding a resonant circuit was placed

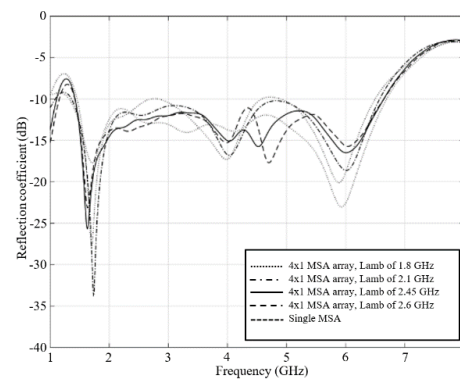


Figure 2. Shows simulated results of S_{11} against frequency for different values of element

in front of the antenna. This allowed us to conduct and control the flow of EM waves as desired. The frequency range in the woodpile EBG structure also propagated modes that could be eliminated in one or more dimensions. This range of frequency eliminated the transmission of radiation performance when performed with antennas. The planar woodpile structure (Weily *et al.*, 2005; Lee *et al.*, 2009) applied for the design of the cylindrical woodpile cavity EBG structure was produced from alumina materials ($\epsilon_r = 9.6$, $\tan\delta = 0.001$). A cylindrical woodpile cavity is distinct from a planar woodpile; horizontal filaments are not inserted but maintained as straight at the same horizontal location. Therefore, a cylindrical woodpile cavity structure can be stimulated by vertical electric fields along the axis of the cylinder that must have vertically aligned gratings. These are achieved by piled horizontal filaments crossing at the same location. A transverse magnetic (TM) resonant mode will arise in the cylindrical woodpile cavity if the structure does not have a 3D band gap, and requires only a band gap with radial direction. The cylindrical woodpile cavity structure is also more appropriate for a beam shaped MSA array because this structure can create equal phases of wave transmission from an MSA array, causes of maximum resonance.

Table 1. Shows results of simulation

Simulated results		MSA antenna			
		Single MSA	4×1 MSA array	4×1 MSA array with EBG	8×1 MSA array
Frequency Range (GHz)		1.33-6.69	1.43-6.64	1.43-6.65	1.36-6.63
Bandwidth		5:1	4.64:1	4.65:1	4.88:1
Gain (dB)	1.8 GHz	1.60	5.41	8.76	8.11
	2.1 GHz	2.08	6.36	9.76	9.18
	2.45 GHz	2.73	7.33	10.73	10.23
	2.6 GHz	3.01	7.71	11.14	10.56
	3.5 GHz	3.99	9.87	13.44	12.82
	5.2 GHz	5.25	7.07	10.89	9.96
	5.8 GHz	4.96	8.23	11.64	10.95
Average		3.37	7.43	10.91	10.26
Dimensions Width × Height (mm)		48×50	48×234	60×244	48×479

Figure 3 shows the cylindrical woodpile cavity EBG structures with different diameters of two filament rings and 18 radial filaments layered together. The design parameters for the cylindrical woodpile EBG structures were (Lee *et al.*, 2010; Kamphikul *et al.*, 2019) filament thickness or diameter (w), height or length (h), number of radial filaments (N_{rad}), number of rings (N_{ring}) of the cylinder, and radius of each ring ($R_1, R_2, \dots, R_n$), where $n = N_{ring}$.

To design and optimize the parameters of a cylindrical woodpile cavity structure, we considered the effect of the variation of the number of rings, as N_{ring} , the distance between the rings, d ($d = R_2 - R_1$), the radius of the innermost ring R_1 , and the height h . First, a rectangular unit cell with w and d fixed at 0.014λ and 0.04λ (λ of 2.45 GHz), respectively was used for a cylindrical woodpile cavity EBG, as shown in Figure 3(a). Then, we investigated the effect of variation of N_{ring} . This was simulated utilizing the periodic boundary condition, and the transmission characteristic was examined as illustrated in Figure 4(a). For EBG design, particularly for antenna applications, the transmission characteristic is adequate for examining the band gap of the EBG structure because it is simple to identify (Yao *et al.*, 2006; Wang *et al.*, 2007). A frequency range with a transmission coefficient or S_{21} less than -10 dB is normally determined as the band gap for an EBG structure (Aminian *et al.*, 2003). We found that the band gap at our design frequency range and level of elimination accrued when N_{ring} increased. Thus, $N_{ring} = 2$ was sufficient. Second, we investigated the effect of the distance d using a rectangular unit cell. Figure 4(b) shows the difference in S_{21} against frequency for variation of distance d . The resonant frequency, 2.45 GHz in this study, of the band gap shifted with distance d , while the transmittance level also varied when distance d altered. As a result, this property is used to control the resonant frequency of a cylindrical woodpile cavity EBG.

Next, a cylindrical woodpile cavity EBG structure was used to study the effect of the radius R_1 and the height h . The radius R_2 and the number of radial filaments or N_{rad} were determined as $R_2 = 1.2R_1$ and $N_{rad} = 18$. A 4×1 MSA array source at the center of the cavity was applied for the excitation. Initially, we studied the effect of R_1 variation versus the average gain of all operating frequencies; h was set at 1λ (36 layers) and the result enhanced as shown in Figure 5(a). Highest average gain was provided when R_1 was around 0.2λ . Then, the effect of the cylindrical woodpile cavity height or h was addressed, as shown in Figure 5(b). This significant parameter was defined as the highest aperture capability, when disregarding unimportant parts in

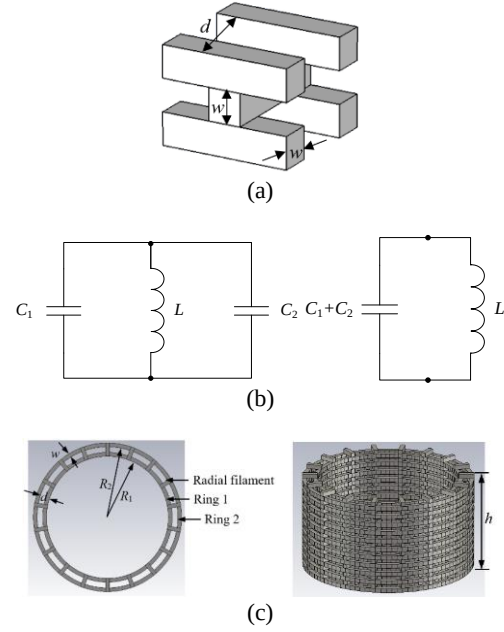


Figure 3. Shows the cylindrical woodpile cavity EBG structure: (a) A rectangular unit cell, (b) The lumped LC circuit, (c) A unit-layer ($N_{ring} = 2$, $N_{rad} = 18$), (d) An eleven-layer unit

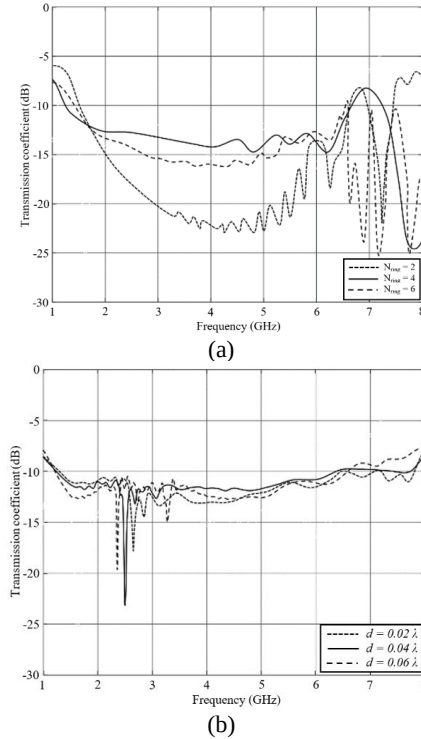


Figure 4. Shows simulated results of S_{21} against frequency of the unit cell: (a) Different numbers of N_{ring} , (b) Different values of distance d

the antenna, that was not conducive to the radiation. We noticed that the gain improved from 7.6 dB to 10.91 dB at h equal to 2λ (72 layers). However, the gain also improved when h increased. When h was higher than 2λ , the frequency range of the bandwidth shifted to undesired frequencies, and the bandwidth did not support sub-6 GHz applications. Finally, the optimized parameters of a cylindrical woodpile cavity EBG structure were selected as the most appropriate and efficient as follows: $w = 0.014\lambda$ (1.7 mm), $N_{rad} = 18$, $N_{ring} = 2$, $d = 0.04\lambda$ (4.8 mm), $R_1 = 0.2\lambda$ (24.4 mm), $R_2 = 0.24\lambda$ (30 mm), and $h = 2\lambda$ (244 mm or 72 layers).

Simulated Results and Discussions

The design of a 4×1 MSA array placed in the cavity of a cylindrical woodpile EBG structure is shown in Figure 6. The match structure of the woodpile EBG can improve the gain of the antenna as an added resonant circuit covering the MSA array. This method radiates the electromagnetic field from a 4×1 MSA array through the cavity of the cylindrical woodpile EBG structure. Equal phases of wave transmission from the MSA array result in ultimate resonance. Operating frequencies for

sub-6 GHz applications are 1.8 GHz, 2.1 GHz and 2.6 GHz for mobile GSM technologies, 2.45 GHz, 5.2 GHz and 5.8 GHz for WLAN applications, and 3.5 GHz for WiMAX applications. Moreover, an 8×1 MSA array model was simulated to compare the antenna gains. Once the optimized parameters of a cylindrical woodpile cavity EBG structure are known, then the simulated results can be calculated using electromagnetic simulation software. The S_{11} and gain of our proposed antenna, plotted in Figures 7 and 8, respectively, were in the frequency range of 1.43-6.65 GHz. This was wide enough to be used for sub-6 GHz applications. Figure 9 shows the normalized radiation patterns of the operating frequencies of 1.8 GHz, 2.1 GHz, 2.45 GHz and 3.5 GHz, while the performance of frequency ranges, bandwidths, and gains of a single MSA, a 4×1 MSA array with and without a cylindrical

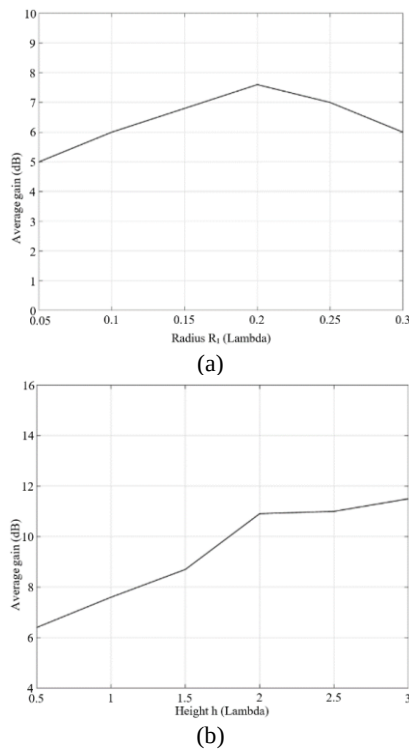


Figure 5. Shows simulated results of average gain of a cylindrical woodpile cavity structure: (a) Different values of R_1 , (b) Different values of h

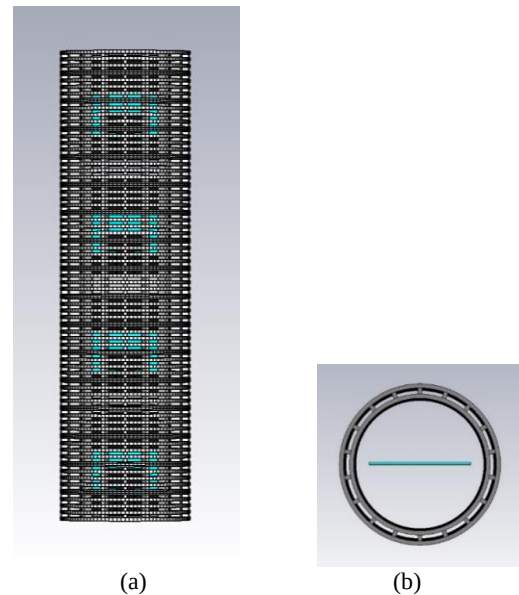


Figure 6. Shows A 4×1 MSA array with a cylindrical woodpile EBG structure: (a) Front view, (b) Top view

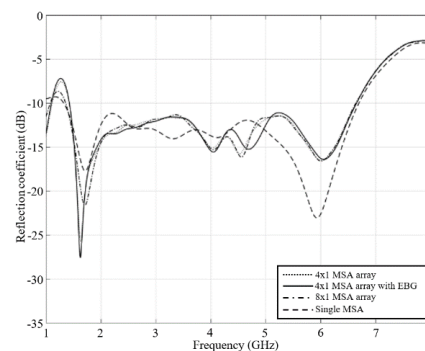


Figure 7. Shows simulated results of S_{11} of MSAs

woodpile cavity EBG structure, and an 8×1 MSA array are summarized in Table 1. Average gain of a 4×1 MSA array with a cylindrical woodpile cavity EBG structure increased by about 3.48 dB when

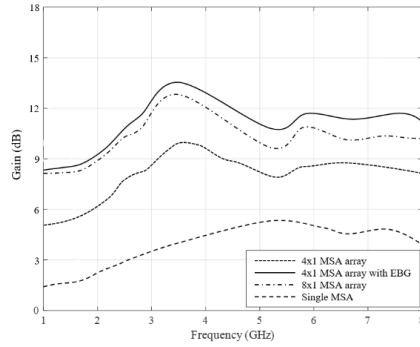


Figure 8. Shows simulated results of gain of MSAs

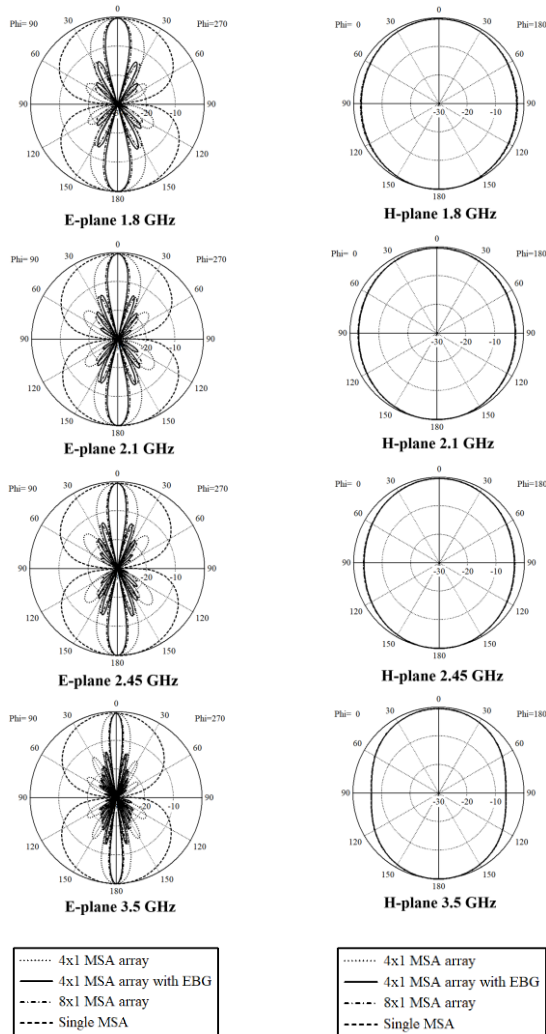


Figure 9. Shows simulated results of radiation patterns of MSAs

compared to a 4×1 MSA array without EBG, with an increase of around 0.65 dB compared to an 8×1 MSA array. In addition, it is observed that this proposed technique offers a good point of reducing the total length of an MSA array, while also increasing gain.

Measured Results and Discussions

The general background and theory behind our proposed antenna for sub-6 GHz applications, and antenna measurements for the final verification are presented. Electromagnetic simulation software often correctly predicts antenna characteristics; however, for some parameters only measurements can provide accurate data. In all cases, it is useful to verify the computed results by simulation with measurements to certify antenna performance. Therefore, the antenna prototype was fabricated and its performances as S_{11} , bandwidth, radiation patterns and gain were measured and discussed.

Our antenna prototype was constructed as shown in Figure 10 to verify the proposed concept. The geometry was composed of a 4×1 MSA array with a cylindrical woodpile cavity EBG structure. A 4-way Wilkinson power divider was applied for antenna array feeding network, which is necessary to calibrate the system before any S-parameter measurements are performed. Both simulated and measured S_{11} of this antenna are shown in Figure 11. From the measured S_{11} , it can be observed that the bandwidth was extend with good matching, but the some frequencies was shifted. This is due to

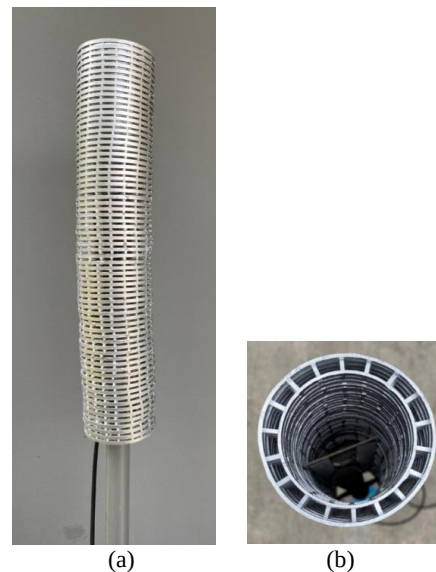


Figure 10. Shows the proposed antenna prototype: (a) Front view, (b) Top view

retaining the desired frequency band gap of the EBG structure. Figure 12 shows the gain of the proposed antenna. The simulated and the measured results were in good agreement. Moreover, the measured result showed that the frequency bandwidth covered the range of 1.38-6.63 GHz, and this was sufficient to cover frequency bands for sub-6 GHz applications. Additional study of our proposed antenna is interested in its radiation efficiency, as shown in Figure 13. The radiation pattern results conform to the S_{11} result. It is noticeable the SLLs and the HPBW are alike between measured and simulated results. Moreover, measured and simulated results of all operating frequency gains are shown in Table 2, and these results showed good agreement with each other.

Abbreviations

CPW	Coplanar waveguide
EBG	Electromagnetic Band Gap
E-Field	Electric field
EM Waves	Electromagnetic waves
H-Field	Magnetic field
HPBW	Half Power Beam Width
IoT	Internet of Things

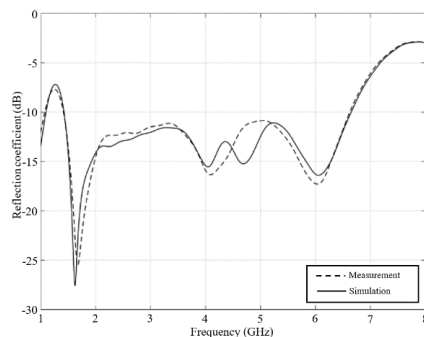


Figure 11. Shows the S_{11} of the proposed antenna

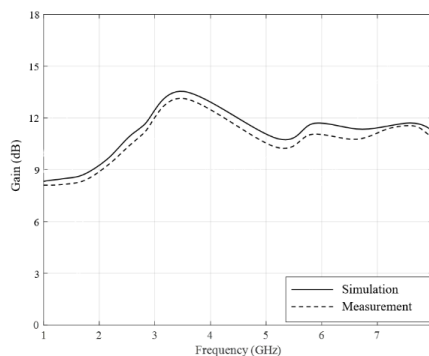


Figure 12. Shows the gain of the proposed antenna

ISM Band	Industrial, Scientific and Medical band
M2M	Machine to Machine

Table 2. Shows results of measurement

Results	4×1 MSA array with EBG	
	Simulation	Measurement
Frequency Range (GHz)	1.43-6.65	1.42-6.62
Bandwidth	4.65:1	4.66:1
Gain (dB)		
1.8 GHz	8.76	8.42
2.1 GHz	9.76	9.47
2.45 GHz	10.73	10.43
2.6 GHz	11.14	10.83
3.5 GHz	13.44	13.15
5.2 GHz	10.89	10.36
5.8 GHz	11.64	10.96
Average	10.91	10.52

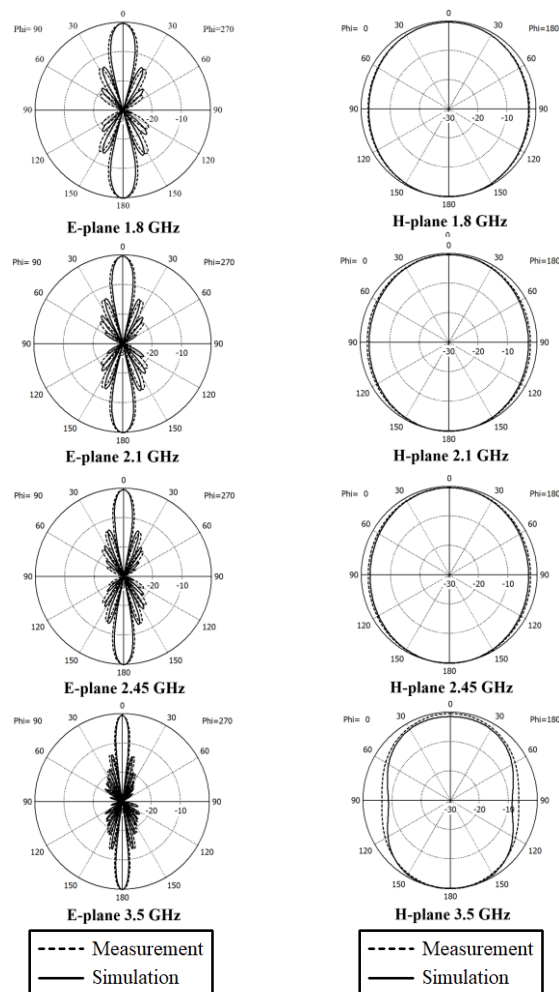


Figure 13. Shows radiation patterns of the proposed antenna

MSA	Microstrip Antenna
SLL	Side Lobe Level
TM	Transverse Magnetic

Conclusions

In this study, we successfully demonstrated a technique using metamaterial on a cavity cylindrical woodpile EBG structure to increase the performance of a MSA array for sub-6 GHz applications. This approach for performance improvement in terms of gains in impedance matching involved transmitting the EM fields radiating from an MSA array through the cavity of a cylindrical woodpile EBG structure. This method improved the overall effectiveness of the antenna. Our proposed technique offers advantages of reducing the total length and losses of the feed network of an MSA array, while also increasing gain with the easy installation of a low profile antenna. Good agreement was accomplished between the experimental results and computer numerical data. This proposed antenna is more appropriate for sub-6 GHz applications in accordance with our requirements.

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References

- Aminian, A., Yang, F., and Rahmat-Samii, Y. (2003). In-phase reflection and EM wave suppression characteristics of electromagnetic band gap ground planes. In: Proceedings of the IEEE Antennas and Propagation Society International Symposium. Digest. Held in conjunction with: USNC/CNC/URSI North American Radio Sci. Meeting (Cat. No.03CH37450), Columbus, OH, p. 430-433.
- Bahl, J.J. and Bhartia, P. (1980). *Microstrip Antennas*. 1st ed. Artech House, 355p.
- Bhartia, P., Garg Inder Bahl, R., and Ittipipoon, A. (2000). *Microstrip Antennas Design Handbook*. 1st ed. Artech House, 875p.
- Chaimool, S., Akkaraethalin, P., and Vivek, V. (2005). Dual-band CPW-fed slot antennas using loading metallic strips and a widened tuning stub. *IEICE Transactions on Electronics*, E88-C(12):2,258-2,265.
- Chen, H.D. (2003). Broadband CPW-Fed square slot antennas with a widened tuning stub. *IEEE Trans. Anten. Propag.*, 51(8):1,982-1,986.
- Gonzalo, R., Maagt, P.de, and Sorolla, M. (1999). Enhanced Path-Antenna Performance by Suppressing Surface Waves using Photonic-Bandgap Substrates. *IEEE Transactions on Microwave Theory and Techniques*, 47(11):2,131-2,138.
- Hongnara, T., Mahatthanajaturphat, M., and Akkaraethalin, P. (2011). Study of CPW-fed slot antenna with fractal stub. In: *Proceeding of the 8th Electrical Engineering/ Electronics, Computer, Telecommunications and Information Technology (ECTI) Association of Thailand - Conference 2011, Khon Kaen*, p. 188-191.
- Kamphikul, P., Kampeephat, S., and Wongsan, R. (2019). Efficiency Improvement of Patch Antenna with Metamaterial Technique for Modern Wireless Communication Applications. In: *Proceedings of the 2019 Photonics & Electromagnetics Research Symposium - Spring (PIERS-Spring)*, Rome, Italy, p. 3,609-3,613.
- Krishna, D.D., Gopikrishna, M., Annandan, C.K., Mohanan, P., and Vasudenan, K. (2009). Compact wideband Koch fractal printed slot antenna. *IET Microwave Antennas Propagations*, 3(5):782-789.
- Kshetrimayum, R.S. (2005). A brief intro to metamaterials. In: *IEEE Potentials*, 23(5):44-46.
- Lee, Y., Lu, X., Hao, Y., Yang, S., Evans, J.R.G., and Parini, C.G. (2010). Narrow-beam azimuthally omni-directional millimetre-wave antenna using freeformed cylindrical woodpile cavity. *IET Microwaves Antennas and Propagation*, 4(10):1,491-1,499.
- Lee, Y., Lu, X., Hao, Y., Yang, S., Evans, J.R.G., and Parini, C.G. (2009). Low profile directive millimeter-wave antennas using free formed three-dimensional (3D) electromagnetic band gap structures. *IEEE Transactions on Antennas and Propagation*, 57(10):2,893-2,903.
- Tang, I.T., Lin, D.B., Liou, G.H., Hong, J.H., and Li, C.M. (2007). A compact slot UWB antenna with CPW-fed. In: *Proceedings of the 2007 IEEE Antennas and Propagation Society International Symposium*, Honolulu, HI, p. 5,143-5,146.
- Thevenot, M., Cheype, C., Reineix, A., and Jecko, B. (1999). Directive Photonic Band-Gap Antennas. *IEEE Transactions on Microwave Theory and Techniques*, 47(11):2,115-2,122.
- Wang, Y., Huang, J., and Feng, Z. (2007). A novel fractal multiband EBG structure and its application in multi-antennas. In: *Proceedings of the 2007 IEEE Antennas and Propagation Society International Symposium*, Honolulu, HI, p. 5,447-5,450.
- Weily, A.R., Horvath, L., Esselle, K.P., Sanders, B., and Bird, T. (2005). A planar resonator antenna based on woodpile EBG material. *IEEE Trans. Anten. Propag.*, 53(1):216-223.
- William, J. and Nakkeeran, R. (2009). A novel compact CPW-fed wideband slot antenna. In: *Proceedings of the 2009 3rd European Conference on Antennas and Propagation*, Berlin, p. 1,471- 1,474.
- Yang, F. and Rahmat-Samii, Y. (2003). Reflection phase characterizations of the EBG ground plane for low profile wire antenna applications. *IEEE Transactions on Antennas and Propagation*, 51(10):2,691-2,703.
- Yang, F. and Rahmat-Samii, Y. (2008). *Electromagnetic Band Gap Structures in Antenna Engineering*. Cambridge: Cambridge University Press.
- Yao, Y., Wang, X., and Feng, Z. (2006). A novel dual-band Compact Electromagnetic Bandgap (EBG) structure and its application in multi-antennas. In: *Proceedings of the 2006 IEEE Antennas and Propagation Society International Symposium*, Albuquerque, NM, USA, p. 1,943-1,946.