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A Small Electromagnetic Bandgap Structure

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***Abstract* — We present a small Electromagnetic Bandgap (EBG) cell which is easy to fabricate on standard PCB material and can be used where space is a premium. The EBG structure is an extension of the classical uni-planar structure where the inductance due to the thin transmission line sections is increased by meandering these microstrip lines within the EBG cell itself. We demonstrate the concept with an EBG surface that was designed and developed at 300 MHz on standard FR4. The size of a 3 × 3 structure is only 7.53 cm × 7.53 cm and provides 10 dB attenuation across the surface.**

***Index Terms* — Electromagnetic Bandgap structures, artificial magnetic conductors, high impedance ground planes.**

I. INTRODUCTION

Electromagnetic Bandgap (EBG) structures, artificial magnetic conductors, metamaterials, or high impedance ground planes [1 – 4] have received much attention due to their interesting electromagnetic properties. These structures can prevent the propagation of electromagnetic energy along their surface over a band of frequencies and therefore can be used to reduce electromagnetic interference in circuits [5], or even reduce radiation in a particular direction when coupled to an antenna [6].

One potential issue related to an EBG structure is the overall size required to make these surfaces effective; essentially the behavior of the EBG structure in based on the interactions between adjacent cells and therefore the larger the number of cells, the more effective the structure. This can be a problem when there is limited real-estate for the structure, especially when trying to integrate EBG surfaces with wireless communication devices/radiators that operate in the lower microwave frequency spectrum (less than 1 GHz). Having said this, the structure presented in [6] was only three cells wide and was still able to operate effectively over the band of interest at 2.4 GHz. However the size of the cell is a critical issue if EBG structures are to be integrated with other RF components for applications below 1 GHz.

Recently there has been research into making the cell of an EBG structure smaller. For example, in the work presented in [7, 8] significant element size reduction was achieved for structures operating above 1 GHz, albeit at the expense of bandwidth which is consistent with fundamental electromagnetic theory [9]. The reduction in operating bandwidth is not a problem for most low microwave frequency wireless applications as the transmission bandwidths are usually less than 10 % of the carrier frequency.

In this paper we present a new small EBG cell that can be used in applications where there is only a limited space available for the EBG structure. The concept is an extrapolation of the EBG structure presented in [2] and is relatively straightforward to design. We will present the design philosophy and equations used to create the new structure. We will also give an example of the EBG structure designed and realized at 300 MHz using low cost FR4 as the substrate. Although the overall structure of this new EBG is only 7.53 cm × 7.53 cm in size, it can still provide 10 dB attenuation of power across its surface.

II. CONFIGURATION AND DESIGN

As described earlier, the design of the proposed EBG structure is based on the uni-planar surface presented in [2]. There are several advantages of the uni-planar EBG structure compared to the 'mushroom' version created by Sievenpiper [1]. Firstly, no vias are required for the uni-planar version which dramatically simplifies the fabrication process. Also, the uni-planar geometry can operate on electrically thin materials, which is important when investigating applications in the low microwave frequency spectrum [10]. Unfortunately the unit cell of the uni-planar EBG structure is typically larger than the 'mushroom' version and therefore for a given number of cells, these surfaces are larger. A photograph of a conventional uni-planar EBG structure designed for operation at 1 GHz is shown in Fig.1 highlighting the unit cell of the surface.

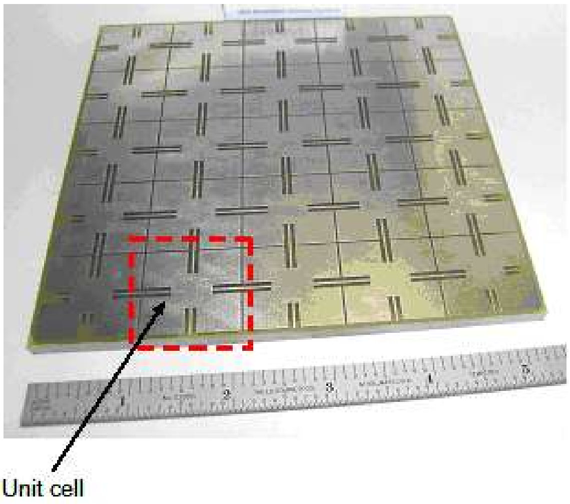

Fig. 1. Photograph of a uni-planar EBG structure.

For the EBG cells in [2], the gap between adjacent cells effectively provides the necessary capacitance for the distributed ‘resonant’ structure and the inductance is provided by the thin interconnecting transmission lines. We showed in [10] that the bandgap nature of this structure can intuitively be derived from the formation of a parallel inductance and capacitance. We can then approximate the inductance, *L*, by the following formula:

$$L = \frac{Z_0 \cdot l \cdot \sqrt{\varepsilon_e}}{c} \qquad (1)$$

where Z_0 is the characteristic impedance of the thin section of microstrip transmission line, l is the length of this line, ε_e is the effective dielectric constant of the transmission line, and c is the speed of light. The capacitance can be derived from the same formula used to determine the capacitance, *C*, of the Sievenpiper structure (see Equation 5.1.3 in [11]):

$$C = w\,(\varepsilon_1 + \varepsilon_2)/\pi\,.\,\cosh^{-1}(a/g) \qquad (2)$$

In Eqn. 2, g is the gap between cells; ε_1 and ε_2 are the effective dielectric constants of the transmission line (for the uni-planar case, ε_1 is the effective dielectric constant of the grounded substrate and $\varepsilon_2 = 1$); W is the width of the cell; and $a = w + g$. Using the two formulae above it is relatively straightforward to design a uni-planar EBG structure for a given material and frequency [10].

When applying Eqns. 1 and 2 to a structure that is required to operate below 1 GHz, the overall size of the surface becomes unwieldy and therefore impractical to integrate with small RF devices or radiators. For example, using 1.6 mm thick FR4 and a geometry similar to that presented in [2] and shown in Fig. 1, the EBG cell dimensions would be 10 cm × 10 cm for a structure to operate at 300 MHz. Using 3 cells in each lateral direction would then require an overall structure approximately 30 cm × 30 cm in size. This size is unrealistic a variety of applications for the purposes of integration with RF devices or radiators.

To lower the frequency of operation of the EBG structure, either the inductance in (1) or the capacitance in (2) must be increased. Increasing the capacitance between adjacent cells is really limited by the fabrication process used to produce the structure, the resolution of which is typically limited to 0.1 mm using standard processes. Incorporating high dielectric constant material can reduce the overall size of the EBG structure for a particular frequency, however for applications where cost is important this is typically not a viable option. In any case, using the uni-planar structure in [2] with a dielectric constant of 10.2 only reduces the size of the cell to 7 cm × 7 cm.

Fig. 2 shows a schematic highlighting the printed pattern of the cell of the proposed EBG structure. The structure is developed on a grounded substrate (not shown in Fig. 2) as for the classical uni-planar EBG surface. To maximize the inductance of the EBG structure, we have used a thin meander microstrip line within the cell. We chose the thinnest line possible such that we maximize the inductance. The length of the line is directly proportional to the overall inductance as defined in (1) and therefore by increasing the length of line, we can reduce the frequency of operation. The meander line is offset from the center such that we can accommodate the required four transmission lines within the one cell and therefore develop the EBG structure in both lateral directions.

Utilizing the structure in Fig. 2 also allows us to achieve a large inductance without compromising the capacitance between the adjacent cells. We accomplish the latter by ensuring that there is a relatively large amount of conductor (represented by the black areas in Fig. 2) at the four edges of the cell. This helps to maintain the capacitance between adjacent cells.

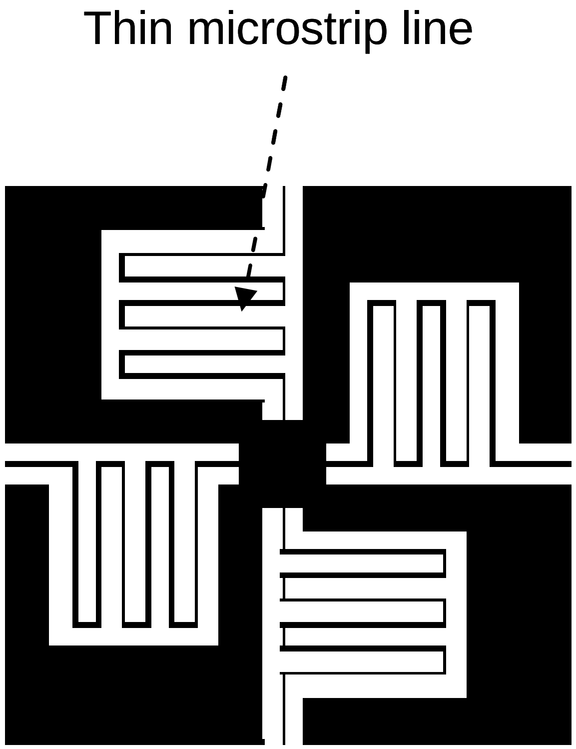

Fig. 2. Schematic of the proposed cell of the EBG structure (thin transmission lines interconnect adjacent cells).

The thin microstrip lines in Fig. 2 are not mitered and so there is a stray capacitance associated with these lines [12]. The stray capacitance helps lower the frequency of operation of the structure. The gap between the meandering microstrip lines and the adjacent conductor of the cell is made approximately five times the width of the transmission line, to ensure the transmission line behaves as a microstrip line.

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III. EXPERIMENTAL INVESTIGATION

Using the equations highlighted earlier, we designed an EBG structure based on the cell presented in Fig. 2 for a frequency of operation of 300 MHz using 1.6 mm FR4 as the grounded substrate. There are several degrees of freedom in the design however the size of the gap between adjacent cells is limited to a value of 0.1 mm due to fabrication tolerances. We chose an EBG cell size of 2.55 cm × 2.55 cm. For the application at hand, the overall area for the entire structure was limited to less than 8 cm × 8 cm. Thus, having a cell size of 2.55 cm × 2.55 cm allowed us to incorporate three cells in the structure; similar to that presented in [6].

As discussed earlier, the key aspect of our new EBG design is the degree of freedom associated with the realization of the inductance. For operation at 300 MHz, the length had to be 5.5 cm. Using our proposed technique we could readily accommodate the thin microstrip line within the small unit cell. Fig. 3 shows a schematic of the overall structure highlighting the thin gap between the adjacent cells and the transmission lines used to interconnect the cells.

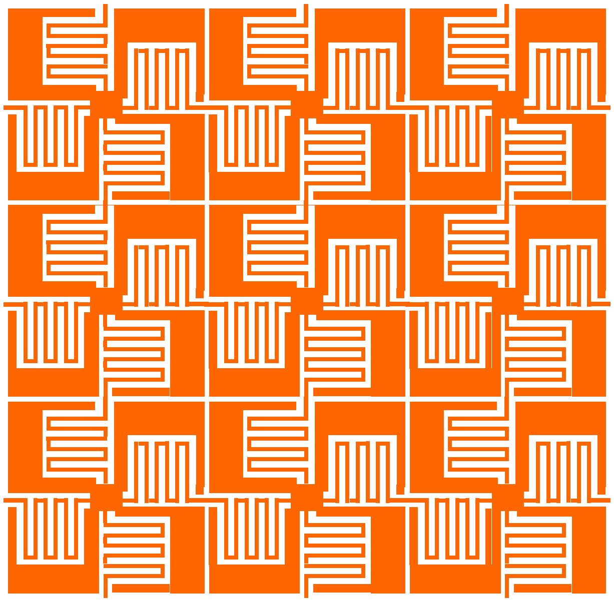

Fig. 3. Schematic of the small EBG structure developed on 1.6 mm FR4.

A photograph of the developed EBG structure is shown in Fig. 4. The EBG surface was fabricated using standard PCB etching techniques. The thin transmission lines are 0.1 mm in width (corresponding to 170 Ω) and the gap between adjacent cells is also 0.1 mm. The overall dimensions of the structure are 7.53 cm × 7.53 cm.

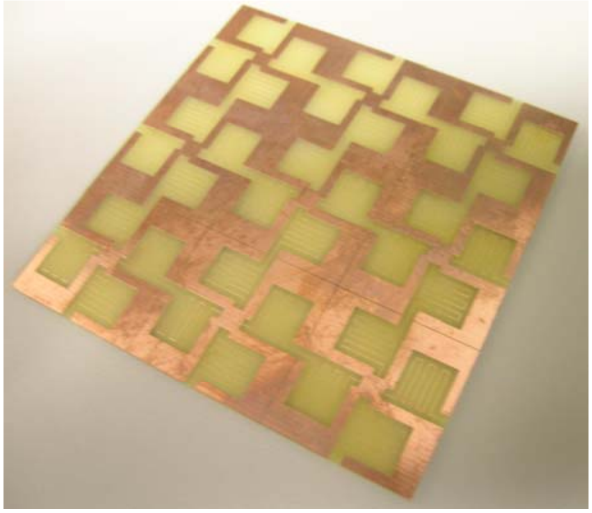

Fig. 4. Photograph of the small EBG structure developed on 1.6 mm FR4.

To measure the performance of the proposed EBG structure we used the procedure outlined in [6] to measure the TE (Transverse Electric) surface waves across the structure. Fig. 5 shows the experimental results for the EBG structure as well as a plot of the TE surface wave transmission response across a conventional ground-plane of the same size. As can be seen in this plot, there is a very defined bandgap near the design frequency of 300 MHz, indicating that the structure is functioning correctly. The 3 dB bandwidth of the structure is approximately 18 %, which is more than adequate for most wireless systems operating in the low microwave spectrum. A deeper null could be achieved by simply increasing the number of cells in the EBG structure, however the objective here was to make the surface as small as possible such that it would be compatible with radiating technologies operating close to that frequency.

IV. THEORETICAL INVESTIGATION

We also undertook a rigorous, theoretical investigation of our new EBG structure using a Finite Element Method. Here we modeled three connecting unit cells in the direction of propagation and used perfect electric boundaries on the adjacent sides of the cells to assist in the speed of the analysis. Because of the computational complexity of the new EBG (very thin lines at low frequencies), care must be taken to ensure that the solution has properly converged. Fig. 6 shows the predicted response, namely the transmission magnitude and phase through the EBG, of the new EBG structure. As can be seen from Fig. 6, the response is similar to the measured characteristics shown in Fig. 5. The bandwidth in terms of the phase response [11] is also consistent with the frequency spectrum of suppressed transmission.

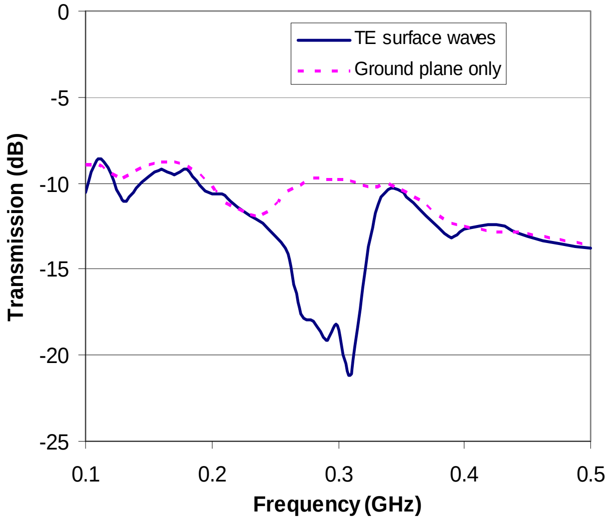

Fig. 5. Measured transmission response of TE surface waves across the proposed new EBG structure.

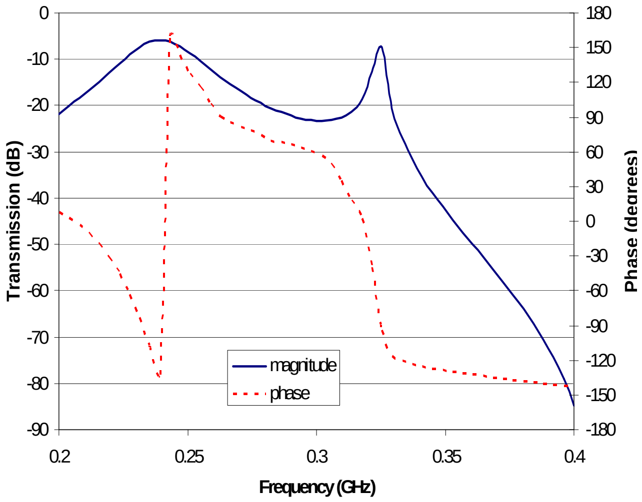

Fig. 6. Predicted transmission response across the proposed new EBG structure.

It is interesting to note that there appears to be good suppression of the surface waves at frequencies greater than 350 MHz in the predicted response of the new EBG structure shown in Fig. 6, however the phase is not between $\pm 90^{o}$. This could be an artifact of the numerical analysis since for this order of magnitude of attenuation, it is extremely difficult to accurately determine the correct phase.

V. CONCLUSION

In this paper we have presented a novel small form-factor EBG cell which enables small EBG structures to be created. The inductance of the cell is increased by meandering the thin microstrip line within the dimensions of the cell. Doing so allows for significant reductions in the size of the EBG cell and therefore the entire structure. We have presented design formulae and strategies in this paper and also experimentally verified the operation of the new EBG structure. The EBG structure is relatively simple to design and straightforward to fabricate. We have also shown that the new EBG cell is useful for low microwave frequency applications (less than 1 GHz) where typically, EBG surfaces are inherently too large. At a design frequency of 300 MHz, a 7.53 cm × 7.53 cm EBG structure reduced the power across the surface by 10 dB.

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REFERENCES

[1] D. Sievenpiper, L. Zhang, F. J. Broas, N. G. Alexopoulos and E. Yablonovitch, “High-impedance electromagnetic surface with a forbidden frequency band,” *IEEE Trans. Microwave Theory & Tech.*, vol. 47, no. 11, pp. 2059 – 2074, Nov. 1999.
[2] F.-R. Yang, K.-P. Ma, Y. Qian, and T. Itoh, “A novel TEM waveguide using uniplanar compact photonic-bandgap (UC-PBG) structure”, *IEEE Trans. Microwave Theory & Tech.*, vol. 47, no. 11, pp. 2092 – 2098, Nov. 1999.
[3] A. Sanada, C. Caloz and T. Itoh, “Planar distributed structures with negative refactive properties,” *IEEE Trans. Microwave Theory & Tech.*, vol. 52, no. 4, pp. 1252 – 1263, Apr. 2004.
[4] F. Yang and Y. Rahmat-Samii, “Microstrip antennas integrated with electromagnetic band-gap structures: a low mutual coupling design for array applications,” *IEEE Trans. Antennas & Prop.*, vol. 51, no. 10, pp. 2936 - 2946, Oct. 2003.
[5] R. Abhari and G. V. Eleftheriades, “Metallo-dielectric electromagnetic bandgap structures for suppression and isolation of parallel-plate noise in high-speed circuits,” *IEEE Trans. Microwave Theory & Tech.*, vol. 51, no. 6, pp. 1629 –1639, June 2003.
[6] F. J. Broas, D. F. Sievenpiper and E. Yablonovitch, “A high impedance ground-plane applied to a cellphone handset geometry,” *IEEE Trans. Microwave Theory & Tech.*, vol. 49, no. 7, pp. 1262 – 1265, July 2001.
[7] S. Tse, B. Sanz Izquierdo, J. C. Batchelor and R. J. Langley, “Reduced sized cells for electromagnetic structures,” *IEE Electronics Lett.*, vol. 39, no. 24, Nov. 2003.
[8] O. Folayan and R. J. Langley, “Wideband reduced size eolectromagnetic bandgap structure,” *IEE Electronics Lett.*, vol. 41, no. 20, Sept. 2005.
[9] J. T. Aberle, “A figure-of-merit for evaluating the gain-bandwdith product of microstrip patch antennas,” *Proc. 1999 AFRICON Symposium*, South Africa, June 1999.
[10] R. B. Waterhouse and D. Novak, “Comparison of performance of artificial magnetic conductors at L-band,” *Dig. 2005 IEEE APS Int. Symp..*, pp. 1629 – 1639, July 2005.
[11] D. F. Sievenpiper, High-Impedance Electromagnetic Surfaces, *Ph.D. dissertation*, University of California, Los Angeles, CA, 1999.
[12] B. Easter, “The equivalent circuit for some microstrip discontinuities,” *IEEE Trans. Microwave Theory & Tech.*, vol. 23, no. 8, pp. 655 – 660, Aug. 1975.