# Investigation into Broadband PBG using a Butterfly-Radial Slot (BRS)

**WE2D-3**

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***Abstract*--A new Butterfly-Radial Slot (BRS) structure has been proposed for broadband PBG applications. The BRS assisted PBG demonstrates broad bandwidth of over 70% and rejection of at least 40 dB in the band of interest. A design ratio has been derived and five sets of PBG structures have been designed, simulated and fabricated. The experimental and simulated results are in good agreement.**

## I. Introduction

Photonic Bandgap (PBG) has been studied extensively by many researchers over the last few years. In a nutshell, PBG is essentially periodic structures that forbid the propagation of energy in a frequency band. Itoh *et al* had introduced the 2-dimensional etched holes as PBG elements [1], and later extended into a PBG plane [2]. Novel 1-dimensional PBG structure has also been proposed in [3] and [4], which integrate PBG cells into the transmission medium. Needlessly, there has been a myriad of application of PBG in the microwave and millimeter-wave regimes such as in the form of harmonic suppression [5-6]. Low pass filters utilizing PBG elements have also been reported [7-8]. However the bandwidth of these PBG works has been relatively small. The primary reason is because of the inherently narrow bandwidth of the PBG cells. As a consequence, more PBG cells have to be deployed in order to achieve wider bandwidth and deeper rejection. Relatively few literatures have reported regarding the bandwidth enhancement of PBG cells. In [9], although a broad bandgap has been achieved, the PBG cells may not be easy to design.

In this paper, a new broadband Butterfly-Radial Slot (BRS) resonator is introduced as the PBG cell. As its name implies, the BRS structure consists of two 90□ radial "wing"-slots on opposite sides of a small square aperture etched in the ground plane as shown in Fig. 1. The BRS structure is inherently broadband and this insight is inspired from the study of broadband antenna theory [10]. The proposed BRS structure could be easily designed and fabricated using conventional printed circuit board technology, yet maintaining a broad bandwidth and deep rejection. It will be shown in the following sections that the bandgap properties can be designed based solely on a simple ratio of the radius of the BRS structure, $r$, to the period, $a$.

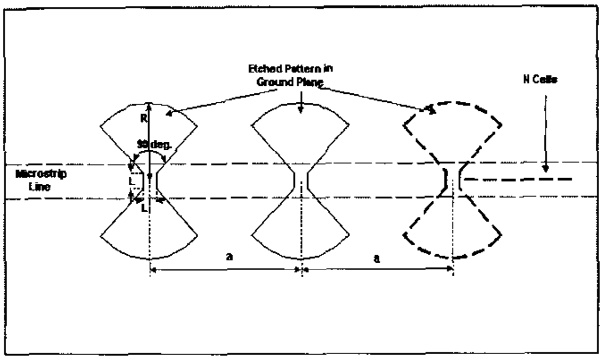


Fig. 1. Microstrip PBG with BRS structures etched underside.

## II. Characterization of BRS Structures

The simulated setup for characterization consists of a 50Ω microstrip with six etched BRS structures in the ground plane as shown in Fig. 1. The radius, $r$, and aperture size of the BRS structures were chosen to be 1.27 mm and 0.254 mm respectively. A period, $a$, of 6.35 mm was used. The circuit is designed using RT/Duroid 6010 with a dielectric constant of 10.2 and thickness of 0.635 mm. The whole structure was then simulated using a commercial Method-of-Moments based *EM* software, *IE3D*.

The preliminary simulation revealed that there was a resonance in the rejection band, which degraded the performance in the bandgap. However by adjusting the period, the resonance was suppressed and good rejection was achieved. The radius and a new period of 2.819 mm was noted and the ratio is given as:

$$\frac{r}{a} = 0.45 . \quad (1)$$

In the following simulations with other radii and periods, it was observed that (1) remains relatively invariant for this substrate. Hence (1) was adopted for subsequent designs.



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## III. SIMULATIONS AND MEASUREMENTS

The two main interesting properties of the BRS assisted PBG are its bandwidth and rejection. Hence experimental work has been carried out to find out the relationship between these properties with (1) as well as the number of BRS structures used. Bandwidth measurement was also carried out using the following expression:

$$BW = \frac{2(f_h - f_l)}{f_h + f_l}, \quad (2)$$

where $f_h$ and $f_l$ are the upper- and lower-side 3-dB roll-off frequencies.

In using (1), three sets of microstrip, each with 6 etched BRS cells in the ground plane, were simulated and fabricated. Fig. 2 shows a prototype belonging to one of the three sets. The radius of the BRS structures was increased in steps to find out its influence on the bandwidth and rejection. The parameters of the BRS cells for each microstrip as well as the measured bandwidth are summarized in Table I. The simulated and measured results are shown respectively for three different radii in Fig. 3.

The measured results in Fig. 3 revealed that for increasing radius of the BRS structure, the bandwidth was also found to improve correspondingly. The low-side cut-off frequency was also found to decrease and this is consistent with our knowledge that the cut-off wavelength being proportional to the dimensions of the BRS structures. The results in Fig. 3 also revealed a broad rejection bandwidth and steep roll-off frequencies. Interestingly, the number of peaks including the bandgap-peak in the $S_{11}$ plots were noted to be always equal to the number of BRS structures (which is 6 in Fig. 3), thus reflecting the order of the PBG structure. This also suggested that steeper roll-offs could be attained by increasing the number of BRS structures, which would be verified subsequently.

TABLE I

SUMMARY OF MEASURED RESULTS OF MICROSTRIP WITH 6 BRS STRUCTURES

| | Radius $r$ (mm) | Period $a$ (mm) | BW | Average Rejection |
|---|---|---|---|---|
| Fig. 3a | 1.524 | 3.378 | 75% | 40 dB |
| Fig. 3b | 2.032 | 4.521 | 84% | 40 dB |
| Fig. 3c | 2.54 | 5.639 | 93% | 40 dB |

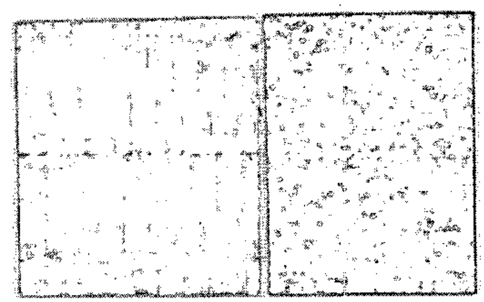
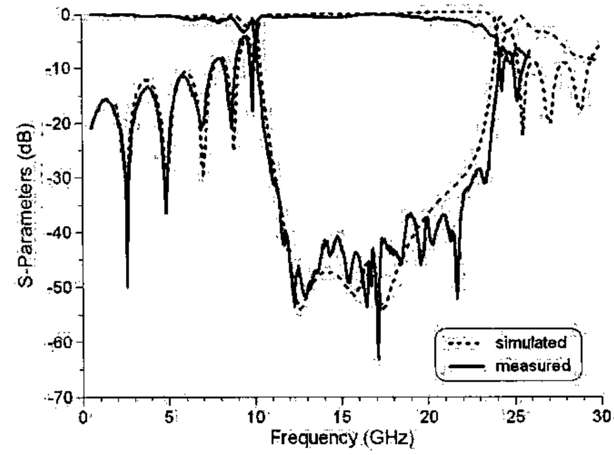
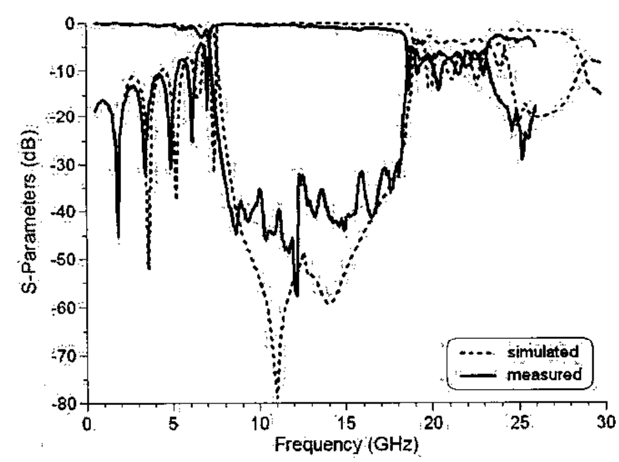


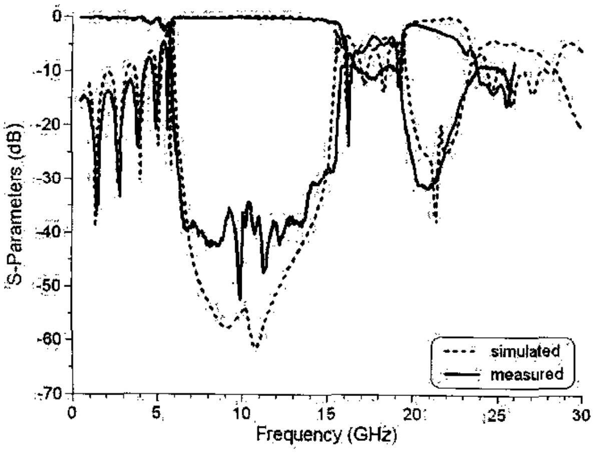
Fig. 2. Photograph of one of the prototypes with 6 BRS cells.




(a)




(b)




(c)

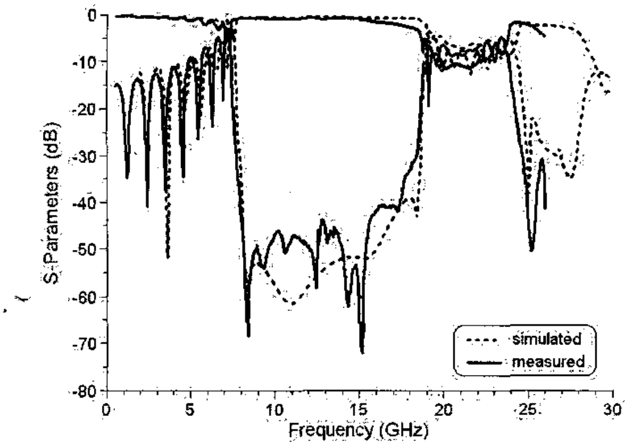
Fig. 3. Simulated and measured results for $N = 6$ with (a) $r$ = 1.524 mm and $a$ = 3.378 mm, (b) $r$ = 2.032 mm and $a$ = 4.521 mm and (c) $r$ = 2.54 mm and $a$ = 5.639 mm.

The effect of increasing the number of BRS structures was investigated for the case of $r$ = 2.032 mm and $a$ = 4.521 mm. While keeping the radius and period constant, the number of BRS structures was increased from $N$ = 6 to $N$ = 12 sequentially. The results were summarized in Table II. The measured and simulated results were also shown respectively in Fig. 4 for the case of $N$ = 9 and $N$ = 12 whereas the case of $N$ = 6 was shown in Fig. 3b.

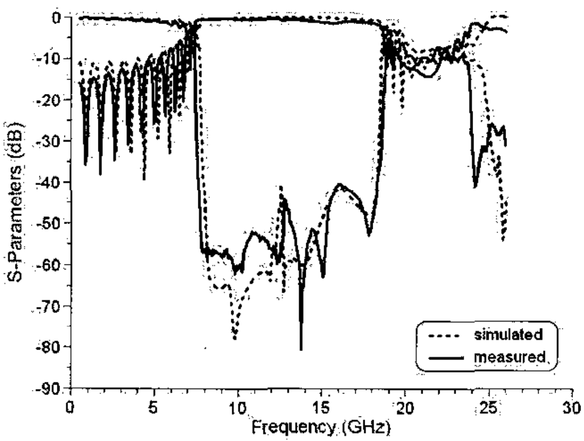
TABLE II

SUMMARY OF MEASURED RESULTS FOR INCREASING NUMBER OF BRS STRUCTURES

| | No. of BRS structures | Average Rejection | BW |
|---|---|---|---|
| Fig. 3b | 6 | 40 dB | 84% |
| Fig. 4a | 9 | 50 dB | 84% |
| Fig. 4b | 12 | 55 dB | 84% |




(a)




(b)

Fig. 4 Simulated and measured results for the case of $r$ = 2.032 mm and $a$ = 4.521 mm with (a) $N = 9$ and (b) $N$ = 12.

From Table II, it was noted that the rejection has improved with increasing number of BRS structures. The low-side roll-off was also observed to improve when more BRS structures were added. More notably in the case where $N$ was increased from 6 to 9, there was an improvement in the rejection by 10 dB. When a further of 3 BRS structures were added to 9, the rejection improved at the high-side and also on average by 5 dB. Hence from this observation, it suggested that further addition of BRS structures will not improved the rejection by much.

## IV. CONCLUSION

A Butterfly-Radial Slot (BRS) is proposed as a new PBG structure. The BRS assisted PBG exhibits broad bandwidth yet maintaining a deep rejection in the bandgap. A unique ratio has been derived for this particular substrate that will result in an optimum design. The number of BRS structures controls the rejection whereas the bandwidth is determined by the size (which is controlled by the radius) of the BRS structure. Such configuration can be employed efficiently where wide-band harmonic rejection is desired.

## ACKNOWLEDGEMENT

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## REFERENCES

[1] V. Radisic, Y. Qian, R. Coccioli, and T. Itoh, "Novel 2-D Photonic Bandgap Structure for Microstrip Lines," *IEEE Microwave Guided Wave Lett.*, vol. 8, no. 2, pp 69-71, Feb 1998.

[2] F. R. Yang, K. P. Ma, Y. Qian, and T. Itoh, "A Uniplanar Compact Photonic-Bandgap (UC-PBG) Structure and Its Applications for Microwave Circuits," *IEEE Trans. Microwave Theory Tech.*, vol. 47, no. 8, pp. 1509-1514, Aug 1999.

[3] T. Y. Yun, and K. Chang, "One-Dimensional Photonic Bandgap Resonators and Varactor Tuned Resonators," *IEEE MTT-S. Symp. Dig.*, pp. 1629-1632, June 1999.

[4] Q. Xue, K. M. Shum, and C. H. Chan, "Novel 1-D Microstrip PBG Cells," *IEEE Microwave Guided Wave Lett.*, vol. 10, no. 10, pp 403-405, Oct 2000.

[5] Y. Horii, and M. Tsutsumi, "Harmonic Control by Photonic Bandgap on Microstrip Patch Antenna," *IEEE Microwave Guided Wave Lett.*, vol. 9, no. 1, pp 13-15, Jan 1999.

[6] Y. Ji, X. S. Yao, and L. Maleki, "High-Q Whispering Gallery Mode Dielectric Resonator Bandpass Filter with Microstrip Line Coupling and Photonic Bandgap Mode-Suppression," *IEEE Microwave Guided Wave Lett.*, vol. 10, no. 8, pp 310-312, Aug 2000.

[7] I. Rumsey. M. P. May, and P. K. Kelly, "Photonic Bandgap Structures Used as Filters in Microstrip Circuits," *IEEE Microwave Guided Wave Lett.*, vol. 8, no. 10, pp 336-338, Oct 1998.

[8] T. Kim, and C. Seo, "A Novel Photonic Bandgap Structure for Low-Pas Filter of Wide Stopband," *IEEE Microwave Guided Wave Lett.*, vol. 10, no. 1, pp 13-15, Jan 2000.

[9] C. Caloz, and T. Itoh, "A Super-Compact Super-Broadband Tapered Uniplanar PBG Structure for Microwave and Millimeter-Wave Applications," *IEEE MTT-S. Symp. Dig.*, pp. 1919-1922, June 2002.

[10] C. A. Balanis, *Antenna Theory: Analysis and Design, 2nd Edition*, New York: John Wiley & Sons, 1997.