Photonic Bandgap Structures Used as Filters in Microstrip Circuits

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***Abstract*— The application of photonic bandgap structures (PBG's) as substrates in microstrip circuits has been investigated. The effects of substrate thickness, microstrip transmission line location, and length of the PBG structure were studied using a finite-difference time-domain (FDTD) simulation and experimental measurement. A low-pass filter with a very wide high-frequency rejection bandwidth was constructed from a serial connection of many different PBG structures.**

I. Introduction

FILTERING of undesired frequencies in microstrip designs can be accomplished with shorted tuned stubs. This technique is typically narrow-band, and occupies valuable circuit layout area. One possible way to reject out-of-band frequencies is to use a photonic bandgap structure (PBG). PBG's are generally infinite periodic lattices of dissimilar dielectrics which prevent propagation in any direction [two dimensions only for two-dimensional (2-D) lattices]. The term PBG will be used loosely to describe the type of structure used, although the lattice is finite periodic and will not have a true bandgap, but rather attenuation over the frequency band. The ratio of the two permittivities, lattice spacing, and relative volume fraction of the two dielectric materials are the independent design variables determining the bandgap characteristics. By using the PBG structure as a substrate (PBGS), circuit components spanning several unit cells on the PBGS will realize frequency filtering, thereby integrating a filter circuit with the etched circuit. Itoh *et al.* [1], [2] have presented stopband characteristics of microstrip lines on several different PBG substrates using finite-difference time-domain (FDTD) simulation and measurement. The use of PBGS allows for a wide stop-band filter to be integrated into the circuit substrate, thus allowing for collocation of other microstrip circuit elements with the filter. This paper examines the PBGS filtering characteristics and topology. The first section describes how the PBG structure was designed. This is followed by a section describing the modeled and measured results.

II. PBG Design

The PBG structure used in the following studies was a 2-D square lattice consisting of circular holes. The background dielectric constant was 10 with a thickness of 62 mils. The lattice spacing was 18 mm with a hole volume fraction of 0.35. The PBG structure design was derived from [6] by replacing the square holes with circular holes of equal volume and scaling to the desired frequency. The bandgap for most of the presented studies was centered at 5 GHz. A microstrip transmission line was etched on a 5-mil-thick overlay of G10 dielectric and placed over the PBGS. By etching the circuit on a secondary (very thin) substrate, the problem of how to make the transmission line span a hole is overcome. Since the secondary substrate is much thinner than the PBGS and the dielectric constant is less, the change in electrical performance due to the secondary substrate is minimal. This was verified by the close agreement between the simulated (no secondary substrate) and measured (with secondary substrate) results.

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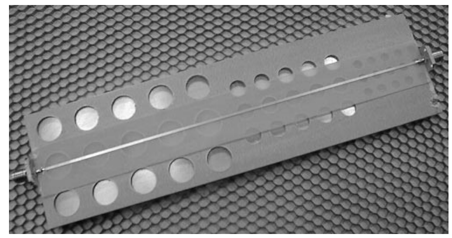

Fig. 1. Photograph of the cascade PBG microstrip circuit under test. The overall dimensions for this substrate are 190 mm long, 50 mm wide, and 1.6 mm thick. The microstrip line is 1.2 mm wide and the hole diameters of the three stages are: 12, 8, and 5 mm.

III. Modeling/Experiment

A. Standard Model

Fig. 1 is a photograph of the series PBG structure used for this study. Sections III and IV of this letter deal with only the first section of this structure, which has the largest holes in the substrate. The full structure is discussed in Section IV. The photonic bandgap structure was designed using [3] and was refined using FDTD simulations to obtain a gap center frequency of 5 GHz. Substrate thickness was chosen to accommodate available materials for construction of the PBGS. A Gaussian pulse was excited on a conventional 50-Ω microstrip transmission line with PBGS. The incident, reflected, and transmitted signals were obtained from the time-domain simulations and transformed to the frequency domain to calculate S_{11} and S_{21} for the microstrip transmission line over five rows of the PBGS. Fig. 2 shows good agreement between the modeled design and the fabricated design for a 5-GHz PBGS with microstrip line.

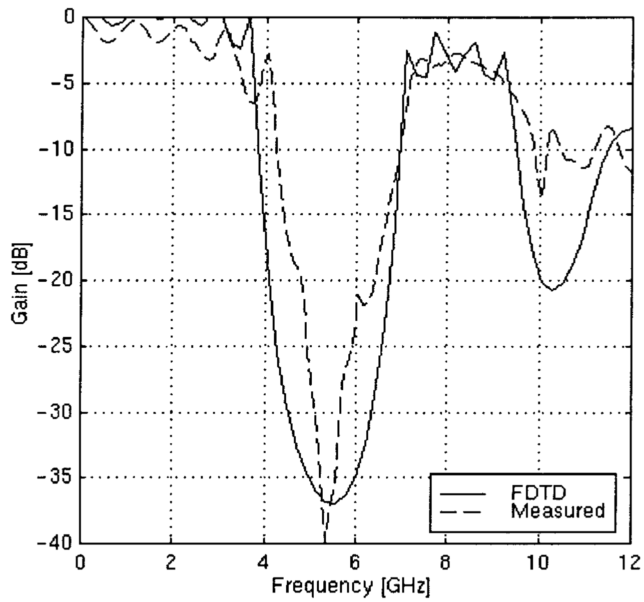

Fig. 2. Measured S_{21} for a microstrip transmission line on 3 by 5 cell single PBG with 12-mm-diameter holes compares favorably to the FDTD model prediction.

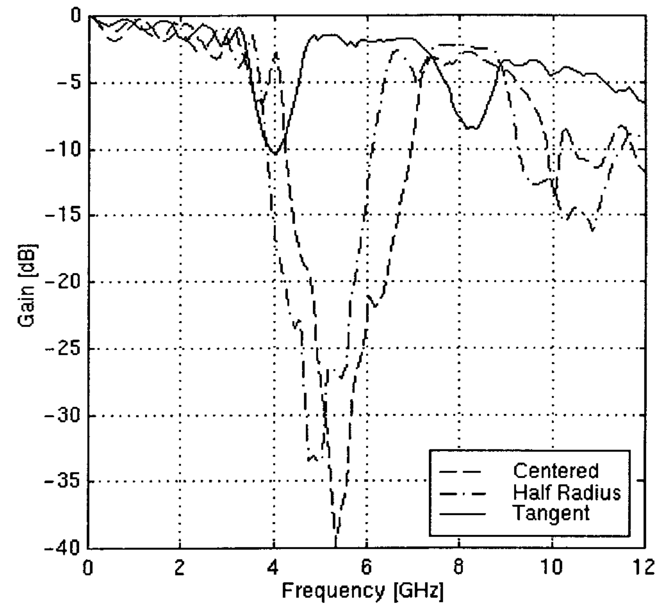

Fig. 3. Measured band gap behavior for the various routes over the 5-cell PBGS. The paths shown are: tangent to the inner surface of the holes; halfway between the hole edge and center; and over the hole centers.

B. Microstrip Placement

The effect of microstrip placement on bandgap performance was observed by running simulations and probing: 1) when the strip was centered over the air holes; 2) when the strip was passed over the holes between the hole center and its edge; 3) when the strip passed over the holes tangent to the edge; and 4) when the strip was centered between the holes over solid dielectric. Experimental measurements were made by constructing the approximate simulated structure and then using a Hewlett-Packard network analyzer to find the S_{21} pattern. Measured data showing the effect of routing on the bandgap behavior is shown in Fig. 3. The significant differences between cases 1, 2, 3, and 4 above, as shown in Fig. 3, suggest that you can obtain different transmission behavior with a single substrate by selectively routing the microstrip. The agreement between measurement and simulation was acceptable. Better agreement could be obtained by reducing the manufacturing tolerances and including the transitions from coaxial to microstrip transmission lines in the simulation. Also, the G10 overlay with the microstrip trace should be bonded to the substrate to avoid air gaps between the trace and the substrate.

IV. Other Observations

Studies were conducted using FDTD simulation to observe the effect of substrate thickness and number of rows on the PBGS performance. Parameters of interest were the stopband rejection in decibels, and the peak-to-peak ripple in the passband.

The first analysis observed the depth of the bandstop null relative to the number of substrate holes traversed. Cases studied were microstrip transmission lines traversing 5, 6, 7, 8, and 9 rows of PBGS holes. The relationship between the depth of the null for both the main 5-GHz bandgap and the next periodic 10-GHz null appeared to be linearly related to the number of PBGS rows traversed. The depth of both the 5- and 10-GHz nulls increase at a rate of -4 dB per row traversed. Future study will show how this trend progresses for very long PBGS structures.

TABLE I
Null Depth Versus Substrate Thickness

Thickness	16 mils	31mils	48mils	62mils
5GHz Null	-39dB	-36.7dB	-33.3dB	-36.9dB
10GHz Null	-21.7dB	-22.7dB	-21.1dB	-20.8dB

The next study observes the magnitude of the peak-to-peak ripple in the passband relative to the number of holes traversed. In both the 0–4- and 7–9-GHz passbands seen in Fig. 2, a linear relationship exists between the passband ripple and the number of rows when more than five rows have been traversed. The ripple appeared to decrease by 0.2 dB with each additional row traversed.

The final study reported here is the depth of the null relative to the thickness of the substrate. Table I shows the results for both the main null and the secondary null. The results indicate that increasing the thickness of substrate affects the performance of both nulls. Further studies will be done to see if this is a periodic response.

V. Wide Bandgap Design

The cascade connection of three photonic bandgap structures with different stopband center frequencies was used to produce an extremely wide stopband for the aggregate structure. The same width transmission line as in the previous cases was used. The PBG structures were designed relative to the 5-GHz design to try to suppress the largest passband in the transmission pattern. It was decided to design a series PBG

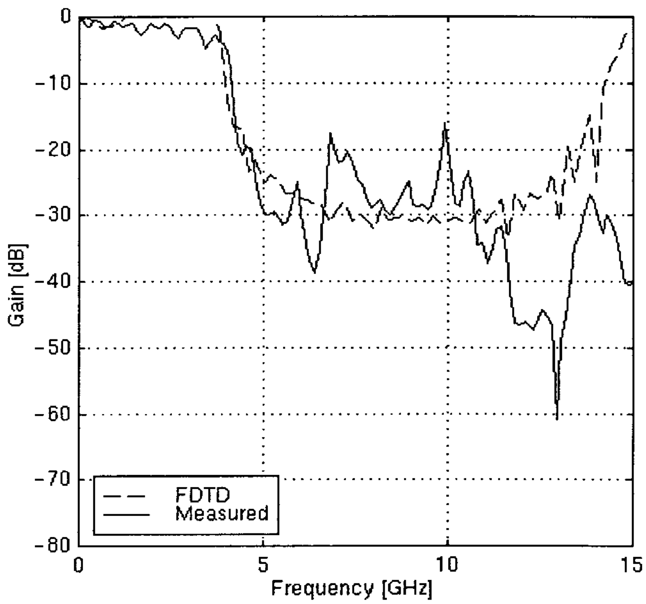

Fig. 4. Modeled and measured data for a cascade PBGS, shown in Fig. 1, making a wide-band gap filter.

with bandstop filters at 5, 7.5, and 12.2 GHz. The physical structures were based on linear scaling of a 5-GHz design as shown in (1)

$$\begin{bmatrix} a_{\text{new}} \\ d_{\text{new}} \end{bmatrix} = \frac{f_{\text{old}}}{f_{\text{new}}} \begin{bmatrix} a_{\text{old}} \\ d_{\text{old}} \end{bmatrix}. \tag{1}$$

The constant a is the center-to-center spacing of the PBGS holes, and d is the diameter of these holes. The design parameters for the series PBG are: 5-GHz bandgap: $a = 18$ mm, $d = 12$ mm; 7.5-GHz bandgap: $a = 12$ mm, $d = 8$ mm; 12.2-GHz bandgap: $a = 7.4$ mm, $d = 5$ mm. Five holes were traversed in each substrate. Fig. 4 shows both the simulated and measured data obtained with this design. We met our design specifications, and at higher frequencies our measurements outperformed the modeled prediction.

VI. Conclusion

The behavior of photonic bandgap structures as substrates for microstrip circuits was studied. It was shown that a finite lattice can produce significant rejection of potentially undesired frequencies. Furthermore, varying degrees of rejection were obtained depending on location of the transmission line relative to the holes in the substrate. Other findings included the effect of substrate thickness on null depth and the amount of passband ripple versus number of rows in the PBGS. A very wide-band filter using the cascade connection of three PBGS was introduced and analyzed. The results from this architecture suggest not only wide-bandwidth filtering but possibly a method for tailoring pulse shapes. Further work will be completed to study layered PBGS and PBGS derived from fractals.

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