A Super-Compact Super-Broadband Tapered Uniplanar PBG Structure for Microwave and Millimeter-Wave Applications

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Abstract — **A novel uniplanar photonic bandgap (PBG) structure, consisting of a tapered array of stepped-impedance slot resonators, is introduced. This structure, which is of low cost and easy design/fabrication, exhibits a low-pass behavior, and is characterized by a super-compact size (much smaller than conventional PBGs), a huge gap (about 150%), an excellent insensitivity to circuitry location on top of it and a very low return loss (negligible radiation) in the stop-band. The working principle of the PBG is explained and its performances are demonstrated by simulation and measurement results for different configurations. Simple design guidelines are provided.**

I. INTRODUCTION

Over the last few years, there has been a tremendous research activity on photonic band-gap (PBG) materials [1],[2]. In the microwave domain, different structures have been proposed [3]-[6], and successfully integrated into a diversity of circuit and antenna applications [7]-[9].

Recently, a novel uniplanar anisotropic PBG structure, characterized by a propagation direction and an attenuation direction, was introduced in [10], and shown to possess unique features, such as very high compactness and insensitivity to the circuitry position on top of it. In the present paper, we propose a variant of this structure, a *tapered* (anisotropic) PBG, exhibiting in addition a much broader stop-band and a very low in-gap return loss. The tapered PBG also presents higher design flexibility than conventional PBGs.

The paper is organized as follows. First, the fundamental properties of the anisotropic PBG are recalled and a corresponding gap map is presented. Then, the principle of the tapered PBG is explained and its performances are demonstrated by simulation and measurement results, and discussed for different PBG configurations. Next, the characteristics of the structure are summarized and compared to previously reported PBGs. Finally, some design guidelines are given.

II. ANISOTROPIC PBG: CHARACTERISTICS AND GAP MAP

The anisotropic PBG is a substrate with a periodic pattern etched in the ground plane and a microstrip line on the other side, with a pattern consisting of a square lattice with an anisotropic unit cell of size $a \times a$ (a = period), as shown in the inset of Fig. 1. The PBG can also be seen as an array of stepped-impedance strips/slots. Fig.1 shows the insertion loss of the structure on the RT/Duroid 6010 substrate ($\varepsilon_r = 10.2$, $h = 25$ mil; $\varepsilon_{eff} \approx 7.1$ and $\lambda = 22.5$ mm at 5 GHz) and with the PBG's period $a = 60$ mil (1.52 mm). The same substrate/PBG parameters have been used in all the circuits presented in this paper.

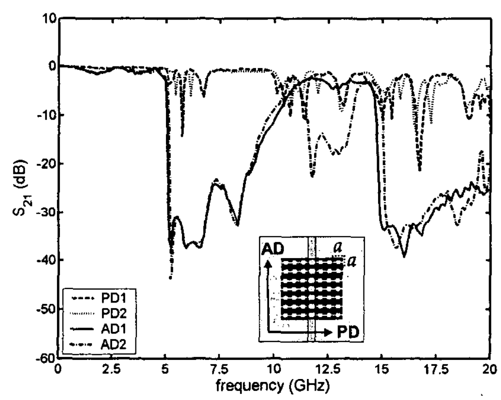

Fig. 1. Insertion loss in the propagation direction (PD) and in the attenuation direction (AD) at different positions of the line (1: centered, 2: shifted by $a/2$) for the "straight" anisotropic PBG including $N_{PD} \times N_{AD} = 7 \times 7$ unit cells. The structure is shown in the inset with the microstip line and the PD/AD (Here the line is in AD1). The lighter regions represent metal and the darker regions represent slots.

The main characteristics of the structure can be inferred from Fig. 1: 1) anisotropy, showed in the existence of a propagation direction (PD) and an attenuation direction (AD) of the line in the range from *5-7* to *10* GHz; 2) existence of a deep/sharp gap, of about *65%*, in the AD; 3) insensitivity to the position of the line both in the PD and in the AD, due to effective impedance behavior, $a << \lambda$ (at cutoff, $a \approx \lambda/15$); 4) very small overall size: the surface of the PBG is only about $\lambda/2 \times \lambda/2$. It should be noted that the small resonators corresponding to a unit cell play the important role of enhancing the resonance of the slots in terms of gap width and depth [11].

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Fig. 2 shows the gap map of the PBG (AD) as a function of the number of cells along the PD, N_{PD}, or length of the slots L_{PD} ($L_{PD} = N_{PD} \times a$). Basically, the lower edge of the gap, or cutoff, corresponds to the first resonance of the slots, $L_{PD} = \lambda/2$, and the gap width varies roughly between *45%* and *65%*. This gap map shows the easy scalability of the structure. Although plotted for a fixed number of cells ($N_{AD} = 7$), or slots, it can be extrapolated to a smaller number of them, since *2* to *3* cells have been observed to be sufficient to achieve the largest *–10* dB bandwidth.

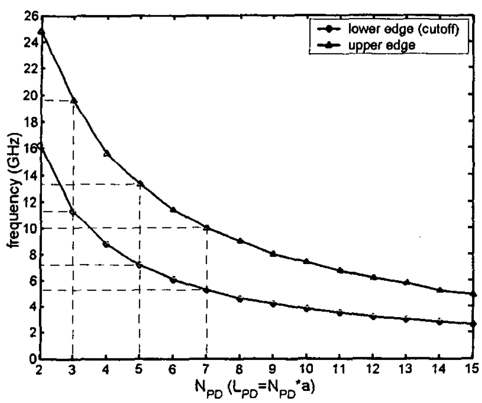

Fig. 2. Gap map (*-10* dB stop-band position and width) as a function of the length of the stepped-impedance strip/slots ($L_{PD} = N_{PD} \times a$) for the "straight" anisotropic PBG ($N_{AD} = 7$).

II. PRINCIPLE OF THE TAPERED PBG

The tapered PBG is still anisotropic, but we will consider here only its AD, where filtering occurs. The idea of tapering is simply to build a composite structure, including slots of different lengths, and therefore exhibiting gaps at different frequency positions according to Fig. 2, such that a broader resulting gap can be achieved from the overlapping of the individual gaps.

Fig. 3 shows two possible geometries for the tapered PBG, an asymmetric and a symmetric geometry. In both cases the slots are combined *in series*. Assuming that the resonance of each group of slots of length L_k is negligibly affected by the presence of the other groups - which was confirmed by simulation/measurement results -, it suffices to select the lengths ensuring the overlapping of the corresponding gaps in the range desired, with the help of the gap map of Fig. 2. For instance, as shown in Fig. 2, the PBGs in Fig. 3, with the lengths L_1-L_4 ($N_{PD} = 7,5,3,1$), should have a gap extending from about *5* GHz (L_1) to more than *25* GHz (L_4), since the consecutive individual gaps overlap in this range.

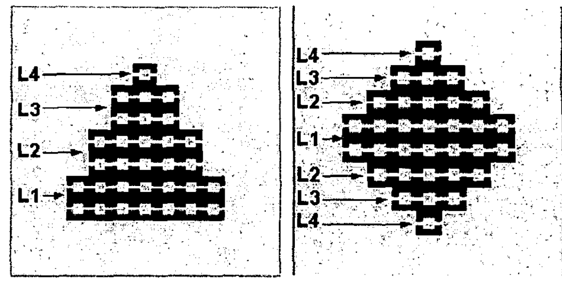

Fig. 3. Possible geometries for tapered PBGs, including groups of slots of different lengths L_k. (a) asymmetric configuration. (b) symmetric configuration.

III. SIMULATION/MEASUREMENT RESULTS AND DISCUSSION

Fig. 4 shows the insertion and return losses for the tapered PBG of Fig. 3a). It can be seen that, as expected from previous section, the structure presents a very broadband behavior, with a gap extending from *5* to more than *20* GHz. Simulations over a broader range revealed that the gap actually extends up to 34 GHz, which corresponds to a huge bandwidth of about *150%*. However, this specific configuration has a weakness: it has significant radiation at around *12* GHz, and this antenna-like behavior might create interferences with other circuit elements and packaging.

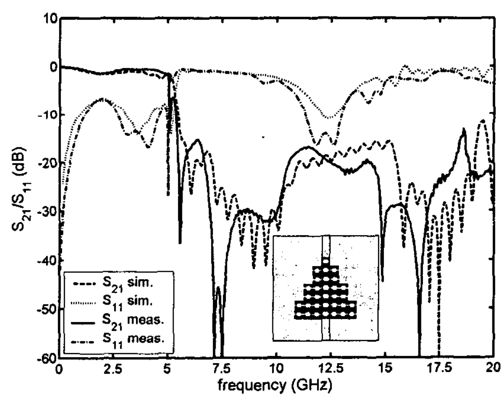

Fig. 4. FDTD-simulated/measured insertion and return losses for the asymmetric tapered PBG shown in the inset ($2\times L_1$, $2\times L_2$, $2\times L_3$, $1\times L_4$, where $(L_1,L_2,L_3,L_4) = (7a,5a,3a,a)$.

The simulations and measurements results for the PBG of Fig. 3b), are not shown here, for the sake of shortness. But they are almost identical to those reported in Fig. 4, except that the radiation peak in S_{11} has completely disappeared and that the in-gap return loss is very close to

0 dB at all frequencies. The symmetric configuration in Fig. 3b) is therefore preferable to its asymmetric counterpart in Fig. 3a). It should be noted that the anti-symmetric configuration that would have the smaller slots in the center and the larger slots at the edges (bow tie shape) is not recommended, because it allows standing waves between its bows, which significantly increase both the pass-band insertion loss and stop-band return loss.

Fig. 5 shows the S-parameters for a symmetric tapered PBG with higher performances. In this case, more slots of each length have been used to achieve a deeper gap. Also, the larger number of largest slots, of length L_1, (*6* instead of *2*) results in a cleaner/sharper cutoff. It can be seen that the structure exhibits a very deep/sharp broad gap, with low insertion loss in the pass-band and a practically zero return loss (negligible radiation) in the stop-band.

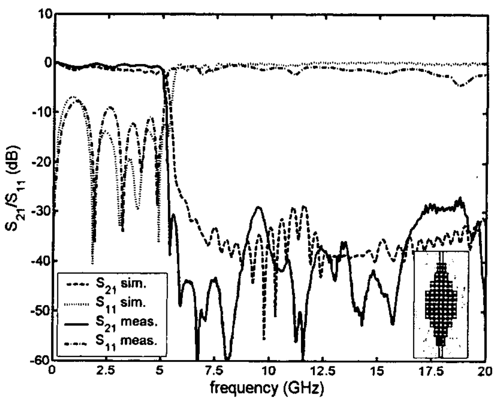

Fig. 5. FDTD-simulated/measured insertion and return losses for the symmetric tapered PBG shown in the inset $(6\times L_1,\ 4\times L_2,\ 4\times L_3,\ 4\times L_4$, where $(L_1,L_2,L_3,L_4) = (7a,5a,3a,2a)$.

The most important characteristics of the tapered PBG are the coexisting *super-compactness* and *super-broad bandwidth*. Its size is much smaller than previous PBGs. For performances comparable to those of Fig. 4, 1D-PBGs typically require *8* cells with $a = \lambda/2$ at cutoff [5],[6], which leads to a length of the order of 4λ. The 2D-UC-PBGs of [7] are more compact in the direction of the line ($a = \lambda/4$ at cutoff), but typically require *4* cells in the other, orthogonal, direction, so that their surface is of the order of $2\lambda \times \lambda$ at cutoff. The tapered PBG, with a typical size of $\lambda/2 \times \lambda/2$, exhibits therefore a remarkably high-compactness. In terms of bandwidth, the tapered PBG exhibits the widest gap ever reported, to the authors' knowledge. One exception is the double-layered PBGs presented in [11], but the in-gap return loss of the tapered PBG is dramatically smaller and its gap is considerably deeper. Needless to say, the monolayer nature of the tapered PBG makes it more convenient than multilayer configurations for practical applications. Insensitivity to the line position, simplicity and design flexibility constitute other advantages of the structure.

V. Design Guidelines

The design guidelines for the tapered PBG can be summarized as follows: 1) After selecting a substrate, compute the corresponding gap map of the PBG, as in Fig. 2 for the RT/Duroid 6010. Note that the period and the shape of the unit cell of the structure are not critical parameters, and can be modulated to some extent, possibly with improvement of transmission in the pass-band. 2) select different lengths for the stepped-impedance strips/slots, such that the individual corresponding gaps overlap in the gap map along the complete desired stop-band's frequency range. 3) choose an appropriate number of strips/slots of each of these lengths such that the gap be deep enough for the needs of the application. If size is not a critical matter, it is recommended to use a relatively large number of slots of each length, as in Fig. 5, which leads to a structure which is still more compact than other PBGs; otherwise, smaller numbers of cells should be used, as in Fig. 4, at the expense of reduced performances. Also, to obtain a sharper and cleaner cutoff, it suffices to increase the number of the largest slots. 4) The small ripples on the insertion loss curve in the pass-band are due to a mismatch effect between the line on uniform PEC (*50* Ω) and on PBG, where the effective impedance is higher (typically *75* Ω). Therefore, insertion loss can be reduced by taking a larger line width just on top of the PBG. Simulations results showed that the maximum insertion loss in the pass-band can be easily reduced from about *1.5* dB (here) to less than *0.5* dB in this manner.

VI. Conclusion

A novel PBG structure, consisting of a tapered array of stepped-impedance slot resonators, has been introduced and characterized. This structure exhibits several unprecedented features, such as super-compactness and super-broad bandwidth, in addition to good pass-band transmission, extremely low in-gap radiation, insensitivity to the line position, easy scalability, low-cost and design flexibility.

Thanks to these interesting features, the tapered PBG introduced here might be used in several applications requiring high-compactness and/or super-broadband characteristics. For instance, it can be used as a harmonics suppressor at the output of power amplifiers to increase the power added efficiency and improve the linearity of the device. It would be especially interesting at very high frequencies, where the too lossy discrete components need to be replaced by distributed elements.

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