# Applications of a Chirping and Tapering Technique on Photonic Band-Gap(PBG) Structures for Bandwidth Improvement

Ming-Sze Tong · Hyeong-Seok Kim · Tae-Gyu Chang

## Abstract

Microwave or optical photonic band-gap(PBG) structures are conventionally realized by cascading distributive elements in a periodic pattern. However, the frequency bandwidth obtained through such plainly periodic arrangement is typically narrow, corporate with a relatively high rejection side-lobe band. To alleviate such problems, a design involving a chirping and tapering technique is hence introduced and employed. The design has been applied in both a planar stratified dielectric medium as well as a strip-line transmission line structure, and results are validated when compared with the corresponding conventional PBG structure.

***Key words*** : PBG, Chirping And Tapering Technique.

## Ⅰ. Introduction

There have been a number of studies on the photonic band-gap(PBG) structures in the area of computational electromagnetics in recent years[1]~[4]. The basic idea of the PBG is to act as a filtering device so as to prohibit a certain frequency range of electromagnetic fields. This is conventionally done through a periodic pattern of distributive elements, such as a network of air-gaps inside a stratified dielectric medium, or a series of perforations on the ground plane of a microstrip line.

However, such plain periodic pattern suffers problems of a narrow bandwidth, and a relatively high rejection level on the low-frequency side-lobe band. Such phenomena were reported in [5], [6] in studies of microstrip PBG structures, where the PBG properties were realized using a set of perforations on the microstrip ground. Thus, in order to alleviate the associated problems, [5] suggested a chirping and tapering technique, which is done by gradual variation of the distance between each period of perforation and the size of perforations through a Gaussian window function.

In this research, this design technique is applied in a stratified dielectric medium. By performing such chirping and tapering procedures, it has been found that the resulting spectrum of the modified PBG structure outperforms the conventional one in terms of stop-band bandwidth and the rejection level of the side-lobes at the lower frequencies. The technique is also applied on a stripline PBG structure for analysis. Numerical results based on solely chirping or tapering technique are also presented for comparison.

## Ⅱ. Theory

An in-house developed solver based on the finite-difference time-domain(FDTD) algorithm[7] is adopted for analysis in this research. Excitation is modeled by a Blackman-Harris window function at the input port of the structures for broadband computations. All supporting substrates and dielectrics are lossless materials with $\mu_r$=1. Any conducting strips and the ground plate are assumed to be perfectly electric conductor(PEC) with infinitesimal thickness. For open boundary treatment, an anisotropic perfectly matched layer(APML) medium[8] is employed as the absorbing boundary conditions(ABCs). The computational stability is ensured by the Courant condition[9], and a steady state time domain response is used to extract the corresponding frequency domain characteristics in terms of the scattering parameters.

### 2-1 1-D Stratified Dielectric PBG Medium

A 1-D stratified dielectric medium is herein taken for studies. A TEM(transverse electromagnetic) mode is assumed to transmit along the medium, which consists of the following dielectric properties: $\varepsilon_r$=11.7, $\mu_r$=1.0, and $\sigma$=0. The direction of propagation and the polarizations of the electromagnetic fields are assumed to be in the $x$, $y$, and $z$ directions respectively.

Now, consider a 1-D PBG structure as given in Fig. 1. It is constructed by inserting a sequence of air-gaps, each with a width $d_i$=250 $\mu$m, in the middle of a dielectric layer of period $w_i$=500 $\mu$m.

Here, $x_{pi}$ and $x_{qi}$ are the observation points, located at

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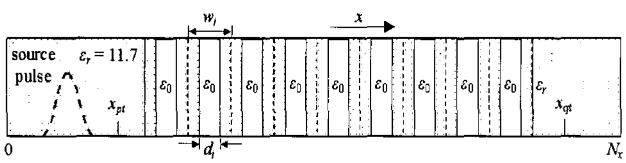


Fig. 1. A stratified dielectric PBG medium of 9 air-gaps, where $w_i$=500 $\mu$m and $d_i$=250 $\mu$m.

the input and output ports, which are for calculations of the S-parameters, i.e., the reflection ($S_{11}$) and transmission ($S_{21}$) coefficients, respectively. In the special case, where only one air-gap is inserted, the characteristic frequency, i.e., the standing-wave frequency on the S-parameters, can be easily calculated based on the width of air-gap, which is

$$f_0 = \frac{n}{2} \times \frac{v_c}{d\sqrt{(\mu_r \varepsilon_r)_{air}}} = n \times 600 \text{ GHz} \tag{1}$$

## 2-2 Design of Chirped and Tapered PBG Structure

To improve the spectral performance, [5] suggests a chirping and tapering technique as follows. The medium is first to be varied in a manner that the period in the middle is fixed at $w_{mid}$=500 $\mu$m, with each of the adjacent period modulated by a factor of $\Lambda$ according to the relationship

$$w_i = w_{mid}(1 \pm i \cdot \Lambda);\ i \in (-N/2, +N/2) \tag{2}$$

as shown in Fig. 2. This is called chirping.

Then, by setting the size of air-gap at the middle at the maximum as $d_{\max}$, each air-gap $d_i$ is modulated by a Gaussian window function given as

$$d_i = d_{\max} \exp\left(-2\left[\frac{|x_i|}{L/2}\right]^2\right) \tag{3}$$

where $L$ is the total length of the medium= $\sum w_i$, and $|x_i|$ is the distance between the centre of the middle air-gap and the centre of the air-gap $i$.

In this study, factor $\Lambda$ is set at $\Lambda$=4 %, i.e., $\Delta w_i = \pm 20$ $\mu$m, and $d_{\max}$=0.8$w_{mid}$=400 $\mu$m.

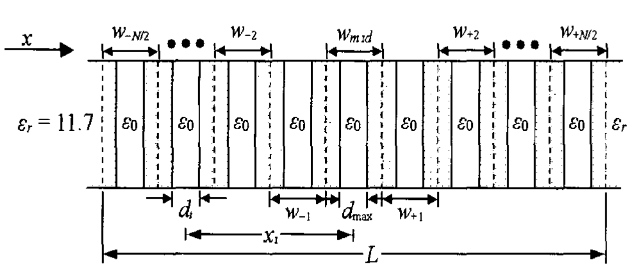


Fig. 2. The chirping and tapering technique for modulations of the slab-widths and air-gaps.

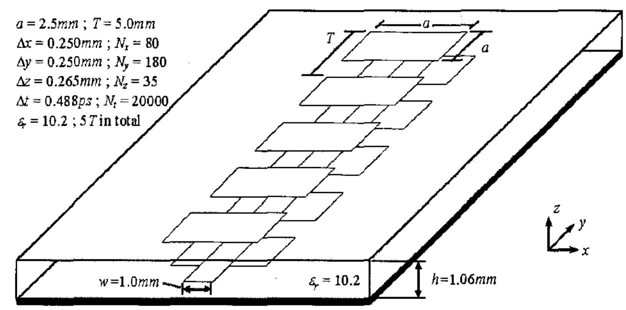


Fig. 3. Configuration of a stripline PBG structure with series of notches.

## 2-3 3-D Stripline PBG Structure

A PBG structure using a stripline circuit is also studied as shown in Fig. 3. It consists of a series of rectangular notches, locating along the top and bottom ground plates.

Herein, the supporting substrate has a dielectric property of $\varepsilon_r$=10.2. Each rectangular notch on the ground plates is kept with a size of $a \times a$ for convenience in analysis. For the original PBG arrangement, the dimensions of the rectangular notches and the period are selected at 2.5 mm×2.5 mm and $T$=5.0 mm, respectively, with an altogether five periods along the stripline circuit.

The chirping and tapering technique is applied to this structure for demonstrate the bandwidth improvement. The modulated factor $\Lambda$ is selected at 4 %, which means $\Delta w_i$=0.96$T$=0.2 mm, and $d_{\max}$= 0.8$w_{mid}$ = 4 mm.

## Ⅲ. Numerical Results

The above designs, including their original PBG structures, are computed by an in-house FDTD solver. The 1-D stratified dielectric PBG medium is first taken for analysis. A grid dimension of $\Delta x$ = 5.0 $\mu$m is adopted, whose frequency resolution is up to 877 GHz. In the chirped and tapering design, the grid size varies between $\Delta x_i$=5.0 $\mu$m±0.5 $\mu$m between the periods in order to realize each $d_i$ and $w_i$. A fixed time step of $\Delta t$ =1.0×$10^{-14}$s (0.01 ps) is used, corresponding to 0.6$\Delta t_{\max}$ of the Courant stability condition[9]. Due to a strong resonance nature, a large time-step number is required to reach the steady state. In this study, $N_t$=2×$10^5$ is used for the original PBG, while $N_t$=5×$10^5$ is taken for the chirped and tapered case. A 16-cell of APML is conducted at the two ends as the ABCs.

The frequency spectrum of the 1-D stratified dielectric PBG medium is displayed in Fig. 4. It is found that there exist pass-and-stop band of window frequen-

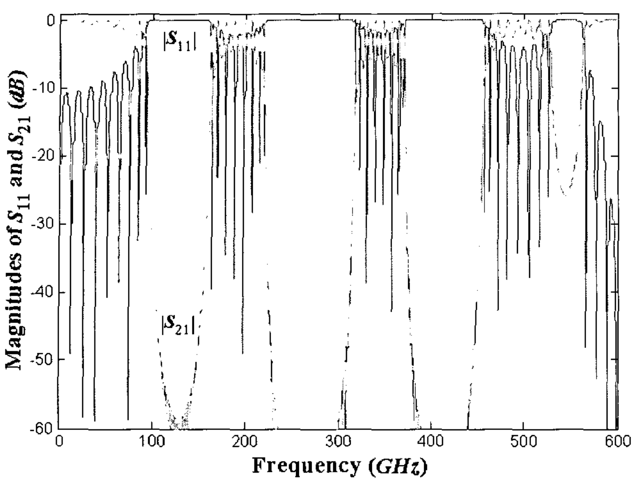


Fig. 4. $|S_{11}|$ & $|S_{21}|$ for the original PBG structure.

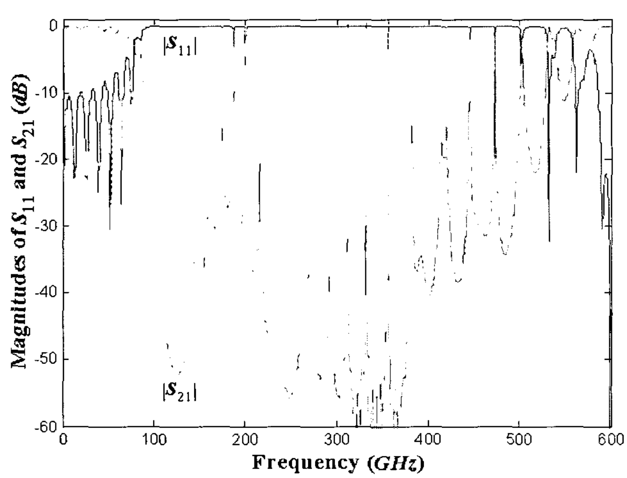


Fig. 5. $|S_{11}|$ & $|S_{21}|$ for the solely chirped PBG structure.

cies within the 600 GHz band. However, the width of stop-band is relatively narrow, as well as the fact that a high rejection level is observed at the low-frequency side-lobes.

Fig. 5 depicts the spectrum obtained from solely the chirped PBG structure, i.e., each $w_i$ varies by (2) while keeping $d_i$ at 250 $\mu$m fixed. It is observed that the stop-band is considerably enlarged within the 600 GHz frequency range. However, there still retains a relatively high rejection level at the low-frequency side-lobes.

Additionally, in order to prove that this passive PBG structure would yield the same frequency response regardless the port of entry, a flipped chirped PBG structure is computed and the results are put together in Fig. 5 using dot lines. It is observed that both structures yield basically the same response as they match each other very well.

Fig. 6 shows the corresponding results of the chirped and tapered PBG structure. From there, it can be seen

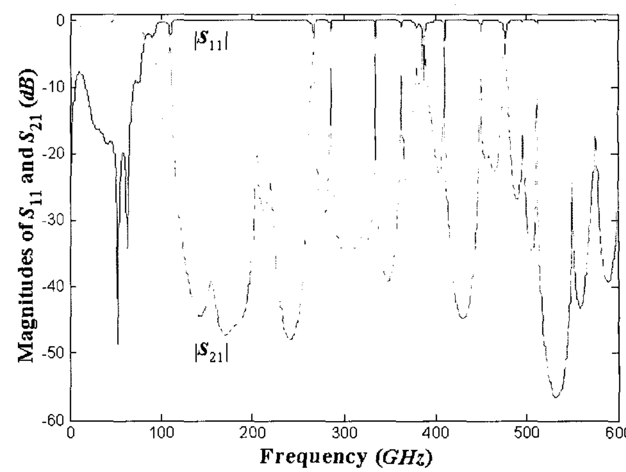


Fig. 6. $|S_{11}|$ & $|S_{21}|$ for the chirped and tapered PBG structure.

that both the stop-band width and the lower frequency side-lobes are improved when comparing with the conventional PBG spectrum. Therefore, through the illustration of the above results, engineering designers can place their desired structure based on their design criteria regarding the properties of bandwidth and the roll-off frequency.

As for further studies, a solely tapered PBG structure, i.e., by varying only the size of each $d_i$ while keeping all $w_i$ as 500 $\mu$m, is taken for analysis. The resulting frequency response is displayed in Fig. 7. From there, it is also seen that the stop-band width and the lower frequency sidelobe are enhanced, even though the low-frequency rejection level is not so optimized as the chirped and tapered one given in Fig. 6, as well as that there are a number of spikes between the frequency range of 300 GHz and 500 GHz.

The proposed stripline PBG structure shown in Fig. 3 is now studied. The frequency spectrum of the original

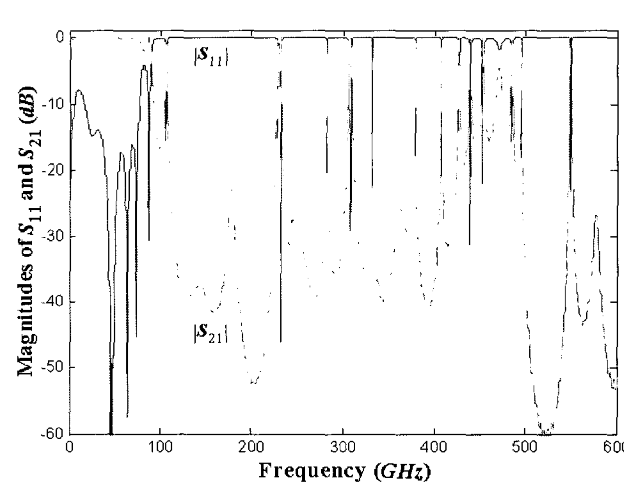


Fig. 7. $|S_{11}|$ & $|S_{21}|$ for the solely tapered PBG structure.

PBG structure whose dimensions of $a$=2.5 mm is plotted in Fig. 8. Though a band-gap filtering characteristic is displayed, the disadvantages of narrow stop-band and high side-lobe rejection level are also observed.

Results on chirping and tapering effects are depicted in Figs. 9 and 10, where Fig. 9 represents a solely chirping effect based on the perforation dimensions $a$=2.5 mm.

It is observed that the chirping technique provides certain bandwidth widening as shown in Fig. 9, but the side-lobe rejection level is still high at the low frequency.

Fig. 10 depicts the combined chirping and tapering technique, where both the bandwidth and rejection side-lobe level are improved comparing with Figs. 8 and 9.

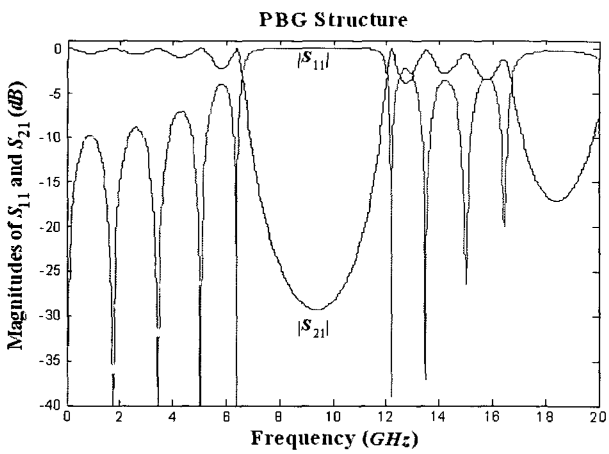


Fig. 8. Magnitudes of $|S_{11}(f)|$ and $|S_{21}(f)|$ for the stripline PBG structure with notch sizes 2.5 mm×2.5 mm on top and bottom ground plates respectively.

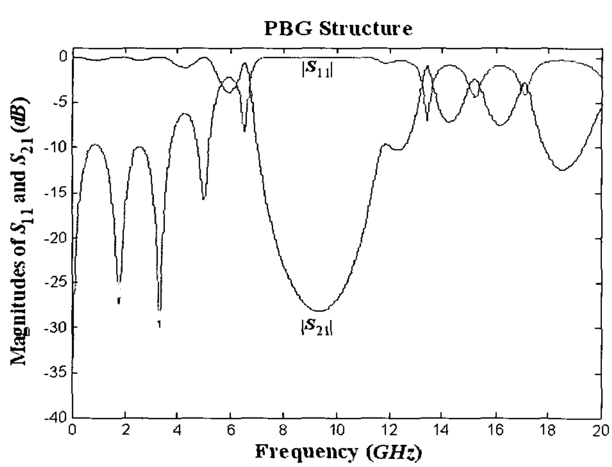


Fig. 9. Magnitudes of $|S_{11}(f)|$ and $|S_{21}(f)|$ for the STP PBG structure with notch sizes 2.5 mm×2.5 mm on top and bottom ground plates respectively, and with chirping technique at $\Lambda$=4 %.

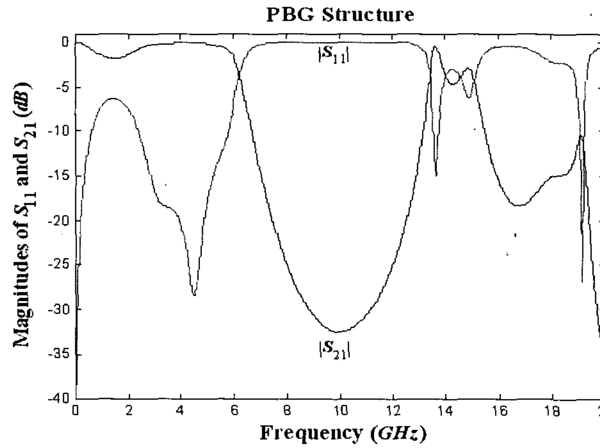


Fig. 10. Magnitudes of $|S_{11}(f)|$ and $|S_{21}(f)|$ for the STP PBG structure with varying notch sizes on top and bottom ground plates respectively, and with chirping and tapering technique.

## Ⅳ. Conclusion

A design involving a chirping and tapering technique was applied into a stratified dielectric PBG medium and a stripline PBG structure. It has been found that, for a chirped and tapered PBG structure, the width of stop-band and the rejection level at the low-frequency side-lobes out-performed the corresponding conventional PBG. The PBG designers thus have a flexibility to place their desired structure based on their design criteria in concern of the properties of bandwidth and critical frequency.

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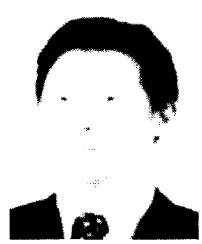

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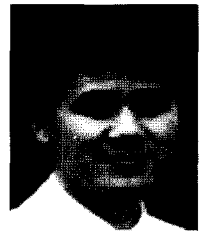

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