Non-uniform Chebyshev distributed chirped dumbbell-shaped photonic bandgap structure (PBGs) low-pass filter

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Abstract
Purpose – The purpose of this paper is to introduce a non-uniform Chebyshev distributed low-pass filter (LPF) with dumbbell-shaped photonic bandgap structure (PBGs), implemented in the 50 Ω microstrip line, with improved defected ground structure.
Design/methodology/approach – By varying filling factor (FF) of the periodic structure from 0.25 to 0.8 of the dumbbell squares can generate better rejection band than uniform dumbbell LPF.
Findings – Different FF of each square can produce different band rejection range and then yields the LPF with different cutoff. By using chirp adjustment of distance between PBGs, the band rejection performance can be optimized.
Originality/value – It can be seen that the chirped and non-uniform dumbbell-shaped PBGs generate excellent bandgap performances in linearly varying period (chirped devices) than those of structures with constant period (non-chirped or uniform devices).

Keywords Microwaves, Electric filters, Dielectric properties

Paper type Research paper

Introduction
The first photonic bandgap structure (PBG) structure for microwave wave filter was proposed in Qain et al. (1997). Photonic crystals are composed of periodic dielectric structures that affect the propagation of electromagnetic waves (EM). It is in the same way as the periodic potential in a semiconductor crystal, which affects the electron motion by defining allowed and forbidden electronic energy bands. From then, many researches have worked on the PBG size and shape selections (Xue et al., 2000; Akaline et al., 2001) and special UC-PBG structures (Yang et al., 1999a, b). Some papers also mentioned the defected ground structure (DGS) (Ahn et al., 2001; Liu et al., 2004), which gives the same meaning of PBGs for it treated the PBG as defected ground. Recently, in terms of the growing market of the personal communication systems, small size and high-performance filters become in very great demand. It can provide better noise and...
harmonics suppression in the unwanted band and maintain low-loss characteristics in
the passband, which in a very great deal of enhance the system performance. In the
conventional low-pass filter (LPF) designs, image parameter method is simple to use,
but frequency response cannot be incorporated into the design, it has to iterate over
and over.

The other method, insertion loss method, utilizes network synthetic circle theorem
and technique to realize filter structure, it requires many stages to realize bandpass
specification. The proposed PBG-based filter design can both reduce the size and
increase design flexibility, which is beneficial to the modern filter design (Pozar, 1998).
The investigated PBG structures can provide better frequency responses in the
passband while steeper cutoff frequency responses in the stopband. Among the
published PBG papers, it is realized that non-uniform distribution of PBGs, namely,
binomial and Chebyshev distribution of PBGs, with varied filling factors (FF), can
provide more control factors and can be stretched beyond the optimized value to yield
ripple-free transmission (Mollah et al., 2006; Karmakar, 2002). Communication chirped
modulation involvement of PBG design is also shown (Laso et al., 2000; Fu et al., 2006).
However, they used only square and circular shape PBG which limited the parameter
varying capabilities.

Recent researches on armed dumbbell-shaped PBG showed deeper rejection and
more control capabilities (Li et al., 2005). In this paper, filters using dumbbell-shaped
PBGs to the Chebyshev distributed chirped structure will be demonstrated. Owing to
the unique feature of single dumbbell caused deep rejection, the chirped structure when
compared to the conventional uniform dumbbell-shaped PBG, is expected to have
improved rejection bandwidth (BW) and amplitude.

The method
The non-uniform distribution of PBGs and dumbbell-shaped DGS of PBGs have been
discussed in open literatures (Li et al., 2005; Karmakar and Mollah, 2003). The FF can
be stretched beyond the optimized value to yield ripple-free transmission (Karmakar
and Mollah, 2003). They have wide bandgap with small ripple and height in the
passband (Mollah et al., 2005). The chirp structure adjustment of distance between
PBGs is conducted by the linear change of the perturbation period applied in linearly
chirped fiber Bragg gratings (Hill and Meltz, 1997).

In this study, we represent the influence of FF of PBGs in dumbbell-shaped PBG. FF is
defined to be the volumetric ratio of one PBG element to one unit cell. If two PBGs
patterned center spacing is “a” and the radius of the uniform circular patterned PBG
element is “r” then FF is said to be r/a. On the other hand, if the arm-length of square
patterned PBG element is “b” then the FF is said to be b/a. Apparently, FF has been
explained to show the stopband performances (Radisic et al., 1998).

In uniform dumbbell-shaped PBG design, deep bandgap was shown (Li et al., 2005).
In this design, however, non-uniform dumbbell-shaped PBG with FF modulated square
pattern is expected to provide even deeper bandgap and ultra rejection band, due to the
combination of equivalent cascaded LC circuits, which resonant at different
frequencies result in a wider BW.

Moreover, by use of the chirped modulation in the dumbbell-shaped PBG is also
expected to achieve further improvement and will generate excellent bandgap and
amplitude performance.
Designs
The following section describes the different designs. Conventional PBG design usually using square patterned PBGs with same size and equal distance as shown in Figure 1. The center frequency of the stopband is by Bragg’s condition (Karmakar and Mollah, 2003), calculated approximately by the following expression:

$$\beta a = \pi$$  \hspace{1cm} (1)

where:

- $a$ = the period of the PBG pattern.
- $\beta$ = the wave number in the dielectric slab.

$\beta$ is defined by the following expression:

$$\beta = \frac{2\pi f_0}{c \sqrt{\varepsilon_{\text{eff}}}}$$  \hspace{1cm} (2)

where:

- $f_0$ = the center frequency of the stopband.
- $\varepsilon_{\text{eff}}$ = the effective relative permittivity of the dielectric slab.
- $c$ = the speed of light in free space.

The Chebyshev distributed structure design is shown in Figure 2. Instead of maximally flat passband characteristics, an equally useful characteristic is one that may permit the transmission coefficient to vary with minute ripples over the stopband (Balanis, 1997). This provides a considerable increase in BW with respect to binomial distribution. This equal-ripple characteristic is obtained by making the distribution

![Figure 1. Geometry of conventional square patterned PBGs](image1)

![Figure 2. Geometry of a microstrip transmission line on non-uniform Chebyshev distributed PBGs](image2)
according to the Chebyshev polynomial. The basic properties of the polynomial (Balanis, 1997), are expressed as followed:

\[ T_m(z) = 2zT_{m-1}(z) - T_{m-2}(z) \]  

where, \( T_m(z) \) is expressed as:

\[ T_m(z) = \cos[m \cos^{-1}(z)] \text{ and } |z| \leq 1 \]  

The coefficients of the polynomial are determined for any prescribed sidelobe level (SLL). In the design example, we take a ten-element PBG array with a tapered distribution according to Chebyshev coefficients. For a prescribed voltage ratio between the peak and SLL, e.g. for 25 dB, the amplitudes are determined as followed.

The chirp design is shown in Figure 3. Chirped modulation, however, makes the central elements have the largest radii of \( r_0 \) and the radii of the adjacent circles decrease proportionally to the amplitude coefficients of the polynomials. The chirped structure period is given by the next equation as a function by the following expression (Laso et al., 2000):

\[ a_i = a_0 \cdot (1 + i\delta) \]  

with:

- \( a_0 \) = the period corresponding to the central hole of the structure.
- \( \delta \) = the chirp parameter that controls the period variation, and \( i = 0, \pm 1, \pm 2, \ldots \)

Conventional dumbbell-shaped structure has two frequency properties (Mollah and Karmakar, 2004); one is pole location, another is existence of cutoff frequencies. Cutoff frequency is mainly dependent on the etched bigger square patterned slot. So, we use FF to change the two etched bigger square, by varying FF of the periodic structure from 0.25 to 0.8. The pole location mainly depends on the width of the narrow vertical slot. The lumped LC equivalent model is calculated approximately by the following expression (Ahn et al., 2001):

\[ c = \frac{\omega_c}{Z_0 g_1} \left[ \frac{1}{(\omega_0^2 - \omega_c^2/\omega_0^2)} \right] \]  

**Figure 3.** Geometry of a microstrip transmission line on chirp structure PBGs
\[ L = \frac{1}{4\pi^2 f_0 c} \]  

where:

- \( f_0 \) = the frequency of the attenuation pole.
- \( \omega_c \) = the angular cutoff frequency.
- \( Z_0 \) = the characteristic impedance of the line.
- \( g_1 \) = the admittance value of the Butterworth LPF response.

To understand the chronological development, we have reproduced the conventional dumbbell-shaped patterned and proposed newer dumbbell-shaped PBGs.

**A. Design 1: conventional dumbbell-shaped patterned PBGs**

The 50-\( \Omega \) microstrip transmission line perturbed by conventional dumbbell-shaped patterned PBGs has been shown in Figure 4. The size of the square patterned slots is 104 \( \times \) 104 mils and the dimension of the narrower vertical slot is 50 \( \times \) 152 mils.

**B. Design 2: proposed dumbbell-shaped PBGs**

The proposed design is shown in Figure 5. Application of non-uniform Chebyshev distribution in the dumbbell-shaped pattern we can design the PBG pattern. In this design, the square patterned 2\( r_0 \), 2\( r_1 \), 2\( r_2 \), 2\( r_3 \), and 2\( r_4 \) are 166 \( \times \) 166, 140 \( \times \) 140, 110 \( \times \) 110, 81 \( \times \) 81 and 52 \( \times \) 52 mils, respectively. The vertical slots are the same as the conventional dumbbell-shaped PBGs in which the interval \( a \) is 208 mils.

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**Figure 4.**  
Geometry of conventional dumbbell-shaped PBGs

**Figure 5.**  
Geometry of proposed non-uniform Chebyshev distributed dumbbell-shaped PBGs
C. Design 3: proposed chirp dumbbell-shaped PBGs

The proposed design is shown in Figure 6. The square patterned slots and vertical slot are the same as the proposed non-uniform Chebyshev distributed dumbbell-shaped PBGs. However, the chirped period variation using \( i = 0, -1, -2, -3, \ldots \) make non-uniform dumbbell-shaped PBGs spacing varied. The minus sign means the compression of spacing. The compact variation may get better performance. The \( a_1, a_2, a_3, \) and \( a_4 \) are distance intervals, the values are \(-26, -52, -104, \) and \(-208 \) mils, respectively. \( a_0 \) is constant distance (208 mils).

The results

The frequency responses of three mentioned dumbbell-shaped PBG designs are shown below.

A. S-parameter performances of conventional dumbbell-shaped PBGs

From the graph of Figure 7, it is seen that the 10 dB passband return loss (RL) RL-BW is found to be 3 GHz and the 20 dB rejection BW due to big jump frequency in the middle part, is found to be 4 GHz, maximum isolation is 58 dB and the passband ripple near cutoff is 1 dB.

B. S-parameter performances of the proposed Chebyshev distributed dumbbell-shaped PBGs

It is seen from Figure 8 that the 10 dB passband RL-BW is found to be 3.28 GHz. The 20 dB rejection BW, however, due to the elimination of big jump, is found to be 12 GHz, maximum isolation is 79 dB and the passband ripple near cutoff is 1 dB.

C. S-parameter performances of the proposed Chebyshev distributed chirp dumbbell-shaped PBGs

From the graph of Figure 9, it is seen that the 10 dB passband RL-BW is found to be 3.28 GHz and the 20 dB rejection BW of 12.4 GHz is about the same as previous result. But due to the elimination of some small jumps, a 40 dB rejection BW of 7.56 GHz wide is shown. Compare to the similar reported chirped PBG designs (Mollah and Karmakar, 2004; Mollah et al., 2007), it is much wider in the rejection BW. The result also shows

\[
a_1 = a_0 (1 + i \delta) \quad a_2 = a_0 (1 + i \delta) \quad a_3 = a_0 (1 + i \delta) \quad a_4 = a_0 (1 + i \delta)
\]
a maximum isolation of 78 dB. The passband ripple near cutoff is 1 dB. The BW-cutoff
frequency ratio is defined as corresponding rejection BW to 3 dB cutoff frequency ratio,
for example, the designed chirped-Chebyshev dumbbell filter has 20 dB rejection to
3 dB cutoff ratio of $12.4/3.3 = 3.75$. The BW-cutoff frequency ratios of 20 dB BW are
3.75, 1.96, and 1.846, respectively, while the ratio of 40 dB BW are 2.29, 0.8, and 0.558,
respectively, as shown in Table I. The rejection BW is improved tremendously.

All the designs are simulated by the EM software Zeland IE3D. The substrate is
Taconic with dielectric constant of 10.2 and height of 25 mils. From the S-parameter
performances shown in Figures 7-9, it is obvious that the proposed design provides
ultra wide bandgap. The maximum isolation and the peak RL are enough to suffice the
design requirements of a standard microstrip LPF.
Conclusions

Novel PBG engineered microstrip transmission lines are designed and investigated theoretically and experimentally. The chronological development of different designs like uniform dumbbell-shaped PBGs, non-uniform Chebyshev and distributed dumbbell-shaped PBGs with standard chirping technique have been investigated and performed for comparison. Final design with chirped modulation is proved to be the best microstrip LPF with widest rejection BW. When compared to other’s work, the best BW-cutoff frequency ratio at 20 and 40 dB rejection are also shown.

References


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