Research Article

Novel Meandered Line EBG Filters with Significant Size Reduction Using Sine Tapering

S. M. Shakil Hassan, Kalyan Kumar Halder, and Md. Nurunnabi Mollah

1Department of Electrical and Electronic Engineering, Khulna University of Engineering & Technology, Khulna, Bangladesh
2Department of Electrical and Electronic Engineering, Eastern University, Dhaka, Bangladesh

Correspondence should be addressed to S. M. Shakil Hassan; shakil.bq@gmail.com

Received 3 May 2023; Revised 3 August 2023; Accepted 25 August 2023; Published 4 October 2023

Copyright © 2023 S. M. Shakil Hassan et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Tapering electromagnetic bandgap (EBG) structures is a common method in designing microstrip filters with different periodic structures. A novel technique for tapering EBG structures with the amplitude coefficients obtained from the sine function has been illustrated. This method deduces mellifluous coefficients that improves the performance with reasonable stopband width, preferable insertion loss level, and much-minimized passband ripples compared to similar designs with other tapering methods (e.g., binomial distribution, Chebyshev distribution, and conventional cosine tapering). It also offers tandem use of tapered EBG structures, leading to the novel meandered transmission line tandem design that significantly reduces the length of the filter; more than 40% is possible, compared to the uniform and conventional tapered designs. Size reduction on such a large scale will benefit the designers with the limited space issues.

1. Introduction

Planer electromagnetic bandgap (EBG) structures are periodic elements in the ground plane of a microstrip transmission line. They have found much attraction for exhibiting bandpass and band rejection properties at microwave and millimeter wave frequencies. Because of their unique property of impeding surface waves, EBG structures have found potential applications in planer transmission lines for realizing different types of microwave filters, phased array antennas, waveguides, high-efficiency power amplifiers, diplexers, power dividers/combiners, and many other devices [1–5]. EBG structures are of different shapes, for example, circular, square, annular ring, spiral, triangular, and dumbbell-shape [5–11]. In much earlier literature, EBG structures were termed photonic bandgap (PBG) structures [7]. However, several techniques for improving the performance of EBG-assisted filters and antennas have been investigated; one of the popular methods for optimum filter design is tapering the EBG elements [12–14].

Tapering of EBG structures has become a very popular trend in designing EBG-assisted microstrip transmission lines due to its significant impact on improving performance in terms of lower ripple heights (RHs) at passband frequencies [15–17]. Tapered EBG structures are also called nonuniform EBG structures [7]. They possess a lower total etching area ($A_{TE}$) compared to the respective uniform EBG structures-assisted microstrip transmission line; therefore, the maximum level of the insertion loss (IL or the $S_{21}$ curve of the $S$-parameter performance) becomes lower. However, several techniques for creating nonuniform EBG structures have been reported in the open literature: these include binomial, Blackman, Chebyshev, Gaussian, Hamming, Welch, and others [18–20]. Among them, the Chebyshev distribution has found a wide range of applications for offering the most promising performance, but it requires substantial effort to solve large equations to get the desired tapering coefficients [21–23].

All of the tapering functions have several inadequacies with the single advantage of offering a much smaller ripple in the passband. The challenges are as follows:
(1) They reduce the stopband width (SBW) significantly as the sizes of the EBG patterns reduce dramatically.

(2) The IL level becomes much lower due to having an inadequately distributed total etching area.

(3) The size of the reference EBG element must be extremely large to provide a sufficient, evenly distributed etching area.

(4) To get appreciable performance, amplitude coefficients have to be selected for too many EBG elements.

(5) Thus, the total number of EBG structures increases; hence, the length of the transmission line becomes unnecessarily longer [18].

(6) EBG patterns at both ends become too small to have significant impacts on performance [24].

In this paper, we have demonstrated a simpler technique of finding the tapering coefficients using the sine function. We have demonstrated the tapering coefficient factor \( T_{cf} \) as a means to evaluate different tapering functions. We have shown that tapering of EBG patterns by the area of the reference EBG element instead of its size (e.g., the radius of a circular or the side of a square EBG structure) is more beneficial.

Furthermore, the sine tapering method mathematically and systematically supports the tandem use of tapered EBG structures that yields the tandem design; based on the tandem design, we have introduced a novel meandered transmission line lattice of EBG structures with reduced physical size of the filter realizations.

2. Design Procedure of EBG Filters

In Figure 1, we can see the basic designs of a uniform EBG structure-assisted microstrip transmission line, where the transmission line is at the top plane and EBG patterns are at the ground plane; these designs are supposed to behave as a bandstop or notch filter. We can see that the inner structure or inner element spacing (i.e., period) is denoted as “\( a \)” as follows:

\[
a = \frac{\pi}{\beta},
\]

where \( \beta \) is the wavenumber in the dielectric slab, which can be expressed as follows:

\[
\beta = \frac{2\pi f_0}{c} \sqrt{\varepsilon_r},
\]

where \( f_0 \) is the considered center frequency of the stopband, \( \varepsilon_r \) is the effective relative permittivity of the used dielectric substance, and \( c \) is the speed of light in free space.

Besides in Figure 1, we can see that the number of periodic EBG structures is denoted as “\( n \)”: for example, \( n = 7 \) and 6 are shown in Figures 1(a) and 1(b) for uniform circular and square EBG structures, respectively. The size of the EBG element can be determined using the filling factor (FF) as defined by the following generalized expression [6]:

\[
FF = \frac{\text{area of an EBG element} \ (A_{\text{EBG}})}{\text{area of a unit cell} \ (A_{\text{cell}})}.
\]

Tapering is done with a set of coefficients known as amplitude or tapering coefficients \( (k) \), where the sizes of the adjacent EBG elements are proportional to the size of the reference EBG element with the corresponding \( k \); two typical tapered designs are shown in Figure 2 for both odd and even values of \( n \). A more detailed process of such a tapered design is discussed in later sections.

However, in our study, we have used Taconic substrate, which has relative permittivity \( \varepsilon_r \) and thickness \( h \) of the substrate as 2.45 and 31 mils, respectively. Hence, the width \( (w) \) of the standard 50 \( \Omega \) transmission line is 2.264 mm. We have considered \( f_0 = 10 \) GHz, and thus \( a = 10.5 \) mm. These parameters are kept identical for all the designs that we have realized for investigation, unless specified otherwise.

3. Different Filters Design, Simulations, and Measurements

In this paper, we have used a method of moments-based software from Mentor Graphics (formerly Zeland Software, Inc.) named IE3D, a widely used software, and experts have found that the simulated results agree well with the measured results [22, 23]. We have investigated the merits of the congruency of our simulations using this software by comparing the simulated performances of some earlier reported designs with measured performances too.

3.1. Uniform EBG Design. A nontapered nine circular EBG elements-assisted design is realized on the substrate having a dielectric constant of \( \varepsilon_r = 10.2 \) and a thickness of \( h = 1.27 \) mm. The width of the transmission line is \( w = 1.2 \) mm, the radius is \( r = 3.525 \) mm, and inner element spacing is \( a = 14.1 \) mm [18]. We have simulated the same EBG filter and compared the simulated S-parameter performance with the reported measured performance, as shown in Figure 3(a). The measured result shows slightly larger passband ripples, a little larger stopband, and a higher rejection level than the simulated result. Such minor dissimilarities are insignificant and are very common in experimental results because of the limitations of measurement tools and since very precise etching of EBG elements is hardly possible in practice.

3.2. Cosine-Tapered EBG Design. By determining the cosine tapering coefficients using (6), we have designed and simulated the cosine-tapered design as reported in [18]. The radius of the reference circular EBG pattern \( r_{\text{ref}} = 3.525 \) mm. A comparison of the reported measured result and the simulated results using IE3D is shown in Figure 3(b). Although the insertion loss curve of the measured and simulated results follows a similar fashion, the SBW and the maximum IL level are a bit higher in the measured result as observed in the abovementioned design.
4. Sine Tapering vs. Reported Cosine, Chebyshev, and Binomial Tapering Function

In this section, we have discussed the proposed method of sine tapering and the traditional cosine tapering that are reported in open literature: [18, 23].

4.1. Fundamentals of Sine Tapering Function. The tapering coefficients of a sine function for the preferred \( n \) have to be calculated as follows:

\[
k_i = \left| \sin \left( \frac{i \times \Delta \theta}{n+1} \right) \right|,
\]

where \( i = 1, 2, 3, \ldots, n \) denote the positions of the EBG element and \( \Delta \theta \) is the angular spacing of each EBG element between 0° and 180° or (0 to \( \pi \) radians) of the sine function to get coefficients for \( n \) EBG elements. For instance, if \( n = 5 \) and 6, then \( \Delta \theta \) is 30° and 25.71°, respectively.

Now, the size of the EBG elements can be calculated by multiplying the tapering coefficients with the size of the reference EBG element as follows:

\[
x_i = k_i \times x_{ref},
\]

where \( x_{ref} \) is the dimension of the reference EBG element; \( x \), for example, can be radius \( r \) or arm length \( b \) for circular or square EBG patterns, respectively [24]. \( x_i \) is the size of the \( i^{th} \) EBG element. Nonuniform or tapered designs having odd and even numbers of EBG patterns are shown in Figure 2.

4.2. Fundamentals of Cosine Tapering Function. A detailed method of finding the coefficients using the cosine tapering function is depicted by Huang and Lee as follows:

\[
k_i = \cos \left( \frac{\pi}{2} \times z_i \right),
\]

where \( z_i \) is the normalized distance of the \( i^{th} \) EBG element from the center of the transmission line [23], and it is defined as follows:

\[
z_i = \frac{2d_i}{L_t},
\]

where \( d_i \) is the actual distance of the \( i^{th} \) EBG element from the center of the transmission line and \( L_t \) is the actual minimum length of the transmission line. \( L_t \) is determined by

\[
L_t = (n-1)a + x_0,
\]

where \( x_0 \) denotes the dimension of the fundamental or reference EBG structure; for example, \( x_0 \) represents the diameter \( (D_0) \) for a circular EBG structure or the side length \( (b_0) \) for a square EBG structure.

Besides, Laso et al. defined the cosine tapering function as follows:

\[
k_i = \left( \cos \left( \frac{\pi Z}{L} \right) \right)^{0.5},
\]

where \( z/L \) is the normalized longitudinal position [18].

Thus, coefficients determined by using (6) and (9) are not identical; besides, both equations depend on the period, the number of EBG elements, and the shape and size of the EBG pattern.

From (6), the length of the actual minimum of the transmission line depends on the size, shape, and period \( a \) of the EBG patterns and, like other tapering methods, obviously on the number of EBG elements \( n \). Therefore, for a given number of EBG structures, the cosine-tapering coefficients depend on the period, \( a \), and the size and the shape of the EBG structures, whereas \( k_i \) of the sine tapering is independent of such variables, but only \( n \).

4.3. Chebyshev and Binomial Tapering Functions. Chebyshev coefficients are related to the Dolph–Tchebyscheff array and polynomial, where designers need to go through a relatively complicated and longer process of calculations to determine the tapering coefficients for different numbers of EBG elements [21–23]. In contrast, the sine tapering coefficients are much easier to determine.
On the other hand, binomial coefficients can easily be determined using Pascal’s triangle derived from binomial polynomials [21, 23, 26].

4.4. Merit of the Tapering Functions. Tables 1 and 2 show the differences in different tapering coefficients for different shapes, sizes, and periods. From the table, we can see that the tapering coefficient factor expresses the merit of tapering different tapering functions for a given $n$.

$T_{cf}$ is defined as follows:

$$T_{cf} = \frac{\sum_{i=1}^{n} k_i}{n}, \quad (10)$$

where $T_{cf} = 1$ means the uniform design and $T_{cf} = 0$ means a blanked transmission line or simple microstrip line.

We can observe from Table 1 that the values of the coefficients for the cosine function are different for circular and square EBG patterns are different, and so is $T_{cf}$; besides, for different inner element spacing, they get changed too. In Table 2, the coefficients of the sine and cosine tapering functions are compared for different numbers of EBG structures. We have observed that the cosine function results in a much smaller $T_{cf}$ than the sine function; whereas $T_{cf}$ of Chebyshev and sine-tapering functions are very close.

5. Performance of Sine-Tapered Designs in Comparison to Other Designs

In this section, we will investigate the performance of sine-tapered designs, and the performances will be compared with the uniform design and with binomial, Chebyshev, and cosine-tapered designs. Besides, we will accomplish the comparison in two different tapering categories, namely, “size tapering” and “area tapering.”

We have considered the following parameters for designing the EBG filters for our investigations: $\varepsilon_r = 2.45$; $h = 31$ mils; $w = 2.264$ mm; $f_o = 10$ GHz; and $a = 10.5$ mm.
see that for the binomial function, since the values of the tapering coefficient are too small (i.e., $T_{cf}$ is lower, see Tables 1 and 2), the IL performance is very poor. On the other hand, the Chebyshev and sine tapering functions have a higher $T_{cf}$ and exhibit very impressive $S$-parameter performance in terms of IL and RL performance. However, the cosine function results in moderate performance, much better than the binomial tapering, but the performance is not much attractive compared to Chebyshev-tapering methods.

Besides, the novel sine tapering method exhibits a little better performance than the Chebyshev method (Figure 5); therefore, the best performance is observed from the sine tapering method. In general, all the tapering functions improve the overall performance by reducing the passband RHs, but at the expense of the SBW. As seen from Table 3 and Figure 5, size tapering results in much smaller sizes of EBG structures; hence, the performances of these designs are too deviated and poor compared to the respective uniform designs. In the table for the design, with $n = 6$ and $b_{ref} = 6.2\, \text{mm}$, we can see that SBW for the uniform design is 5.885 GHz, but for the binomial tapering, no appreciable stopband is formed. SBWs for the cosine, Chebyshev, and sine tapering are 2.484 GHz, 3.751 GHz, and 4.063 GHz, respectively, and the maximum passband RHs are much lower for all. From the whole study, we can observe that among the compared tapering functions, the novel sine tapering method shows better performance.

### 5.1. Uniform Design

To evaluate the merit of the sine tapering function by performing a comparative analysis on the performance of different tapering functions, we have considered two design variables: the size of the reference EBG element, as uniform designs, and the number of the EBG elements.

Performances of the uniform square shape EBG element-assisted designs for two different sizes and different numbers of elements are tabulated in Table 3; we observe that as the size and the number of EBG elements increase, the IL increases and results in a wider $-20\, \text{dB}$ rejection bandwidth [25, 27].

The uniform designs usually suffer from spurious ripples in the passband and thus result in poor RL performance. Figure 5(a) shows the scattering parameters of a uniform design, with $n = 6$ and $b_{ref} = 6.2\, \text{mm}$, that results in $-20\, \text{dB}$ rejection bandwidth (BW) of 5.885 GHz and a maximum level of isolation ($S_{21}$) of $-50.57\, \text{dB}$; but at the center frequency, 10.416 GHz, the isolation is $-48.98\, \text{dB}$. Moreover, the $-10\, \text{dB}$ RL bandwidth which is also known as passband width (PBW) is 6.151 GHz. Here, $-5.19\, \text{dB}$ maximum passband ripple and 7.036 GHz $-3\, \text{dB}$ cutoff frequency are observed. As can be seen in Table 3, uniform designs exhibit poor RL performance near the cutoff frequency, with high spurious ripple on $S_{21}$ in the passband (in Figure 5). These ripples can be significantly minimized by using tapering methods that, in effect, improve complete performance.

### 5.2. Size Tapering

The tapering coefficients are applied directly to the dimension-denoting parameters of EBG structures that yield size tapering. In Figure 5 and Table 3, we can see that the performance of the tapered designs to $T_{cf}$ shown in Tables 1 and 2, we can see from Tables 3 and 4 that with higher $T_{cf}$ (except $T_{cf} = 1$, uniform design), the performance of $S_{21}$ improves noticeably. The sine tapering function offers relatively higher values of
We have seen that as the number of EBG structures and the optimal size of the reference EBG basically, refers to the use of the optimal number of EBG elements to meet the desired goal regarding the space limitation (if any). In Table 5, we have presented the dependencies of the performance parameters on two variables: \( n \) and \( S_{\text{ref}} \). For the square EBG pattern, during the first investigation (dependency with \( n \)), we considered the reference size of the square, \( b_{\text{ref}} \), to be 6.2 mm. We have seen that as the number of EBG structures increases, the SBW, PBW, level of \( S_{21} \), and RHs increase. As reported in [27], the minimum level of IL after the SBW remains lower as \( n \) increases. From the table, we can see that \( n \) can be suitably chosen in the range of 5 to 8, as they show better performance with a smaller size of the line.

### 6.2. Optimum Size of the Reference EBG Element

In the second investigation, the dependency of the performance on the size of the reference EBG element, we can observe that for a fixed \( n = 7 \), as the size of the reference element is increased, the SBW, the maximum level of \( S_{21} \) in the stopband, and the RHs get increased, and then band minimum \( S_{21} \) level remains lower. From Table 5, we can observe that the sizes of the reference square EBG pattern of 7.04 mm and 8.13 mm are \(-10.96 \text{ dB} \) and \(-19.71 \text{ dB} \), respectively, whereas, for \( b_{\text{ref}} = 4.7 \text{ mm} \) and 5.79 mm, the after-stopband levels of \( S_{21} \) are \(-2.25 \text{ dB} \) and \(-5.31 \text{ dB} \), respectively, which is much more appreciable with much better SBWs and IL levels. Hence, the too-large size of the reference EBG element exhibits detrimental performance. Therefore, with \( n = 7 \), the optimum performance of the sine function (based on the area tapering method) can be obtained by choosing the size of the reference element between 4.7 mm and 5.79 mm. As the performance also depends on the number of EBG elements, for different \( n \), the optimum size of the reference EBG structure should be readjusted.

### 6.3. Performance Optimization

In the above two optimizations, we have chosen the size of the EBG structure by calculating the filling factor, which is defined as (3), the ratio of the area of the reference EBG element to the area of a unit

### 6 International Journal of Antennas and Propagation

#### Table 1: Tapering coefficients obtained from different methods for \( n = 6 \).

<table>
<thead>
<tr>
<th>Tapering function</th>
<th>( a ) (mm)</th>
<th>Shape; size (mm)</th>
<th>( k_1 )</th>
<th>( k_2 )</th>
<th>( k_3 )</th>
<th>( k_4 )</th>
<th>( k_5 )</th>
<th>( k_6 )</th>
<th>( k_7 )</th>
<th>( k_8 )</th>
<th>( k_9 )</th>
<th>( k_{10} )</th>
<th>( T_{cf} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binomial</td>
<td></td>
<td>Circular; ( r = 3.5 )</td>
<td>0.18</td>
<td>0.67</td>
<td>0.96</td>
<td>0.96</td>
<td>0.67</td>
<td>0.18</td>
<td>0.603</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sine</td>
<td></td>
<td>Square; ( b = 6.2 )</td>
<td>0.17</td>
<td>0.67</td>
<td>0.96</td>
<td>0.96</td>
<td>0.67</td>
<td>0.17</td>
<td>0.600</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sine</td>
<td></td>
<td>Square; ( b = 4.7 )</td>
<td>0.09</td>
<td>0.63</td>
<td>0.96</td>
<td>0.96</td>
<td>0.63</td>
<td>0.09</td>
<td>0.560</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cosine</td>
<td>10.5</td>
<td>Circular; ( r = 3.5 )</td>
<td>0.12</td>
<td>0.64</td>
<td>0.96</td>
<td>0.96</td>
<td>0.64</td>
<td>0.12</td>
<td>0.573</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Square; ( b = 6.2 )</td>
<td>0.12</td>
<td>0.64</td>
<td>0.96</td>
<td>0.96</td>
<td>0.64</td>
<td>0.12</td>
<td>0.573</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Cosine-tapering coefficients are determined by using (6).

#### Table 2: Tapering coefficients for square EBG structure and different \( n \).

<table>
<thead>
<tr>
<th>Tapering function</th>
<th>( n )</th>
<th>( k_1 )</th>
<th>( k_2 )</th>
<th>( k_3 )</th>
<th>( k_4 )</th>
<th>( k_5 )</th>
<th>( k_6 )</th>
<th>( k_7 )</th>
<th>( k_8 )</th>
<th>( k_9 )</th>
<th>( k_{10} )</th>
<th>( T_{cf} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sine</td>
<td>3</td>
<td>0.71</td>
<td>1</td>
<td>0.71</td>
<td>0.97</td>
<td>0.97</td>
<td>0.78</td>
<td>0.43</td>
<td>0.727</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sine</td>
<td>4</td>
<td>0.50</td>
<td>0.87</td>
<td>1</td>
<td>0.87</td>
<td>0.50</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sine</td>
<td>5</td>
<td>0.16</td>
<td>0.76</td>
<td>1</td>
<td>0.76</td>
<td>0.16</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cosine</td>
<td>3</td>
<td>0.54</td>
<td>0.76</td>
<td>0.91</td>
<td>0.99</td>
<td>0.99</td>
<td>0.91</td>
<td>0.76</td>
<td>0.54</td>
<td>0.28</td>
<td>0.696</td>
<td></td>
</tr>
<tr>
<td>Cosine</td>
<td>4</td>
<td>0.40</td>
<td>0.67</td>
<td>0.88</td>
<td>0.99</td>
<td>0.99</td>
<td>0.88</td>
<td>0.67</td>
<td>0.40</td>
<td>0.07</td>
<td>0.602</td>
<td></td>
</tr>
<tr>
<td>Cosine</td>
<td>5</td>
<td>0.07</td>
<td>0.29</td>
<td>0.67</td>
<td>1</td>
<td>1</td>
<td>0.67</td>
<td>0.29</td>
<td>0.07</td>
<td>0.01</td>
<td>0.408</td>
<td></td>
</tr>
<tr>
<td>Binomial</td>
<td>10</td>
<td>0.36</td>
<td>0.48</td>
<td>0.71</td>
<td>0.89</td>
<td>1</td>
<td>1</td>
<td>0.89</td>
<td>0.71</td>
<td>0.48</td>
<td>0.36</td>
<td>0.688</td>
</tr>
</tbody>
</table>

Cosine-tapering coefficients are determined by using (6).

\( T_{cf} \) among the considered functions. From the complete analysis of the different mentioned tapering methods, we have observed that the sine-tapered designs result in appreciable performance in all respects; hence, higher \( T_{cf} \) results in relatively wider stopband performance with higher insertion loss. Therefore, by \( T_{cf} \), a preliminary prediction regarding the number of EBG elements and the required size of the reference EBG element is possible to obtain the desired performance. Furthermore, area tapering is the most appropriate type of tapering tactic for getting good bandwidth and IL performance since it offers a more distributed etching area under the transmission line.

### 6. Optimization of Sine-Tapered Design

Optimization of an EBG filter comprises two things: (a) deducing the optimized design (i.e., design optimization) and (b) performance optimization. Design optimization, basically, refers to the use of the optimal number of EBG structures and the optimal size of the reference EBG pattern.

#### 6.1. Optimum Number of EBG Structures

First, to determine the most optimized design of the filter, we need to deduce the minimum required number of EBG elements to meet the desired goal regarding the space limitation (if any). In Table 5, we have presented the dependencies of the performance parameters on two variables: \( n \) and \( S_{\text{ref}} \). For the square EBG pattern, during the first investigation (dependency with \( n \)), we considered the reference size of the square, \( b_{\text{ref}} \), to be 6.2 mm. We have seen that as the number of EBG structures increases, the SBW, PBW, level of \( S_{21} \), and RHs increase.

#### 6.2. Performance Optimization

In the above two optimizations, we have chosen the size of the EBG structure by calculating the filling factor, which is defined as (3), the ratio of the area of the reference EBG element to the area of a unit
cell, observing identical performance from the identical area of different EBG shapes [6]. Based on identical performance from different shapes, we have examined the impact of differing the number of EBG structures, \( n \), in the area-based tapered designs while keeping the total etching area (\( A_{TE} \)) identical.

Table 6 shows that different sizes of reference EBG patterns are used in the designs for different \( n \) to maintain \( A_{TE} \leq 168.14 \text{mm}^2 \). The size of the reference elements, \( x_{ref} \) (\( b_{ref} \) for square shape), is calculated by (5) and (11) as follows:

\[
A_{TE} = \sum_{i=1}^{n} A_i. \tag{12}
\]

From Table 6, we can notice that the maximum levels of \( S_{21} \) at the stopband are much lower with much higher values of minimum levels of \( S_{21} \) after the stopband for \( n = 3 \) and 4; furthermore, RHs are quite significant. On the other hand, as \( n \) increases, performance improvements are detected in terms of lower RH, the minimum level of \( S_{21} \) after stopband, and the maximum level of \( S_{21} \); however, SWB reduces while passband width increases; and with a larger number of EBG structures, the total size of the design becomes longer.

Therefore, keeping \( n = 5 \) to 8 in a sine-tapered design with a moderate \( A_{TE} \) (around 168 mm²) will show optimum performance for the sine tapering method. With the area tapering method, engineers can achieve improved BW and IL performance. It eliminates the need to use a greater number of EBG elements and a very larger size of the reference EBG element; therefore, the whole design (i.e., length) becomes significantly smaller.

### 7. Tandem Designs and Performances

Tandem nonuniform EBG structures, basically, refer to the repeated use of the same set of nonuniform EBG patterns next to the one set, as shown in Figure 2.

#### 7.1. Tandem Sine Tapering Function

Tandem design, in other words, means the use of the sine function for several half cycles of the angular distance since (4) represents that a set of coefficients is determined only by the angular distance of a sine wave for a half cycle. Tandem tapering coefficients, however, are determined by (4), where \( i \) is defined as a set of all discrete values in

\[
i = 1, 2, 3, \cdots, \lfloor (n + 1) \times C_r - 1 \rfloor, \tag{13}
\]

where \( C_r \) is the number of repetitions of a set of tapered EBG structures (i.e., cycles) in the tandem design. The total number of EBG structures in a tandem design, \( N \), is calculated by

\[
N = C_r \times n. \tag{14}
\]

Tandem coefficients might consist of several null points: values of \( i \) for which \( k_i \) becomes zero. For instance, if \( C_r = 2 \), then for \( n = 5 \), and we will have \( N = 10 \). Hence, the value of \( k_6 \) will become zero. There are three ways to treat the null point.

#### 7.1.1. Type-1

Null locations will be kept in between the smallest EBG structures of two consecutive cycles of tapered EBG elements. The null location will have the spacing \( a \), as in Figure 6(a).
7.1.2. Type-2. Null points will be eliminated, and the next smallest EBG structures will be shifted to occupy the blank locations, as in Figure 6(b). Hence, the length of the transmission line becomes shorter than the Type-1 design, and it will be similar to the conventional tapered design with ten EBG elements.

7.1.3. Type-3. The two adjacent smallest EBG structures are merged as one, as shown in Figure 6(c); hence, \( N \) becomes 9 in this case. As a result, the length of the transmission line \( L_t \) is shortened by a when compared to the conventional tapered design with ten EBG elements and Type-2 designs.

Figure 5: For different tapering functions, (a) insertion loss and (b) return loss of size-based tapered designs and (c) insertion loss of area-based tapered designs.
Moreover, as of Table 6, we have considered area tapering using sine tapering coefficients, and the other tandem designs with square EBG elements and considered designs using circular EBG patterns, but we have realized the performances of the tandem designs with different EBG patterns; hence, the total etching area will be lower than because \( L_\text{ref} \) is usually assumed to be equal to \( N_\alpha \). The total number of EBG elements in Type-3 designs will be

\[ N_{\text{type-3}} = N - C_r + 1. \tag{15} \]

In Figure 6, we have depicted three types of tandem designs using circular EBG patterns, but we have realized the tandem designs with square EBG elements and considered area tapering using sine tapering coefficients, and the other designing specifications are identical to the earlier designs. Moreover, as of Table 6, we have considered \( A_{\text{TE}} = 168.14 \text{ mm}^2 \) for calculating the referent element for different \( n \), \( C_r \), and \( N \). The size of the reference EBG element is calculated by

\[ A_{\text{ref}} = \frac{A_{\text{TE}}}{C_r \sum_{i=1}^{n} 1}. \tag{16} \]

Since the Type-3 tandem design has a lower number of EBG patterns; hence, the total etching area will be lower than the considered \( A_{\text{TE}} \).

### 7.2. Performance of Different Tandem Designs

The performances of the tandem designs with \( b_{\text{ref}} = 4.74 \text{ mm} \) are shown in Figure 7, where, unlike the conventional sine-tapered design, we can see two weird ripples in the \( S_{21} \) performance just before and after the stopband in the case of Type-1 and Type-2 designs for different values of \( n \). Type-2 performs better than Type-1. Although they show undesired ripples near the stopband, the rest of the performance appears to be interesting when compared with the conventional sine-tapered designs that are presented in Table 6.

Besides, Type-3 exhibits better performance than the other two since it reduces the weird ripples significantly, as shown in Table 7. Since the Type-3 design possesses fewer EBG elements than the other tandem designs and their corresponding tapered designs, the total etching area is lower with a smaller transmission line. The transmission line becomes shorter by

\[ T_{\text{str-3}} = \left(1 - \frac{N_{\text{type-3}}}{N}\right) \times 100\% \]

\[ = \frac{C_r - 1}{N} \times 100\%. \tag{17} \]

Thus, the numerical size of the transmission line is reduced by \((C_r - 1) \times a\).

Although using the Type-3 tandem design for relatively suitable values of \( n \) and \( C_r \), allows for smaller filters to be designed, a little malicious ripple near the stopband is the only factor preventing their use. We believe that the multiperiodicity issue is solely responsible for causing such abnormal ripples near the stopband [28].

### 7.3. Multiperiodicity in Tandem Designs

As we all know, electromagnetic bandgap structures should be placed at the bottom of transmission lines regularly because band-rejection properties are solely dependent on the period [6, 18, 23]. The period, \( a \), is

\[ a = \frac{c}{2f_0 \sqrt{\varepsilon_{\text{eff}}}}, \tag{18} \]

where \( \varepsilon_{\text{eff}} \) is the effective relative permittivity of the dielectric slab, \( c \) is the speed of light in free space, and \( f_0 \) is the center frequency of the stopband.

EBG structures, in tandem designs, experience multiperiodicity in two ways: (a) periodicity caused by the adjacent significant EBG elements of the smallest or edged elements of a cycle (primary cause) and (b) periodicity caused by the consecutive bigger elements from both sides of the smaller EBG structures (i.e., periodicity among the EBG elements of the same size in the nonuniform EBG array). Figure 8 illustrates the multiperiodicity clearly.

### Table 4: Performance of different area-based tapered designs.

<table>
<thead>
<tr>
<th>( b_{\text{ref}} ) (mm)</th>
<th>( n )</th>
<th>Type of EBGs</th>
<th>(-3 \text{~dB} f_t ) (GHz)</th>
<th>(-20 \text{~dB} \text{~SBW} ) (GHz)</th>
<th>( f_0 ) (GHz)</th>
<th>( S_{21} ) at ( f_0 ) -dB</th>
<th>Max. ( S_{21} ) (–dB)</th>
<th>(-10 \text{~dB} \text{~PBW} ) (GHz)</th>
<th>Near SB RH (–dB)</th>
<th>Max. PB RH (–dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.7</td>
<td>6</td>
<td>Binomial</td>
<td>7.553</td>
<td>—</td>
<td>—</td>
<td>17.81</td>
<td>7.14</td>
<td>0.13</td>
<td>0.36</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Chebyshev</td>
<td>7.681</td>
<td>2.310</td>
<td>10.517</td>
<td>26.24</td>
<td>26.26</td>
<td>7.45</td>
<td>0.17</td>
<td>0.44</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cosine</td>
<td>7.564</td>
<td>—</td>
<td>—</td>
<td>19.87</td>
<td>7.24</td>
<td>0.13</td>
<td>0.38</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sine</td>
<td>7.701</td>
<td>2.515</td>
<td>10.510</td>
<td>27.12</td>
<td>27.13</td>
<td>7.49</td>
<td>0.32</td>
<td>0.47</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>Binomial</td>
<td>7.771</td>
<td>1.657</td>
<td>10.96</td>
<td>23.75</td>
<td>23.80</td>
<td>7.42</td>
<td>0.13</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Chebyshev</td>
<td>7.92</td>
<td>3.694</td>
<td>10.423</td>
<td>42.60</td>
<td>45.16</td>
<td>7.69</td>
<td>0.10</td>
<td>0.52</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cosine</td>
<td>7.830</td>
<td>3.596</td>
<td>10.431</td>
<td>36.65</td>
<td>37.92</td>
<td>7.68</td>
<td>0.27</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sine</td>
<td>7.872</td>
<td>3.824</td>
<td>10.415</td>
<td>42.89</td>
<td>45.64</td>
<td>7.75</td>
<td>0.14</td>
<td>0.53</td>
</tr>
<tr>
<td>6.2</td>
<td>6</td>
<td>Binomial</td>
<td>7.000</td>
<td>3.365</td>
<td>10.587</td>
<td>29.14</td>
<td>29.15</td>
<td>6.64</td>
<td>0.14</td>
<td>0.70</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Chebyshev</td>
<td>7.096</td>
<td>4.969</td>
<td>10.477</td>
<td>42.35</td>
<td>42.92</td>
<td>6.93</td>
<td>0.37</td>
<td>0.90</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cosine</td>
<td>7.031</td>
<td>4.279</td>
<td>10.541</td>
<td>34.57</td>
<td>34.60</td>
<td>6.83</td>
<td>0.12</td>
<td>0.78</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sine</td>
<td>7.097</td>
<td>5.094</td>
<td>10.473</td>
<td>43.51</td>
<td>44.40</td>
<td>6.88</td>
<td>0.72</td>
<td>0.92</td>
</tr>
<tr>
<td>6.2</td>
<td>10</td>
<td>Binomial</td>
<td>7.172</td>
<td>4.696</td>
<td>10.464</td>
<td>37.54</td>
<td>39.87</td>
<td>6.78</td>
<td>0.13</td>
<td>0.74</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Chebyshev</td>
<td>7.309</td>
<td>5.358</td>
<td>10.415</td>
<td>54.90</td>
<td>57.83</td>
<td>7.06</td>
<td>0.29</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cosine</td>
<td>7.254</td>
<td>5.414</td>
<td>10.412</td>
<td>50.77</td>
<td>62.59</td>
<td>7.11</td>
<td>0.35</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sine</td>
<td>7.288</td>
<td>5.482</td>
<td>10.414</td>
<td>51.10</td>
<td>56.10</td>
<td>7.19</td>
<td>0.16</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Cosine-tapering coefficients are determined by using (6).
where \( a \) is the original period; due to the much smaller EBG elements at the edge, the nearest bigger EBG elements offer a larger inner element spacing \( (a' = 2a) \), since smaller EBG elements have almost negligible effects on rejection property [24]. Moreover, the next bigger elements will offer different periods: \( a' = 4a \) and so on. Hence, the dominating larger period due to significantly bigger EBG elements causes such a high ripple that it seems another stopband is about to appear at another subsequent center frequency related to that period.

Since Type-3 tandem designs exhibit better performance than the other two types, therefore, we will consider only the Type-3 format as tandem use of tapered EBG elements, and by referring to tandem design, the Type-3 tandem fashion will be regarded. Now, with the objective of eliminating the unwanted near-band ripples, we have proposed the meandered line tandem (MLT) EBG filter with an even shorter physical size of the filter realization.

### 8. Proposed Meandered Line Tandem Design

In this section, we propose the method of meandered line tandem designs, where the smallest EBG structure between two consecutive cycles of tapered EBG elements is placed along the \( Y \) axis by bending the transmission line at a right angle on the top plane to go along all of the EBG elements at the ground plane. The length of the vertically bent part of the transmission line is always “\( a \)” for each smallest periodic element in the tandem design except the smallest elements at the corners; thus, the total minimum bending required is \( C_r - 1 \). However, bending for the corner element could also be incorporated as in Figure 13(c), but with no further advantage in size reduction. Therefore, the length will be shortened by \( (C_r - 1) \times a \).

The tandem design of Figure 8 is converted as MLT design, as shown in Figure 9(a). The vertical length of the transmission line is \( a \); thus, the horizontal length of the line becomes shorter by the length of a period, \( a \). Therefore, the physical length of the filter realization becomes significantly shorter when compared to the conventional tapered design of the originally considered number of EBG elements. However, some differently bent transmission lines have been reported in [29, 30].

#### 8.1. Realization of MLT Design

Let us first consider the same design illustrated in the conventional Type-3 tandem design \( \left( n = 5, \quad C_r = 2; \quad b_{ref} = 4.74 \text{ mm}, \quad A_{TE} = 168.14 \text{ mm}^2 \right) \) in the earlier section, as shown in Figure 8, whose performance is shown in Figure 7: \(-6.30 \text{ dB} \) and \(-6.94 \text{ dB} \) ripples before and after the stop-band, respectively. The MLT realization of this design is shown in Figure 9(a), where we can see that the smallest

<table>
<thead>
<tr>
<th>( n )</th>
<th>( b_{ref} ) (mm)</th>
<th>( -3 \text{ dB} f_c ) (GHz)</th>
<th>( -20 \text{ dB} \text{ SBW} ) (GHz)</th>
<th>( f_0 ) (GHz)</th>
<th>( S_{21} ) at ( f_0 ) (dB)</th>
<th>( \text{Max. } S_{21} ) (dB)</th>
<th>( -10 \text{ dB} \text{ PBW} ) (GHz)</th>
<th>( \text{Near SB RH} ) (dB)</th>
<th>( \text{Max. PB RH} ) (dB)</th>
<th>( \text{After SB } S_{21} ) (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>8.34</td>
<td>6.251</td>
<td>3.617</td>
<td>10.332</td>
<td>25.642</td>
<td>27.309</td>
<td>5.871</td>
<td>2.03</td>
<td>2.03</td>
<td>10.88</td>
</tr>
<tr>
<td>4</td>
<td>7.39</td>
<td>6.64</td>
<td>5.168</td>
<td>10.378</td>
<td>35.881</td>
<td>36.448</td>
<td>6.476</td>
<td>0.76</td>
<td>1.10</td>
<td>10.00</td>
</tr>
<tr>
<td>5</td>
<td>6.71</td>
<td>6.881</td>
<td>5.271</td>
<td>10.464</td>
<td>40.774</td>
<td>41.599</td>
<td>6.694</td>
<td>0.68</td>
<td>0.99</td>
<td>8.61</td>
</tr>
<tr>
<td>6</td>
<td>6.2</td>
<td>7.097</td>
<td>5.094</td>
<td>10.473</td>
<td>43.508</td>
<td>44.401</td>
<td>6.881</td>
<td>0.72</td>
<td>0.92</td>
<td>6.64</td>
</tr>
<tr>
<td>7</td>
<td>5.79</td>
<td>7.316</td>
<td>4.869</td>
<td>10.457</td>
<td>46.684</td>
<td>47.109</td>
<td>7.183</td>
<td>0.31</td>
<td>0.82</td>
<td>6.42</td>
</tr>
<tr>
<td>8</td>
<td>5.45</td>
<td>7.507</td>
<td>4.6</td>
<td>10.447</td>
<td>50.206</td>
<td>50.506</td>
<td>7.375</td>
<td>0.12</td>
<td>0.75</td>
<td>6.93</td>
</tr>
<tr>
<td>9</td>
<td>5.16</td>
<td>7.627</td>
<td>4.494</td>
<td>10.425</td>
<td>43.266</td>
<td>44.695</td>
<td>7.634</td>
<td>0.26</td>
<td>0.68</td>
<td>4.02</td>
</tr>
<tr>
<td>10</td>
<td>4.92</td>
<td>7.802</td>
<td>4.272</td>
<td>10.415</td>
<td>48.803</td>
<td>48.383</td>
<td>7.705</td>
<td>0.28</td>
<td>0.60</td>
<td>3.31</td>
</tr>
<tr>
<td>11</td>
<td>4.7</td>
<td>7.919</td>
<td>4.041</td>
<td>10.409</td>
<td>49.154</td>
<td>49.682</td>
<td>7.907</td>
<td>0.30</td>
<td>0.55</td>
<td>3.00</td>
</tr>
<tr>
<td>12</td>
<td>4.52</td>
<td>8.059</td>
<td>3.827</td>
<td>10.398</td>
<td>47.932</td>
<td>48.281</td>
<td>7.954</td>
<td>0.31</td>
<td>0.51</td>
<td>2.23</td>
</tr>
</tbody>
</table>

\( A_{TE} = 168.14 \text{ mm}^2 \).
element in between two consecutive cycles is placed vertically just beneath a deliberately bent transmission line, by which we have shortened the longitude of the transmission line by a. Using (15), for conventional Type-3 tandem design, the required \( L_t \) is 9a for \( n = 5 \) and \( C_r = 2 \), and for \( n = 3 \) and \( C_r = 3 \), it is 7a; hence, the size is reduced by 10% and 22.22%, respectively, compared to the uniform and conventional tapered design having \( N = 10 \) as well. Therefore, the MLT design and the Type-3 tandem design offer various scales of size reduction depending on the values of \( n \) and \( C_r \), shown in Table 7.

Furthermore, for the MLT design, the size is reduced by twice that of the Type-3 tandem design, 2a \((C_r - 1)\). The length of the meandered transmission line is

\[
L_{MLT} = N_{MLT} \times a,
\]

where

\[
N_{MLT} = N - 2(Cr - 1).
\]

Thus, the transmission line becomes shorter by

\[
T_{sr-MLT} = \left(1 - \frac{L_{MLT}}{Na}\right) \times 100\%
\]

\[
= 2T_{sr+3}.
\]

Note that, while designing the MLT design for \( n = 3 \), we deduced \( b_{\text{ref}} = 5.89 \text{ mm} \) for \( C_r = 2 \) (i.e., \( N = 5 \)) and \( A_{\text{TTE}} = 168.14 \text{ mm}^2 \), but while we tried to design the MLT design as exactly similar to that shown in Figure 9(a), the two adjacent bigger EBG elements overlapped with the vertically placed EBG structure at the corners. Hence, designers should be careful about the limitation while deciding \( n \) and \( C_r \).

However, such problems could be reduced in several ways: (a) we could reduce the size of the reference EBG elements to overcome the overlapping issue, (b) we could increase the cycle \((C_r)\) of the tapered EBG elements, and (c) we could adopt the both to get optimum performance. Figure 9(b) shows a typical MLT design with \( n = 3 \) and \( C_r = 3 \) for a better understanding of the designing strategy with higher \( C_r \), where we observed a 28.57% reduction in length for the nonmeandered line Type-3 design considered and the design is 44.44% shorter compared to the corresponding uniform and conventional tapered designs.

8.2. Performance of the MLT Design. The proposed MLT design exhibits quite impressive performance that significantly reduces the malicious ripples, as shown in Figure 10(a) with a reduced longitude of the design. Table 7 shows that the passband maximum RH is only \(-0.76 \text{ dB}\) and the after-stopband ripple is eliminated; in addition, the SBW has increased to 4.523 GHz, which is very similar to the performance of the conventional area-based sine-tapered designs, shown in Figure 10(b); besides, the MLT design, in addition, offers a significant reduction in the filter size.
Te MLT design with \( C_r = 3 \) results in a larger stopband and maximum level of isolation compared to both Type-3 tandem designs for \( C_r = 2 \) and 3, shown in Figure 11 with smaller RHs. Tables 6 and 7 show that the SBW of the MLT realization for \( n = 3 \) and \( C_r = 3 \), and \( N = 7 \) is 5.217 GHz, which is significantly higher than the SBWs of conventional tapered design: 4.869 GHz and 4.494 GHz for \( n = 7 \) and \( n = 9 \), respectively; however, a slight increase in the maximum RH is observed, which is happily acceptable with the benefit of huge size reduction and significant improvement in SBW.

Optimum performance can be achieved by choosing the proper size of the reference EBG element. In Figure 12, we observe that the smaller the reference EBG element, the lower the passband ripples, along with the lower maximum isolation level and smaller rejection bandwidth. Overall, it is clearly understood that the proposed MLT design based on the sine tapering function is very effective for relatively shorter filter realizations as long as area tapering and the Type-3 tandem strategy are considered.

### Table 7: Size reduction and performance of the MLT designs.

<table>
<thead>
<tr>
<th>Type</th>
<th>( b_{ref} ) (mm)</th>
<th>( n )</th>
<th>( C_r )</th>
<th>( N )</th>
<th>( L_t )</th>
<th>( T_{3dB} ) (%)</th>
<th>( -3 \text{ dB } f_c ) (GHz)</th>
<th>( -20 \text{ dB } \text{SBW} ) (GHz)</th>
<th>( -10 \text{ dB } \text{PBW} ) (GHz)</th>
<th>Max. PB RH ( (-dB) )</th>
<th>After SB ( S_{21} ) ( (-dB) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type-2</td>
<td>5.89</td>
<td>3</td>
<td>2</td>
<td>6</td>
<td>6a</td>
<td>0.7349</td>
<td>4.953</td>
<td>7.404</td>
<td>5.30</td>
<td>7.40</td>
<td></td>
</tr>
<tr>
<td>Type-3</td>
<td>4.81</td>
<td>3</td>
<td>3</td>
<td>7</td>
<td>7a</td>
<td>22.2</td>
<td>8.09</td>
<td>3.134</td>
<td>2.16</td>
<td>2.66</td>
<td></td>
</tr>
<tr>
<td>MLT</td>
<td>5.22</td>
<td>4</td>
<td>2</td>
<td>7</td>
<td>6a</td>
<td>16.7</td>
<td>7.176</td>
<td>4.714</td>
<td>7.173</td>
<td>2.85</td>
<td></td>
</tr>
<tr>
<td>Type-2</td>
<td>5.22</td>
<td>4</td>
<td>2</td>
<td>7</td>
<td>6a</td>
<td>16.7</td>
<td>7.176</td>
<td>4.714</td>
<td>7.173</td>
<td>2.85</td>
<td></td>
</tr>
<tr>
<td>Type-3</td>
<td>4.74</td>
<td>5</td>
<td>2</td>
<td>9</td>
<td>9a</td>
<td>10</td>
<td>8.05</td>
<td>3.922</td>
<td>8.068</td>
<td>6.30</td>
<td></td>
</tr>
<tr>
<td>MLT</td>
<td>4.39</td>
<td>6</td>
<td>2</td>
<td>11</td>
<td>11a</td>
<td>8.33</td>
<td>7.672</td>
<td>3.431</td>
<td>7.428</td>
<td>0.48</td>
<td></td>
</tr>
<tr>
<td>Type-2</td>
<td>4.39</td>
<td>6</td>
<td>2</td>
<td>11</td>
<td>11a</td>
<td>8.33</td>
<td>7.672</td>
<td>3.431</td>
<td>7.428</td>
<td>0.48</td>
<td></td>
</tr>
<tr>
<td>Type-3</td>
<td>4.09</td>
<td>7</td>
<td>2</td>
<td>13</td>
<td>13a</td>
<td>7.14</td>
<td>7.967</td>
<td>3.48</td>
<td>7.936</td>
<td>0.66</td>
<td></td>
</tr>
<tr>
<td>MLT</td>
<td>4.09</td>
<td>7</td>
<td>2</td>
<td>13</td>
<td>13a</td>
<td>7.14</td>
<td>7.967</td>
<td>3.48</td>
<td>7.936</td>
<td>0.66</td>
<td></td>
</tr>
</tbody>
</table>

Sine tapering method is used and \( A_{TE} = 168.14 \text{ mm}^2 \). \( T_{3dB} \) is the reduction of the length in percentage compared to corresponding uniform and conventional tapered designs.

Figure 8: Illustration of multiperiodicity for Type-3 tandem design having \( n = 5 \) and \( C_r = 2 \); length of the transmission line is reduced by \( a \) compared to the conventional tapered design for \( N = 10 \), thus, \( L_t = 9 \) \( a \) in this design.

Figure 9: MLT designs based on area-based sine tapering function for (a) \( n = 5 \) and \( C_r = 2 \), and (b) \( n = 3 \) and \( C_r = 3 \). \( L_t \) for (a) and (b) are 8\( a \) and 5\( a \), respectively; therefore, the lengths of the designs are reduced by 11.11% and 28.57%, respectively, than the corresponding tandem designs having \( N = 9 \).
9. Simulated vs. Measured Performance

All the simulations, studied in this article, are simulated using the IE3D simulator, the software has found wide acceptance and gained popularity over the decades in the fields of EM designs and simulations as the simulated results well agree with the measured results [7, 22, 23, 25]. However, to investigate the validation of the simulated results in our case, we have considered the uniform circular EBG structure-assisted design illustrated in [31]. The design was simulated using HP™ momentum and ADS software and measured with HP™ 8753-D network analyzer.

Besides, the novel MLT approach for designing EBG filters improves the performance further with a much smaller filter realization. MLT design has potential applications in microstrip filters and microstrip array antenna designing with much smaller sizes in practice.

9.1. IE3D Simulation vs. Measured Performance. Since we currently lack the necessary experimental arrangement to measure the performances of our reported designs, hence, we have compared the simulated performance (obtained from IE3D software) of the same design with the measured and simulated performance reported by Chiau et al. in [31]. The designing parameters are $\varepsilon_r = 10.2$; $h = 1.27$ mils; $w = 1.2$ mm; and $a = 23.9$ mm for $f_s = 2.5$ GHz with $n = 9$ uniform circular EBG structures having the radius, $r = 5.975$ mm. The reported uniform design is shown in Figure 13(a).

![Figure 10: Performances of (a) Type-3 tandem vs. MLT designs with $n = 5$ and $C_r = 2$ and (b) conventional sine tapered vs. MLT design.](image)

Figure 11: Performances of Type-3 tandem vs. MLT designs with $n = 3$ and $C_r = 3$.

![Figure 11: Performances of Type-3 tandem vs. MLT designs with $n = 3$ and $C_r = 3$.](image)

The simulated performance using IE3D is compared with the reported measured result in Figure 14(a). We can see in the figure that the simulated result well agrees with the
measured result that was obtained from HP™ 8753-D network analyzer. A little deviation is noticed that is generally well accepted by experts and researchers [18, 23, 25]. Moreover, in Figures 3 and 4, we have noticed such good agreement between the simulated results (using the IE3D software) and the measured results of different designs reported in [18, 25].

9.2. IE3D Simulation vs. ADS Simulation. In Figure 14(b), we observe that the simulated result of the earlier described uniform design using IE3D identically agrees with the reported simulated performance using ADS software that is presented in [31].

Moreover, from the comparison of Figures 14(a) and 14(b), we can notice that the similar deviation between simulated and measured results is accepted by the authors too in [31].

9.3. Performance Validation of the Latest Designs. As from the abovementioned discussions, we have observed very well agreement of our simulated results with measured results and simulated results using other software; therefore, we have applied the proposed sine tapering method (Figure 13(b)) of improving the performance and the meandered line tandem design (Figure 13(c)) approach to reduce the size of the whole design to the earlier illustrated design and compared the
simulated performances with the performance of the conventional uniform design (Figure 13(a)).

In Figure 13, we notice that the MLT design consists of $C_r = 4$ with $n = 3$; thus, the size of the physical design becomes 44.44% shorter compared to the corresponding uniform design and corresponding sine-tapered design as well as any other tapered design, as shown in Table 8.

In Figure 15, we see the performance of the MLT design is quite matched with the performance of the corresponding uniform design. Besides, the performance patterns of sine-tapered designs are similar to the performance pattern of the uniform design with expected behavior. Therefore, we are confident that our studies’ simulated results agree with the measured results.

However, in Table 8, we observe that the performance of the MLT design results in a wider stopband width and smaller passband ripples compared to the uniform design. On the other hand, identical area sine-tapered design exhibits a wider stopband with much smaller passband ripples. However, the proposed MLT designing strategy will certainly benefit the designers where limited space is a concerning issue, e.g., in satellites and space communication applications.

Table 8: Uniform design vs. sine tapered and meandered line tandem design.

<table>
<thead>
<tr>
<th>Type</th>
<th>No. of EBG element (N)</th>
<th>Length ($L_n$)</th>
<th>% size reduction ($T_{sr}$)</th>
<th>$-3,\text{dB},f_c$ (GHz)</th>
<th>$-20,\text{dB},\text{SBW}$ (GHz)</th>
<th>$-10,\text{dB},\text{PBW}$ (GHz)</th>
<th>Max. PB RH (−dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uniform*</td>
<td>9</td>
<td>$9\pi$</td>
<td>0</td>
<td>1.90</td>
<td>1.19</td>
<td>1.77</td>
<td>4.01</td>
</tr>
<tr>
<td>Sine tapered#</td>
<td>9</td>
<td>$9\pi$</td>
<td>0</td>
<td>1.91</td>
<td>0.98</td>
<td>1.88</td>
<td>0.84</td>
</tr>
<tr>
<td>Identical area sine tapered**</td>
<td>9</td>
<td>$9\pi$</td>
<td>0</td>
<td>1.86</td>
<td>1.26</td>
<td>1.87</td>
<td>1.28</td>
</tr>
<tr>
<td>MLT</td>
<td>9</td>
<td>$5\pi$</td>
<td>44.44</td>
<td>1.81</td>
<td>1.22</td>
<td>1.77</td>
<td>2.14</td>
</tr>
</tbody>
</table>

* $A_{TE} = 1009.414\,\text{mm}^2$. # Area-based sine tapering method is used. ** Total etching area is identical to the uniform design.
Acknowledgments

This research work was partially funded by the Center for Research and Development (CRD), Eastern University, Road 6, Block B, Ashulia Model Town, Savar, Dhaka, Bangladesh (https://www.easternuni.edu.bd/CRD).

References


Data Availability

The data used to support the findings of this study are made available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.
Modern Circuits and Systems Technologies (MOCAST), pp. 1–4, IEEE, Bremen, Germany, June 2022.


