

Research on Terahertz Band-stop Filter based on Circular Quasi-periodic Waveguide

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Abstract

The terahertz filtering behavior of quasi-periodic waveguide based Fibonacci sequence is investigated by finite element research method. The long-range order of quasi-periodic waveguide has achieved the functions of band-stop and narrow band filter. The waveguide generation can directly influence the number of bandgaps. Periodic processing can enable low generation waveguides to have the band-stop filtering function, too. The length ratio can be used to regulate the number of forbidden bands, operating frequency and bandwidth. The maximum bandwidth of a single bandgap is 192 GHz. The total operating frequency of a single waveguide can reach up to 281 GHz. The 8th generation waveguide also realizes narrow band filtering function with a bandwidth of 14 GHz. Quasi-periodic waveguides can provide new ideas for the design of terahertz filters.

Keywords

Terahertz; Band-stop Filter; Quasi-periodic; Waveguide.

1. Introduction

In recent years, the development and utilization of the terahertz band have been continuously advancing. The terahertz technologies have exhibited unique advantages in fields, such as biomedical science [1, 2], security detection [3], communication [4, 5], and industry [6, 7]. Terahertz waves possess penetrating power, security [8, 9], fingerprint spectroscopy [10, 11], and high bandwidth [12]. These characteristics are the fundamental reasons for the widely application of terahertz technology. The functional devices are guarantee for operation of electromagnetic wave systems. The communication optical band devices cannot be directly applied to terahertz systems. The functional devices are indispensable to apply terahertz technology in practice, such as optical switches [13,14], filters [15,16] and sensors [17], and so on. The band-stop filter is key component for enhancing system performance, which can significantly increase the signal-to-noise ratio. For example, Xu et al. achieved terahertz band-stop filtering function within the range of 0.13-0.92 THz by metamaterial structures [18]. Ali Dehghanian et al. obtained the terahertz band-stop filter with a bandwidth of 200 GHz by using apodized Bragg gratings [19]. The mixed vanadium dioxide metamaterial designed by Chen et al. and achieved a band-stop filter with center frequency of 0.95 THz [20]. They still cannot meet the practical application requirements at all, although there are many reports on the design schemes of band-stop filters in the terahertz band. Quasi-periodic structure is an intermediate state between ordered structure and disordered structure. They show disorder at short distances but can demonstrate a certain degree of order at long distances. This feature enables the quasi-periodic structure to regulate transmission of waves and obtain specific bandgap properties. The quasi-periodic structures have more flexible bandgap characteristics, and are excellent schemes for the design of functional devices, compared with periodic structures. The application field of quasi-periodic

structure is very wide. Existing reports have involved sound waves, microwaves and communication light waves. For example, N. M. Lučić et al. studied the propagation characteristics of light in quasi-periodic Fibonacci waveguide arrays [21]. Amita Biswal et al. constructed one-dimensional quasi-periodic photonic crystals by using GaAs and AlAs. The research results show that the structure can be applied to design optical band-pass and band-stop filters [22]. Liu et al. obtained interface states in the acoustic band by applying quasi-periodic waveguides [23].

Here, we design a band-stop filter in the terahertz band based on a quasi-periodic waveguide. The waveguide is cylindrical tube in which radius varies according to Fibonacci sequence. Due to the change in radius, orthogonal characteristics between radial modes in the waveguide are broken and resonance occurs. The bandgaps appear in the transmission spectrum of quasi-periodic waveguide, and band-stop filtering function in terahertz band are achieved. The periodic processing of low generation quasi-periodic waveguides can also realize filtering functions. Here, the influence of length ratio on filtering performance will be studied. The research results show that this structure can realize more superior performance of band-stop filter than the periodic structure. The quasi-periodic waveguide structures can provide a reference scheme for design terahertz band-stop filters.

2. Quasi-periodic Waveguide Structures and Band-stop Filtering Function

2.1 Quasi-periodic Waveguide Structures

Generally, a quasi-periodic structure is constructed by drawing on sequences of mathematics. The Fibonacci sequence and the Octonacci sequence are usually used. Among them, the Fibonacci sequence is called the golden section. The characteristic of this sequence is that each term starting from the third one is equal to the sum of the previous two terms, that is, the Fibonacci sequence satisfies the following recurrence relation:

$$\left. \begin{array}{l} F_0 = 0 \\ F_1 = 1 \\ \dots \\ F_n = F_{n-1} + F_{n-2} \end{array} \right\} (n \geq 2, n \in \mathbb{N}^+) \quad (1)$$

In this paper, the quasi-periodic waveguides are constructed by using the recurrence relation of the Fibonacci sequence. The units *a* and *b* are used instead of numbers to build waveguide. The specific rule is as follows [22]:

$$\left. \begin{array}{l} S_0 = a \\ S_1 = b \\ S_2 = ba \\ \dots \\ S_n = S_{n-1}S_{n-2} \end{array} \right\} \quad (2)$$

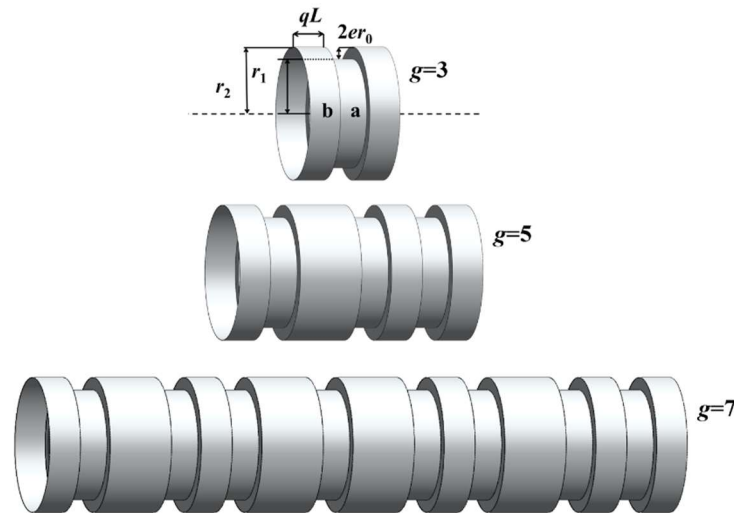


Fig. 1 Schematic diagrams of the 3rd, 5th and 7th generation quasi-periodic waveguides

Here, units a and b represent two types of straight tube waveguides with different radii, where the radius of a is thinner and that b is thicker. The schematic diagram of quasi-periodic waveguides are shown in Fig. 1, where g represents the generation of the quasi-periodic waveguides. In the Figure, $r_0=200\ \mu\text{m}$ represents the average radius of two waveguide units. The radial difference of thick waveguide and thin waveguide is $2er_0$, where e represents the fluctuation coefficient. The radii of thin and thick waveguides are $r_1=r_0-er_0$ and $r_2=r_0+er_0$, respectively. The length sum of two waveguide units is $L=200\ \mu\text{m}$, which is a fixed value, but lengths of each units can vary. Here, p represents the proportion of thick waveguide length to L , which is called the length ratio.

2.2 Quasi-periodic Waveguide Band-stop Filtering Function

In this paper, the quasi-periodic waveguide designed is evolved by using Fibonacci sequence, so sequence generation plays a major role in longitudinal structure. From the arrangement rule of Equation (2), it can be known that the 0th generation and the 1st generation waveguides are only thick waveguides and thin waveguides, respectively. The second generation is merely a simple superposition of thick and thin waveguides. The longitudinal lengths of these three waveguides are relatively short, and cannot demonstrate the long-range order. Therefore, the research significance is relatively small and they will not be analyzed. Here, the 3rd to 8th generation quasi-periodic waveguides will be studied. It can be seen from Figure 1, the length of quasi-periodic structure waveguide shows a rapid increasing trend with increase of generations. The fluctuation coefficient e of quasi-periodic waveguide is 0.1. The radii of thin waveguide and thick waveguide are $180\ \mu\text{m}$ and $220\ \mu\text{m}$, respectively. The length ratio q is 0.5, and the lengths of two waveguides are $100\ \mu\text{m}$, respectively.

By using the finite element method, terahertz wave transmission characteristics of quasi-periodic waveguide have been studied. Here, the 3rd to 8th generation quasi-periodic waveguides are studied. The transmission spectra of 6 structures are shown in Fig. 2. It can be seen from the Figure 2, that the 5th to 8th generations of quasi-periodic waveguides all generate forbidden bands in the 0.7-1.1 THz. In this band, the 3rd and 4th generation quasi-periodic waveguides have relatively small inhibitory effect on terahertz wave transmission and do not form a stable forbidden band. It can be seen from transmission spectrum that the suppression effect of quasi-periodic waveguide has been enhanced with the increase of generation.

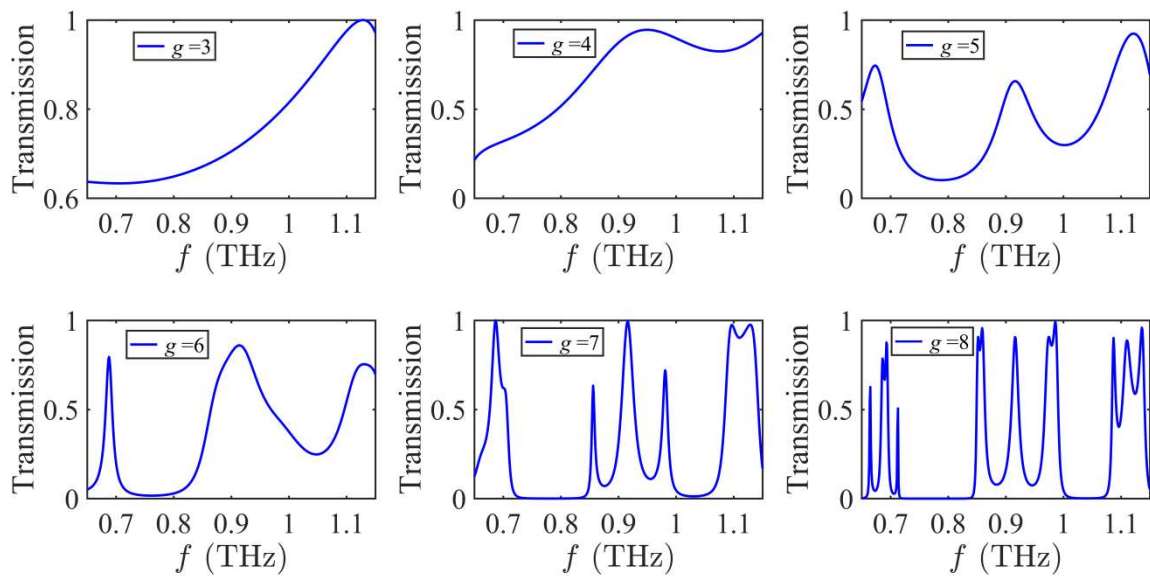


Fig. 2 The transmission spectra of the 3rd to 8th generation quasi-periodic waveguides

5th and 6th generation quasi-periodic waveguides exhibit a forbidden band in transmission spectrum, thereby achieving band-stop filtering function in the terahertz frequency range. 7th and 8th generation quasi-periodic waveguides have realized the dual frequency domains band-stop filtering function, which generate two bandgaps near 0.7-0.8 THz and 1-1.1 THz, respectively. The suppression effect of quasi-periodic waveguide on terahertz waves gradually increases as generation number increases. The edges of forbidden band become increasingly steep, and transmission coefficient is decreasing. As shown in Table 1, the frequency range and bandwidth of forbidden band under different generation are presented. Here, the maximum band-stop filtering bandwidth of quasi-periodic waveguide is 171 GHz. The long-range order of quasi-periodic waveguide is manifested when generation is greater than 5. It achieves the transmission control of terahertz waves and exhibits excellent filtering characteristics. The 8th generation quasi-periodic waveguide has an extremely narrow transmission peak within frequency range of 0.909-0.923 THz. The center frequency of narrow band is 0.917 THz, with a bandwidth of only 14 GHz, and the maximum transmission coefficient can reach over 0.9. The waveguide not only has the band-stop filtering function of dual frequency bands, but also can be used for narrow band filter. The above results indicate that the quasi-periodic waveguide possesses flexible filtering capabilities, which can achieve band-stop filtering for two different frequency bands, and even narrow band filtering function.

Table 1. The forbidden band frequency range and bandwidth of the 3rd to 8th generation quasi-periodic waveguides

g	Forbidden band frequency range (THz)		Bandwidth (GHz)	
3	-		-	
4	-		-	
5	0.705-0.876		171	
6	0.695-0.860		165	
7	0.706-0.853	0.986-1.084	147	98
8	0.696-0.849	0.991-1.084	153	93

3. Optimization of Quasi-periodic Waveguide Performance

3.1 Periodic Processing of Quasi-periodic Waveguide

The quasi-periodic waveguides of high generation exhibit distinct long-range order, that can realize function of dual-band terahertz band-stop filter. But they will lose the advantage of small structural size. We have carried out periodic processing on the waveguide of low generation, thereby meeting requirement of small size. The low generation quasi-periodic waveguides are used as periodic units for repeated construction along longitudinal direction. As shown in Fig. 3, it is the schematic diagram of the 4th generation quasi-periodic waveguide with five cycles periodicity.

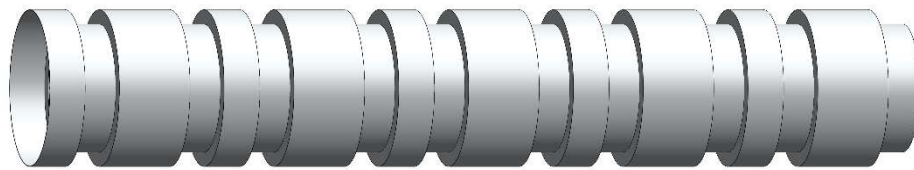


Fig.3 Schematic diagram of the 4th generation quasi-periodic waveguide with five cycles periodicity

The simulation result of 4th generation quasi-periodic waveguide with 5-cycle period is shown in Fig. 4. Here, length ratio is 0.5 and fluctuation coefficient is 0.1. As shown in the Figure, two forbidden bands have been formed in the transmission spectrum, their frequency ranges are 0.721-0.875 THz and 0.962-1.078 THz, respectively. The bandwidths are 154 GHz and 116 GHz, respectively. The total bandwidth for band-stop filter can reach 270 GHz. Furthermore, this waveguide allows the majority terahertz waves energy to pass through at around 0.9 THz, with frequency range of 0.875-0.962 THz. The periodicized 4th generation quasi-periodic waveguide not only possesses dual working frequency of band-stop filter, but can also be used for band-pass filter. Periodic processing enables low generation waveguides to also achieve band-stop filtering function.

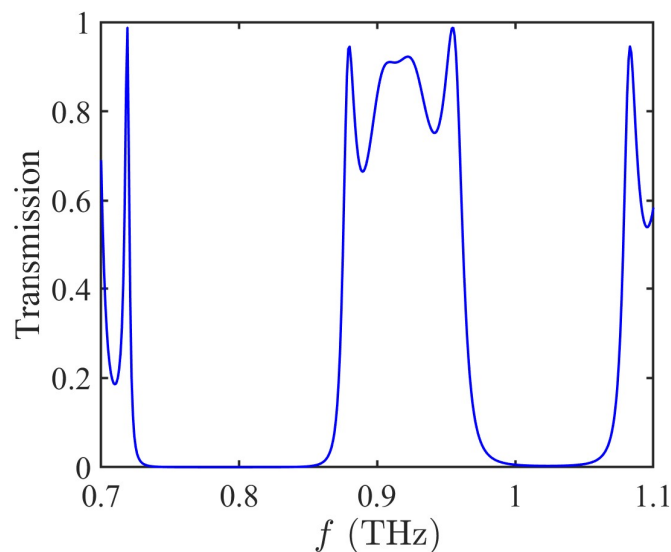


Fig. 4 The transmission spectrum 4th generation quasi-periodic waveguide with 5-cycle period

3.2 The Band-stop Filtering Performance Influence of Length Ratio

The length ratio is an important parameter of quasi-periodic waveguide, and can affect filtering performance. Here, 4th generation quasi-periodic waveguide of five period are studied with length

ratio from 0.3 to 0.7. As shown in Fig. 5, the transmission spectra for each length ratio are presented respectively.

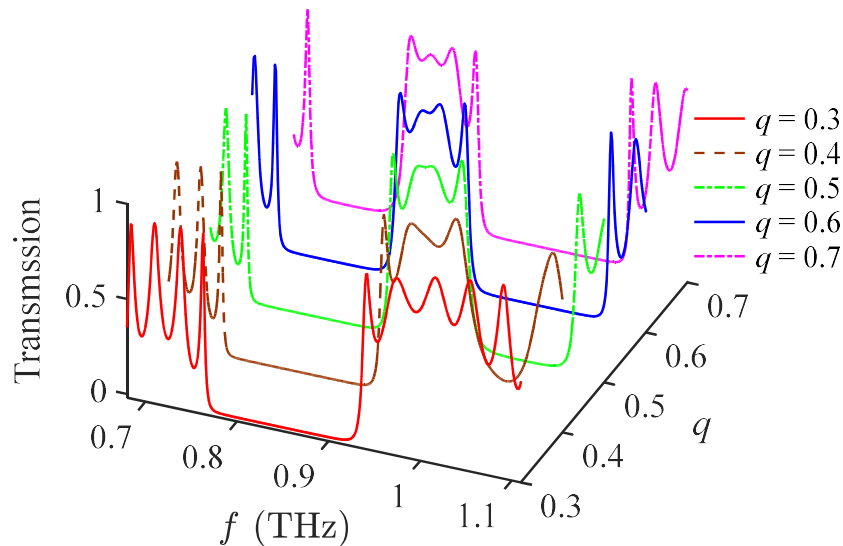


Fig. 5 Transmission spectra with length ratio from 0.3 to 0.7

The waveguide can only achieve band-stop filtering function within a single frequency band when length ratio q is 0.3. Its operating bandwidth is 192 GHz. There are two forbidden bands in the transmission spectrum, when q is 0.4. It realizes the band-stop filtering function of dual frequency bands. Both forbidden bands shift to lower frequencies as the q parameter increases. The forbidden band of low-frequency range is relatively wide, when q are 0.4 and 0.5. The widths of the two forbidden bands are closest when the q value is 0.6. They are 129 GHz and 152 GHz, respectively. In this case, the total working bandwidth is limited to a maximum of 281 GHz. The forbidden band of low-frequency becomes narrower, when q value is 0.7. The length ratio can not only regulate operating frequency of band-stop filter, but also enable change number of forbidden bands. These results all demonstrate that quasi-periodic waveguide exhibits more flexible and superior band-stop filtering performance compared to periodic waveguide.

4. Conclusion

We have proposed a quasi-periodic waveguide constructed based on Fibonacci sequence. The waveguide exhibit long-range order, when generation value exceeds 5. It can show influence of terahertz waves on the transmission. 5th and 6th generation waveguides can achieve single-band band-stop filtering function. On the other hand, 7th and 8th generation waveguides have two working frequency bands for band-stop filtering. The 8th generation waveguide also has the narrow band filtering function with a bandwidth of only 14 GHz. The periodic processing of 4th generation quasi-periodic waveguide can realize band-stop filtering with two operating frequency ranges, and it can also perform band-pass filtering. The length ratio not only enables adjustment number of forbidden bands, but also can change operating frequency and bandwidth. The maximum forbidden bandwidth is 192 GHz, and total working bandwidth can reach up to 281 GHz. The spectral band characteristics of quasi-periodic waveguide can provide research ideas for development of terahertz filters, sensors, and wave modulation devices.

Acknowledgments

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