Terahertz propagation in metal templates

HAN Jia-Guang, ZHANG Wei, ZHU Zhi-Yuan, WANG Zhen-Xia, YU Li-Ping, SUN Li-Tao, WANG Ting-Tai

(Shanghai Institute of Applied Physics, the Chinese Academy of Sciences, Shanghai 201800)

Abstract Terahertz (THz) propagation in a metal template has been theoretically demonstrated. The possible propagating frequencies and power transmittance have been calculated. The power transmittance curves are displayed with different incident frequency and different geometric parameters. The oscillations of transmittance dependent on length of the template and the theoretical propagating bandwidth have been found.

Keywords Metal templates, Transmission, Waveguide

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1 Introduction

Terahertz (THz) technology is becoming an extremely attractive research field and its applications have involved semiconductor, tomographic imaging, label free genetic analysis, cellular level imaging, biological sensing and so on.[1] The recent progress in THz wave generation and detection techniques has generated much interest in low loss THz wave guide which are essential for the construction of compact THz devices and measurement systems.[2] Recently there have been several reports on the THz propagation in some kinds of waveguides, such as the plastic photonic crystal fiber, sapphire fiber and plastic ribbon waveguides.[3,4] The study of transmission characteristic of metal templates in THz region is valuable for application.

In 1973 Chen presented a theoretical analysis of the transmission characteristics of diachronic filters in the microwave range[5] and late the analysis was checked by experiments.[6-8] In recent years Chen's waveguide theory has been used in THz region and produced good results.[8] In this paper, we do some theoretical calculation about electromagnetic wave propagating through the metal template in THz range based on the theory given by Chen.

2 Calculation

Typical metal templates, also known as quasi-optical filters, have been used as high-pass filters throughout the microwave and FIR region. As shown in Fig.1, the template is a metal plate with many holes, each of which can be seen as a circular waveguide and has the same radius. The frequency dependence of the transmission is determined by the hole radius r_0, hole spacing distance d, and plate's length l. For frequencies below the cutoff frequency f_c, the template acts as a plane mirror with a very low leakage rate. Firstly, we consider a single hole with radius r_0 and use a perfect conducting circular waveguide model. We assume that the electromagnetic waves with the frequency k_{mn} propagate inside the hole along the axis-direction and this can be described by Helmholtz equations.[9] The solution of wave equations in cylindrical coordinates has radial parts yielding Bessel function $J_m(k_{mn}r)$.

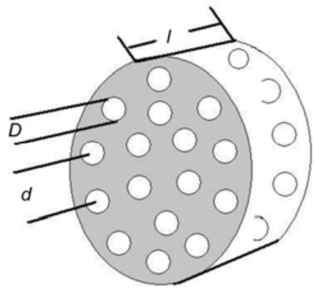

Fig.1 Sketch of the metal template. $D=2r_0$ is hole diameter, d is the spacing between two holes and l is length of the template.

For TE_{mn} modes, the n-th root of $J_m'(k_{mn}r_0)=\frac{\mathrm{d}}{\mathrm{d}r}J_m(k_{mn}r)\big|_{r=r_0}=0$ is denoted by μ'_{mn}, and for TM_{mn} modes, the n-th solution of $J_m(k_{mn}r_0)=0$ is expressed by μ_{mn}. Then we have:[10]

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$$k_{mn} = \frac{\mu'_{mn}}{r_0}, \qquad \text{TE}_{mn} \text{ modes,}$$

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Moreover, the cut-off frequency is defined by:

$$f_{c,\text{TE}_{mn}} = f_{c,\text{TM}_{mn}} = \frac{k_{mn}c}{2\pi}$$

For the typical modes TE_{11} and TM_{01}, $\mu'_{11} = 1.841$ and $\mu_{01} = 2.405$. For example if we assume $r_0 = 3$ mm, the cut-off frequencies are $f_{c,\text{TE}_{11}} = 2.93\times10^{10}$ Hz and $f_{c,\text{TM}_{01}} = 3.83\times10^{10}$ Hz. When the incident frequency is above the cut-off frequency, the TE_{11} and TM_{01} can propagate through the wave-guide.

Next we consider the metal templates for the first dominant propagation mode TE_{11}. The general description for the transmission is given by the theory of Chen.[5] Chen claimed that the transmission and reflection properties of the metal template are traced from the matching Floquet and waveguide models. Above the cut-off frequency, the template represents one of the Bragg diffraction orders. When the frequency is below the cut-off frequency, just the surface wave goes through the template.[8] According to Chen, the complex transmission amplitude T is given by:[5, 8]

$$T = \frac{1}{1-\text{i}(A+B\tanh(\beta l))} - \frac{1}{1-\text{i}(A+B\coth(\beta l))}$$

where the function A, B and β are commonly written as follows:

$$A = 12\sqrt{\frac{4}{3}\left(\frac{\lambda}{d}\right)^2-1}\left[\frac{J_1'\left(\frac{4\pi r_0}{\sqrt{3}d}\right)}{1-\left(\frac{4\pi r_0}{1.841\sqrt{3}d}\right)^2}\right]^2 - \frac{12}{\sqrt{\frac{4}{3}\left(\frac{\lambda}{d}\right)^2-1}}\left[\frac{J_1\left(\frac{4\pi r_0}{\sqrt{3}d}\right)}{\frac{4\pi r_0}{\sqrt{3}d}}\right]^2,$$

$$B = 0.33\left(\frac{d}{r_0}\right)^2\sqrt{\left(\frac{0.293\lambda}{r_0}\right)^2-1},$$

$$\beta = \frac{2\pi}{\lambda}\sqrt{\left(\frac{0.293\lambda}{r_0}\right)^2-1}.$$

The power transmittance which is an interesting quantity is denoted by: $T_\text{p}=TT^*$.

In actual numerical calculations, electromagnetic waves with different frequency and different geometric parameters d, l, and r_0, which are respectively indicated in Fig.2, are taken into consideration.

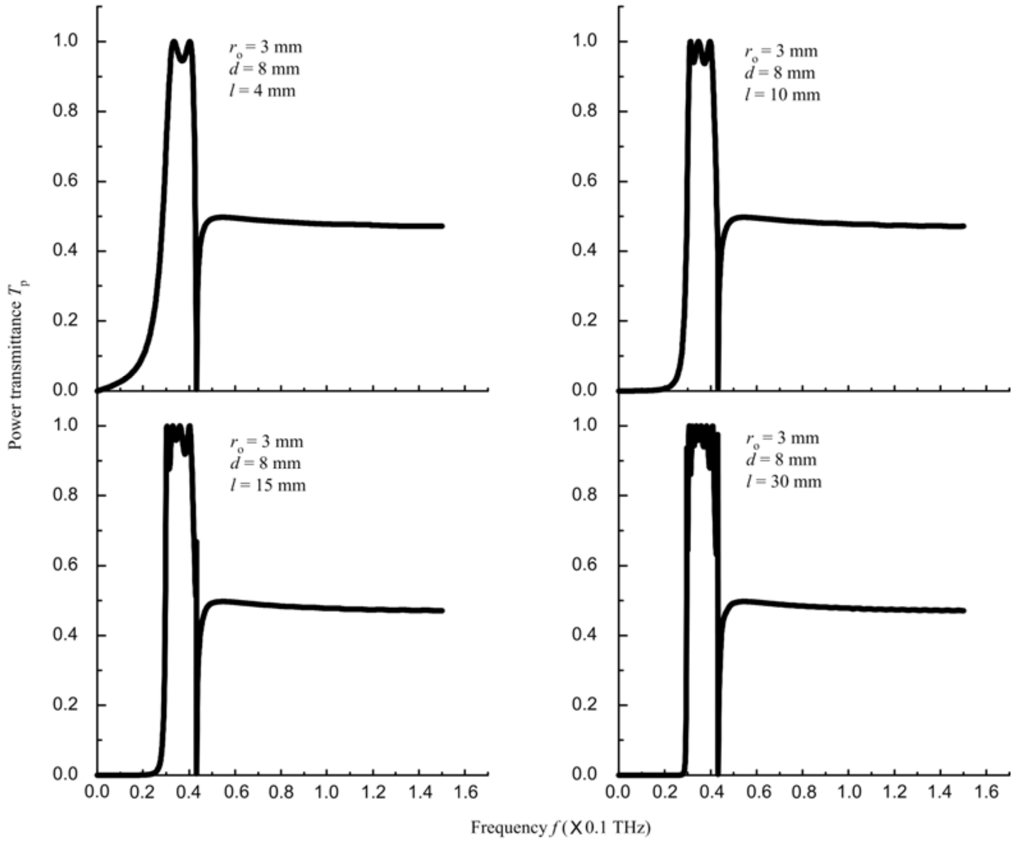

Fig.2 Dependences of power transmittance T_p on geometric parameters and incident frequencies. The incident frequency is in far-infrared range. The curves show that the oscillation of power transmittance becomes more intense with the increase of length l.

3 Results and discussion

As shown in Fig.2, the transmittance does not increase or decrease monotonously with the increase of incident frequency or the change of dimension parameters. For the same radium and spacing distance the power transmittance curves display a similar shape although the thickness of templates is different. T_p gets a high value within 0.02 ~ 0.17 THz, yet becomes oscillating and this oscillation is more intense with the increase of length *l*. As shown in Fig.2, there is an increase in the numbers of transmittance peaks. When the frequency is above 0.045 THz, the transmittance is close to a constant and this will be useful in actual application if one wants to get a steady transmittance. However, being similar to other conventional waveguide structures such as microstrips, coplanar and coplanar striplines waveguides, the metal templates can support only a limited bandwidth. As represented by Fig.2, in the frequency range of 0.02 ~ 0.17 THz, there is a high transmission just within 0.02 ~ 0.04 THz. A possible interpretation for this phenomenon is that there exists more reflection with the increase of length. As a result, some waves would traverse, others would vanish and so the power transmittance exhibits oscillating. A more detailed investigation about the properties of metal templates in THz region would be done in the near future.

Although the Chen’s theory was derived for the case of a periodic array of holes in a perfect conductor, it is valid for the normal plane wave incidence. On the other hand we want to demonstrate that when the electromagnetic wave frequency is in the X-ray range, the theory should be treated carefully. Suppose the radium is $r_0 = 25$ nm, the cut-off frequency of this template is $f_{c,\mathrm{TE}_{11}} = 0.352\times10^{16}$ Hz, the numerical calculation with Chen’s theory shows that the X-ray can not propagate in such a nanoscale metal template. But as in Refs.[11] and [12], when the total reflection is taken into account, the template with nanometer geometry is almost transparent for X-ray. We consider they are two different mechanisms and are not contrary. Using these results one can estimate which incident frequency is feasible to propagate through the templates and how to design the dimension parameters. We also want to note that in our calculation only the TE_{11} mode is taken into account but for other modes and other frequencies’ waves, this calculation is also helpful.

4 Conclusion

In summary, we have theoretically investigated the transmission characteristics of the metal template based on Chen’s theory. Above the cut-off frequency, we found the electromagnetic wave is dependent on the geometric parameters and incident frequency. The interesting fact we found is that the T_p becomes oscillating and the oscillation will become stronger with increasing length of the templates. We also find a limited propagation bandwidth in our calculation. The possible transmittance is discussed when the parameters are in the nanometer range. Such metal templates have an actual application in fabricating compact THz devices and systems. A more rigorous analysis of propagating properties of metal templates will be undertaken in the future work.

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