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# The Transmission Properties of the Metal-coated THz PS Tube with Grooves

**Wu Pan, Tianbo Duo*, Jun Chen, and Zichen Liu**

**Abstract**—When the metal film is thicker than the skin depth in the working frequency band, the transmission characteristics of outer coated type are superior to the transmission properties of inner coated type under the same size. Further more, the transmission properties of the single, double, three and four groove both for inner coating and outer coating terahertz (THz) polystyrene (PS) tubes are studied in this paper. In result, the transmission properties of single and double slot are good, but the three and four slots' transmission characteristics deteriorate. In addition, slots width affects the transmission characteristics of PS tubes evidently, and the attenuation coefficient of outer coated PS tube with single slot is proportional to the slot width, so as to optimize the transmission properties of PS tube. It is a compromise for the slot width (it is better to choose appropriate slot width).

## 1. INTRODUCTION

Terahertz (THz) derived from oscillation frequency is almost $10^{12}$ Hz (1 THz = $10^{12}$ Hz), which is a specific band of electromagnetic wave. It lies in the frequency gap between the microwave and infrared and refers to frequency from 0.1 THz to 10 THz. Transmission of THz wave is an important part in system of THz communication [1]. In a sense, it is difficult to guide and control the transmission loss in the free space. In order to overcome the difficulty, the waveguide which can propagate the THz wave is needed urgently.

The refractive index of dry air is close to 1, and there is almost no loss in THz field [2], so the dry air is the most common medium for the transmission of THz wave [3], and the THz waveguide based on the dry air has always been paid the most attention. In addition, polymer tube is better than solid waveguide from the aspect of the loss characteristics. And polymer tube is easy to be designed and fabricated, which has a large mode field area. So it is a new potential kind of low loss THz waveguide [4].

## 2. THE TRANSMISSION CHARACTERISTICS OF COATED THZ PS TUBE

There is a rough 47 GHz frequency band suited for the communication and transmission of terahertz wave in the atmosphere around 350 GHz [5]. So in this article, the working frequency band is 330 GHz∼380 GHz.

To improve the transmission characteristic of terahertz wave by using the polymer tube, the method of coating film is used, and metals are often used as the coating materials.

According to the theory of multilayer film reflection, if the material loss is ignored, when the light incident vertically, and the optical thickness of the film is about a quarter wavelength, then the reflectance is the largest, which is known as the quarter wavelength conditions [6].

When the center frequency $f = 350$ GHz, the corresponding wavelength $\lambda = 857.1\,\mu$m, $\lambda/4 = 214\,\mu$m. The inner radius of tube $\mathbf{R}$ is 214 μm. Because traditional coating thickness is $\lambda/4$ and the tube's inner radius $\mathbf{R}$ is $\lambda/4$, now the coating film is taken as $\lambda/8$, namely 107 μm.

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PS is selected as the material of polymer tube, whose relative dielectric constant $\boldsymbol{\varepsilon}_r$ is 2.6, relative permeability $\boldsymbol{\mu}_r$ 1, and bulk conductivity $\sigma = 1 \times 10^{-16}$ S/m. Gold, silver, copper, iron and aluminum are chosen as the metal coating layer, and the thickness of coating layer is 107 µm, namely $\lambda/8$ at $f = 350$ GHz.

The geometry sizes of terahertz polymer tube model are: the height is 3 mm; the polymer layer's thickness is 107 µm, as well as the coated layer; the radius of the center tube is 214 µm; the tube is filled with the air.

According to the electromagnetic theory, the skin depth which the electromagnetic field transmit in the metal is

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} = \frac{2}{\sqrt{2\omega\mu\sigma}} \tag{1}$$

where, $f$ is the working frequency, $\omega$ the angular frequency, $\mu$ the magnetic permeability of metal, and $\sigma$ the electrical conductivity of metal. The skin depth of THz wave in the metal is approximately 50∼70 nm [7].

By comparing with the $S$ parameters between the inner and outer coated PS tube, as shown in Figure 1, it is easy to find that the return loss of outer coated PS tube is smaller than the inner coated. This is mainly because for inner coated PS tube, when the thickness of the metal film is much larger than the skin depth of this metal in the corresponding frequency, the transmission characteristics of the PS tube is similar to the transmission properties of metal tube, namely the polymer tube is the metal tube which is coated the outside medium film rather than polymer tube with inner metal film, and the transmission properties of dielectric tube is better than metal tubes'.

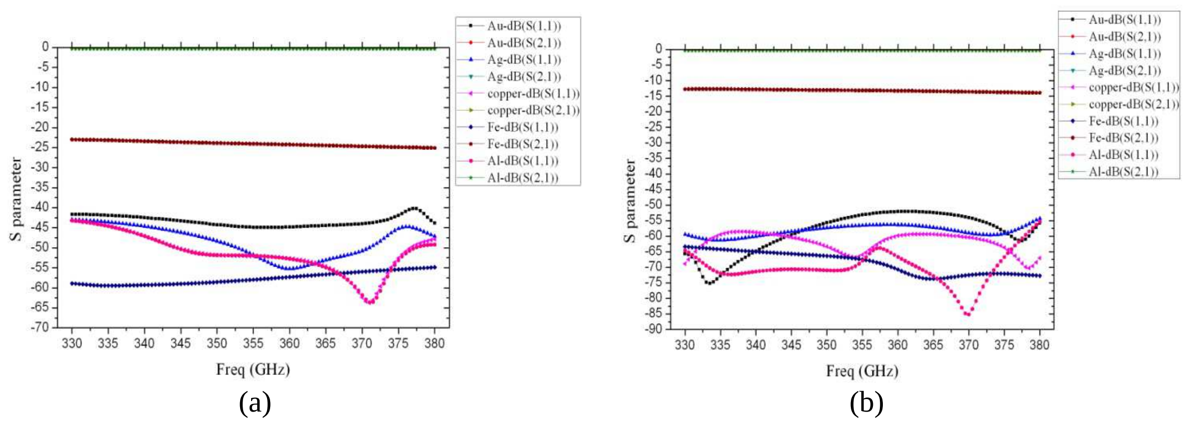



**Figure 1.** The $S$ parameters of PS tube coated metal film ((a) inner coating; (b) outer coating).

## 3. COATED THz PS TUBE WITH GROOVES

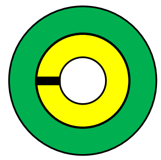
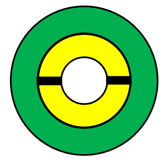
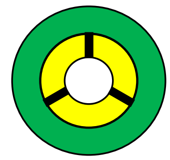
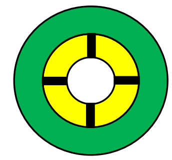
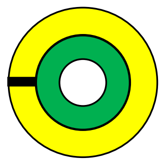
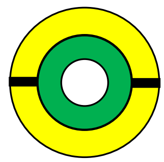
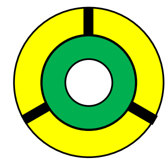
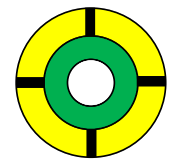
In order to further reduce the attenuation, grooves [8] on the coating layer of the PS tube will be tried, which can take single slot, double slots, three and four slots structure in longitudinal direction, as shown in Table 1, and the slots are 30 µm wide.

Where, the black part is the groove which is filled with air. The yellow part is the metal, and the green part is the PS in the Table 1.

### 3.1. The Transmission Characteristics of the Inner Coated THz PS Tube with Groove

THz PS tube has a 30 µm wide slot, with radius $\mathbf{R} = 214$ µm and the thickness of tube and coating layer $\mathbf{d} = 107$ µm. The insertion loss of coating iron is around −23 dB, and other metal coatings are less than 1 dB for the insertion loss and return loss is less than −25 dB. The return loss of Ag and Al under the geometry sizes within the working frequency band is highly consistent, as shown in Figure 2(a).

**Table 1.** Four kinds of coating structure for the THz PS tube.

| | 1 slot | 2 slots | 3 slots | 4 slots |
|---|---|---|---|---|
| Inner coated type |  |  |  |  |
| Outer coated type |  |  |  |  |

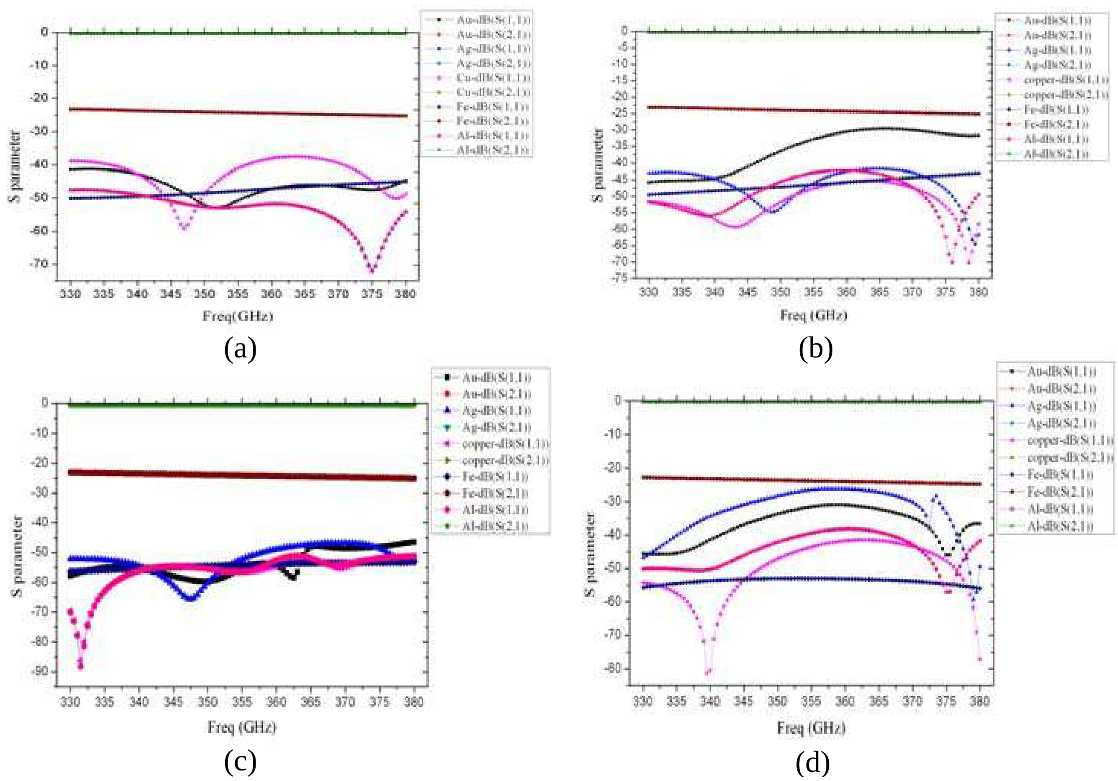



**Figure 2.** $S$ parameters of inner coated THz PS tube with groove: (a) single slot; (b) double slots; (c) three slots; (d) four slots.

And the return loss of Cu and Al coated THz PS tube for three slots with 120° angle under the same size is highly similar within the working frequency band, which is most ideal, as shown in Figure 2(c).

The return loss of Cu coated THz PS tube for four slots with 90° angle under this geometric size within the working frequency band is the most ideal, but compared with other three groove structures, $S$ parameters of the four slots are relatively poor.

### 3.2. The Transmission Characteristics of the Outer Coated THz PS Tube with Groove

The radius of THz PS tube $\mathbf{R} = 214\,\mu\text{m}$, the thickness of tube and coating layer $\mathbf{d} = 107\,\mu\text{m}$, and slot width is $30\,\mu\text{m}$. From the $S$ parameters of outer coated THz PS tubes with grooves, as shown in Figure

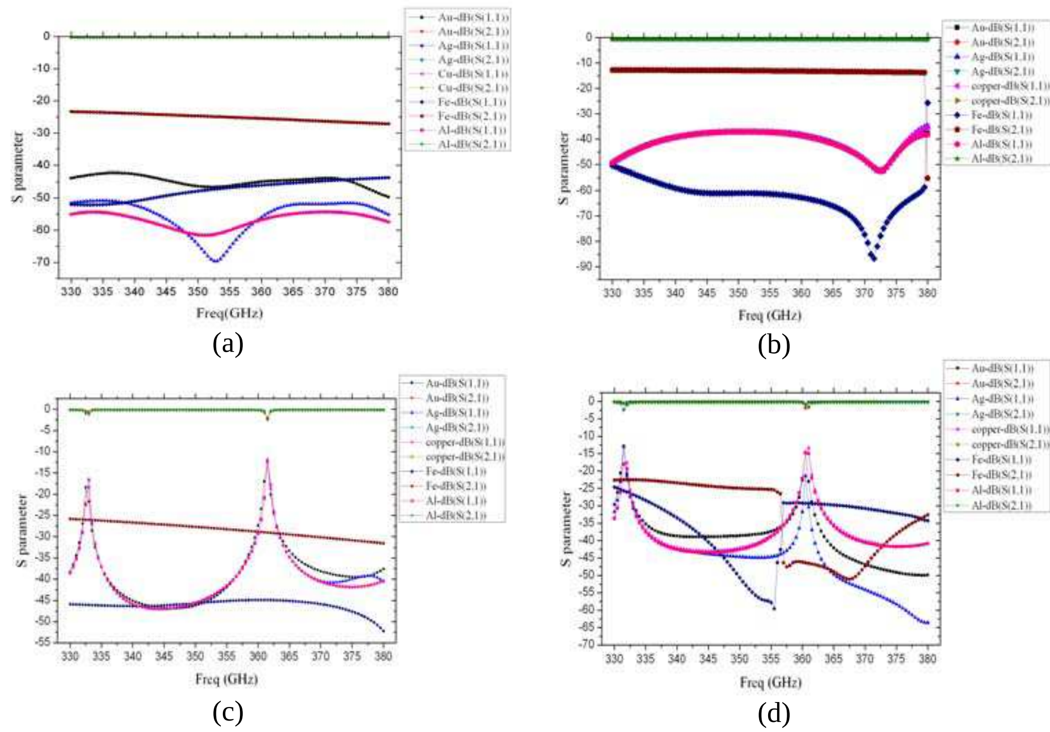



**Figure 3.** $S$ parameters of outer coated THz PS tubes with groove: (a) single slot; (b) double slots; (c) three slots; (d) four slots.

3, the insertion loss of coated iron is around 23 dB; however, the insertion losses of coated other metals are less than 1.5 dB for the insertion loss of outer coated THz PS tube with groove. And its insertion loss and return loss for the outer coating iron THz PS tube with four slots have a leap near 356 GHz, which makes a reversal between the insertion loss and return loss. Meanwhile, it is easy to find that the return loss of outer coating Cu and Al under the geometry is highly consistent within the working frequency band.

Around 332 GHz and 360 GHz, $S_{11}$ has two peaks for the three slots and four-slots structure, and the main reason attributes to the grooves, which is similar to a method of in Fabry-Perot cavity structure [9].

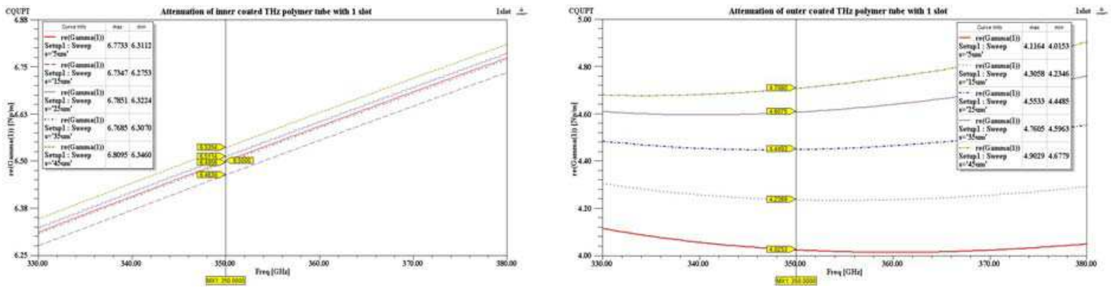
$$s = N \cdot \frac{c}{2f\sqrt{\varepsilon_r}} \cos\left[\arcsin\left(\frac{1}{\sqrt{\varepsilon_r}} \sin\theta\right)\right] \tag{2}$$

where $N = 1, 2, 3, \ldots$; $c$ is light velocity, $\theta$ is the incidence angle, $\theta = 90°$.

### 3.3. The Influence of the Groove Width on Transmission Characteristics

The groove width **s** of the copper coated THz PS tube with a single slot is optimized. The optimization goal is to optimize $S$ parameter, and the optimization uses the most common method: contraction step by step from coarse to fine (Firstly the optimization range is chosen from 50μm to 0μm, with step 5μm, then find the narrow range that the $S$ parameter is better than others. Secondly contract the new range and use new optimization step). The initial structure parameter is: the inner radius of tube $\mathbf{R} = 214$ μm, tube thickness and the film thickness $\mathbf{d} = 107$ μm, width of groove $\mathbf{s} = 30$ μm.

By the propagation constant $\gamma = \alpha + j\beta$, the real part of $\boldsymbol{\gamma}$ is attenuation coefficient $\boldsymbol{\alpha}$. The imaginary part of $\boldsymbol{\gamma}$ is the phase constant $\boldsymbol{\beta}$, in which the unit of $\boldsymbol{\alpha}$ is Np/m, and rad/m is the unit of $\boldsymbol{\beta}$. When **s** takes 5 μm, 15 μm, 25 μm, 35 μm and 45 μm, from Figure 4, for the THz PS tube with single slot which is the inner coating copper film, as shown in Figure 4(a), the attenuation coefficient curves within the frequency under various **s** values, approximate a linear curve and are close to each other,




(a) (b)

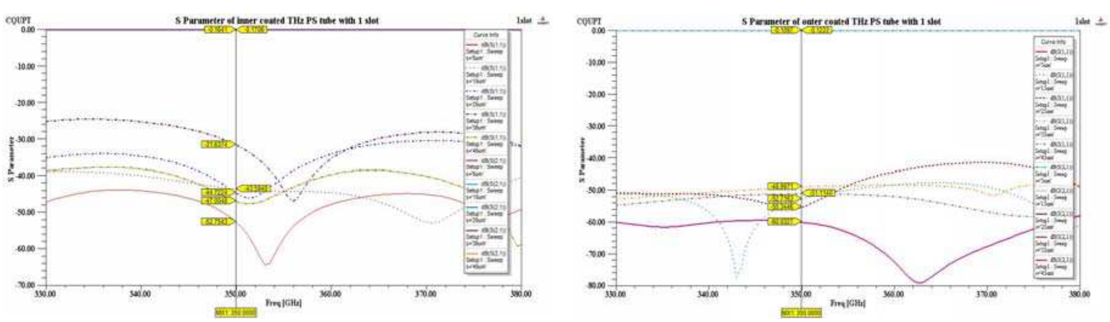
**Figure 4.** The attenuation curve of copper coated THz PS tube with single slot under different groove widths: (a) inner coating type; (b) outer coating type.

when $\mathbf{s} = 15\,\mu\text{m}$ gains the minimum attenuation within the working frequency band. From Figure 4(b), the attenuation coefficient of outer coated copper type THz PS tube with single slot increases with $\mathbf{s}$, and the attenuation coefficient curve within the working frequency approximates parabola. Among them, when $\mathbf{s} = 5\,\mu\text{m}$, the attenuation coefficient is minimum, and also attenuation coefficient minimized around 360 GHz.

$$\alpha = \frac{4u^2}{\kappa_0^2 d^3} \cdot \frac{n}{n^2 + \kappa^2} \left(1 + \frac{n_d^2}{\sqrt{n_d^2 - 1}}\right)^2 \tag{3}$$

where $u$ is a mode constant that is 2.405 for the $\text{HE}_{11}$ mode, $k_0$ the wave number in vacuum, ($k_0 = 2\pi/\lambda$), and $n - jk$ a complex refractive index of the metal cladding [10].

While $\mathbf{s}$ is taken $5\,\mu\text{m}$ and $15\,\mu\text{m}$, $25\,\mu\text{m}$, $35\,\mu\text{m}$ and $45\,\mu\text{m}$, $S$ parameters of copper coating THz PS tube with single slot as shown in Figure 5, it is obvious to find that the change of $S$ parameters along with groove width $\mathbf{s}$ for the inner coating type relative to the outer coating type. When $\mathbf{s} = 5\,\mu\text{m}$, $S_{11}$ of the two types of THz PS tube is optimal within the working frequency, and $S_{11}$ of inner coating is less than $-42$ dB, while the outer coating is less than $-56$ dB.




(a) (b)

**Figure 5.** $S$ parameter of copper coated THz PS tube with single slot under different groove width: (a) inner coating type; (b) outer coating type.

**Table 2.** The optimal value of groove width for copper plating membrane type groove THz polystyrene tube.

| Groove type / Coating type | Single slot | Double slots | Three slots | Four slots |
|---|---|---|---|---|
| Inner coating | 30.70 μm | 5.15 μm | 47.22 μm | 0.03 μm |
| Outer coating | 5.01 μm | 4.60 μm | 1.75 μm | 5.24 μm |

In order to find the optimal value of groove width **s** accurately, the optimization begins from coarse to fine, and the optimal step length starts from 5 μm to 0.01 μm in the optimization range. Finally, under the condition of keeping the PS tube geometry invariable for copper coating THz PS tube with groove, its optimal values of the groove width are shown in Table 2.

## 4. CONCLUSIONS

The hollow THz PS waveguide is designed, and the common metals like gold, silver, copper, iron and aluminum are selected to be the coated film of the THz PS tube. From the $S$ parameters of coated THz PS tube, the performance of the outer coating type PS tube is better than the inner coating type. Then the transmission characteristics of the coating PS tube with longitudinal grooving have been studied, including single slot, double slots, three slots and four slots. The transmission properties of inner coated PS tube with groove are obviously better than the transmission properties of outer coated PS tube with groove. Taking copper coating THz PS tube with single slot as an example, the groove width **s** and its impacts on the transmission characteristics have been analyzed. It is found that when the groove width **s** increases, the attenuation coefficient of outside copper coated THz PS tube also increases. And the width of grooves has more influence on the $S$ parameters of PS tube. In conclusion, adjusting the width of grooves will make a compromise between $S$ parameter and attenuation coefficient, so as to make the transmission characteristics of coated THz PS tube better and reduce the attenuation losses.

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