Terahertz Wave Antireflection Filter Using Nanostructure Multilayers

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In this paper, we report a nanostructure multiplayer as broadband antireflection coating used at terahertz frequencies region. The whole multiplayer stack was composed of four layers of dielectric material, and which was adhered on one side of a single-crystal germanium substrate. Then we analyze the effect about the change of incident angle and find that the polarizing effect shows more and stronger as the increasing of incident angle. To reduce the polarizing effect, we designed a multilayer nanostructure which comprises silicon wafers and dry air-ring. The two materials were fitted together by a high density polyethylene frame.

The organization of this paper is as follows. In Sec. II, we describe the characteristic matrix method, which is required to analyses the response of a multiplayer structure. The result of design, nanostructure multilayer as broadband antireflection coating used at terahertz frequencies region is given in Sec. III. Finally, a conclusion is given in Sec. IV.

II. THEORY

For decades, FTIR (Fourier transform infrared) spectroscopy has been widely employed in the study of materials in the frequency range around the mid-infrared. Correspondingly, multiplayer interference structures operative in this frequency range, made from a number of different materials and configurations, are widely available. Provided there is no absorption, the structure can be operated either as a filter or mirror dependent on the alignment, as the two functions are complementary. Some multilayer structures used as FTIR mirrors are, for example: zinc sulphide/polyethylene[9], silicon – air[10].

Similar multilayer structures are designed for T-rays, i.e. from 0.1 to 1.0 THz, and characterised by THz-TDS. A series of these designs are, for example: StyroluxTM/PE and polyethylene/air, polypropylene/silicon, alumina/alumina-zirconia, polypropylene/polypropylene+TiO2 . These earlier studies focus on finding materials and fabrication techniques suitable for the operation of the multiplayer structures in the T-ray frequency range. The fabricated structures are expected to be used as mirrors for short-range or indoor T-ray communication. Thus, particular interest is given to an economic material fabrication, which provides a structure with the highest reflectivity and broadest reflection band at any angle of incidence.

A multilayer interference filter is composed of several dielectric layers with different indices of refraction. The following subsection briefly discusses the characteristic matrix method, which is required to analyses the response of a multiplayer structure [11]. In order to analyze the response of the described structure, the characteristic matrix method is engaged. In brief, a characteristic matrix for high-indexed material, in the case that the wave propagation direction is
parallel with the stacking direction, is given by

\[ M_{n} = \begin{bmatrix} \cos \left( \frac{\omega n_{l} l_{t}}{c} \right) & j \sin \left( \frac{\omega n_{l} l_{t}}{c} \right) \\ j n_{t} \sin \left( \frac{\omega n_{l} l_{t}}{c} \right) & \cos \left( \frac{\omega n_{l} l_{t}}{c} \right) \end{bmatrix} \]

where \( n_{l} \) and \( l_{t} \) are the refractive index and the thickness attributed to a high-indexed material. Likewise, a matrix for the low-indexed material is

\[ M_{l} = \begin{bmatrix} \cos \left( \frac{\omega n_{l} l_{t}}{c} \right) & j \sin \left( \frac{\omega n_{l} l_{t}}{c} \right) \\ j n_{t} \sin \left( \frac{\omega n_{l} l_{t}}{c} \right) & \cos \left( \frac{\omega n_{l} l_{t}}{c} \right) \end{bmatrix} \]

Here \( n_{l} \) and \( l_{t} \) are the refractive index and the thickness attributed to a low-indexed material. When slabs of these materials are layered using a periods, with the high-indexed material terminating both ends, the resulting characteristic matrix is simply obtainable via matrix multiplications in the proper order:

\[ M_{\text{total}} = (M_{n} M_{l})^{\infty} M_{n} \]

The transmission function of the structure in free space is calculated from the total characteristic matrix:

\[ T(\omega) = \frac{2}{m_{1} + m_{2} + m_{3} + m_{4}} \]

This transmission function, \( T(\omega) \), is related to the transmittance, \( \Gamma(\omega) = |T(\omega)|^{2} \).

When terahertz wave at oblique incidence on multilayer structure, the incidence angles on each interface were related by Snell’s law

\[ n_{0} \sin \theta_{0} = n_{H} \sin \theta_{H} = n_{L} \sin \theta_{L} = n_{S} \sin \theta_{S} \]

where \( n_{0} \), \( n_{H} \), \( n_{L} \) and \( n_{S} \) were the refractive index of incident media, high-index, low-index and substrate material respectively. \( \theta_{0} \), \( \theta_{H} \), \( \theta_{L} \), and \( \theta_{S} \) corresponding to the angle of terahertz wave in various materials as shown in Fig.1.

Based on the theory of electromagnetic wave transmission, in general, plane wave at oblique incidence on a dielectric material will have transverse electric (TE) and transverse magnetic (TM) fields respectively. They will experience different reflectances \( R_{TE} \) and \( R_{TM} \) or transmission \( T_{TE} \) and \( T_{TM} \). Such polarization-dependent properties were inherent and intolerable in many applications.

![Fig.1 Schematic diagram of the terahertz wave transmission at oblique incidence on multilayer structure](image)

The tangential parts of TE and TM should keep consecutive when electromagnetic wave transmits at the interface of multilayers. This physical essence leaded to TE and TM show different equivalent index

\[ n_{TM} = \frac{n}{\cos \theta} \]

\[ n_{TE} = n \cos \theta \]

So \( n_{H} \), \( n_{L} \), \( n_{0} \) and \( n_{S} \) in equation (1), (2) and (5) should be substituted by

\[ n_{H,TM} = \frac{n_{H}}{\cos \theta_{H}} \]

\[ n_{L,TM} = \frac{n_{L}}{\cos \theta_{L}} \]

\[ n_{S,TM} = \frac{n_{S}}{\cos \theta_{S}} \]

for TM field, and

\[ n_{H,TE} = n_{H} \cos \theta_{H} \]

\[ n_{L,TE} = n_{L} \cos \theta_{L} \]

\[ n_{S,TE} = n_{S} \cos \theta_{S} \]

for TE field respectively. Then strong polarization effects (PE) can be gained from equation (4) in theory.

### III. Design and Result

In the design of coating, Hydrogenated amorphous silicon (a-Si[H]) and silicon oxide (SiO2) were chosen as coating materials because: the ratio of refractive indices of the two materials is relatively large (a-Si[H] \( n=3.7-2.8 \); SiO2 \( n=2 \)) and the extinction coefficients of these materials at terahertz frequencies are not so large (10-2).

As shown in Fig.2, the optical constants of the materials that were used in our design can be found in corresponding literature[12].

![Fig.2 The optical constants of the materials that have been used in the design](image)

From which, we can find that the refractive index of c-Si remains constant at 3.42 throughout the plotted region and there is a gradual increase in the refractive index of SiO2 from 1.96 (20 cm-1) to 2.94 (at 440 cm-1) with an increase in wavenumber.

Based on these data and the characteristic matrix method which have be shown in section II, an antireflection coating structure consisting of four layers was designed for using in terahertz frequencies region. The nanostructure multilayers were adhered on one side of a single-crystal germanium (Ge) substrate. The structure of whole system is Ge Substrate/Si 8.23 \( \mu \)m/SiO2 3.71 \( \mu \)m/Si 2.32 \( \mu \)m/SiO2 15.25 \( \mu \)m/Air, which has be shown in Fig.3. Corresponding antireflection for design structure has be shown in Fig. 4, and we can find it has a residual reflectivity of less than 0.08 and average
reflectivity about 0.06 throughout the 50–140 cm⁻¹ region.

Then we analysed the effect of incidence angle change on spectrum of this design. Fig.5(a-d) showed the spectral response of the TE and TM polarization, when the incidence angle equals to 5°, 15°, 30° and 45°, respectively.

For the case of 5° incidence angle, Fig.5 (a) showed that the deviation between the reflection of TE and TM fields was very small and can be neglected. But with the increasing of incident angle, polarization effect became more and more strong. Fig.5(b) showed that the deviation between the reflection of TE and TM fields with incident angle 15° was already very evident. From Fig.5(c), we can find that the average residual reflectivity with incident angle 30° was almost the same as the case of vertical incident, but the deviation between the reflection of TE and TM fields reach to about 0.06. From Fig.5(d), we can find that not only the deviation between the reflection of TE and TM fields with incident angle 45° even reach 0.14, but the average residual reflectivity also increased to about 0.08. So we can say that the increasing of incident angle will make the spectral character of the design bad, including the largen of average residual reflectivity and the enhancement of polarization-dependent deviation effect especially. To design depolarizing broadband antireflection is essential to terahertz wave in oblique incidence. But this work was very difficult because the polarization effect was inhered to single layer dielectric materials.

One method to reduce polarization effect was adopting a multilayer structure with appropriate materials combinations. Silicon and dry air were selected as materials for construction of the depolarizing broadband antireflection operating at terahertz region in our paper. Silicon material was known to have a negligible absorption, low dispersion and a constant refractive index of 3.418 in terahertz regime. Dry air has a unity refractive index, nearly zero absorption and dispersion.

The difference of refractive index between silicon and air was large; it was advantageous factor for reducing polarizing effect in our design.

Then proper material arrangement should be designed to achieve required spectrum character on terahertz wave region. A multilayer structure, comprising silicon layer and air layer, was an attractive option because of its structural simplicity yet optical functionality. Air layer was created by open rings and silicon layer as shown in Fig.6. The two materials were fitted together by a high density polyethylene frame.
As shown in Fig. 7, a depolarizing antireflection coating structure consisting of four air layers and five silicon layers was designed for using in terahertz frequencies region. The multilayers structure was adhered on one side of a single-crystal germanium (Ge) substrate. The structure of whole system was Ge Substrate/Si 9.36 μm/air 3.50 μm/Si 3.97 μm/air 8.36 μm/Si 2.49 μm/air 14.54 μm/Si 1.36 μm/air 21.26 μm/Si 0.55m/Air.

Then we found that the increasing of incident angle will make the spectral character of the design bad, including the largen of average residual reflectivity and the enhancement of polarization-dependent deviation effect especially. We designed a depolarizing broadband antireflection by adopting a silicon-air multilayer structure. Its residual reflectivity was small and corresponding polarization effect can be neglected.

### IV. CONCLUSION

In conclusion, we have achieved a nanostructure multilayer as broadband antireflection used at terahertz frequencies region. In our design, we choose hydrogenated amorphous silicon and silicon oxide as high and low refractive index coating materials respectively for their large refractive index ratio and small extinction coefficients at terahertz frequencies region. The whole multilayer stack was adhered on one side of a single-crystal germanium substrate. The results of our design shows that the structure has a residual reflectivity of less than 0.08 and average reflectivity about 0.06 throughout the 50–140 cm-1 region. Then we found that the increasing of incident angle will make the spectral character of the design bad, including the large of average residual reflectivity and the enhancement of polarization-dependent deviation effect especially. We designed a depolarizing broadband antireflection by adopting a silicon-air multilayer structure. Its residual reflectivity was small and corresponding polarizion effect can be neglected.

### REFERENCES


