

Terahertz Bessel Beam Applied to Thickness Measurement of Ellipsometry Methods

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How to cite this paper: Tu, S.Y., Wang, K.J., Liu, J.S. and Yang, Z.G. (2021) Terahertz Bessel Beam Applied to Thickness Measurement of Ellipsometry Methods. *Journal of Computer and Communications*, 9, 125-132. <https://doi.org/10.4236/jcc.2021.912010>

Received: August 28, 2021

Accepted: December 28, 2021

Published: December 31, 2021

Abstract

This paper introduces a Terahertz (THz) ellipsometer thickness measurement method based on Bessel beams. The ellipsometry method is used to measure the thickness of film in the THz band. And the thickness of film could be measured in the range of hundreds of microns which the measurement of film thickness by ellipsometer is usually only a few hundred nm in visible light. In addition, the photon energy of the THz-wave is very low and has little damage to the film. The THz Bessel beam has the characteristics of self-healing and diffraction-free. It can make the film thickness measurement within the diffraction-free distance, which is conducive to the flexibility of the ellipsometer system. We use a multi-frequency method to measure film with two-dimensional finite different time domain (FDTD) to numerical simulation analysis of light intensity successfully.

Keywords

Bessel-Beam, Ellipsometry, Diffraction-Free, THz

1. Introduction

Terahertz (THz) waves are electromagnetic waves with a frequency from 0.1 THz to 10 THz and a wavelength from 30 μm to 3 mm, which are between microwaves and infrared waves. THz waves have the characteristics of both microwaves and infrared waves. Macroscopically, THz waves can penetrate many dielectric materials and non-polar liquids. Microscopically, THz waves contain rich sample spectral information due to their broad spectrum [1] [2]. The unique characteristics of THz waves have brought far-reaching influence on communication (broadband communication), radar, electronic countermeasures, electromagnetic weapons, astronomy, medical imaging, non-destructive testing, safety inspection [3]-[8].

With thin film technology in information storage, electronic components, aerospace technology and optical instruments, etc. The accurate measurement of optical properties and surface morphology of film has gradually become an important direction of film research. Moreover, the physical properties of the film are closely related to the optical properties and thickness of the film. Therefore, the precise measurement of the optical properties and thickness of the film has become the primary research issue. The current methods for measuring the refractive index and thickness of the film include ellipsometry, heterodyne interferometry, equal thickness interferometry, reflection spectroscopy, transmission spectroscopy and other measurement methods [9] [10]. Ellipsometry is a non-contact and non-destructive measurement, which can measure samples under vacuum, atmosphere, moisture, and harmful environments with low environmental requirements [11] [12]. In addition, the ellipsometry is simple to operate and has a short measurement period. It can measure multiple physical quantities (film thickness, film refractive and absorption coefficient) at the same time. Hence, ellipsometry is widely used to measure films.

The Bessel beam has diffraction-free characteristics, the intensity distribution remains unchanged during propagation and has a high degree of localization [13] [14] [15]. It is widely used in precision measurement, laser processing and other fields in the optical waveband. The diffraction-free and long focal depth of Bessel beams could be further used in THz three-dimensional (3D) tomography systems, such as THz CT systems [16]. The THz imaging system based on Bessel beam has unique advantages in applications such as long-distance standing human security inspection and non-destructive inspection of thick sample.

The film thickness measured by ellipsometer in the optical band is mainly in the range of hundreds of nanometers. For samples with a thickness of millimeters and hundreds of microns, the visible light waveband cannot be measured. Therefore, we proposed the application of THz waves to accurately measure the thickness of samples in the order of millimeters and hundreds of microns. In addition, the photon energy of the THz wave is relatively low, which hardly cause damage to the sample. The THz Bessel beam has the characteristics of diffraction-free and self-healing, and can realize precise measurement of samples within its diffraction-free distance. Thus, an ellipsometer thickness measurement method based on THz Bessel beam is proposed in this paper. This paper is organized as follows. In Section 2, the theory of ellipsometry calculation of film thickness and the generation of THz Bessel beams are showed. In Section 3, numerical simulation calculation of the thickness of film measured by THz Bessel beam is carried out by two-dimensional finite difference time domain (FDTD). Finally, our conclusion is summarized in Section 4.

2. Theory

2.1. The Generation of THz Bessel Beam

A Gaussian beam with a waist radius of ω_0 is normally incident on the front

surface of the axicon [17]. By geometric optics analysis, the Gaussian beam is regarded as a straight line, in **Figure 1**. According to refraction law:

$$n_0 \sin(\theta) = n \sin(\gamma),$$

$$\alpha_0 + \gamma = \theta, \tau + 2\gamma = \pi,$$

the refractive index of atmosphere is $n_0 = 1$:

$$\theta = \arcsin\left[\frac{n}{n_0} \cos(\tau/2)\right] = \arcsin[n \cos(\tau/2)],$$

the angle between the Gaussian beam and the z-axis after refractive:

$$\alpha_0 = \arcsin[n \cos(\tau/2)] + (\tau - \pi)/2,$$

when γ is small:

$$\theta = n\gamma,$$

$$\alpha_0 = (n-1)\gamma.$$

Therefore, the Bessel beam with a diffraction-free distance of $z_{\max} = \omega_0 / \tan(\alpha_0)$ is generated.

2.2. Ellipsometry Measurement Theory

The basic principle of ellipsometer measurement is to incident a beam of elliptic polarization light onto the sample to be tested at a certain angle of incidence. Since the sample has different reflection and transmission coefficients for the p-light and s-light of the incident light, the polarization state of the light reflected from the sample changes with respect to the incident light which is showed in **Figure 2**. The variation of polarization state is closely related to the structure of sample. The specific structure of sample can be determined according to the variation of polarization state. The variation of the polarization state of the light before and after reflection is observed to determine the reflection coefficient ratio ρ , which the information related to the optical parameters of the sample could be obtained.

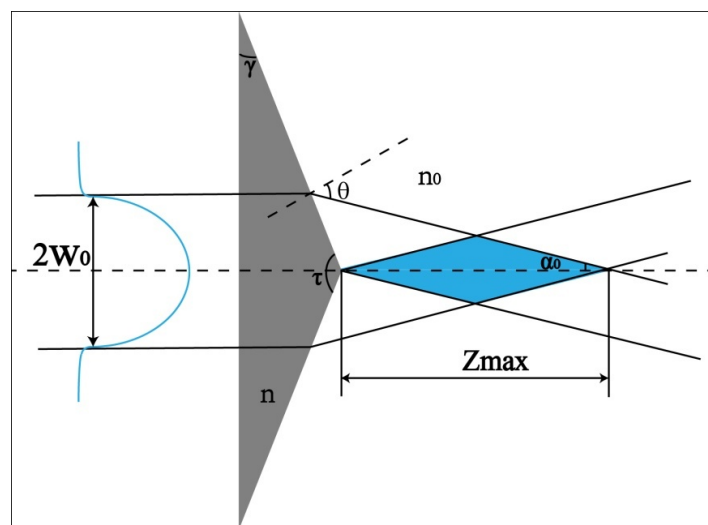


Figure 1. The theory of Bessel beam.

The electric vector of incident light can be decomposed into p-light and s-light. E_{ip} and E_{is} represents the p-light and s-light of the incident light respectively. E_{rp} and E_{rs} represents the p-light and s-light of the incident light respectively.

$$r_p = E_{rp} / E_{ip}$$

$$r_s = E_{rs} / E_{is}$$

The Fresnel formula for the reflection of wave on the interface:

$$r_p = \frac{n_2 \cos \varphi_1 - n_1 \cos \varphi_2}{n_2 \cos \varphi_1 + n_1 \cos \varphi_2}$$

$$r_s = \frac{n_1 \cos \varphi_1 - n_2 \cos \varphi_2}{n_1 \cos \varphi_1 + n_2 \cos \varphi_2}$$

The relationship between the complex amplitude of the total reflected wave and the incident wave is:

$$E_{rp} = \frac{r_{1p} + r_{2p} \exp(-i2\delta)}{1 + r_{1p} r_{2p} \exp(-i2\delta)} E_{ip}$$

$$E_{rs} = \frac{r_{1s} + r_{2s} \exp(-i2\delta)}{1 + r_{1s} r_{2s} \exp(-i2\delta)} E_{is}$$

The total reflection coefficients of the film are:

$$R_p = E_{rp} / E_{ip}$$

$$R_s = E_{rs} / E_{is}$$

The reflectance coefficient:

$$\rho = R_p / R_s = \frac{E_{rp} / E_{ip}}{E_{rs} / E_{is}} = \left| \frac{E_{rp} / E_{ip}}{E_{rs} / E_{is}} \right| \exp \left\{ i \left[(\beta_{rp} - \beta_{ip}) - (\beta_{rs} - \beta_{is}) \right] \right\}$$

$$= \tan \psi \exp(i\Delta)$$

According to the Fresnel formula and the law of refraction:

$$\begin{cases} r_{1p} = (n_2 \cos \varphi_1 - n_1 \cos \varphi_2) / (n_2 \cos \varphi_1 + n_1 \cos \varphi_2) \\ r_{2p} = (n_3 \cos \varphi_2 - n_2 \cos \varphi_3) / (n_3 \cos \varphi_2 + n_2 \cos \varphi_3) \\ r_{1s} = (n_1 \cos \varphi_1 - n_2 \cos \varphi_2) / (n_1 \cos \varphi_1 + n_2 \cos \varphi_2) \\ r_{2s} = (n_2 \cos \varphi_2 - n_3 \cos \varphi_3) / (n_2 \cos \varphi_2 + n_3 \cos \varphi_3) \\ n_1 \sin \varphi_1 = n_2 \sin \varphi_2 = n_3 \sin \varphi_3 \\ 2\delta = (4\pi d n_2 \cos \varphi_2) / \lambda \end{cases}$$

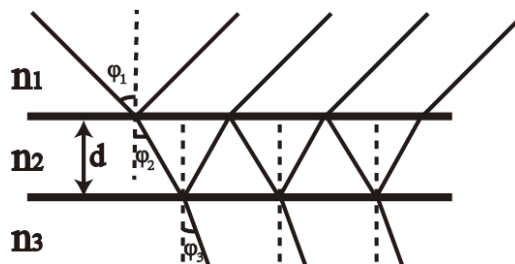


Figure 2. The film reflection.

Therefore, the relevant parameters of the film can be obtained by the variation of the polarization state of the incident beam before and after reflection.

3. Simulation Results

The 2D FDTD (Finite Difference Time Domain) numerical stimulation method is utilized to conduct a simulation on the model. In **Figure 3**, a Gaussian beam with a waist radius of 20 mm is incident on an axicon with base angle of 15° . The Bessel beam is generated by the axicon. The sample is within the diffraction-free distance of the Bessel beam. And the Bessel beam is incident on the film obliquely at an incident angle of 45° . A line monitor is set in the reflection direction of the beam.

The basic setup of the model is as follows. Since the thickness of the measured film is related to the polarization state of the incident beam, the polarization state is specially set when setting Gaussian beam source. We choose to use circularly polarization beam as the incident light. In FDTD, a Gaussian beam source can only set a certain angle of linear polarization light. Therefore, we set up two Gaussian beam sources. The amplitudes of two sources are same. Their polarization angles are 0° and 90° respectively as the p-light and s-light. The phase difference between the two Gaussian beams is 90° . In Solidworks software, an isosceles triangle with a base angle of 15° and a bottom margin of three inches is created. The isosceles triangle is rotated 360° around its center line to form axicon. The axicon is exported from Solidworks in STL format and imported it to FDTD. A sample with film thickness of 1 mm, refractive index $n = 1.6$, substrate thickness of 20 mm, refractive index $n = 3.4$ was established in FDTD. The position of the Gaussian sources, axicon, sample, monitor are respectively designed in the appropriate position.

In **Figure 4**, it is showed that the Gaussian beam is incident on the axicon to produce a Bessel beam. And the Bessel beam is incident on the film, part of the Bessel beam is reflected, part of the beam pass through the substrate. **Figure 5** are the light intensity measured by the line monitor. It can be seen that the strong middle peak is the reflected beam of the main lobe of the Bessel beam. **Figure 5(a) & Figure 5(b)** is the p-light and s-light of the Bessel beam generated by the axicon respectively, which is also the incident light. **Figure 5(c) & Figure 5(d)** is

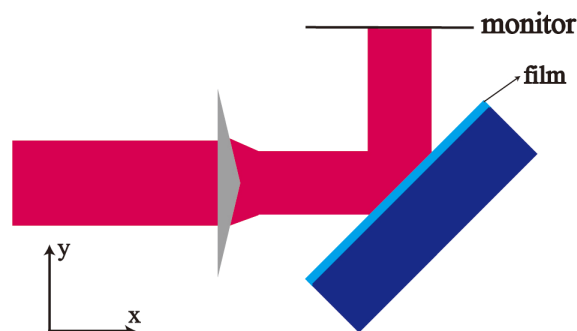


Figure 3. Simulation model.

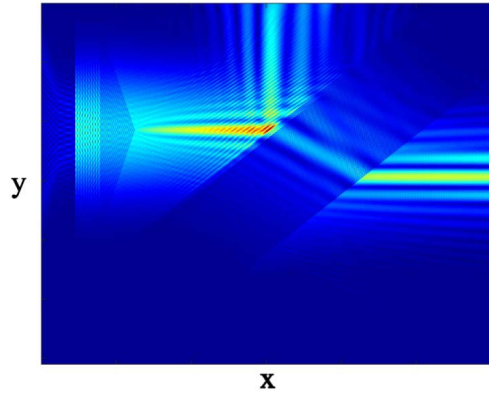


Figure 4. The electric field of xy cross-section.

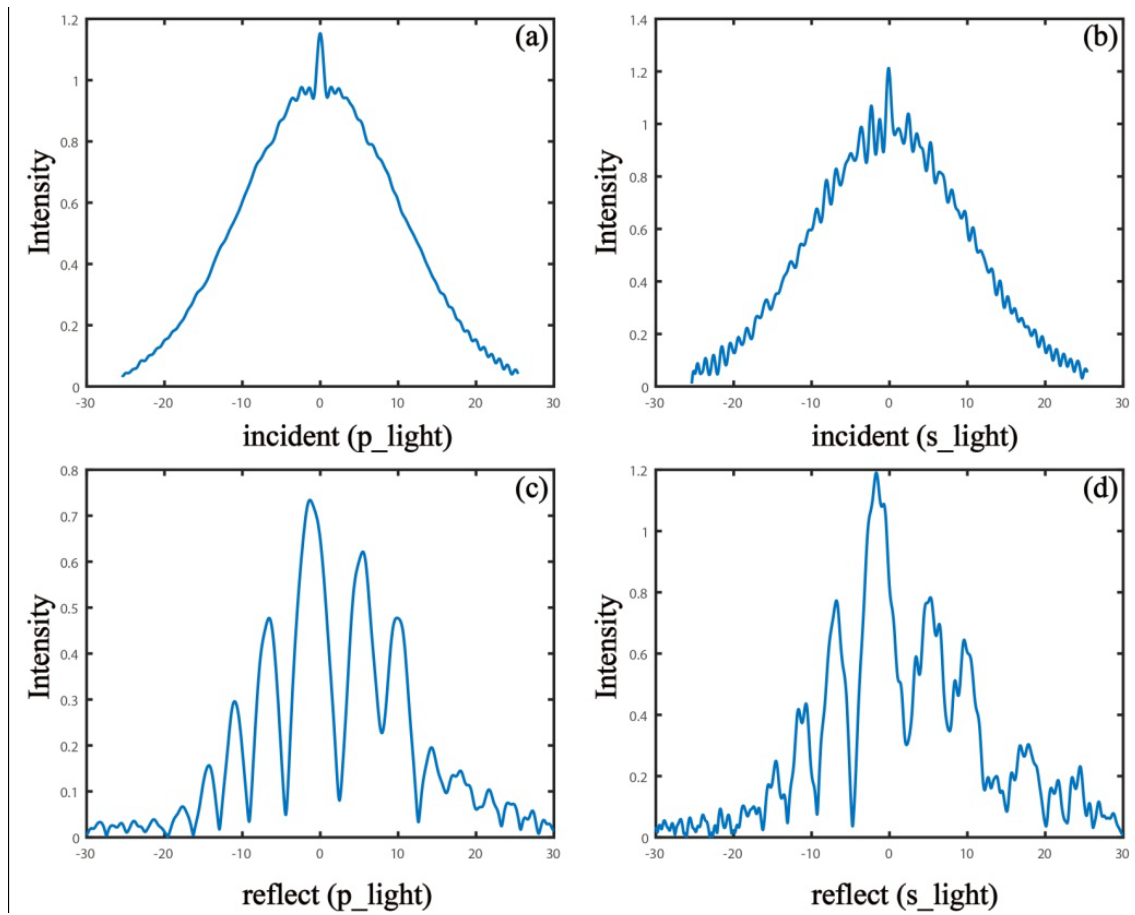


Figure 5. (a) The intensity of incident p-light, (b) The intensity of incident s-light, (c) The intensity of reflect p-light, (d) The intensity of reflect s-light.

the p-light and s-light reflected by film. The ellipsometric parameters can be calculated by the light intensity of the incident and reflected p-light and s-light of simulation. The p-light to s-light ratio of incident light is 0.9959, the p-light to s-light of reflected light is 0.6524. According to calculation, the r_{1p} is 0.1155, the r_{2p} is 0.3218, the r_{1s} is -0.3399 , the r_{2s} is -0.3971 , the ellipsometric parameters is $\tan \psi = 0.655062567862263$. By:

$$2\delta = (4\pi n_2 \cos \varphi_2) / \lambda,$$

the Periodic film thickness is obtained.

The Periodic film thickness value is as follows:

Table 1. Part of the periodic film thickness.

<i>d</i> /mm	0.7558	0.8322	1.0279	1.2897	1.5852	1.8987	2.2226
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Table 1 gives part of the Periodic film thickness. When setting up model in simulation, the film thickness is 1 mm. Therefore, the value of the calculated periodic film thickness closest to 1 mm is the actual value of the film thickness. The 1.0279 mm is closest to 1 mm, and there is only 0.02 mm error which proves that the Bessel beam model is correct.

4. Conclusion

This paper proposed a method of measuring film thickness by THz Bessel beam. It is proved that precise thickness measurement of thin films of millimeters and hundreds of microns can be achieved in the THz band. And the THz Bessel beam is a diffraction-free beam, which can realize the measurement system with a long depth of field. We have employed the ellipsometric calculation method in FDTD to verify the feasibility of this theory. In the future, we will further implement ellipsometric thickness measurement in the THz experimental system.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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