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Temperature-dependent Goos–Hänchen shift in the terahertz range

Mengdi Zang, Ting He, Bo Zhang, Liang Zhong, Jingling Shen*

Beijing Key Laboratory for Terahertz Spectroscopy and Imaging, Key Laboratory of Terahertz Optoelectronics, Ministry of Education, Department of Physics, Capital Normal University, Beijing 100048, China

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A B S T R A C T

In this work, an observation of Goos–Hänchen shift in the terahertz range on a metal surface with a change in temperature is reported. A s-polarized terahertz wave incident at 45° onto an aluminum surface produces a positive GH shift that increases with temperature. We used an interference method by observing the change of interference fringes of two THz beams to verify the existence of the GH shift and indirectly measured the quantity of it. Based on experimental data and theoretical analysis, the increase of GH shift on the aluminum surface as a function of temperature between 23 °C and 101 °C has been obtained. Considering the effect of the thermal expansion, the maximum variation of GH shift is 267.2 μm with the temperature changing 78 °C.

1. Introduction

The Goos–Hänchen (GH) shift is a kind of "abnormal" optical phenomenon. According to reflection law, when a beam of light is incident to an interface, the point of incidence and reflection should be in the same place. In some cases, there exists a tiny lateral shift between the practical reflected light and geometric reflected light from a planar interface. This phenomenon is called a GH shift. In 1947, the GH shift was confirmed for the first time [1]. In the case of total internal reflection, the evanescent wave appears to travel along the boundary between the two materials, leading to the GH shift. The GH shift was also observed in other reflection surfaces. GH shifts have been extensively studied for different applications such as optical sensing, optical wave guides and other fields.

In general, Artmann's stationary phase theory from Fresnel–Maxwell equations was put forward to explain this phenomenon [2,3]. According to previous reports, plentiful studies on GH shifts have been carried out and the researchers have dealt with the situation from total internal reflection [3,4], the reflection on dielectric gratings [5], the reflection of metal surfaces [6], and then extended to multilayer structure and multilayer dielectric reflection [4,7]. In addition, studies have covered many optical regions including visible light [8,9], infrared [10,11], microwave [12], and terahertz (THz) waves [3,4]. In initial studies, the GH shift was calculated for total internal reflection to be positive in most cases [5]. Later, negative GH shifts were predicted and observed in different media or structures, such as metallic gratings [13], transparent dielectric slabs [14], weakly and strongly absorbing media [15,16], and photonic crystals [17].

Moreover, theoretical simulation and experimental tests of GH shifts on metal caused by temperature change have been reported in visible light [18–20] and infrared waves [10,21]. In 2007, Chih-Wei Chen et al. indicated that temperature effect on negative GH shifts took place at grazing incidence on a metal-dielectric surface [21]. They found that the variation of GH shift was enhanced by an increase in temperature. In 2013, Wang et al. found that the GH shift in a symmetrical metal-cladding waveguide was linear along with increasing temperature in theory and experiment [19]. However, temperature-dependent GH shifts in the THz range have not been reported and are of interest to be investigated.

In this work, we study GH shifts on a metal surface as a function of temperature in the THz range. Due to the limitation of source and detection, the study of GH shift in the THz range is more difficult than that in other electromagnetic frequency ranges. Here we introduced an interference method by observing the change of interference fringes of two THz beams to verify the existence of GH shift and then indirectly measured the change of GH shift on an aluminum surface. Based on experimental data and theoretical analysis, the changing amount of GH shift on the aluminum surface as a function of temperature between 26 °C and 101 °C has been obtained, which is in agreement with previous studies in other frequency ranges.

2. Theoretical analysis and experiment

H. Wolter was the first man to consider the GH effect theoretically when the second medium is metal [22,23]. According to the

* Corresponding author.
E-mail address: sjl-phy@cnu.edu.cn (J. Shen).

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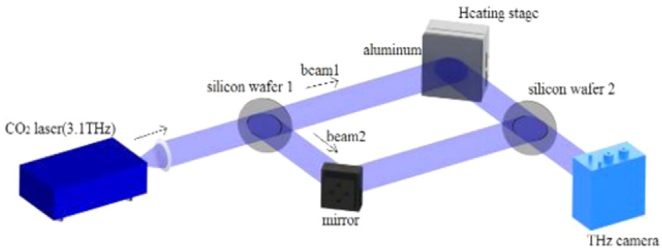

Fig. 1. Schematic diagram of the experimental system. The CO_2 laser produces the THz wave with vertical polarization. Silicon wafer 1 divides the terahertz wave into two beams. The temperature of the aluminum reflection surface can be controlled by a heating stage. Silicon wafer 2 is used to make beam1 and beam2 interfere. A THz camera is used to record the interference fringes.

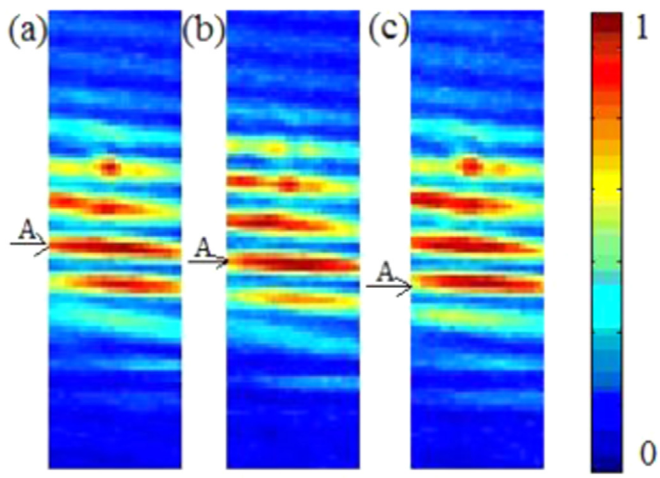

Fig. 2. Observed interference fringe patterns on the screen of the THz camera at three temperatures. (a) 23 °C, (b) 41 °C, and (c) 59 °C. The brightest fringe A pointed by an arrow moved down half-fringe (b) and another half (c). The fringes moved down one fringe when the temperature changed 36 °C. The intensity of the interference fringes are shown in color. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

stationary phase method, the GH shift is $S = -\frac{1}{k} \times \frac{d\varphi}{d\theta}$ [23], where $k = \frac{2\pi}{\lambda}$ is the incident wave number, θ is the incident angle, and φ is the phase of the complex reflection coefficients. According to the Fresnel formula the phase of the complex reflection coefficients for the s polarization is $\varphi_s = \mathrm{Im}\left(\ln\left[\frac{n_1\cos(\theta) - (\hat{n}_2^{\,2} - n_1^2\sin^2(\theta))^{1/2}}{n_1\cos(\theta) + (\hat{n}_2^{\,2} - n_1^2\sin^2(\theta))^{1/2}}\right]\right)$ [6], where $n_1 = \sqrt{\varepsilon_1}$ is the refractive index of the incident medium, and $\hat{n}_2 = \sqrt{\varepsilon_2} = n_2 + i\kappa$ is the complex refractive index of metal. Theoretical studies indicate that the refractive index $\hat{n}_2$ is a function of temperature [21]. Therefore, a GH shift can be affected by a change in temperature.

The experimental setup is shown in Fig. 1, which is a typical Mach–Zehnder interference structure. Because the amount of GH shift is usually in the order of wavelength, the direct measurement of GH shift is difficult. In 2013, we measured the GH shift at the frequency of 0.206 THz in the COC double-prism structure [3]. In this work, the THz frequency we used is 3.1 THz, at which the wavelength is shorter and therefore more difficult to measure a GH shift directly. To measure the small GH shift at 3.1 THz we used an interferometric technique by observing the change of interference fringes of two THz beams and obtained indirectly the GH shift.

In the experiment, the terahertz wave was generated by a CO_2 gas laser (SIFIR-50 FPL), which is a continuous THz source with a frequency of 3.1 THz and vertical polarization. Using a silicon wafer (silicon wafer 1) the terahertz wave was divided into two beams. Silicon wafer 1 can also be used to balance the THz intensity of the transmission (beam1) and reflection (beam2) by adjusting its angle. Silicon wafer 2 is used to make beam1 and beam2 interfere. A THz camera (Pyroelectric Array Camera Pyrocam III Series) was employed to detect the interference fringes in the overlap areas of beam1 and beam2.

The optical path was adjusted initially at room temperature (23 °C) to decrease the optical path difference (OPD) between beam1 and beam2. Beam1 is incident to the aluminum surface at a 45° angle, and is reflected from the aluminum surface where it undergoes the GH shift. We can vary the temperature of the aluminum surface from the room temperature to over 100 °C by controlling a heating stage (AZY2020) that is attached behind the aluminum surface. The change of the interference fringes can be observed whenever the temperature increased in the experiment. We can get maximal fringe visibility by controlling the relative intensity of the terahertz wave components. The THz interference fringes were detected and the location of each fringe was recorded at every temperature point to obtain the movement of the fringes.

3. Results and discussion

In the experiment, about 30 patterns of interference fringe was recorded with the temperature of aluminum reflection surface changing from 23 °C to 101 °C in increments of 3 °C. Fig. 2 shows three recorded patterns of the interference fringe at three different temperature points, 23 °C, 41 °C and 59 °C. From Fig. 2 we can see that the position of the brightest center fringe (marked as A) changed with the increase in temperature of the aluminum reflection surface. When the temperature reached 41 °C, the brightest center fringe (A) moved down about half an interference fringe compared to the location at 23 °C. In addition, with the temperature variation from 23 °C to 59 °C, the interference fringes moved down about one fringe. As the temperature increases further the interference fringes consistently moved down. A separate experiment in which a silicon plate was inserted into beam1 indicates that the interference fringes move down when the optical path length of beam1 is increased. Therefore, with an increase in aluminum temperature, the optical path length of beam1 also increases. In other words, the optical path difference (OPD) between beam1 and beam2 increased.

The position of the interference fringes on the screen of the THz camera was numerally recorded as shown in Fig. 3. Fringe spacing is about 6 pixels (one pixel on the THz camera is 85 μm). For clarity, the brightest fringe is marked in Fig. 3(a) as "A." When changing the temperature from 23 °C to 59 °C in 3 °C increments, we observed that the position of the fringe "A" moved one fringe or about 6 pixels (Fig. 3(b)), and it moved another one fringe when the temperature reached 89 °C (Fig. 3(c)). According to the principle of interference, one fringe displacement means one wavelength (96.8 μm for 3.1 THz) change in OPD. When the temperature reached 101 °C, the interference pattern moved more than two fringes as shown in Fig. 3(d) and therefore the change in OPD is over 200 μm. The change of OPD, Δ_{exp}, as a function of temperature obtained in the experiment is given in Fig. 4, in which some of the data are identical due to the resolution limitation of the THz camera. In fact, the detection resolution in the interferometric measurement system is determined by the resolution of the THz camera, which is 85 μm for one pixel.

There are two reasons for the change of OPD between beam1 and beam2, Δ_{exp}, in the experiment. One reason is thermal expansion, which makes the aluminum surface move in such a direction that it shortens the optical path with the increase in the temperature as schematically shown in Fig. 5(a). The other reason,