# Optical temperature sensing based on the Goos–Hänchen effect

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The possibility of constructing an optical sensor for temperature monitoring based on the Goos–Hänchen (GH) effect is explored using a theoretical model. This model considers the lateral shift of the incident beam upon reflection from a metal–dielectric interface, with the shift becoming a function of temperature due mainly to the temperature dependence of the optical properties of the metal. It is found that such a sensor can be most effective by using long wavelength *p*-polarized incident light at almost grazing incidence onto the metal, where significant variation of negative GH shifts can be observed as a function of the temperature. © 2007 Optical Society of America

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## 1. Introduction

The monitoring and control of the temperature of a system using optical means has been an interesting topic of research for over thirty years [1]. The advantages of such an approach include its remote, nonperturbative nature; its time-resolving capability; and its high sensitivity and broad range in these temperature measurements. For example, optical reflection (and transmission) measurements have been applied previously to monitor temperatures of metal during alloy coating process [2]; as well as to monitor explosive superheated liquids at absorbing interfaces in real time down to nanosecond time scales [3]. In addition, powerful optical techniques based on surface plasmon resonance (SPR) for temperature measurements have also been developed in the literature [4–7], with high sensitivity as well as temporal resolution achieved in the development of these techniques. In this work we explore, via a theoretical model, the possibility of employing another optical phenomenon—the Goos–Hänchen (GH) effect—for temperature sensing which hitherto has not yet been applied in this direction to our knowledge. We shall see that while the GH temperature sensor will not have high sensitivity comparable to that from a SPR sensor in general, it does provide more convenient remote sensing capability like the conventional approach which monitors change in reflectivity [2,3]. While the optical fiber approach in the SPR sensor design also achieved remote temperature sensing [7], our current approach will have the additional feature of “noncontact” probing. In one of the latest developments of the SPR sensor, Yin and Hesselink [8] merged the two techniques and constructed a SPR-GH sensor, though this new sensor has not yet been applied to temperature sensing. However, the GH sensing technique explored in our present work is limited to the “conventional GH shifts” from an absorbing medium (see below) and does not count on the SPR mechanism.

The GH effect refers to the lateral shift of a well-collimated incident beam upon reflection from an interface [9–13]. Traditionally, this most often refers to the situation of total reflection, with the incident beam

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in a transparent medium (e.g., glass) reflected back at the interface of this medium and another one of lower reflective index (e.g., air). In this case with transparent optical media, such GH shifts are not sensitive to the temperature change of the environment, since the transparent medium (e.g., glass) will have its optical properties very insensitive to the change of temperature in general (e.g., the refractive index of glass varies with temperature at a rate with $dn/dT \sim 10^{-6}/K$) [6]. Hence, to have the GH shifts to depend on temperature, we have to consider a different kind of GH shifts, namely, that takes place when the beam from a transparent medium (such as air or glass) is reflected from an absorptive or strongly-attenuating one such as metal or semiconductor at frequencies from IR to UV. This kind of GH shift was previously studied theoretically by Wild and Giles [14], and subsequent works by other researchers have shown that this type of shift can occur at all incident angles for both *s*- and *p*-polarized incident waves, and can lead to both positive and negative lateral shifts for the case with *p*-polarized waves [15]. In a recent study [16], we have observed large negative GH shift for long wavelengths of light at almost grazing incidence onto a metallic substrate.

In the following, we shall present a theoretical study of the temperature effect on these negative shifts we recently observed [16], and demonstrate the possibility of performing temperature sensing based on this approach. Optimal conditions for the operation of such a sensor will also be established from our modeling results. We start by recapturing the essence of various models we have studied in several of our previous works.

## 2. Theoretical Model

In our recent work to calculate the GH shifts (D) from a metallic surface [16], we have followed the previous works [14,15] to apply the following Artmann formula to absorbing interfaces:

$$D = -\frac{1}{k}\frac{d\varphi}{d\theta} = -\frac{\cos^2\varphi}{k}\frac{d\tan\varphi}{d\theta}, \tag{1}$$

where $k = \frac{2\pi}{\lambda}$ is the incident wave number, $\theta$ the incident angle, and $\varphi$ the phase of the reflection amplitude. By applying standard Fresnel formula for *p*-polarized incident light, one easily obtains the following result [14]:

$$D_P = \mathrm{Im}\left\{\ln\left[\frac{\hat{n}_2{}^2\cos\theta - n_1(\hat{n}_2{}^2 - n_1{}^2\sin^2\theta)^{1/2}}{\hat{n}_2{}^2\cos\theta + n_1(\hat{n}_2{}^2 - n_1{}^2\sin^2\theta)^{1/2}}\right]\right\}, \tag{2}$$

with a similar result for *s*-polarized light. In the above equations, $n_1 = \sqrt{\varepsilon_1}$ is the real refractive index of the incident medium, and $\hat{n}_2 = \sqrt{\hat{\varepsilon}_2} \equiv n + i\kappa$ is the complex index of the metal. For metal at IR frequencies, we expect $\kappa \gg n$, and it is straight-forward to derive the following expression for the phase in Eq. (1) [16]:

$$\tan\varphi \approx \frac{2\kappa^2\cos\theta(\kappa^2 + \sin^2\theta)^{1/2}}{\kappa^4\cos^2\theta - \kappa^2 - \sin^2\theta}, \tag{3}$$

where a singularity occurs when

$$\sin^2\theta = \frac{\kappa^2(\kappa^2 - 1)}{\kappa^4 + 1}. \tag{4}$$

For $\kappa \gg 1$, Eq. (4) implies very large value for (3) and hence large negative value for $D_P$ in (1) and in (2) at close to grazing incidence ($\theta \sim 90°$) [16]. We shall show below that it is also under such a condition that the GH shifts are mostly sensitive to temperature change for the system under consideration.

To study the temperature (T) dependence of the shift in Eq. (2), we follow our previous works [4,17] to adopt the Drude model for $\hat{\varepsilon}_2$:

$${}_2 = 1 - \frac{\omega_P{}^2}{\omega(\omega + i\omega_c)}, \qquad (5)\hat{\varepsilon}$$

where $\omega_c$ is the collision frequency and $\omega_p$ the plasma frequency given by:

$$\omega_p = \sqrt{\frac{4\pi Ne^2}{m^*}}, \tag{6}$$

with N and m* the density and effective mass of the electrons, respectively. Hence, assuming the variation of m* with T can be ignored [18], $\omega_p$ depends on T via volumetric effects as follows:

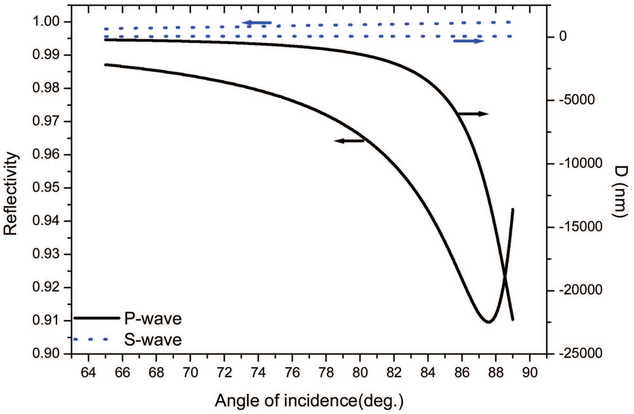


Fig. 1. (Color online) Typical results for Goos–Hänchen shift and reflectivity as a function of incident angle for *p*-polarized light at long wavelengths ($\lambda$ = 3390 nm) calculated using the Drude model for the metal at room temperature. Also shown are the corresponding results for *s*-polarized (broken lines). The incidence is from vacuum onto a silver surface.

$$\omega_p = \omega_{p0}[1 + \gamma(T - T_0)]^{-1/2}, \tag{7}$$

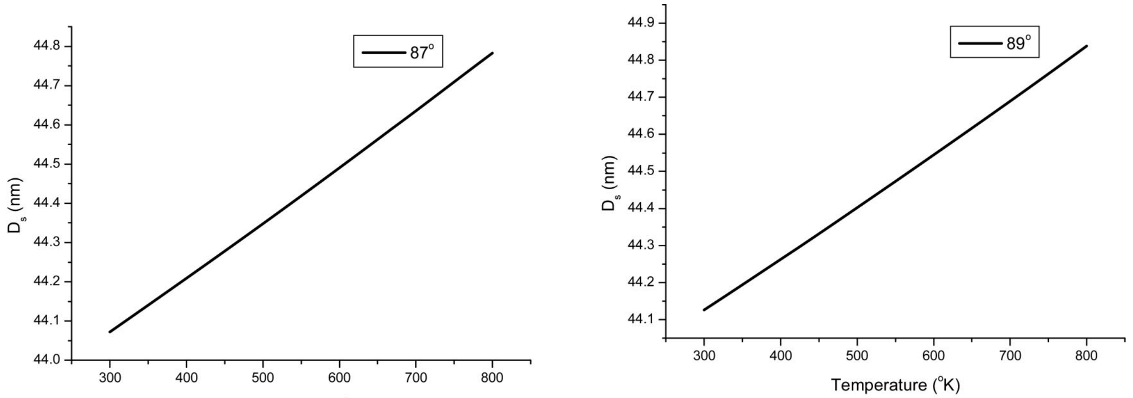
where $\gamma$ is the expansion coefficient of the metal, and $T_0$ is a reference temperature taken to be the room temperature. The collision frequency will have contributions from both phonon-electron and electron-electron scattering:

$$\omega_c = \omega_{cp} + \omega_{ce}, \tag{8}$$

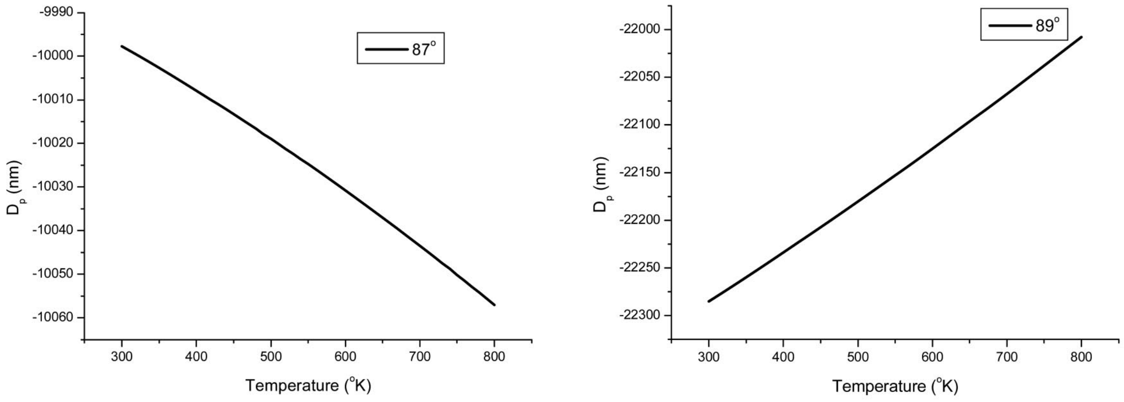
and can be modeled using the various scattering models in the literature. we thus obtain [17]

$$\omega_{cp}(T) = \omega_0\left[\frac{2}{5} + 4\left(\frac{T}{\theta}\right)^5 \int_0^{\theta/T} \frac{z^4\, dz}{e^z - 1}\right], \tag{9}$$

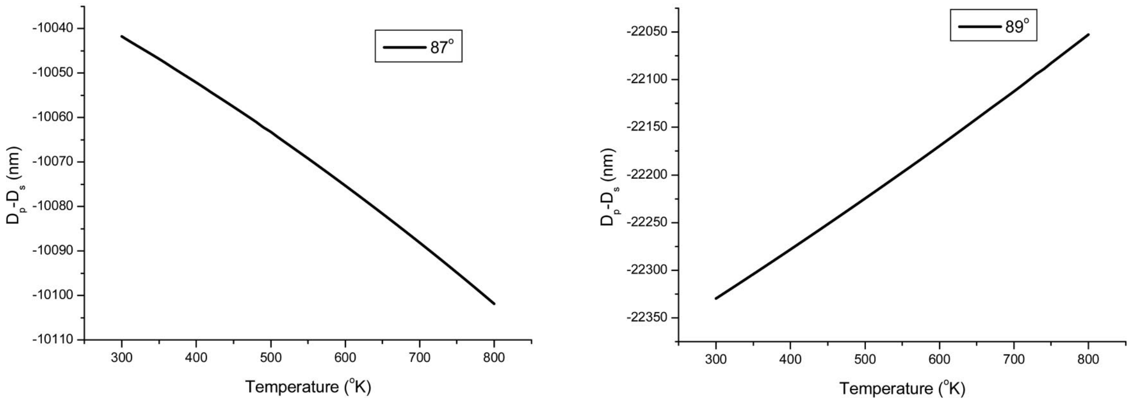
where $\theta$ in (9) is the Debye temperature and $\omega_0$ is a constant to be determined from the static limit of the



**(a) $D_S$ vs T**



**(b) $D_P$ vs T**



**(c) $(D_P - D_S)$ vs T**

Fig. 2. Goos–Hänchen shifts as a function of temperature of the metal at an incident wavelength of 3390 nm at two different incident angles below and above the Brewster angle of the metal. The GH shifts for both *s*- and *p*-polarized waves [(a) and (b)], as well as the difference between them [(c)] are plotted.

above expression together with the knowledge of the d.c. conductivity. In addition, we have [17]

$$\omega_{ce}(T) = \frac{1}{12}\,\pi^3\,\frac{\Gamma\Delta}{\hbar E_F}\left[(k_B T)^2 + (\hbar\omega/2\pi)^2\right], \qquad (10)$$

where $\Gamma$ and $\Delta$ are defined in [17]. Thus Eqs. (5)–(10) provide a model for the temperature dependence of $\hat{n}_2 = \sqrt{\hat{\varepsilon}_2}$, which when used in Eq. (2) will lead to a description for the temperature variation of the GH shifts for *p*-polarized light onto the metal.

## 3. Numerical Results

To illustrate the temperature effects, we have considered a light beam incident from vacuum onto a silver surface. In a previous work, we have shown that one can achieve large negative GH shifts with long-wavelength *p*-polarized light incident at almost grazing direction onto a metal surface, with insignificant restriction from the Brewster angle phenomenon for the observation of such negative shifts, since even at Brewster angle (defined as the dip angle in the reflectivity for *p*-polarized light), reflectance from the surface of a metal (such as silver) remains relatively high [16]. In Fig. 1, we have shown a typical result for the GH shift and reflectance, respectively, obtained using the Drude model to illustrate the aforementioned effects. Note that these results are qualitatively very similar to those obtained from using table values for the metal optical constants as done in [16]. Note also that this is unique for *p*-polarized light and the corresponding *s*-polarized light (at 3390 nm) shows no significant effects. As can be seen, even when the Brewster angle is also close to grazing, one still has reflection ~90% which will enable the corresponding large negative shift to be observable.

To demonstrate the temperature effects on the GH shifts, we have applied our model in Eqs. (5)–(10) to Eq. (2) and the corresponding result for *s*-polarized light, for several common laser wavelengths (632 nm, 1150 nm, and 3390 nm, respectively; with only the 3390 nm case is shown here), and have considered a large range of variation in temperature (300 K − 800 K). In general, the following results are observed: (a) the GH shifts ($D_S$) for *s*-polarized light have small positive values for all wavelengths, and with completely negligible temperature dependence; (b) those for *p*-polarized light ($D_P$) can become highly negative (~10 microns for 3390 nm incident light) at close-to-grazing incidence [16], and can have significant temperature-dependence for these negative shifts for the longer wavelengths; and (c) the temperature-dependence in (b) is such that $D_P$ will become more negative at higher temperatures for incident angles just below the Brewster angle, and just the other way for angles above the Brewster. All these can be illustrated from the modeling data shown in Fig. 2, in which we show the results for the 3390 nm incident light on a silver surface. From this, one concludes (from Fig. 2(c)) that a temperature sensitivity of ~0.6 nm/K can be obtained by monitoring the relative shift between a *p*- and *s*-polarized light beam as a function of temperature.

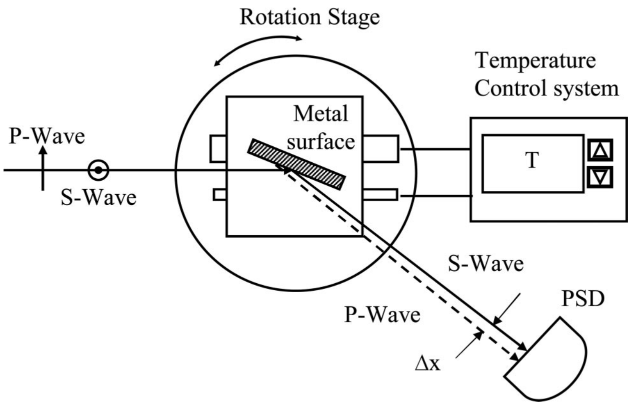


Fig. 3. Schematic design of the GH shift sensing proposed in this work.

Indeed, in practice, one possible way to measure this change of GH shifts with temperature is to incident a mixed beam with both *s*-and *p*-polarized waves onto the metallic surface, in the a way similar to what was done in the recent SPR-GH sensor proposed by Yin and Hesselink [8]. The only difference in our case is that a prism coupler is not needed and the incident angle is close to 90°. A convenient way of achieving almost grazing incidence is discussed in Han *et al.* [19]. The relative shifts can then be monitored by employing certain position sensitive device as was done previously [8]. A possible experimental setup to verify the proposed sensing technique is schematically shown in Fig. 3.

## 4. Discussion and Conclusion

In this work, we have explored the possibility of optically monitoring temperature via the negative GH shifts which take place when a *p*-polarized beam of long wavelength is reflected from a metallic surface. The maximum change in these shifts as temperature increases is observed to be in the order of 1 nm/K from 3390 nm incident onto a silver surface at almost grazing incidence. Presumably even greater rate of change of shifts over temperature can be achieved using longer (e.g., microns) wavelengths of light. Moreover, it is not expected that the temperature sensitivity of this GH sensor will be comparable to that of those based on the SPR mechanism [4–8], especially the SPR sensor based on phase measurements [4]. In addition, in the case when the incident medium is air, convectional fluctuation at high temperatures may also affect the accuracy of the position measurement of the reflected beams. However, an advantage of the present approach is that no coupling prisms are needed such as that required in the case for SPR excitations. This will lead to greater flexibility in case of remote (and noncontact) sensing of the temperature of metallic surfaces is desired, providing an alternative to the previous approach based on the measurement of intensity changes in reflectance [1,2]. Experimental exploration and demonstration of the mechanism proposed in the present work should be of interest.

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