Influence of Temperature on Reflectivity of Symmetrical Metal-Cladding Optical Waveguide

Jinbing Hu, Jiabi Chen, Binming Liang, Qiang Jiang, Yan Wang, and Songlin Zhuang, *Fellow, IEEE*

***Abstract*— The influence of temperature on the reflectivity of symmetrical metal-cladding optical waveguide (SMCOW) is studied theoretically by means of single-factor investigation under spectral and angular interrogation mode of operation. The theoretical model for temperature dependence of reflectivity includes the temperature dependence of refractive index and thickness of guiding layer, the temperature dependence of the metal film thickness and metal-dielectric function. It is found that the effect of temperature on the reflectivity of SMCOW is mainly attributed to the temperature dependence of refractive index and thickness of guiding layer; on the contrary, the temperature properties of metal film hardly contribute to the influence of temperature on the reflectivity. Based on the analysis, the sensitivities of SMCOW with guiding layer made up of different optical glasses are computed under both spectral and angular interrogation. This letter is supposed to provide direction in designing SMCOW sensors against the temperature variation.**

***Index Terms*— Guided mode, reflectivity, sensor, symmetrical metal-cladding optical waveguide, temperature.**

I. Introduction

SENSORS with high sensitivity are urgently needed in application fields, including biochemical detecting, environment monitoring, food safety, and inspection services [1]–[6]. In order to improve the sensitivity of sensing device, various techniques of coupling as much incident electromagnetic wave into working field as possible are always the interest of researchers. The commonly used coupling techniques are end-face coupling [7], prism coupling [8], grating coupling [9], and tapered film coupling [10]. Recently, a symmetrical metal-cladding optical waveguide (SMCOW) structure proposed by Li [11] *et al* has drawn much attention because the incident wave is directly coupled from free space into symmetrical metal-cladding optical waveguide, which makes efficient, convenient coupling possible in guided-wave optics experiment and devices. Unlike conventional dielectric waveguides, the effective index of guided mode in SMCOW has wider range, even approximately 0 for the highest order mode. For guided mode, the smaller the effective index, the longer the optical path will be, and the more sensitive the structure to ambience [11]. Based on the above advantages of SMCOW structure, a broad range of applications including oscillating wave sensors [12], picometer displacement sensor [13], polarization-insensitive narrow band filter [14]. low voltage electro-optic polymer light modulator [15], $LiNbO_3$ waveguide voltage sensor [16] *et al*. are available.

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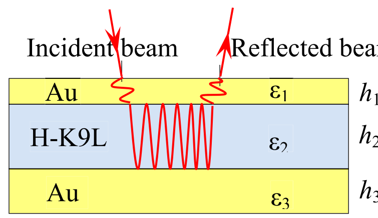

Fig. 1. The schematic diagram of SMCOW.

Since the fact that the highest-order mode of SMCOW is very sensitive to ambience, including ambient temperature and the properties of guiding layer [17], the latter characteristic can be employed to design sensors to determine the concentration of solution [18]. And in practical application, the environment temperature often fluctuates in a narrow range, even in laboratory experiments. Hence, it is essential to eliminate the influence of temperature when SMCOW sensors are used to detect puny physical quantities. Thus the investigation on the properties of SMCOW with variation in temperature is of practical significance.

This letter studies the influence of temperature on the properties of materials of SMCOW structure. At first, in the theoretical mode, the temperature dependences of refractive index and thickness of the guiding layer have been considered, along with the temperature effects on the thickness and metal-dielectric function of metal film. After that, the influence of temperature on the reflectivity of symmetrical metal-cladding optical waveguide (SMCOW) is studied theoretically by means of single-factor investigation under spectral and angular interrogation mode of operation. Finally, some kinds of optical glasses with different thermal expansion coefficient and thermo-optic coefficient are compared to design SMCOW sensors against the variation of temperature.

II. Theory

The schematic diagram of SMCOW is plot in Figure 1, in which the materials and corresponding parameters of each layer are also marked. The upper gold film with thickness of 38nm acts as cladding and coupling layer whereas the bottom gold film with thickness of 200nm sever as reflective layer and substrate. That in the middle of those two gold films is the glass slab (H-K9L) with thickness of 210μm acting as guiding layer. The reflectivity of SMCOW can be written as [19]

$$R=\left[\frac{r_{01}-r_{01}r_{12}^2\exp(2\kappa_2h_2)+r_{12}[1-\exp(2\kappa_2h_2)]\exp(2\kappa_1h_1)}{1-r_{12}^2\exp(2\kappa_2h_2)+r_{01}r_{12}[1-\exp(2\kappa_2h_2)]\exp(2\kappa_1h_1)}\right]^2 \quad (1)$$

$$r_{ij}=\begin{cases}\dfrac{\kappa_i-\kappa_j}{\kappa_i+\kappa_j} & \text{TE}\\ \dfrac{\varepsilon_j\kappa_i-\varepsilon_i\kappa_j}{\varepsilon_j\kappa_i+\varepsilon_i\kappa_j} & \text{TM}\end{cases} \quad (2)$$

$$\kappa_j=\kappa_0\sqrt{\varepsilon_j-n_{air}sin\theta} \quad (3)$$

where κ_j and κ_0 are the normal wave number component and the wave number in free space, respectively. Because of the negative permittivity of the metal film, the effective index of guided mode $N=\beta/\kappa_0$ has the value in the range of (0, n_2 $(=\varepsilon_2^{1/2})$), which is wider than that available to the dielectric waveguide. Hence, there is no restriction on the incident angle, which can vary from 0° to 90°. Theoretical calculation shows that there are a large amount of dips in reflection spectrum, implying that SMCOW can accommodate a great number of guided modes (usually more than 1,000 for guiding layer with thickness of 0.2mm). In the case of large incident angle, the mode density is too high so that guided modes cannot be distinguished. On the contrary, the mode density becomes sparser and sparser with the decrease of incident angle.

Now, we analyze how temperature influences the reflectivity of SMCOW. It is clear from Eq.1 that the temperature effect can be understood by analyzing temperature dependences of metal film (ε_1, h_1) and guiding layer (n_2, h_2).

It is well known that the complex and frequency-dependent dielectric function of noble metals can be appropriately described by the traditional Drude model. However, if frequencies within the range of the visible spectrum are required for a specific letter, the traditional Drude model may not be enough to provide accurate results. To get accurate results, the traditional Drude model in the range of visible spectrum should be modified as follow [20]

$$\varepsilon_1(\omega)=\varepsilon_\infty-\frac{\omega_p^2}{\omega(\omega+i\omega_c)} \quad (4)$$

where ε_∞ is the permittivity in infinite frequency, and equals unity in traditional Drude model. ω_p denotes the temperature-dependent plasma frequency given as [21]

$$\omega_p(T)=\omega_p(T_0)\,exp\left\{-\frac{1}{2}\int_{T_0}^{T}\alpha_V(T)\,dT\right\} \quad (5)$$

where $\omega_p(T_0)=(4\pi Ne^2/m^*)^{1/2}$, and N, m^* are the density and the effective mass of the conduction electrons at room temperature T_0, respectively. α_v(T) represents the volumetric thermal expansion coefficient of the metal and varies with temperature [22]. ω_c is the temperature-dependent collision frequency and can be expressed as [23]

$$\omega_c=\frac{1}{6}\pi^4\frac{\Gamma\Delta}{h_PE_F}\left[(k_BT)^2+\left(\frac{h_P\omega}{4\pi^2}\right)^2\right]+\omega_0\left[\frac{2}{5}+4\left(\frac{T}{T_D}\right)^5\int_0^{T_D/T}\frac{z^4}{e^z-1}dz\right] \quad (6)$$

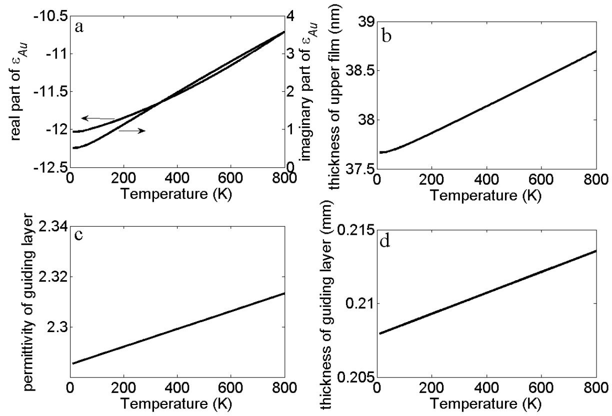

Fig. 2. Variations of (a) permittivity of gold film (b) thickness of gold film (c) permittivity of guiding layer (d) thickness of guiding layer with temperature. The incident wavelength is 632.8nm.

where Γ is a constant giving the average over the Fermi surface of the scattering probability, and Δ is the fractional Umklapp scattering. h_p, k_B, T_D are Plank constant, Boltzmann constant, Debye temperature, respectively. ω_0 is a constant to be determined from the static limit of second term of Eq. (6).

Taking the variation of thermal expansion of metal film with temperature into account, the temperature-dependent film thickness h_j is written as [22]

$$h_j(T)=h_{j0}exp\left\{\int_{T_0}^{T}\alpha_L(T)\,dT\right\} \quad (7)$$

where h_{j0} (j = 1,3) is the thickness of upper or bottom metal film at room temperature. α_L(T) is the linear thermal expansion coefficient of the bulk metal, expressed as [22]

$$\alpha_L(T)=\frac{\alpha_V(T)}{3}\frac{1+\mu}{1-\mu} \quad (8)$$

where μ is the Poisson number of metal.

The temperature-dependent properties of gold film are depicted in figure 2(a) and 2(b), which show that both the permittivity and thickness of gold film are nearly proportional to temperature.

Then, let us analyze the temperature-dependent properties of guiding layer which is usually optical glasses. For optical glasses, the temperature-dependent refractive index can be described as

$$n_2(\mathrm{T})=n_2(T_0)+(T-T_0)\frac{dn_2}{dT} \quad (9)$$

where $n_2(T_0)$ is the refractive index of guiding layer at room temperature. dn_2/dT is the thermo-optic coefficient of guiding layer.

Considering the temperature dependence of thermal expansion coefficient (α) of optical glasses, the temperature-dependent thickness of guiding layer h_2 is

$$h_2(T)=h_2(T_0)(1+(T-T_0)\alpha) \quad (10)$$

where $h_2(T_0)$ is the thickness of guiding layer at room temperature.

Similarly, both the permittivity and thickness of guiding layer are proportional to temperature, as shown in fig.2(c) and 2(d). The values we used in our calculations are taken

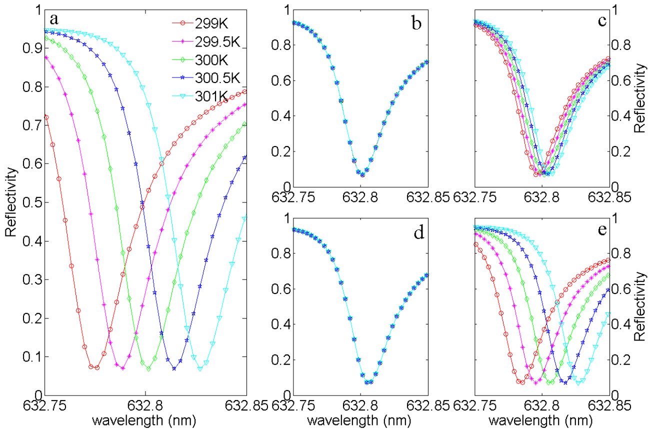

Fig. 3. The reflectivity under spectral interrogation mode with variation of (a) ε_1, h_1, h_3, ε_2, h_2, (b) ε_1, (c) ε_2, (d) h_1, h_3, (e) h_2 with temperature taken into accounted. The incident angle is 3.5°.

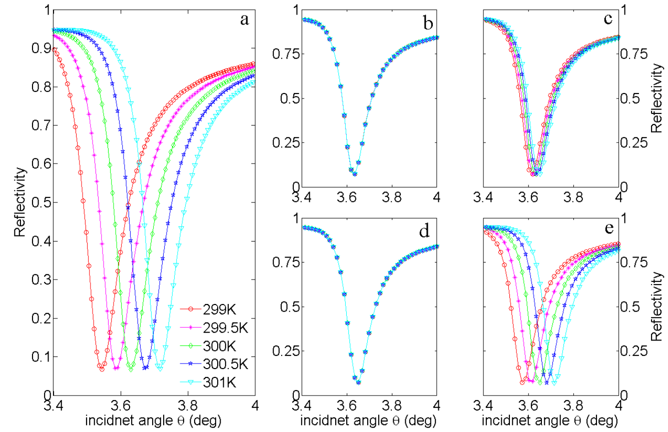

Fig. 4. The reflectivity under angular interrogation mode with variation of (a) ε_1, h_1, h_3, ε_2, h_2, (b) ε_1, (c) ε_2, (d) h_1, h_3, (e) h_2 with temperature taken into accounted. The incident wavelength is 632.8nm.

as follow [20], [21], [24]: $\varepsilon_\infty = 8.8535$, $\omega_p(T_0) = 1.3544 \times 10^{16}$ rad/s, $\omega_0 = 1.089 \times 10^{14}$ rad/s, $n_2 = 1.51509$, $\Gamma = 0.55$, $\Delta = 0.77$, $\mu = 0.42$, $T_D = 165$ K, $E_F = 5.53$ eV, $dn_2/dT = 1.16 \times 10^{-6}$/K, $\alpha = 83 \times 10^{-7}$/K.

III. Result and Discussion

Through the above analysis associated with Eq.1, we can infer that the sharp dips in reflection spectrum will shift with the variation in temperature. Now, we simulate the temperature dependence of resonance wavelength of the highest guided mode with incident angle operating at $\theta = 3.5°$. As shown in Fig. 3(a), a very tiny fluctuation in temperature causes striking resonance shift in wavelength and thus the alteration in reflectivity, which implies that the SMCOW structure is very sensitive to ambient temperature. If the ambient temperature is altered by dT, the resonance wavelength is shifted by $d\lambda$. The sensitivity (S_λ) of such structure with spectral interrogation is defined as [24] $S_\lambda = d\lambda/d$T. The sensitivity of SMCOW with spectral interrogation S_λ is about 21.89pm/K, which is higher than that of silica FBGs and PFBGs [25], [26],

In order to ascertain the main contribution to the shift of resonance wavelength when temperature alters, the influence of single property of guiding layer and gold film (for example, only the thickness of guiding layer) with temperature has been calculated. The results are presented in Figs. 3(b)-3(e). It is clearly revealed that the dominant contribution to the shift of resonance wavelength comes from the temperature dependence of thickness of guiding layer (approx. 21.30pm/K), which is much larger than that of temperature-dependent refractive index of guiding layer (approx. 0.3908pm/K). However, the temperature dependence of gold film hardly attributes to the shift of resonance wavelength.

Apart from the shift of resonance wavelength with temperature, the temperature dependence of reflectivity versus incident angle of the highest-order mode with incident wavelength operating at 632.8nm is also calculated. Meanwhile, the same method as in spectral interrogation is utilized to explore the main contribution to the shift of resonance angle. The results are shown in Figs.4 (a)-4(e). Similar to the spectral interrogation, if the ambient temperature is changed by dT, the resonance angle is shifted by $d\theta$. The sensitivity (S_{ang}) with angular interrogation is defined as [24] $S_{ang} = d\theta/d$T. The sensitivity S_{ang} with angular interrogation is 1.449×10^{-3}rad/K, which is much larger than that of prism-based SPR ($\sim$7.604 $\times 10^{-5}$rad/K) [27]. Thus, the sensors based on SMCOW structure operating in angular interrogation have better performance than that of prism-based SPR against temperature variation. Similar to the situation of wavelength interrogation, the main contribution to the shift of resonance angle is the variation of thickness of guiding layer with temperature; the corresponding S_{ang} is 1.400×10^{-3}rad/K, as shown in fig.4 (e). The properties of gold film with temperature hardly attributes to the shift of resonance angle.

The dominant contribution to the resonance shift can be understood as follow: the field inside the upper gold film decreases exponentially with the distance from the interface because of its negative dielectric constant. However, due to the existence of guiding layer and the fact that the upper gold film is very thin, the evanescent field in upper gold film can be coupled into guiding layer to propagate as guided mode under certain conditions, as seen in Fig. 1. And after propagating some distance, the guided mode in the guiding layer radiates energy into air through the upper gold film. The contrubution to the resonance shift is closely related to the interacting time between the electromagnetic field and the components. For the highest order mode, its effective index is extremely small, even approximately 0, thus its optical path is much longer than that of evanescent wave in upper gold film. Thus the temperature-dependent properties of guiding layer play more important role than the temperature-dependent properties of gold film in the resonance shift.

To design SMCOW sensors against the variation of temperature, we must choose those optical glasses whose thermal expansion coefficient (α) and thermo-optic coefficient (dn_2/dT) are as small as possible. Table I gives some optical glasses with different α and dn_2/dT, along with the corresponding S_λ and S_{ang}. From Table.1, some conclusions can be drawn. If SMCOW sensors are working under spectral

TABLE I
OPTICAL GLASSES WITH DIFFERENT α, *dn/dT* AND THE CORRESPONDING S_λ, S_{ang}

Index	α (10^{-7}/K)	dn_2/dT (10^{-6}/K)	S_λ (pm/K)	S_{ang} (10^{-3}rad/K)
H-K9L	83	1.16	21.89	1.449
H-ZF62	68	-0.9	19.54	1.791
F2	105	0.9	32.24	2.473
H-ZPK2	91	-2.4	26.38	1.620
H-FK61	141	-6.6	40.06	2.132
H-QK3L	96	-2.1	28.33	1.876
F6	101	1.0	30.29	2.814
H-ZK7	65	1.7	20.52	1.620
H-LaK52	60	2.5	19.54	3.411

interrogation mode of operation, then, H-ZF62 is a suitable option to be the guiding layer duo to its relative small S_λ, while if the SMCOW sensors are working under angular interrogation mode of operation, the H-K9L is more appropriate to be guiding layer. If a SMCOW sensor with capacity of resistant to ambient temperature under both spectral and angular interrogation is needed, then, H-ZK7 or H-ZF62 will be better.

IV. CONCLUSION

The temperature effect of the reflectivity of SMCOW structure is comprehensively analyzed under spectral and angular interrogation mode of operation. The result shows that a very small fluctuation in environment temperature will cause large shift in resonance angle or/and resonance wavelength, and then in the reflectivity of SMCOW. And further analysis finds that it is the temperature-dependent property of guiding layer rather than the metal film that largely attributes to the shift of resonance wavelength and angle. Then, the effects of temperature on the sensitivity of SMCOWs consisting of different kinds of optical glasses are compared, which provides direction to design SMCOW sensors against the variation of temperature. What's more, the sensors based on SMCOW structure feature an extremely simple structure, fabrication process and a very low cost.

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