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A temperature-independent filter based on a surface plasmon polariton resonator

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ABSTRACT

Both the size and the refractive index of the materials which form the optical element are influenced by the temperature. So the characteristics of a surface plasmon polariton (SPP) element are always affected by the temperature. In this paper, we show that the deformation can be used to compensate the influence of the temperature. A temperature-independent filter based on SPP resonator is presented and this method can be used to develop novel nano-optical elements in the future.

1. Introduction

Surface plasmon polaritons (SPPs) are electromagnetic waves existing at the metal-dielectric interface with an exponentially decaying field in both sides [1,2]. SPPs show broad application prospects because of the ability of overcoming the diffraction limits of light and of the easy manipulation on the subwavelength scale [3,4]. Therefore, many nanoscale optical elements based on SPPs have attracted enormous attention, such as beam splitters [5,6], nano-sensors [7], switches [8,9], filters, modulators [10] and so on.

The characteristics of the SPP elements are relative to the refractive index of the materials and the size of the elements. Both of them are influenced by the temperature and this makes it possible to form an SPP temperature sensor. S. K. Ozdemir and G. Turhan-Sayan raised an optical temperature sensor based on prism utilizing the effect of temperature on the refractive index of the materials [11]. Wu et al. proposed a temperature sensor based on a cavity filled by ethanol, due to the changes in the refractive index of ethanol with different temperatures [12]. Actually, All the SPP elements will be influenced by the temperature. The metal-insulator-metal (MIM) waveguide has been widely investigated, which is one kind of plasmonic waveguides, possesses unique advantages such as strong confinement, low bend loss and so on [13]. Wu et al. designed an optical pressure sensor based on an SPP resonator, which deforms under the pressure [14]. And our previous works show that the deformation can be induced by the temperature variation. It indicates a possible way to compensate the effect of temperature.

A filter is an element which can select a certain wavelength band of the electromagnetic waves. Due to the demand of the modern life, the filters are widely studied [15,16], and the nanoscale filters based on SPPs with various resonators are systematically researched [17,18]. In this work, we propose a method to form a temperature-independent SPP element. We select a filter as an example and this structure consists of a rectangular resonator and two MIM waveguides. Finite element method (FEM) is utilized to study the deformation and the reflectance spectra at different temperature.

2. Structure and method

Fig. 1 shows the geometry of a two-dimensional symmetric MIM structure consisting of an input waveguide, a rectangular cavity, and an output waveguide. The length and the width of the cavity are respectively L and w, the width of the two waveguides is also w, and the gap between the waveguides and the cavity is d_g. The blue, gray, and white parts represent Zinc (Zn), silver (Ag) and air, respectively. A layer of silver with thickness δ_{Ag}, covers the cavity. The Silver layers above the two waveguides extend to δ=600 nm to decrease the deformation of the rest of the structure. In order to adjust the characteristic wavelength to be 860 nm which is in one of the three communication windows of the optical fiber, we set these parameters as L=868.13 nm, d_g=10 nm, and w=50 nm, δ_{Ag}=90 nm. The deformation of the resonator can lead a wavelength shift which maybe enhance or reduce the temperature effect. We select a bimetal layer (BL) which deforms with temperature changing. Thus a layer of Zn is symmetrically deposited on the silver layer. The thickness and the length of the Zn layer are denoted as δ_{Zn} and L_{Zn}, respectively. After the optimization, we set δ_{Zn}=43.7 nm and the deformation of the BL reaches its maximum. The Zn/Ag BL keeps flat at room temperature (RT, defined

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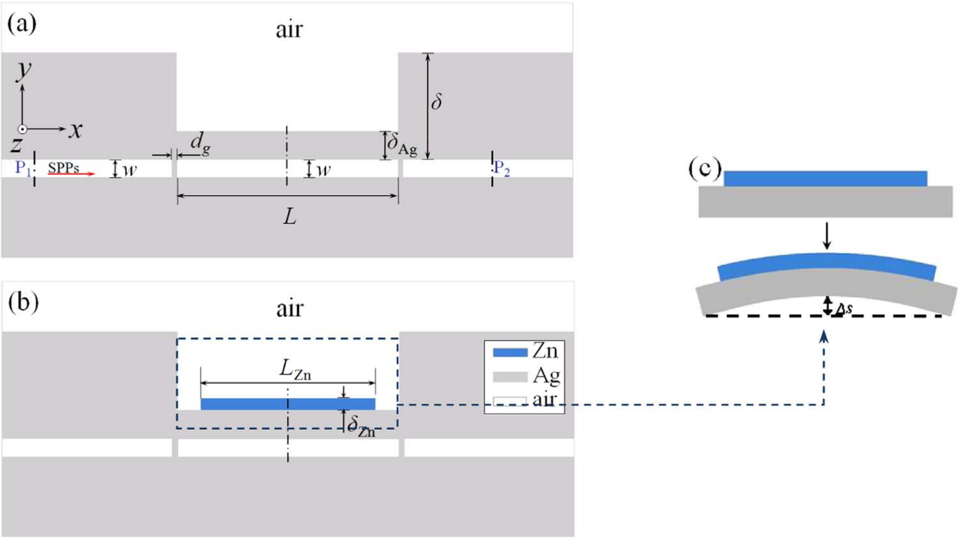

Fig. 1. The MIM structures (a) without Zn layer and (b) with the Zn layer and (c) the schematic of the Ag/Zn bimetal layer bending upward at a higher temperature.

as 20 °C). And when the temperature increases, the BL will arch up as shown in Fig. 1(c). The reason is that the coefficient of thermal expansion of Zn is greater than that of Ag, and when the temperature increase, the length of Zn layer will be longer than the counterpart of the Ag. So the BL will bend to the Zn side. The mechanical and thermal parameters of Ag and Zn at RT are listed in Table 1 [19,20], and they are weakly dependent on the temperature except the coefficient of linear thermal expansion of Ag which will obviously change below 200 K [19]. The coefficients of linear thermal expansion and the melting point will affect the temperature range of the filter. Above the entire structure is the open air.

Only the transverse magnetic (TM) modes can exist in the MIM structure [9]. So the electric field E of the incident light is along the y direction, and the magnetic field H of the excited SPPs is along the z axis. In order to investigate the optical responses of the proposed structure, its reflectance spectra are numerically calculated by the FEM with the software COMSOL Multiphysics. P_1 and P_2 (marked in Fig. 1(a)) are the input and output ports, respectively. The SPPs, excited by a TM-polarized plane wave, propagate along the x direction. The scattering boundary conditions are in use to make the outer boundaries transparent for the scattered waves. The refractive index of Zn is given by the reference [21]. The relative permeability in both air and silver and the relative permittivity in the air are supposed to be 1. And the permittivity of Ag is frequency dependent and characterized by the Drude model [22]:

$$\varepsilon(\omega) = \varepsilon_\infty - \frac{\omega_p^2}{\omega^2 + i\gamma\omega} = (n + ik)^2 , \tag{1}$$

where ω is the frequency of electromagnetic waves, ε_∞ is the dielectric constant at infinite frequency, ω_p is the plasma frequency of Ag, γ is the damping constant, n and k are the real and imaginary parts of the refractive index. We set the parameters ε_∞=3.8344, ω_p=9.175 eV, γ=0.018 eV at RT, and ω_p and γ will change at different temperatures [11] as well as the refractive index. From our previous calculations, we know that n will increase and k will decrease linearly with a small temperature rise [23]. The penetration depth of SPPs in silver is about 20 nm at a medium or long wavelength [24], which is much smaller than the thickness of the Ag layer above the cavity. So the optical parameters of the Zn have little effect on the optical properties of the structure, and we don't take the refractive index of Zn into consideration.

Table 1
the mechanical and thermal parameters of Ag and Zn.

Metal	Ag	Zn
Density(kg/m^3)	10.5×10^3	7.14×10^3
Coefficient of linear thermal expansion(1/K)	18.9×10^{-6}	30.2×10^{-6}
Young modulus(Pa)	82.7×10^9	108×10^9
Poisson ratio	0.367	0.25
Melting point(°C)	961.8	419.5

3. Results and discussions

Fig. 2(a) shows the reflectance spectra of this structure without Zn at 20 °C and 120 °C, respectively. There are two narrow stop bands in the range between 800 nm and 1500 nm, and the center wavelength of the left trough marked as mode ① is 860 nm which is just in one of the three low loss windows of silica fibers. The right trough is at about 1280 nm. The dispersion equation of the SPPs in the MIM waveguide can be described as [14].

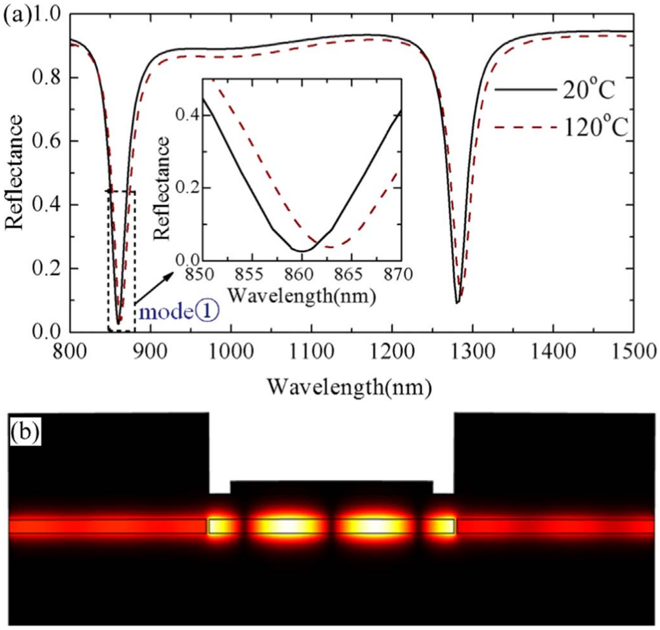

Fig. 2. (a) The reflectance spectra at 20 °C and 120 °C Inset: the enlargement of mode ① at 20 °C and 120 °C (b) The contour profiles of the magnetic field |Hz| at 860 nm.