Nanoscale Temperature Sensor Based on Plasmonic Waveguides with Nanocavity Resonator

A. Dolatabady and N. Granpayeh

Optical Communication Lab., Faculty of Electrical and Computer Engineering, K. N. Toosi University of Technology, Tehran 1431714101, Iran

*Corresponding author: granpayeh@eetd.kntu.ac.ir

ABSTRACT—In this paper, the performance of a nanoscale temperature sensor in two-dimensional plasmonic waveguides with nanocavity resonator has been investigated. The results are based on the theoretical relations describing the nanocavity resonator. The results demonstrate the linear correlation between the resonance wavelengths of the nanocavity of the sensor, the refractive index of the material inside the nanocavity, and therefore, the ambient temperature. The resolution of the sensor depends on the wavelength resolution of the detection system. This sensor can be employed in diverse systems such as chemical and bio systems.

KEYWORDS: Nanocavity, plasmonic, refractive index, resonator, temperature sensor.

I. INTRODUCTION

The precise measurement of temperature variations of fluid is imperative for variety of devices and systems, such as chemical reactors and biosensors. Optical sensors which convert the quantity of being measured to one of the features of a lightwave can provide high speed and accurate instrument for realizing sensors such as temperature sensors [1]. On the other hand, the great attention to nanotechnology which is the study of manipulating matter on an atomic and molecular scale has grown the necessity for nanoscale temperature sensors [2]. By utilizing the Surface Plasmon Polaritons (SPPs), which are waves excited on the surfaces of metal-dielectric interfaces and attenuate exponentially perpendicular to the interface, some suitable sensors like Surface Plasmon Resonance (SPR) sensors can be realized [3]. So far, various SPR sensors have been studied and developed to sense variations of different quantities [4, 5].

In some SPR sensors, the changes in some structural parameters of the plasmonic resonators cause changes in resonance wavelength of the structure and provide an approach for measuring the quantity under sense. Therefore, an optical temperature sensor based on SPR, which can be shown to be a promising approach to be used in the development of chemical, physical, and biomedical applications, is proposed [6].

In our proposed sensor, the resonance wavelength is extremely sensitive to the refractive index of the material inside the nanocavity, which can be a liquid, gas, or solid [7].

The resonance wavelength, or the refractive index of the nanocavity, can be affected by the concentration of chemicals, humidity,
pressure, temperature, and biomolecular interactions [8].

In addition, temperature changes in the sensing environment have multiple effects on the physical parameters of the sensor structure. Thus, the change in resonance wavelength stems from several causes simultaneously [6]. Therefore, resonance wavelength and the refractive index of the nanocavity are sensitive to the changes in the temperature of the environment. Temperature effects show themselves as the changes in the refractive index of the nanocavity, the coupling distance between the waveguides and nanocavity, the radius of the nanocavity, and the width of the waveguides [6].

However, we can regard some assumptions and design considerations to avoid the unwanted changes in other structural parameters, except the refractive index, to achieve a precise sensor.

The resolution of the temperature measurement is dependent on the wavelength resolution of the detection system and the temperature sensitivity of the sensing material in the nanocavity [7].

II. THE STRUCTURE AND RESONANCE FEATURE OF THE NANOCAVITY

Our proposed structure is based on the simple nanocavity resonator, shown in Fig. 1. The input and output waveguides are coupled in the resonance wavelengths of the nanocavity.

As we will discuss, the resonance wavelengths depend on the refractive indices of the material in the nanocavity resonator. So, the refractive index can be obtained from the resonance wavelengths, and the material can be recognized.

To explain analytically, let us assume that a lightwave is incident upon a two-dimensional circular cavity. The incident, scattered, and transmitted fields, by imposing the boundary conditions for tangential magnetic and electric fields at the surrounding surface of the cavity, can be expressed as [9]:

\[
\begin{align*}
    a_i k a_i J_n(k a) + a_s k a_s H_\nu^{(2)}(k a) &= a_t k a_t J_n(k a) \\
    \eta_i k a_i J_n(k a) + \eta_s k a_s H_\nu^{(2)}(k a) &= \eta_t k a_t J_n(k a)
\end{align*}
\]

where the subscripts \(i\), \(s\), and \(t\) are corresponding to the incident, scattered and transmitted fields. The coefficients \(a_i\), \(a_s\), and \(a_t\) are the amplitudes of the incident, scattered and transmitted fields, respectively. \(\eta_i\) and \(\eta_s\) represent the intrinsic impedances of dielectric and metal, respectively. \(k_{s,m} = k \sqrt{\varepsilon_{s,m}}\) are the wave numbers in the dielectric and metal, \(k_s\) is the free space wave number and \(\varepsilon_s\), \(\varepsilon_m\), and \(\alpha\) are the permittivity of dielectric, metal, and the radius of the cavity, respectively. \(J_n\), \(H_\nu^{(2)}\), \(J'_n\), and \(H_\nu^{(2)}\) signify the first kind Bessel function, the second kind Hankel function of the order \(n\) and their derivatives, respectively. The metals have been assumed to be silver whose relative permittivity function can be described by Drude model. For the time variation of \(e^{j\omega t}\), the model can be expressed as [10]:

\[
\varepsilon_s(\omega) = \varepsilon_s - \frac{\omega_p^2}{\omega(\omega - j\gamma)}
\]

where the material-depndant constants \(\omega_p\) and \(\gamma\) are the bulk plasma and damping frequencies, respectively, \(\varepsilon_s\) is the dielectric
permittivity at the infinite frequency and \( \omega \) is the angular frequency of the incident lightwave. These parameters for silver can be assumed as \( \varepsilon_\infty = 3.7 \), \( \gamma = 0.018 \text{eV} \), and \( \omega_p = 9.1 \text{eV} \) [10].

We can solve Eqs. (1) and (2) for unknown coefficients \( a_n \) and \( s_n \). For a nontrivial solution, the determinant of the matrix of the coefficients must be zero to attain [10]:

\[
\begin{align*}
\sum_{n \neq m} (k_s H_2^0(k, \chi) k_n J_n(k, \chi)) &= k_n J_n(k, \chi) \\
\sum_{n \neq m} (k_s J_2^0(k, \chi) k_n H_n(k, \chi)) &= J_n(k, \chi)
\end{align*}
\] (4)

The resonance wavelengths of a nanocavity with radius \( a \) and specified electrical parameters can be obtained from solution of Eq. (4). As it is clear in Eq. (4), there is direct relation between the resonance wavelengths of the structure and refractive index of the material of the nanocavity. Figs. (2) and (3) imply the relation.

We have set the structural parameters as \( a=200 \text{nm} \), \( d=20 \text{nm} \), \( w=30 \text{nm} \). To achieve the transmittance spectra \( (P_{\text{out}}/P_{\text{in}}) \) in Fig. (2), a two-dimensional FDTD scheme is applied to examine the properties of the structure with the convolutional perfectly matched layers (CPML) absorbing boundary conditions at all boundaries of the simulation domain [11]. It can be noticed the shift of the resonance wavelengths as a function of the refractive index.

Fig. (3) illustrates a linear relation between the resonance wavelengths and refractive index of the material in nanocavity by use of Eq. (4). It can be concluded that \( d\lambda_i/dn \) is equal to 357.1 nm per refractive index unit \( (dn/d\lambda_i=0.0028 \text{nm}^{-1}) \) for the first resonance wavelength, whereas it equals to 222.2 nm per refractive index unit \( (dn/d\lambda_i=0.0045 \text{nm}^{-1}) \) for the second resonance wavelength. Due to this linear relation, a useful refractive index sensor was proposed and investigated in our last work [7].

With the wavelength detection resolution of \( \Delta \lambda = 1 \text{pm} \), which a high-resolution optical spectrum analyzer can possess it, the sensing resolution of the refractive index sensor, defined as \( SR=(dn/d\lambda)\Delta \lambda \), will be \( 2.8 \times 10^{-6} \) and \( 4.5 \times 10^{-6} \) for the first and the second resonance modes, respectively [7].

![Fig. 2](image2.png) Fig. 2 The transmittance spectra of the structure for different refractive indices.

![Fig. 3](image3.png) Fig. 3 Resonance wavelengths of the structure versus the refractive index for the first and the second resonance modes, by solution of Eq. (4).

### III. Temperature Sensor

As we deduce from last section, there is linear relation between the resonance wavelength and refractive index. On the other hand, there is a particular dependence between refractive index and temperature. In a simple description and by assumption that the chemical composition of material does not change, temperature can affect the density of material, which in turn, affects its refractive index. The idea can be employed to expand the refractive index sensor of [7] to a temperature sensor.

Temperature variations have multiple effects on the physical and structural parameters of the sensor, and consequently, its resonance...
wavelength. Therefore, we can consider the resonance wavelength as the following function:

\[ \lambda = \lambda(n, d, r, w) \]  

where \( n, d, r, \) and \( w \) stand for the refractive index of the material in the nanocavity, coupling distance, the radius of the nanocavity, the width of the waveguides, respectively. However by proper design we can assume to decrease the other parameters dependence on temperature, such that the only main temperature dependant to be refractive index. We have also assumed the ambient pressure, to be constant. Under this assumption, we can write the wavelength variation respect to temperature as:

\[ d\lambda /dT = (d\lambda /dn)(dn/dT) \]  

To realize this sensor, we have used bismuth tellurite crystal (\( \text{Bi}_2\text{TeO}_3 \)) as the material in the nanocavity. There are some literature about this material, its important features, and physical parameters. A linear temperature dependence of its refractive indices was found. It also shows a strong photorefractive effect using both continuous wave and picoseconds pulse beams [12]. Refractive indices of \( \text{Bi}_2\text{TeO}_3 \) have been measured at a range wavelength between 450 and 700 nm. The temperature dependence of the refractive indices has been approximated by a linear function as [12]:

\[ n = n(T = 0\, ^\circ C) + (dn/dT)T \]  

The values of \( n(T = 0\, ^\circ C) \) and \( dn/dT \) for this material in vicinity of wavelength 510 nm, are equal to 2.45 and \( 47 \times 10^{-6} \, K^{-1} \), approximately [12]. So, according to Eq. (4), the wavelength of 510 nm, lays in the second resonance mode of the nanocavity. Thus, by use of the results from last section, the over all changes in resonance wavelength versus the temperature will be:

\[ d\lambda /dT = (d\lambda /dn)(dn/dT) = 10443.4 \times 10^{-6} \]  

or \( dT /d\lambda = (d\lambda /dT)^{-1} = 9.57 \times 10^{5} \). With the wavelength detection resolution of \( \Delta \lambda = 1 \, \text{pm} \):

\[ dT = (dT /d\lambda) \Delta \lambda = 0.0957 \pm 0.1 \]. Hence, we can realize a sensor whose accuracy is on the order of 0.1 \( \text{K} \), approximately.

IV. PRACTICAL CONSIDERATIONS

As we mentioned several causes, especially the effects due to linear expansion coefficients of the metals and their wave absorption, affect the performance of the sensor. So, the calibration of the temperature sensor turns out to be a very complicated task. To simplify sensor calibration, the number of physical parameters affected by temperature must be minimized as much as possible by choosing the sensor configuration and construction materials.

This procedure may be possible, if we choose the thickness of the structure (the third dimension that has not been considered here) large enough to eliminate or minimize the effects. However, availability of such approaches can not be guaranteed in practice.

V. CONCLUSION

In this paper, a simple plasmonic temperature sensor is proposed. The sensing process is dependent to the detection of the variation in the resonance wavelengths of the sensor’s nanocavity. This compact structure can have extensive potential in nanoscale industrial sensing especially as a biosensor.

Some assumptions were made to neglect the effects of structural parameters variations. However, to investigate more elaborated design, all of these effects should be considered.
REFERENCES


