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High sensitivity plasmonic refractive index sensing and its application for human blood group identification

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ABSTRACT

An enhanced structure for compact and high sensitivity plasmonic refractive index sensor by using the coupling of two metal-insulator-metal (MIM) waveguides with a silver nanorods array embedded into a square resonator is proposed and analyzed in this paper. We placed silver nanorods inside the resonator due to their unique optical properties in nanoscale confinement and low propagation losses. Based on obtained results, the resonance wavelengths of the sensor having an approximate linear relationship with the refractive index of the materials under detecting that are placed into the square resonator. With an optimum design and considering a tradeoff among detected power, structure size and sensitivity, the finite difference time domain simulations show that the refractive index and temperature sensitivity values can be obtained as high as 2320 nm per refractive index unit (RIU) and 0.84 nm/°C. The achieved sensor can be used in nanophotonic and plasmonic integrated circuits and in this research; we show its applicability for the detection of different human blood groups as well.

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1. Introduction

Surface plasmon polaritons (SPPs) are guided electromagnetic waves that propagate along the interface between a metal and dielectric with an exponential decay to both sides [1]. During recent years, surface plasmon resonance (SPR) attracted lots of the scientist's interests and has been investigated experimentally and theoretically [2,3]. Plasmonic devices are well known for their ability to overcoming the traditional diffraction limit and light manipulation within sub-wavelength scales [4,5].

Numerous SPR based devices have been proposed and applied widely such as plasmonic demultiplexer [6], splitters [7], filters [8] and sensors [9–11]. In order to develop applications in biomedical, environmental and clinical fields, plasmonic sensors are being widely studied owing to their excellent performance in miniaturization, fast reaction and a high level of sensitivity to the refractive index (RI) and environment temperature. With placing different sensing materials in the structure, the effective RI will also change that in turn leads to measuring the sensitivity of plasmonic sensors.

Various plasmonic RI sensors has been proposed recently using a slit waveguide coupled with a nanodisk resonator [12], a ring resonator [13], a hexagonal cavity [14], a slit cavity [15] and a single defect [16]. As the combination of plasmonic waveguide and nanocavity presents a good mechanism for realizing wavelength selectivity; plasmonic RI sensors achieve high degree sensitivity to 1000–2000 [17]. Moreover, more kinds of RI sensors by the fiber-tip plasmonic resonators [18], ellipsoidal Al nanoshell [19] and side-core holey structure [20] have been proposed.

Among all the metallic elements, silver (Ag) has the smallest damping constant Γ and is the best performing choice at optical frequencies [21]. Silver rods behave like surface plasmon resonators and electromagnetic energy transport through metallic nanorods deposited on the dielectric substrate [22]. Hence the properties of nanostructured silver make it most suitable for the next generation plasmonics [23]. Metal nanorods are appropriate for designing compact plasmonic waveguides since they are mainly attractive because of their unique optical properties including: nanoscale confinement, guiding, imaging and showing comparatively low propagation losses [24].

In this paper, we propose a design for compact SPP RI sensor in which square lattice array of silver nanorods are embedded in square resonator substrate, mainly to show higher sensitivity with appreciable value of 2320 nm/RIU. It also can be efficiently implemented in high density on-chip circuits due to its planar geometry and ultra-compact structure. Finally, the application of this structure is examined as a sensor for identification of human blood group. Its RI and temperature sensing performance and transmission properties are investigated by the finite difference time

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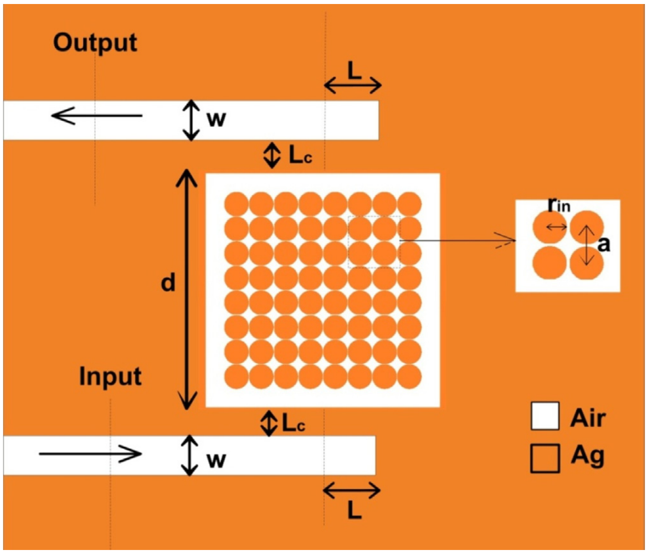

Fig. 1. The schematic diagram of the proposed sensor structure.

Table 1
Summary of the simulation model parameters.

Parameter	Symbol	Quantity	Unit
Waveguide width	w	50	nm
Coupling distance	L_c	15	nm
Distance between reflector and coupling region	L	40	nm
Resonator length	d	380	nm
Nanorods' radius	r	0.5a	nm
Nanorods' period (lattice constant)	a	40	nm
Metal thickness	–	100	nm
Resonator refractive index	n	1	–
Refractive index of Waveguides	–	1	–

domain (FDTD) method. Optimization of sensor structural parameters for the sensing performance is studied with more details. Also, the effects of the concentration and the temperature on RI of different blood group samples are measured.

2. Structure and theoretical analysis

The proposed sensor structure is schematically shown in Fig. 1, consisting of a square resonator, Ag nanorods in square array, and two waveguides. Square resonators with long lateral interaction length along the entire flat resonator sidewalls are of high importance [25]. Therefore, they can ease the tight constraint on the gap separation between the resonator and the side-coupled waveguide effectively. This feature is a main advantage compared to conventional ring or disk resonators. The material under sensing is filled in the resonator while its RI changes caused a shift in wavelength of output channel. Simply, the gaseous sample will be diffused into the resonator based on the gas diffusion force in the vacuum circumstance. The liquid sample can be filled up into the resonator by using the nanofilling technique based on capillarity attraction. The complete set of simulation parameters is summarized in Table 1. Here, the values of w, L_C and L are fixed throughout this paper.

The incident wave emitted from the input port is partly reflected and partly coupled into the square resonator and then transmits out along the output port. We suppose that the medium of the resonator and waveguides is air and its RI is 1 ($n = 1$). The background metal and nanorods are silver, and their permittivity function could be characterized by the Lorentz-Drude model [26]:

$$\varepsilon(\omega) = 1 - \frac{\omega_p^2}{\omega(\omega - i\Gamma_0)} + \sum_{n=1}^{6} \frac{f_n\omega_n^2}{\omega_n^2 - \omega^2 + i\omega\Gamma_n} \tag{1}$$

where ω_p and ω_n are indicating the plasma and resonance frequency. As well as, Γ_0, Γ_n and f_n are the damping constant (or collision frequency), damping frequency and oscillators strength, respectively. We have analytically calculated the permittivity function of silver for different wavelengths by solving Eq. (1), that the numerical values of physical parameters for silver and the permittivity characteristics are given entirely in Ref. [6].

The transmission spectra near the resonance modes in our system can be described by the temporal coupled mode theory; the transmission T for the sensor structure can be derived from Ref. [27]:

$$T = \left|\frac{1/\tau_\omega}{1/\tau_\omega + 1/\tau_i + j(\omega - \omega_0)}\right|^2 \tag{2}$$

where ω presents the frequency of incident light, ω_0 denotes the resonance frequency, $1/\tau_i$ and $1/\tau_\omega$ stand for the decay rate of field induced by the internal loss in the square resonator and the power escaping through the waveguide, respectively. According to Eq. (2), we can find that the resonance mode is excited and the incident light is transmitted at the resonance frequency ω_0, thus there exists a transmitted peak equaling $T_{max} = \left(1/\tau_\omega\right)^2/\left(1/\tau_i + 1/\tau_\omega\right)^2$ at ω_0.However, when ω is far from the resonance frequency ω_0 the transmission T is near zero. In the square cavity, the accumulated phase shift per round trip for the SPPs is [28]:

$$\Phi = 4\pi Re\left(n_{eff}\right)L/\lambda + 2\varphi \tag{3}$$

where φ and n_{eff} are the phase shift of the SPPs reflected off at the end of the square cavity and the effective RI of the SPPs, respectively. The incident power at the resonance wavelength λ_0, can pass though and results in a peak in the transmission spectra, and the resonance condition is:

$$\Phi = 4\pi Re\left(n_{eff}\right)L/\lambda + 2\varphi = 2m\pi \tag{4}$$

where m is an integer. According to Eq. (4), the resonance wavelength can be described as:

$$\lambda_0 = 2Re\left(n_{eff}\right)L/\left(m - \varphi/\pi\right) \tag{5}$$

Only those wavelengths satisfy Eq. (5) can be transported efficiently, while others are stopped.

The silver nanorod arrays can fabricate with ultra-small gaps through electron beam lithography (EBL) followed by ion milling [22]. By controlling their geometries, such nanorod arrays are capable of tuning the plasmon resonance.

3. Discussions and results

The two-dimensional FDTD method is used to investigate the properties of the SPP propagation in the structure. The mesh sizes in FDTD simulations are $\Delta x = \Delta y = 0.5$ nm and the perfectly matched layers (PML) as the absorbing boundary condition for all the boundaries of the computational window are used to absorb outgoing waves. In Fig. 2 (a), it is shown that when the RI of resonator material is 1 ($n = 1$; this means that the insulator is air), the two transmission peaks is observed at the resonance wavelengths of 2279 nm and 1126 nm, corresponding to the first and second resonance modes of the square resonator. Fig. 2(b) shows the field pattern of $|H_y|$ at these resonance wavelengths. The transmissions at the first and second resonance modes are close to 46% and 67%, respectively;

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