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Review Article

Design and Manufacture of Refractive Index Sensors Based on a Resonator System with Two Plasmonic Waveguides and Two Connected Cavities

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Abstract
In this paper, a plasmonic refractive index sensor based on metal insulated metal (MIM) waveguide with two resonator cavities is proposed and designed. Resonance wavelengths and refractive index of resonators have been investigated and simulated by the time domain finite difference method. Considering that the sensor largely depends on its materials and structure, as a result, by changing the dimensions of the cavity and changing the distance between the cavities, and changing the refractive index, we can weaken or strengthen the transmission coefficient in resonant modes. These plasmonic sensors with a simple framework and high optical resolution can be applied to on-chip sensor systems and optical integrated circuits. Optical sensors are widely used to measure the refractive index in the medical, chemical, and food industries, and due to the specific correct distribution of resonances, they are highly sensitive to changes in the refractive index of the environment. We also draw all the diagrams of this sensor using MATLAB software.

Keywords: Optics, Plasmonics, Plasmon surface polaritons, Insulation metal, Refractive index sensor.

1. Introduction

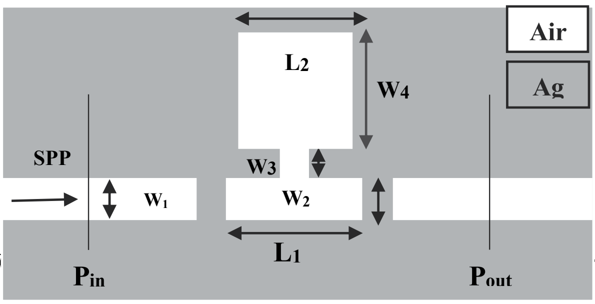
With the approach of science and technology towards the accumulation of optical circuits, researchers thought of compressing plasmonic structures in order to reduce problems, so that the use of plasmonic structures and waves becomes easier. These structures are made of metal and dielectric with dimensions below the excitation wavelength. Plasmonic science means the ability to enclose electromagnetic waves in dimensions much smaller than the radiation wavelength, and it is expressed from the interaction of radiation electromagnetic waves with the surface of metals and their conducting electrons. Plasmonic is divided into two parts: localized surface plasmons and surface polariton plasmons. The property of encapsulating electromagnetic waves by means of plasmonic structures and plasmonic resonators in the nanometer range and below the scattering limit has opened a new window for more use of nanophotonic structures. Plasmonic structures for investigating wave propagation are divided into metal-dielectric-metal and dielectric-metal-dielectric structures, which are due to supporting modes with deep scales of sub-wavelength and high group velocity and very high optical confinement and acceptable propagation length. We choose the metal structure of metal insulation.

Also, the most important plasmonic components are based on the structure of active and passive devices. Inactive media are isotropic and have only one refractive index and are unsuitable for switches and sensors, but active media are anisotropic and we can change the refractive index and length by applying an external agent. Parameters such as high transmission efficiency, high resolution, high-quality factor, optical stability, improved sensitivity, and adjustability in a range of wavelengths, should be investigated in the structure of plasmonic sensors because obtaining and improving these parameters increases the speed of information processing. It becomes light in integrated circuits. In this research, arrays of metal-insulator-metal plasmonic waveguides and resonators are simulated and analyzed for the design and construction of plasmonic sensors. The basic equations resulting from the interaction of electromagnetic waves and matter are expressed by Maxwell's equations. The optical properties of metals above a frequency range are explained by the plasma model. In response to the applied electromagnetic field, the electrons oscillate and their movement is carried out by collisions

with frequency $\upsilon=1/\tau$ and finally, they are damped. The dielectric function in the free electron model tends to zero at frequencies much higher than the plasma frequency. For noble metals, the generalization of this model in the frequency region larger than the plasma frequency, due to the filling of the band close to the Fermi level, causes a highly polarized environment. The simulation using the time domain finite difference method (FDTD) with the Drood model for real metals is as follows [5]:

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

Here, ω shows incident light angular frequency, ε∞ =1 gives the medium constant for the infinite frequency, ω_p = 1.37 × 1016refers to bulk frequency for plasma and γ = 3.21 × 1013 means damping frequency for electron oscillation. The proposed structure is shown in Figure.1, which includes two waveguides and two cavities that are connected by a micro waveguide. The input wave goes to the two holes from the left waveguide and then goes to the output waveguide. The width of two waveguides is w_1=50 nm. The middle cavity has a width of w_2=160 nm and a length of L_1=50 nm, and the upper cavity, which is connected to the middle cavity by a small waveguide, has a width of w_4=100 nm and a length of L_2=170 nm. The micro waveguide has a width of w_3=30 nm and a length of 20 nm. Pin and Pout are input and output monitors, respectively, which are used to measure input and output waves. The transfer is calculated by T = Pout.



We consider the environment inside the cavities and waveguides to be air and the simulation substrate to be silver. Due to the importance of the width of the resonance modes to calculate the figure of merit (FOM), the experimental refractive index of silver was used in our simulations, the results of which are much more accurate. Because the width of the waveguides is smaller than the wavelength of the radiation light, only the TM plasmonic ground state can exist in the structure. The TM polar plane wave, which is shown by the arrow in Figure.1 and is located in the left waveguide, is launched from the left side and is used for SPP excited waves, and propagates in the waveguide and closer to the output port. It gets wet, and its intensity decreases. Each of the resonators reflects a part of the input signal. We see the electric field distribution at the resonance frequency of the simulated structure in Figure.2. According to the figure, the maximum radiation occurs in the middle cavity. When the field distribution in two cavities is similar, the energy loss is reduced. In order to achieve the maximum field distribution in the simulated structure, all dimensions must be optimized, otherwise, we must change the dimensions of the structure to achieve the maximum field distribution.

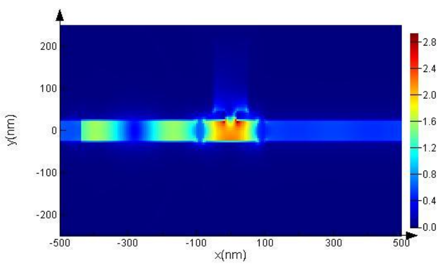


Figure 2: Distribution of the electric field at the resonant frequency.

2. Methods of Simulation and Measurement of Refractive Index

The resonance behavior of the proposed plasmonic structure is investigated numerically and theoretically. For the numerical approach, we use the time domain finite difference method (FDTD) with 8 perfectly matching layers absorbing boundary conditions [5]. The mesh size for both the x and y directions is considered to be 8 nm and the transmission line model is used to analyze the structure theory. The two-dimensional simulation is done in an infinite dimension, which was done to reduce the simulation time and achieve the desired result. The transmission spectrum obtained from the sensor device is shown in Figure.3.

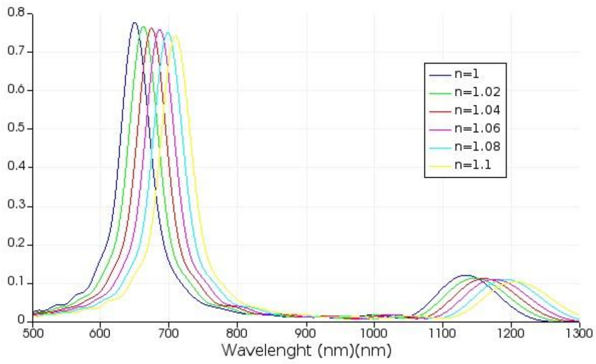


Figure: 3 Resonance wavelengths of plasmonic refractive index sensor with two cavities.

We increased the refractive index of the dielectric with a step of 0.02 from 1 to 1.1, which leads to a change in the spectra and resonance wavelength. The first characteristic to be measured for a sensor is the sensitivity S, which is described as the change in resonance wavelength when the dielectric has a unit change:

$$S = \Delta\lambda / \Delta n \text{ (nm / RIU)} \qquad (2)$$

In this equation, Δλ is the change in resonance wavelength, and Δn is the change in refractive index. We can see the diagram of the sensitivity coefficient of the plasmonic sensor in Figure.4.

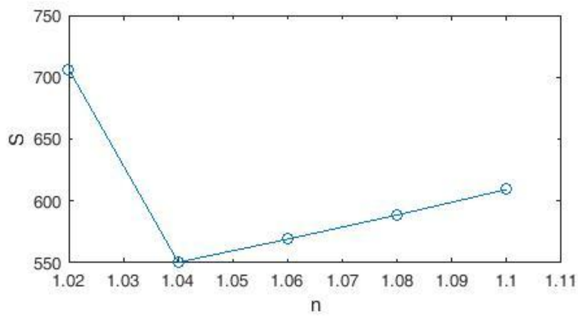


Figure 4: Diagram of sensitivity coefficient of the plasmonic sensor.

According to Figure 5, the highest sensitivity is for the refractive index n = 1.02, which is equal to 707.6 nm / RIU, and the lowest value is for the refractive index n = 1.04, which is equal to 550.45 nm / RIU. According to this diagram, there is a relatively linear relationship between the two parameters of resonance wavelength and refractive index.

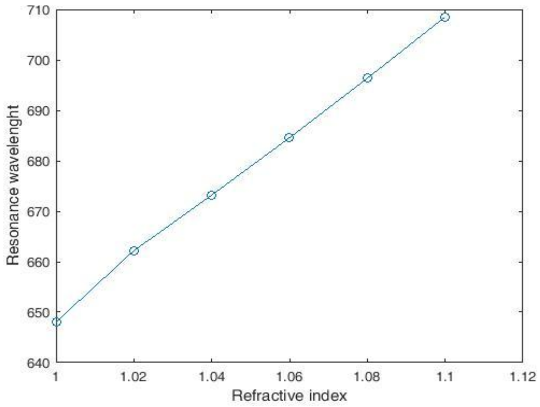


Figure: 5 Resonance wavelengths against the index of refractive index analysis.

Since sensitivity alone is not a good performance measure to compare different types of sensors, and optical clarity is also very important for sensors, a high FOM is required to compare sensors:

$$FOM = S / FWHM \qquad (3)$$

We can see the figure of merit (FOM) diagram of the plasmonic sensor in Fig.6

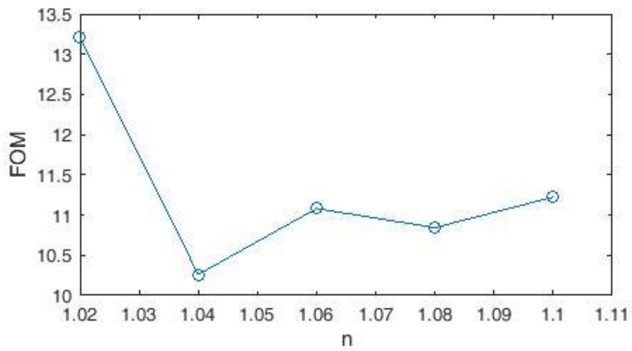


Figure: 6 Figure of merit (FOM) diagram of the plasmonic sensor.

We also need the quality factor of the sensors:

$$Q = \lambda res / FWHM \qquad (4)$$

We can see the graph of the quality factor of the plasmonic sensor in Figure: 7. Equations 2, 3, and 4 are the measurement capabilities of plasmonic sensors obtained by changing the refractive index in the structure. Using equations 2, 3, and 4, we draw graphs of sensitivity coefficient, quality coefficient, and competence. When two cavities with a distance of 20 nm are connected by a micro waveguide and we change their refractive index, the sensitivity is equal to 706.6 nm / RIU, 550.45 nm / RIU, 569.1 nm / respectively as shown in Figure.5. RIU is 588.65 nm/RIU and 609.3nm/RIU. FOM is 13.21, 10.26, 11.08, 10.84, and 11.22 respectively. Obviously, increasing the size of the length of the cavities can improve the sensitivity performance of the sensor with a smaller figure of merit (FOM) size, which may result from a longer optical path and more energy dissipation, respectively. Also, according to Figure.2, when the field distribution in the simulated structure is similar, the quality factor Q increases and the FWHM reaches the maximum value. According to Figure.7, We obtain the quality factor using equation 4 and by dividing the wavelength by the FWHM, which reaches 12.38 nm at the refractive index n=1.02, which has the highest sensitivity factor.

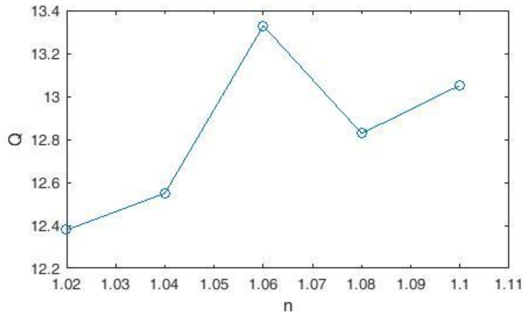


Figure: 7: Plasmonic sensor quality factor diagram.

3. Conclusion

Sensors based on surface plasmon resonance have become very popular in the field of chemical and biological sensing due to the high sensitivity of surface plasmon polaritons. This sensor is noticed because a small change in the refractive index of the cavities causes a significant change in the wave propagation characteristics. Also, as a sensor, it needs both high sensitivity (S) and a high figure of merit (FOM) to provide excellent performance with high optical resolution. In this research, we designed a refractive index sensor using two cavities and two waveguides. To clarify the results and for a better comparison, the refractive index of the structure is changed from 1 to 1.1 and the resonance wavelength is calculated in each step. It has been shown that this sensor can easily detect a change in the refractive index of 0.02 for materials whose refractive index is between 1 and 1.1 due to its high-resolution accuracy. This configuration is very suitable for use in fully integrated circuits due to its small size and high FOM value.

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