Multiple Fano Resonances in a Metal–Insulator–Metal Waveguide for Nano-Sensing of Multiple Biological Parameters and Tunable Slow Light

Ruiqi Zhang, He Tian *, Yang Liu and Shihang Cui

Abstract: A surface plasmonic waveguide made of metal–insulator–metal (MIM) capable of generating triple Fano resonances is proposed and numerically investigated for multi-biological parameter sensing as well as tunable slow light. The waveguide is made up of a bus waveguide with a silver baffle, a square split-ring cavity with a square center (SSRCSC), and a circular ring cavity with a square center (CRCSC). Based on the triple Fano resonances, human blood temperature and plasma concentration are measured simultaneously at different locations in the waveguide, and the maximum sensitivities were 0.25 nm/°C and 0.2 nm · L/g, respectively. Furthermore, the two biological parameters can be used to achieve tunable slow light, and it was found that the group delay responses to human blood temperature and plasma concentration all conformed to cubic functions. The MIM waveguide may have great applications in future nano-sensing of multiple biological parameters and information processing of optical chips or bio-optical chips.

Keywords: biosensing; biological parameters; slow light; surface plasmon; MIM waveguide; Fano resonance

1. Introduction

Since Ugo Fano initially proposed it in 1961, Fano resonance has established itself as one of the key components in the advancement of optical sensing [1–4]. Unlike conventional Lorentz resonance with a symmetric lineshape, Fano resonance, which emerges when a broad continuous state is connected to a narrow discrete state, usually has a sharp and asymmetric lineshape. Due to the unique lineshape, small changes in the geometry or environment can significantly affect Fano resonance [5–9]. Electromagnetic waves known as surface plasmon polaritons (SPPs) are found solely between a metal and a nonconductor, at their intersection. Molecular signals can be strengthened by strong SPPs at the metal–dielectric contact site, which is helpful in biomedicine [10–12], chemistry [13,14], and information technology [15]. Because the SPPs also have the excellent characteristic of breaking the classical diffraction limit [16,17], the combination of SPPs and Fano resonance has very important applications in modern micro- and nano-chip optics [18–22].

The SPPs in MIM waveguides, which have adequate propagation lengths, low bend losses, and ease of sample manufacturing, have gained significant study interest [23–26]. Fano-resonance-exciting MIM waveguide designs have gained popularity recently for use in filters [27–29], wavelength division multiplexers [30], all-optical switches [31,32], slow-light devices [33,34], and especially in sensors [6,35–39]. For instance, Chen et al. proposed an SSRC on a MIM waveguide that is non-through and could achieve multiple Fano resonances, and the highest sensing sensitivity for refractive index was up to 1290.2 nm/RIU [38]. A waveguide system with end coupling capable of Fano resonances was designed by Fang et al. The sensing sensitivity of the refractive index could reach 1059.2 nm/RIU [40]. In addition, Wang et al. achieved a square-ring and triangle-cavity
MIM waveguide to obtain triple Fano resonances and a maximal sensitivity to refractive index of 2259.56 nm/RIU [41]. All of these results showed that Fano resonance could be effectively used for integrated optical sensing with high sensitivity.

In this study, we aimed to increase the parallel processing capability of biosensing and obtain tunable slow light, based on easily adjustable multiple Fano resonances. To implement the simultaneous measurement of multiple biological parameters and tuning of slow light effects at selected wavelengths, we proposed multi-ring cavities. This will also make it easier to use Fano resonances in integrated optical biosensing. A MIM surface plasmonic waveguide with ring cavities was designed to generate triple Fano resonances. By altering the refractive index, individual tuning of the triple Fano resonances was examined, and glucose solution concentration and plasma concentration were measured simultaneously using this waveguide. In addition, tunable slow light was achieved using these two biological parameters, and the response of the group delay to these biological parameters was fitted.

2. Materials and Methods

The envisioned waveguide for the MIM waveguide is shown in Figure 1, which is composed of a square split-ring cavity with a square center (SSRCSC), a circular ring cavity with a square center (CRCSC), and a waveguide with a silver baffle for a bus. Silver and air are represented by the white and green regions, respectively. A silver baffle was added to the upper part of the square ring, in order to obtain sufficient distances between Fano resonances for measuring multiple parameters at the same time, and increase the sharpness and transmittance of Fano resonances for realizing larger sensitivity and lower slow light. \(d, L, a, R, b, G_1\) and \(G_2\) are the width of this silver baffle, the side length of the external square of the SSRCSC, the side length of the internal square of the SSRCSC, the radius of the external circle of the CRCSC, the side length of the internal square of the CRCSC, the distance between the SSRCSC and the bus waveguide, and the distance between the CRCSC and the bus waveguide, respectively. To ensure that only the basic transverse magnetic mode may exist in this configuration, the bus waveguide’s width \(w\) is specified as 50 nm. The silver baffle in the center, whose width is given by \(t\), blocks the bus waveguide. The SSRCSC, CRCSC, and bus waveguide all have geometric centers that are on the reference line, so the overall waveguide is symmetrical about the reference line.

![Figure 1](image_url)

**Figure 1.** A schematic diagram of a MIM waveguide composed of a square split-ring cavity, a bus waveguide with a silver baffle, and a circular ring cavity.
The Drude model represents the frequency-dependent complicated relative permittivity of silver [42,43]:

\[
\varepsilon(\omega) = \varepsilon_\infty - \frac{\omega_p^2}{\omega^2 + i\omega\gamma}
\]

(1)

where \(\varepsilon_\infty = 3.7\), \(\omega_p = 9.1\) eV, \(\omega\), and \(\gamma = 0.018\) eV represent the dielectric constant at infinite frequency, the plasma frequency of free conduction electrons, the angular frequency of the incident wave in vacuum, and the electron collision frequency, respectively.

The standing wave theory states that constructive interference should occur when the resonance condition is satisfied, and the transmitted wavelength is calculated by using the resonance condition [44,45]:

\[
\lambda = \frac{2\text{Re}(n_{\text{eff}})L_{\text{eff}}}{m - \frac{\phi}{2\pi}}, m = 1, 2, 3, \ldots
\]

(2)

where \(\lambda\), \(m\), \(\phi\), \(\text{Re}(n_{\text{eff}})\), and \(L_{\text{eff}}\) represent the resonant wavelength, the order of the resonant mode, the phase shift due to reflection, the real part of the effective refractive index, and the effective length of the resonant cavity, respectively.

The waveguide’s optical transmission characteristics are simulated by the finite element method (FEM), and the numerical values of the waveguide parameters utilized in the simulation are shown in Table 1. Here, all the parameters were optimized in order to obtain multiple Fano resonances with high transmittance. In order to absorb the escaping waves, perfect matching layers (PMLs) are positioned at the waveguide’s top and bottom. Moreover, fine triangular meshes with a maximum size of 10 nm were chosen to provide precise area segmentation in the simulation. In practice, the MIM waveguide may be fabricated in the following way: First, a thick enough Ag layer is prepared by the chemical vapor deposition (CVD) method on a silicon substrate [46]. Then, the SSRCSC, the CRCSC, and the bus waveguide with a silver baffle are etched on the Ag layer through electron beam etching.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Quantity</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of the side of the external square of the SSRCSC</td>
<td>(L)</td>
<td>440</td>
<td>nm</td>
</tr>
<tr>
<td>Split length of SSRCSC</td>
<td>(d)</td>
<td>10</td>
<td>nm</td>
</tr>
<tr>
<td>Length of the side of the internal square of the SSRCSC</td>
<td>(a)</td>
<td>300</td>
<td>nm</td>
</tr>
<tr>
<td>The separation between the bus waveguide and the SSRCSC</td>
<td>(G_1)</td>
<td>10</td>
<td>nm</td>
</tr>
<tr>
<td>The radius of the external circle of the CRCSC</td>
<td>(R)</td>
<td>110</td>
<td>nm</td>
</tr>
<tr>
<td>Length of the side of the internal square of the CRCSC</td>
<td>(b)</td>
<td>140</td>
<td>nm</td>
</tr>
<tr>
<td>The separation between the bus waveguide and the CRCSC</td>
<td>(G_2)</td>
<td>10</td>
<td>nm</td>
</tr>
<tr>
<td>The size of the bus waveguide</td>
<td>(w)</td>
<td>50</td>
<td>nm</td>
</tr>
<tr>
<td>The size of the bus waveguide’s silver baffle</td>
<td>(t)</td>
<td>10</td>
<td>nm</td>
</tr>
<tr>
<td>Index of refractive of bus waveguide</td>
<td>(-)</td>
<td>1</td>
<td>–</td>
</tr>
<tr>
<td>Index of refractive of SSRCSC</td>
<td>(n_1)</td>
<td>1</td>
<td>–</td>
</tr>
<tr>
<td>Index of refractive of CRCSC</td>
<td>(n_2)</td>
<td>1</td>
<td>–</td>
</tr>
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3. Results
3.1. Mechanism of Fano Resonance and Distribution of Magnetic Fields

As shown in Figure 2, we set the waveguide in SSRCSC with the CRCSC’s mode, single bus waveguide mode, and full waveguide mode to illustrate the mechanism of Fano resonance generation. The bus waveguide with the silver baffle removed produced three transmission dips at 1107 nm, 1849 nm, and 2428 nm, which, as represented by the red line,
may be thought of as a narrow discrete state. The blue line represents the state produced by the bus waveguide, which is a wide continuous state. The entire waveguide generated three asymmetric and sharp Fano resonances at 1097 nm, 1795 nm, and 2407 nm, known as FR1, FR2, and FR3, as a consequence of interference between the discrete state and continuous state.

Figure 2. Schematic diagram of the formation mechanism of the structurally excited Fano resonance proposed in this paper.

The dispersion of the magnetic fields (|\(H_z|\)) of FR1, FR2, and FR3 are shown in Figure 3a–c, and the corresponding heights are shown in Figure 3d–f. The distributions of magnetic field energy in the SSRCSC and the CRCSC are symmetric about the reference line parallel to the y-axis. For FR1, almost all of the energy was confined in the CRCSC, so FR1 is sensitive to the parameters of the CRCSC, while the majority of energy of FR2 and FR3 was confined in the SSRCSC, proving that the characteristics of the SSRCSC mostly impact FR2 and FR3. As a result, the SSRCSC and CRCSC characteristics may be individually changed to control the triple Fano resonances.

Figure 3. (a–c) Patterns of the FR1, FR2, and FR3 magnetic fields. (d–f) Expressions in height for FR1, FR2, and FR3’s magnetic field patterns.
3.2. Refractive Index Sensing

For practical applications, it is difficult to change the structural parameters of waveguides, but the waveguide’s refractive index may be changed much more easily than its structural properties, which makes it possible to accomplish independent tuning of the Fano resonances that are more suited for sensing [47]. The following is the definition of the sensitivity of refractive index sensing [41,48]:

\[ S = \frac{\Delta \lambda}{\Delta n}, \quad (3) \]

where \( \Delta \lambda \) denotes the alteration in resonance wavelength and \( \Delta n \) denotes the alteration in the index of refraction.

In Figures 4 and 5, the index of refraction \( n_1 \) of the SSRCSC and the index of refraction \( n_2 \) of the CRCSC both increased from 1.30 to 1.42 with an interval of 0.03. In biological parameter sensing, the chosen range of the index of refraction is easily attained. As the index of refraction of the SSRCSC increases, FR1 remained essentially unchanged, but FR2 and FR3 exhibited significant redshifts. In contrast, only FR1 exhibited a considerable redshift when the CRCSC’s refractive index increased, as shown in Figure 5a. According to the findings, it is possible to independently adjust the triple Fano resonances by altering the waveguide’s index of refraction.

Figure 4. (a) The effect of different refractive indexes of SSRCSC on waveguide Fano resonance \((n_2 = 1.00)\). (b) Associations between the index of refraction of the SSRCSC and the resonance wavelengths of FR1, FR2, and FR3 are linear.

Figure 5. (a) The effect of different refractive indexes of CRCSC on waveguide Fano resonance \((n_1 = 1.00)\). (b) Associations between the index of refraction of the CRCSC and the resonance wavelengths of FR1, FR2, and FR3 that are linear.
As shown in Figures 4b and 5b, FR1, FR2, and FR3 all possessed strong linear correlations with linear correlation coefficients greater than 0.99999, and the sensitivities of FR1 and FR2 were 1093.33 nm/RIU and 1833.33 nm/RIU, respectively. According to Equations (3) and (4), the sensitivity is proportional to the proportion of the resonance mode order to the effective length of the resonant cavities, so the sensitivity of FR3 was 2453.33 nm/RIU greater than that of FR2, as shown in Figure 4b. Table 2 demonstrates that this waveguide has a relatively high sensitivity to refractive index sensing when compared to other architectures [38,47,49–53]. Based on the above analysis, the refractive index within the waveguide at different positions can be obtained by resonant wavelength measurements.

Table 2. Utilizing different references to compare the sensitivity.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Waveguide</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>[6]</td>
<td>Baffle and an X-shaped cavity make up the MIM waveguide</td>
<td>1303 nm/RIU</td>
</tr>
<tr>
<td>[38]</td>
<td>MIM waveguide containing a rectangular split-ring resonance cavity</td>
<td>1290.2 nm/RIU</td>
</tr>
<tr>
<td>[47]</td>
<td>MIM waveguide containing a semi-ring cavity</td>
<td>1550.38 nm/RIU</td>
</tr>
<tr>
<td>[49]</td>
<td>MIM waveguide containing ring-splitting cavity and tooth cavity coupling</td>
<td>1200 nm/RIU</td>
</tr>
<tr>
<td>[50]</td>
<td>MIM waveguide-coupled structure-based simple and small plasmonic sensor</td>
<td>1820 nm/RIU</td>
</tr>
<tr>
<td>[51]</td>
<td>Inverted U-shaped resonator</td>
<td>840 nm/RIU</td>
</tr>
<tr>
<td>[52]</td>
<td>A MIM waveguide with an end-coupled ring-groove junction</td>
<td>1050 nm/RIU</td>
</tr>
<tr>
<td>[53]</td>
<td>Three-racetrack resonators in two concentric rings with plasmonic MIM waveguides</td>
<td>1618 nm/RIU</td>
</tr>
<tr>
<td>This paper</td>
<td>MIM waveguide consisting of square split-ring and circular ring cavities</td>
<td>2453.33 nm/RIU</td>
</tr>
</tbody>
</table>

3.3. Multi-Biological Parameter Sensing

Next, two biological parameters, the temperature of human blood and the concentration of plasma, were chosen to be measured using this waveguide. The SSRCSC was filled with human blood, while the CRCSC was filled with plasma. Thus, the refractive indexes of the SSRCSC and the CRCSC were determined by the temperature and concentration of the biological parameters, respectively. In practice, human blood and plasma should be separated in advance, and then filled into the SSRCSC and CRCSC, respectively. In addition, it is unnecessary for the SSRCSC and CRCSC to be fully filled. When they are partially filled with human blood and plasma, the waveguide can still produce similar Fano resonances, just with different resonant wavelengths. The refractive indexes of human blood and plasma are expressed as [54,55]:

\[
    n_b = 1.36 - 0.0001046 T_b \\
    n_p = 1.32459 + 0.000184 C_p
\]

where \( T_b \) is the temperature of human blood and \( C_p \) is the concentration of plasma.

In Figure 6, the temperature of human blood in the SSRCSC was increased from 10 °C to 50 °C with an interval of 10 °C, while the concentration of plasma in the CRCSC was increased from 0 g/L to 400 g/L with an interval of 100 g/L. As a result, the SSRCSC’s refractive index dropped from 1.358954 to 1.35477 with an interval of 0.001046, whereas the CRCSC’s index of refraction change increased with an interval of 0.0184 from 1.32459 to 1.39819. It is evident that FR1 exhibited a redshift, and FR2 and FR3 exhibited blueshifts.
The linear fittings between the concentrations of the plasma and the resonant wavelengths are shown in Figure 7a, and Figure 7b displays the linear association between resonant wavelength and human blood temperature. For FR1, FR2, and FR3, each linear correlation coefficient was greater than 0.99. Here, the sensing sensitivity of the waveguide can be defined as $S_{\text{plasma}} = \frac{\Delta \lambda}{\Delta C}$ as well as $S_{\text{human blood}} = \frac{\Delta \lambda}{\Delta T}$, where $\Delta C$ denotes the alteration in concentration and $\Delta T$ denotes the alteration in temperature. Thus, 0.2 nm·L/g was the sensitivity of plasma concentration sensing. Moreover, the sensitivity of human blood temperature to FR2 was 0.2 nm/°C, and the sensitivity to FR3 was 0.25 nm/°C. Obviously, the waveguide is far more sensitive to temperature than practically applied fiber grating sensors, which typically have a sensitivity of 0.01 nm/°C. In this way, the concentration of plasma and the temperature of human blood are simultaneously measured using this waveguide.

**Figure 6.** The waveguide's transmission spectra at various plasma concentrations and blood temperatures.

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**Figure 7.** (a) FR1’s resonant wavelength versus plasma concentration. (b) The resonant wavelengths of FR2 and FR3 versus human blood temperature.

3.4. Tunable Slow Light

Due to the sharp and asymmetric lineshape, Fano resonance is accompanied by an abrupt change in transmission phase, resulting in smaller group velocities, so the waveguide designed here can also be used to generate slow light, especially based on the
effects of human blood temperature and plasma concentration on Fano resonance, which may achieve tunable slow light. The slow light characteristics can be described in terms of the group delay, which can be derived from the phase:

\[ \tau_g = \frac{d\phi(\omega)}{d\omega} \]  

(6)

As a result of the sharp characteristics of Fano resonance, three group delay peaks can be found near the three Fano resonances, marked as GD1, GD2, and GD3. Then, we verified the proposed conjecture by measuring the biological parameters in the waveguide. In Figure 8, the human blood temperature in the SSRCSC increased with an interval of 10 °C, while the plasma concentration in the CRCSC increased with an interval of 10 g/L. It can be seen that GD1 experienced a redshift, while GD2 and GD3 experienced a blueshift. Subsequently, we locally enlarged GD1, GD2, and GD3, as shown in Figures 9a, 10a, and 11a. We selected the wavelength corresponding to the group delay peak at a temperature of 10 °C and concentration of 0 g/L as the reference wavelength, which was 1508 nm, 2287 nm, and 3585 nm for GD1, GD2, and GD3, respectively. We also plotted the response of the group delay to the biological parameters at each reference wavelength, as shown in Figures 9b, 10b, and 11b. The responses of the group delay to the two biological parameters were not exactly the same. For plasma concentration, it can be seen in Figure 9b that in the initial stage of concentration increase, group delay rapidly decreased. However, after the concentration was high, although the step size of concentration increase was still 10 g/L, the speed of the group delay decreased significantly. In b and 11b, it can be seen that for human blood temperature, the response of GD2 changed slowly during the low and high temperature stages, while the response of GD3 was different. For GD3, at relatively low temperatures, group delay slowly decreased with increasing temperature, and after a certain degree of temperature increase, the response of the group delay to temperature became faster.

**Figure 8.** The waveguide’s group delay at various plasma concentrations and blood temperatures.
Next, we fit the response of the group delay to these two biological parameters. We first performed a quadratic fit on the response of the group delay to the biological parameters, and the residual sum of squares of the fit results were larger than the expected results. Then, we performed a cubic fit on the three responses, and the residual sum of squares of the fitting curves was much smaller, resulting in a significant improvement in the fitting effect.
The results showed that the two biological parameters can be used to adjust slow light, and it is worth noting that the responses of the group delay to human blood temperature and plasma concentration all conformed to cubic functions. In this way, tunable slow light was achieved in this waveguide by varying the temperature of human blood and the concentration of blood plasma.

It should be noted that the largest group delay obtained in this paper was only about 0.1 ps. One reason is that the size of the waveguide was small. The other is that the structural parameters of the waveguide were optimized in order to obtain multiple Fano resonances with high transmittance, failing to take into account the group delay. One can obtain a large group delay by increasing the contrast of Fano resonance and reducing the bandwidth of Fano resonance. Here, only a potential solution for adjusting slow light in the MIM waveguide was proposed, combined with biological parameters.

From current research results, it can be seen that the coupling efficiency between a MIM waveguide and external optical devices is relatively low, due to the small width of the waveguide. If the coupling efficiency can be improved, the application of the MIM waveguide may be greatly promoted.

4. Discussion

Triple Fano resonances were achieved in the MIM waveguide made up of a SS-RCSC, CRCSC, and bus waveguide. The refractive index may be changed to tune the Fano resonances individually. The maximum sensitivity of refractive index sensing was 2453.33 nm/RIU. The cavities of this waveguide can be filled with biological solutions as a biosensor, which make it possible to measure several biological parameters at once. Human blood temperature and plasma concentration sensing had maximal sensitivities of 0.25 nm/°C and 0.2 nm·L/g, respectively. Meanwhile, tunable slow light can be realized using this waveguide, and the group delay responses to human blood temperature and plasma concentration all conformed to cubic functions. The significant advantage of this waveguide is that two separate resonant cavities allow for the simultaneous measurement of multiple biological parameters and slow light tuning of multiple wavelengths. In conclusion, the waveguide proposed in this paper can play a role in biosensing and optical information processing in nanoscale applications.

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