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Jun Zhu (✉ zhujun1985@gxnu.edu.cn)

Guangxi Normal University

Ge Wang

Guangxi Normal University

Research

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Multiple Fano resonances Based on the Rectangular cavity resonator and crescent-shaped cavity resonator

JUN ZHU^{1*}, GE WANG¹,

1 College of Electronic Engineering, Guangxi Normal University, Guilin 541004, China

*Correspondence and requests for materials should be addressed to JUN ZHU (zhujun1985@gxnu.edu.cn)

Abstract: World is rich in unconventional oil and various alternatives to petroleum. However, conventional oil production declines so quickly that it is likely these unconventional oil resources cannot be put into production fast enough, and thus will not be compensated sufficiently. We realize detecting rapid detection of water content in heavy oil. The waveguide consists of a metal-insulator-metal (MIM) waveguide, rectangular cavity resonator, and crescent-shaped cavity resonator. The effects of the coupling distance, geometry of the crescent-shaped cavity resonator and its rotation angle, and length and width of the rectangular cavity resonator on the Fano resonance lines were numerically analyzed. Multiple Fano resonances can be produced as the rotation angle of the crescent-shaped cavity resonator is adjusted, and the sensor's refractive index sensitivity was found to be 935.71 nm/RIU. By measuring the water content in heavy oil, we found that the Fano resonance lines shift toward shorter wavelengths as the volume fraction of water content increases. The detection resolution in heavy oil 1.79×10^{-9} . The results presented here show that water content in heavy oil can be calculated using the measured change in the Fano resonance wavelength.

Keywords: Water Content in Heavy Oil; Crescent-shaped Cavity Resonator; Fano resonances

1. INTRODUCTION

World is rich in unconventional oil and various alternatives to petroleum. However, conventional oil production declines so quickly that it is likely that these unconventional oil resources cannot be put into production fast enough, and thus will not be compensated sufficiently [1-5]. Surface plasmon polaritons (SPPs) are electromagnetic fields that propagate along a metal-insulator interface. Because they can modulate light at the nanometer scale, they can generate extremely strong local electromagnetic fields and break the diffraction limit. They have attracted a great deal of research interest [6-9], and they could be used in unique devices. So far, various plasma devices have been proposed for measuring water content, such as optical filters [10], wavelength demultiplexer [11], and information modulators [12], all of which could be integrated into system-on-a-chip devices. In addition, the Fano resonance [13-15] has become the focus of SPP devices due to its considerable asymmetry in line-shape. In addition, the resonance wavelength and peak intensity are highly sensitive to small disturbances [16-18]. And because the MIM waveguide structure has a strong restraint ability on SPPs, and the Fano resonance effect generated in the MIM waveguide. It is extremely sensitive to changes in environmental refractive index, structural parameters, and polarization state of incident light. Combining the advantages of both, it has become a new research direction of SPP devices. In recent years, due to the characteristic of Fano resonance, a lot of research has been done on it. For example, based on the plasmon hybridization theory, He et al. [19] studied the Fano resonance in an asymmetric ring and its sensing characteristics by offsetting the centers of the inner and outer walls. They obtained sensitivity of 626 nm/RIU [19]. In 2018, Guo et al. [20] proposed a multi-channel refractive index sensor that takes advantage of coupling between a sub wavelength metal-insulator-metal (MIM) waveguide and a tangent-ring cavity resonator. This sensor exhibited sensitivity 880 nm/RIU.

To realize rapid detection of water content in heavy oil, we designed an MIM waveguide structure composed of a rectangular cavity resonator and a crescent-shaped cavity resonator. The finite element method was used to numerically simulate the structure under a perfectly matched layer (PML) boundary conditions [21,22]. Simulations were performed with various coupling distances, geometry of the rectangular and crescent-shaped resonators, and rotation angles, and the effects of these changes on the transmission characteristics were calculated. We obtained a relationship between the water content in heavy oil and the Fano resonance wavelength in the sensor. The structure presented here could also be used for the detection of other trace elements in liquids.

2. MODEL AND CALCULATION METHOD

2.1 MODEL

The structure diagram is as follows, as shown in Figure 1. The width and height of the rectangular cavity resonator are W and H , respectively. $D = 50$ nm is the width of the linear waveguide and G is the coupling distance between the rectangular and crescent-shaped resonators. The transmittance T at the output port is the ratio of the output power P_{out} to the input power P_{in} , i.e., $T = P_{out}/P_{in}$, where $P_{in} = \int P_{oav} dx dS_1$, $P_{out} = \int P_{oav} dx dS_2$, and $P_{oav} x$ is the time-averaged power flow in the axial direction.

Fig. 1 3D and 2D renderings of the system

2.2 Fano resonance

As shown in Figure 2, $R1$ and $R2$ are the radii of the inner and outer arcs of the crescent-shaped cavity, respectively; d is the distance between the two centers of the arcs, and α is the rotation angle. Figures 3a-m shows the transmission spectra of α in 30° increments ranging from 0° to 360° . Figure 3a shows a transmission spectrum with asymmetric Fano line width in the coupled rectangular and crescent resonators. The peak in the spectrum is Peak I, at this time $\alpha = 0^\circ$. Comparing Figures 3a and 3b, one can see a new Fano resonance line shape appears on the right side of the original transmission spectrum as α increases from 0° to 30° . The valley on the right is referred to as Dip I. Figure 3b–e shows that the position and transmittance of Peak I remain constant while Dip I is redshifted as α increases from 30° to 120° . Figure 3i–l shows the peak position and transmittance of Peak I remain constant, while Dip I is blueshifted, as α increases from 240° to 330° . Furthermore, Figures 3a, 3g, and 3m show that the transmission spectra for $\alpha = 0^\circ$, 180° , and 360° are the same. We can also see that the transmission spectra in Figures 3b ($\alpha = 30^\circ$) and 3l ($\alpha = 330^\circ$), 3c ($\alpha = 60^\circ$) and 3k ($\alpha = 300^\circ$), 3d ($\alpha = 90^\circ$) and 3j ($\alpha = 270^\circ$), 3e ($\alpha = 120^\circ$) and 3i ($\alpha = 240^\circ$), and 3f ($\alpha = 150^\circ$) and 3h ($\alpha = 210^\circ$) are the same. Based on the above results of the transmissions and FWHM (full width at half maximum), we selected $\alpha = 60^\circ$. Finally, the magnetic field diagram of A, B and C at the three resonance wavelengths in Fig.3c is given, as shown in the lower right corner of Fig. 3.

Fig. 2 Schematic diagram showing the structure of the crescent-shaped cavity resonator.

Fig. 3 Transmission spectra from the designed structure at different the rotation angle α . Figure A-C is the magnetic field distribution diagram

3 Parameters on Fano resonanc

3.1 Effect of parameters on Fano resonance line

In this section we discuss how changes in the structure's geometry affect the Fano resonance lines. Figure 4 shows the transmission spectra and FWHM of the Fano resonance lines as $R2$ (radius of the outer arc of the crescent-shaped resonator) increases from 120 to 160 nm. The resolution of the sensor refers to the smallest change in the refractive index of the sample that can be detected by the sensing system and is expressed in terms of FWHM. The other parameters were set $R1 = 120$ nm, $d = 100$ nm, $W = 300$ nm, $H = 500$ nm, $G = 10$ nm, $\alpha = 60^\circ$, and $n = 1$. Figure 4a shows that, as $R2$ increases, the position of Peak I remains unchanged, while the transmittance peak of Peak I decrease slightly from 0.678 to 0.67. Meanwhile, Dip I is redshifted from 803 to 1046 nm, and the transmittance of Dip I increased from 0.036 to 0.155. Figure 4b shows the change in FWHM of the Fano resonance line as $R2$ increases from 120 to 160 nm. As $R2$ increases from 120 to 130 nm, the FWHM of Peak I first decreases from 10 to 9 nm and then remains constant. As $R2$ increases from 120 to 140 nm, the FWHM of Dip I decreases rapidly from 30 to 13 nm, and the decline is smaller as $R2$ increases from 140 to 160 nm. Based on these transmittance and FWHM results, we selected $R2 = 150$ nm.

Fig.4 (a) The transmission spectra of $R2$; (b) FWHM with the Fano resonance lines.

Figure 5a shows the transmission spectra as $R1$ (radius of the inner arc of the crescent-shaped resonator) increases from 100 to 160 nm. The other parameters were set $R2 = 150$ nm, $d = 100$ nm, $W = 300$ nm, $H = 500$ nm, $G = 10$ nm, $\alpha = 60^\circ$, and $n = 1$. As $R1$ increases, the peak wavelength and transmittance of Peak I remain unchanged, while Dip I is slightly redshifted, and its transmission decreases from 0.17 to 0.1. Furthermore, as $R1$ increases, the FWHM of Dip I gradually increases. When $R1$ is between 130 and 140 nm, the FWHM of Dip I remains at 12 nm. The FWHM of Peak I remains at 9 nm, as shown in Figure 5b. Based on these transmittance and FWHM results, we selected $R1 = 140$ nm. Figure 5 c-d shows the transmission spectra and FWHM of the Fano resonance lines as d (distance between the centers of the inner and outer arcs of the crescent-shaped resonator) increases from 80 to 120 nm, with the other parameters set to $R2 = 150$ nm, $R1 = 140$ nm, $W = 300$ nm, $H = 500$ nm, $G = 10$ nm, $\alpha = 60^\circ$, and $n = 1$. Figure 5c shows that the wavelength and transmittance of Peak I remain virtually constant as d increases, while the peak wavelength of Dip I is blueshifted from 1081 to 927 nm, and its transmittance varies around 0.1. Figure 5d shows that the FWHM of Peak I remains at 9 nm, while the FWHM of Dip I decreases first and then increases as d increases. Based on these transmittance and FWHM results, we selected $d = 110$ nm. From these simulation results, we can see that changing the radii of the inner and outer arcs in the crescent-shaped resonator, as well as the distance between the centers of the inner and outer arcs, induce significant changes on Dip I but only small changes in Peak I.

Fig. 5 (a) The transmission spectra of $R1$ (b) $R1$ and FWHM. (c) Transmission spectra of d . (d) d and FWHM

Figure 6a shows how the transmission spectra change as W increases from 280 to 320 nm. The other parameters were set to $R2 = 150$ nm, $R1 = 140$ nm, $d = 110$ nm, $H = 500$ nm, $G = 10$ nm, $\alpha = 60^\circ$, and $n = 1$. As can be seen from the figure, the resonance wavelength of Peak I is redshifted from 675 to 746 nm, and the transmittance of Peak I increases from 0.51 to 0.7 as W increases. Meanwhile, the position of Dip I remains unchanged and the transmittance of Dip I varies around 0.1. Figure 6b shows the FWHM of the Fano resonance lines as W increases from 280 to 360 nm. The FWHM of Peak I first increases, then levels off, and subsequently increases again. The FWHM of Dip I consistently decreases. We can clearly see that, when $W = 330$ nm, the FWHM of Peak I and the FWHM of Dip I are both 10 nm. Based on these transmittance and FWHM results, we selected $W = 330$ nm. Figure 7a shows the transmission spectra as H increasing from 460 to 540 nm, with the other parameters set to $R2 = 150$ nm, $R1 = 140$ nm, $d = 110$ nm, $W = 330$ nm, $G = 10$ nm, $\alpha = 60^\circ$, and $n = 1$. One can see from the figure that the resonance wavelength position of Peak I is slightly blueshifted from 764 to 762 nm and its transmission decreases from 0.797 to 0.677 as H increases. The resonance wavelength of Dip I is slightly redshifted from 956 to 959 nm, and its transmission increases from 0.129 to 0.146. Figure 7b shows that the FWHM of Peak I and Dip I change in the same manner as H increases: they first decrease and then level off. Based on the results of transmission and FWHM, we selected $H = 490$ nm. In the above, we analyze the effect of the width and height of the rectangular cavity on the Fano resonance line. One can see that changing W significantly changes Peak I and creates small changes in Dip I. One can also see that changing H of the rectangular cavity resonator changes both Peak I and Dip I.

Fig. 6 (a) Transmission spectra a of the rectangular cavity resonator (b) W and FWHM

Fig. 7 (a) Transmission spectra of the height H (b) H and FWHM

Finally, Figure 8 shows the transmission spectra and FWHM of the Fano resonance lines as G (coupling distance between the rectangular resonator and the crescent-shaped resonator) increases from 0 to 20 nm. The other parameters were set to $R2 = 150$ nm, $R1 = 140$ nm, $d = 110$ nm, $W = 330$ nm, $H = 490$ nm, $\alpha = 60^\circ$, and $n = 1$. Figure 8a shows that the position of the Fano resonance line is blueshifted as G increases. As G increases from 0 to 5 nm, the resonance wavelength of Peak I shift from 782 to 767 nm. As G increases from 5 to 20 nm, the resonance wavelength of Peak I shift from 767 to 759 nm. As G increases from 0 to 5 nm, the resonance wavelength of Dip I shifts from 1070 to 982 nm, while the resonance wavelength of Dip I shifts from 982 to 941 nm G increases from 5 to 20 nm. At $G = 0$ nm, the FWHM of Dip I is 180 nm, which is a very large value, while the FWHM of Peak I is 9 nm. Figure 8b shows the change of the FWHM of the Fano resonance lines as G increases from 5 to 20 nm. We see that the FWHM of Peak I change slowly, while the FWHM of Dip I decreases rapidly. Based on the results of transmission and FWHM, we selected $G = 10$ nm.

Fig. 8 (a) Transmission spectra with distance G (b) G and FWHM

3.2 Analysis of sensitivity of Fano resonance

Figure 9a shows the transmission spectra as the refractive index of the material under test, which fills the structure, increases from 1 to 1.06. We used a linear fit to the Fano resonance wavelength as function of n , yielding $S = 750 \text{ nm/RIU}$ for Peak I and $S = 935.71 \text{ nm/RIU}$ for Dip I. The FWHM of Peak I and Dip I are 10 nm. The FOM values for Peak I and Dip I are 75 and 93.571, respectively. Finally, we offer a comparison with other research results in Table I. The structure proposed in this paper has significantly greater refractive index sensitivity.

Fig. 9 (a) Transmission spectra as the refractive index n . (b) Fano resonance wavelength with refractive index

4 APPLICATION TO TESTING ON WATER CONTENT IN HEAVY OIL

World is rich in unconventional oil and various alternatives to petroleum. Water in heavy oil has a great impact on combustion and metallurgical reaction processes in smelting furnaces, and the water content will also have a certain effect on normal equipment operation. Figure 10 shows the transmission spectra for heavy oils with water content of 0%, 20%, 40%, and 60%. The results were obtained with the designed structure filled with heavy oil. One can see that the Fano resonance line moves to shorter wavelengths with little changes in transmission as the water content increases. We have compiled data for the volume percentage of water content with the corresponding refractive index and Fano resonance wavelength into Table II.

Fig. 10 Heavy oils with different water content

Fig. 11 . Volume fraction of water with the Fano resonance wavelength.

The data in Table II were to fit to a linear function of water volume fraction, as shown in Figure 11. The fitting functions for Peak I and Dip I are $\lambda_{\text{Peak I}} = -143.27N + 1152.5$ and $\lambda_{\text{Dip I}} = -179.27N + 1442.4$, respectively, with coefficients of determination as high as 0.999. The water volume fraction resolution in heavy oil is 1.79×10^{-9} .

Table II. Water in heavy oil corresponds to the refractive index and resonance wavelength.

N	n_c	$\lambda_{\text{Peak I}}$ (nm)	$\lambda_{\text{Dip I}}$ (nm)
0%	1.520	1154	1444
10%	1.500	1139	1425
20%	1.480	1124	1406
30%	1.460	1109	1388
40%	1.441	1094	1370
50%	1.421	1080	1352

60%	1.403	1065	1334
70%	1.384	1052	1316
80%	1.366	1038	1299
90%	1.348	1024	1281
100%	1.330	1011	1265

5. Results and Discussion

World is rich in unconventional oil and various alternatives to petroleum. Water in heavy oil has a great impact on combustion and metallurgical reaction processes in smelting furnaces, and the water content will also have a certain effect on normal equipment operation. The relationship between the structure's geometry and its transmission spectrum was studied in detail using FEM simulations. Multiple Fano resonances can be produced by changing the rotation angle of the crescent-shaped resonator. The refractive index sensitivities of the systems reported in [25], [19], and [20] are 596, 626, and 880 nm/RIU, respectively. With respect to these values, the refractive index sensitivities proposed in this paper are 56.9%, 49.5%, and 6.3% greater, respectively.

Table I Sensitivity of similar devices reported in the literature.

References	Sensitivity (nm/RIU)
[25] Zhidong, Zhang, Liang, Luo, Chenyang, Xue, Wendong, Shubin, Yan. Fano Resonance Based on Metal-Insulator-Metal Waveguide-Coupled Double Rectangular Cavities for Plasmonic Nanosensors[J]. Sensors, 2016, 16(5):642-652.	596
[19] He, J. , Fan, C. , Wang, J. , Ding, P. , Cai, G. , & Cheng, Y. A giant localized field enhancement and high sensitivity in an asymmetric ring by exhibiting Fano resonance [J]. Journal of Optics, 2013, 15(2):025007.	626
[26] Shu-Bin, Y. , Liang, L. , Chen-Yang, X. , & Zhi-Dong, Z. . A Refractive Index Sensor Based on a Metal-Insulator-Metal Waveguide-Coupled Ring Resonator[J]. Sensors, 15(11):29183-29191.	868.4
[20] Zicong, G. , Kunhua, W. , Qinyang, H. , Wenhui, L. , Jiyan, L. , & Yihong, F. . Plasmonic Multichannel Refractive Index Sensor Based on Subwavelength Tangent-Ring Metal-Insulator-Metal Waveguide[J]. Sensors, 2018, 18(5):1348-1357.	880
This study	935.71

The main innovations are as follows:

- 1) A nano-scale refractive index sensor with a high sensitivity 935.71 nm/RIU.
- 2) The FOM as high as 935.71 can be constructed by filling the area reserved for material under test with materials that have different refractive index.

This structure was used to detect the water content in heavy oil. As the volume fraction of water increases, the Fano resonance line moves toward shorter wavelengths. The results show that the water content in heavy oil can be calculated using a measured change in the Fano resonance wavelength. The resolution of the sensor was found to be 1.79×10^{-9} . The structure designed in this paper provides a new way to measure liquid solvent contents in solutions.

6. Declarations

Availability of data and materials: The experiments of our paper have no ethical issues. And the experimental protocols were approved by the Animal Care and Protection Committee of *Guangxi Normal University*.

Competing interests: No conflict of interest exists in the submission of this manuscript

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Authors' contributions: Ge Wang and JUN ZHU contributed equally to this work. Ge Wang and JUN ZHU drafted the manuscript. Cong hu participated in the design of the study and performed the statistical analysis. All authors read and approved the final manuscript.

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Authors' information : Jun ZHU and Wang, College of Electronic Engineering, Guangxi Normal University, Guilin 541004, China

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Figures

Figure 1

3D and 2D renderings of the system

Figure 1

3D and 2D renderings of the system

Figure 2

Schematic diagram showing the structure of the crescent-shaped cavity resonator.

Figure 2

Schematic diagram showing the structure of the crescent-shaped cavity resonator.

Figure 3

Transmission spectra from the designed structure at different the rotation angle α . Figure A-C is the magnetic field distribution diagram

Figure 3

Transmission spectra from the designed structure at different the rotation angle α . Figure A-C is the magnetic field distribution diagram

Figure 4

(a) The transmission spectra of R2 (b) FWHM with the Fano resonance lines.

Figure 4

(a) The transmission spectra of R2 (b) FWHM with the Fano resonance lines.

Figure 5

(a) The transmission spectra of R1 (b) R1 and FWHM. (c) Transmission spectra of d. (d) d and FWHM

Figure 5

(a) The transmission spectra of R1 (b) R1 and FWHM. (c) Transmission spectra of d. (d) d and FWHM

Figure 6

(a) Transmission spectra a of the rectangular cavity resonator (b)W and FWHM

Figure 6

(a) Transmission spectra a of the rectangular cavity resonator (b)W and FWHM

Figure 7

(a) Transmission spectra of the height H (b) H and FWHM

Figure 7

(a) Transmission spectra of the height H (b) H and FWHM

Figure 8

(a) Transmission spectra with distance G (b) G and FWHM

Figure 8

(a) Transmission spectra with distance G (b) G and FWHM

Figure 9

(a) Transmission spectra as the refractive index n . (b) Fano resonance wavelength with refractive index

Figure 9

(a) Transmission spectra as the refractive index n . (b) Fano resonance wavelength with refractive index

Figure 10

Heavy oils with different water content

Figure 10

Heavy oils with different water content

Figure 11

Volume fraction of water with the Fano resonance wavelength.

Figure 11

Volume fraction of water with the Fano resonance wavelength.