This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/LPT.2015.2437850, IEEE Photonics Technology Letters

A refractive index nanosensor based on Fano resonance in the plasmonic waveguide system

Zhao Chen, Li Yu, Lulu Wang, Gaoyan Duan, Yufang Zhao, and Jinghua Xiao

***Abstract*—A novel and compact refractive index sensor based on Fano resonance in the plasmonic waveguide system, which comprises with a stub and groove resonator coupled with a metal-insulator-metal (MIM) waveguide, is proposed and investigated by the finite element method. Due to the interaction of the narrow discrete resonance and a broad spectrum caused by the stub resonator and the groove, respectively, the transmission spectrum exhibits a sharp asymmetrical profile. Simulation results show that the Fano resonance can be easily tuned by changing the parameters of the structure. These characteristics offer flexibility to design the devices. This nano-sensor yields a sensitivity of ~1260 nm/RIU (per unit variations of the refractive index) and a figure of merit of ~2.3x10^4. This work is significant for design and application of the sensitive nanoscale refractive index sensor.**

***Index Terms*—Plasmonic, MIM waveguide, Fano resonances, Figure of merit, Sensor.**

I. Introduction

FANO resonances, which arise from the coupling and interference of a non-radiative mode and a continuum of radiative electromagnetic waves, have been extensively studied in recent years due to the narrow and asymmetric line shapes [1], [2]. These resonances have been observed in various plasmonic structures, such as planar oligomers [3], [4], multi-metallic layered nanostructures [5], [6], rings [7]-[8], nano-cavities [9]-[10], and metal-insulator-metal (MIM) waveguides [11]-[13]. Compact and light-weight diagnostic devices hold significant promise for early detection and monitoring of diseases in field settings. Plasmonic nanosensors are one of the key components [14]-[16]. They play an important role in the biological, chemical detection. As an important plasmonic waveguide, the MIM waveguide has attracted many researchers attention due to its deep-sub-wavelength confinement of light [17]-[21]. These structures are more suitable for the highly integrated optical circuits. Thus, the MIM waveguide has wide applications in deep subwavelength optical devices, such as sensors [22], [23], filters [24]-[26], demultiplexers [27]-[30]. It should be noted that these devices based on the MIM waveguides usually used the single resonator effect to realize their functionalities [24]-[26], [28]-[30]. However, the single resonator typically exhibits broadband transmission spectra with nearly symmetric Lorentzian-like line shapes [24]-[26], [28]-[30], which is difficult to achieve a high-resolution results and greatly limits the performances of these functional optical devices. To address these problems, *Chen* and co-workers proposed a special structure by adding a metallic baffle achieving a high resolution demultiplexers based on Fano interference [31]; *Lu et al* designed a dual resonator structure to achieve a plasmonic nanosensor [32]. These results may open up a pathway in photonics and offer prospects of smaller devices for the manipulation and transmission of light. Therefore, combining the Fano-like response with MIM plasmonic structures would create the possibility of achieving ultracompact functional optical components for use in highly integrated optics [33]. However, reports in this area are still very rare.

Manuscript received November 16, 2014. This work was supported by the National Natural Science Foundation of China under Grants Nos.11374041, 11404030 and Fund of State Key Laboratory of Information Photonics and Optical Communications (Beijing University of Posts and Telecommunications), P. R. China.

Z. Chen is with the State Key Laboratory of Information Photonics and Optical Communications, Beijing University of Posts and Telecommunications, Beijing, 100876, China. He is with School of Science, Beijing University of Posts and Telecommunications, Beijing, 100876, China (e-mail: chenzhao1073@163.com).

L. Yu, L. Wang, G. Duan, Y. Zhao, and J. Xiao are with State Key Laboratory of Information Photonics and Optical Communications, Beijing University of Posts and Telecommunications, Beijing 100876, China. They are with School of Science, Beijing University of Posts and Telecommunications, Beijing, 100876, China (e-mail: bupt.yuli@gmail.com, llwang@bupt.edu.cn).

In this letter, Fano resonance is obtained in a compact plasmonic structure, comprising a MIM waveguide coupled with a stub and groove resonators. Simulation results show that by introducing a plasmonic groove, a sharp and asymmetric transmission profile is formed in the broad stop-band of the stub resonator. The interaction of the narrow discrete resonance and a broad spectrum caused by the stub resonator and the groove, respectively, gives rise to the Fano resonance. The asymmetrical line shape and the resonant wavelength can be easily tuned by changing the geometrical parameters of the structure. The proposed sub-structure can serve as an excellent plasmonic sensor with a sensitivity of ~1260 nm/RIU and a figure of merit of ~2.3x10^4. The proposed structure can find widely applications in the plasmonic nano-sensing area.

II. Structure and Simulations

Figure 1(a) schematically shows the MIM waveguide coupled with a groove and a stub resonator. This system is a two-dimensional model, and the white and blue parts denote air (ε_d =1.0) and Ag (ε_m), respectively. The length and height of the groove is L and H, the width and height of the stub resonator is w and S, respectively, and the width of the MIM waveguide is w. Here, the value w=50 nm is fixed throughout this paper. The characteristics of the single stub resonator have been widely investigated before, and it typically exhibits broadband transmission spectra with nearly symmetric Lorentzian-like line-shapes [6], [21]. In the proposed structure, another groove is added besides the stub resonator, and the two resonators would affect and couple with each other through the bus waveguide. This could greatly affect the line-shapes of the transmission spectra.

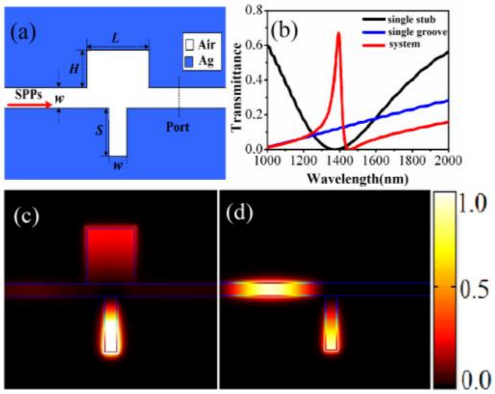

Fig. 1. a) Schematic configuration and geometric parameters of the plasmonic waveguide system. b) Transmission spectra of the plasmonic waveguide system: The red, black and blue line represent the transmission spectra of the system, the single-stub resonator and the single groove in the MIM waveguides, respectively. The parameters are set as L=200 nm, H=225 nm and S=225 nm. c, d) The $|H_z|^2$ field distributions with and without the groove at the resonance wavelength λ=1392 nm.

In order to investigate the optical responses of the proposed structure, its transmission spectra are numerically calculated using the finite element method (FEM) of COMSOL Multiphysics. The transmittance of SPPs is defined as the quotient between the SPP power flows (obtained by integrating the Poynting vector over the channel cross-section) of the observing port with structures (groove and stub resonator) and without structures [11], [18], [21]. The permittivity of Ag is characterized by the Drude model: $\varepsilon_m=\varepsilon_\infty-\omega_p^2/(\omega^2+i\omega\gamma)$ with $\varepsilon_\infty=3.7$, $\omega_p=9.1$ eV, $\gamma=0.018$ eV [34]. In the simulations, first perform the boundary mode analysis on the input port of the structure, then solve the wave propagation problem using the mode shape obtained by the first step as a boundary condition. The parameters of the proposed structure are set as: L=200 nm, H=225 nm and S=225 nm, and the calculated transmission spectra are displayed in Figs. 1(b). It is found that the transmission spectrum in the plasmonic waveguide system exhibits sharp and asymmetric response line-shape [red line in fig. 1(b)]. This is quite different from the line-shape in the single stub [black line in fig. 1(b)] or the groove [blue line in fig. 1(b)]. From Fig. 1(b), it can be also observed that the transmittance in the plasmonic waveguide system can decrease sharply from the peak to the valley of the spectra. Moreover, the system response also maintains the spectral features of the groove except the asymmetric parts. Figures. 1(c) and (d) show the field distributions of $|H_z|^2$ at the resonance peak of 1392 nm with and without the groove. It is observed that the field in the stub becomes much stronger [fig. 1(c)] in the asymmetric response peak than that in the single stub resonator case [Fig. 1(d)], yielding a high-quality resonance. The sharp and asymmetric spectra, usually termed as Fano profiles, result from the coupling of the narrow discrete state (stub resonator) and the broad spectrum (groove resonator) [1], [2].

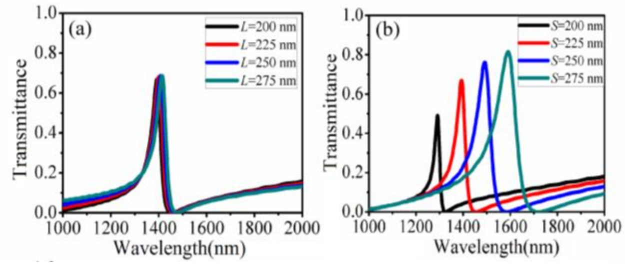

Fig. 2. a) Transmission spectra for different L with S=225 nm and H=225nm. b) Transmission spectra for different S with L=200 nm and H=225nm.

Next, we investigate the properties of the proposed structure using FEM. First, we calculate the transmission spectra for different L with S=225 nm and H=225 nm, as shown in Fig. 2(a). It is obvious that the length of the groove L hardly influences the transmission profiles when S and H are fixed. From the field distribution at the resonant wavelength in Fig. 1(c), we know that a strong field distribution is confined in the stub resonator (one antinode in the standing wave pattern). This resonant mode is an inherent mode in the stub resonator, and its resonant wavelength is determined by the stub dimension [21], [24], [29]. Therefore, the variation of the groove length L nearly has no influence on the position of the Fano resonance, as shown in Fig. 2(a).

Successively, we investigate the influence of the length of the stub resonator S on the transmission spectra, and the results are displayed in Fig. 2(b). In this case, the length and the height of the groove are fixed to be L=200 nm, and H=225 nm, respectively. It is observed that increasing S can greatly redshift the resonant wavelength of the Fano profiles [18], [24], [29]. In addition, the resonant wavelength has a nearly linear relationship with S. Therefore, the resonant wavelength can be easily manipulated by adjusting the length of the stub resonator.

III. Sensing Applications Based on Fano Resonances

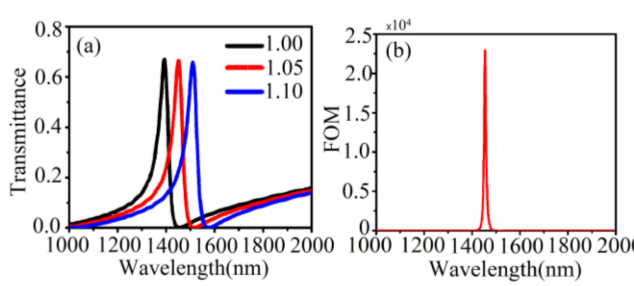

Fig. 3. a) Transmission spectra for different refractive index. b) The calculated FOM at different wavelength.

Because of the strongly trapped resonance, the Fano resonance exhibits sharp asymmetric profile, where the transmittance can drop sharply from the peak to the valley of the spectra. Such a short wavelength change can provide a high sensitivity of spectrum response to the index variations of nearby or surrounding medium for the structure [1], [35]. Therefore, the insulator with different refractive index is employed to investigate the spectral response. The parameters of the structure are set to be: L=200 nm, H=225 nm and S=225 nm, and the transmission spectra are shown in Fig. 3 (a). It is found that the resonance wavelength varies linearly with the refractive index. This feature provides an excellent scheme for the applications toward nanoscale sensing [36]. The sharp asymmetric Fano line shape enhances the sensitivity of sensors. The sensitivity of a sensor (nm/RIU) is usually defined as the shift in the resonance wavelength per unit variations of the refractive index [37]. Thus, the sensitivity of the proposed structure is 1260 nm/RIU. These results are higher than those in the references [32], [36]. To better evaluate the performance of the plasmonic sensor, the figure of merit (FOM) is studied, which defined as FOM=$\Delta T/(T\Delta n)$ [38], [39], where T denotes the transmittance in the proposed structure. The calculated FOM are displayed in Fig. 3(b). The values of FOM is as high as ~$2.3\text{x}10^4$ at λ=1454 nm, which is due to the sharp asymmetric Fano line shape with ultra-low transmittance at this wavelength. These FOM values are significantly greater than that in the previous reports [32], [38].

IV. Conclusion

In summary, Fano resonance in an MIM waveguide coupled with stub and groove resonators are numerically predicted. Simulation results show that by introducing a plasmonic groove, a sharp and asymmetric transmission profile is formed in the broad stop-band of the stub resonator. The interaction of the narrow discrete resonance and a broad spectrum caused by the stub resonator and the groove, respectively, gives rise to the Fano resonance. The asymmetrical line shape and the resonant wavelength can be easily tuned by changing the geometrical parameters of the structure. A nano-sensor was designed based on the sharp asymmetrical profiles, which yielded a sensitivity of ~1260 nm/RIU and a figure of merit of~$2.3\text{x}10^4$. The utilization of Fano resonance in the MIM waveguide provides a new possibility for designing high performance plasmonic devices.

References

[1] B. Luk' yanchuk, N. Zheludev, S. Maier, N. Halas, P. Nordlander, H. Giessen, and C. Chong, "The Fano resonance in plasmonic nanostructures and metamaterials," Nat. Mater. vol. 9, pp. 707-715, Sep. 2010.

[2] A. Miroshnichenko, S. Flach, and Y. Kivshar, "Fano resonances in nanoscale structures," Rev. Mod. Phys. vol. 82, pp. 2257-2298, Aug. 2010.

[3] M. Rahmani, B. Luk'yanchuk and M. H. Hong, "Fano resonance in novel plasmonic nanostructures," Laser Photonics Rev., Vol. 7, no. 3, pp. 329-349, Dec. 2012.

[4] L. V. Brown, H. Sobhani, J. B. Lassiter, P. Nordlander, and N. J. Halas, "Heterodimers: plasmonic properties of mismatched nanoparticle pairs," ACS Nano, vol. 4, no. 2, pp. 819–832, Jan. 2010.

[5] O. Pena-Rodriguez, A. Rivera, M. Campoy-Quiles, and U. Pal, "Tunable Fano resonance in symmetric multilayered gold nanoshells," Nanoscale, vol. 5, no. 1, pp. 209-216, Aug. 2012.

[6] A. D Khan, "Multiple Fano resonances in bimetallic layered nanostructures," Int Nano Lett, Vol. 4, pp. 110, Jun. 2014.

[7] A. Cetin, and H. Altug, "Fano Resonant Ring/Disk Plasmonic Nanocavities on Conducting Substrates for Advanced Biosensing," ACS Nano, vol. 6, no. 11, pp. 9989-9995, Aug. 2012.

[8] Y. H. Fu, J. B. Zhang, Y. F. Yu, and B. Luk'yanchuk, "Generating and Manipulating Higher Order Fano Resonances in Dual-Disk Ring Plasmonic Nanostructures," ACS Nano, vol. 6, no. 6, pp.5130-5137, Feb. 2012.

[9] S. H. Fan, "Sharp asymmetric line shapes in side-coupled waveguide-cavity systems," Appl. Phys. Lett., Vol. 80, no. 6, pp. 908-910, Feb. 2002.

[10] B. Sun, L. X. Zhao, C. Wang, X. Y. Yi, Z. Q. Liu, G. H. Wang, and J. M. Li, "Tunable Fano resonance in E-shape Plasmonic nanocavities," J. Phys. Chem. C, Vol. 118, no. 43, pp. 25124–25131, Sep. 2014.

[11] Z. Chen, and L. Yu, "Multiple Fano resonances based on different waveguide modes in a symmetry breaking plasmonic systems," IEEE Photonics Journal, Vol.6, no. 6, pp. 4802208. Nov. 2014.

[12] J. J. Chen, Z. Li, R. Zhang, Z. L. Deng, J. H. Xiao, and Q. H. Gong, "Response Line-Shapes in Compact Coupled Plasmonic Resonator Systems," Plasmonics, vol. 8, pp.1129-1134, Mar. 2013.

[13] X. J. Piao, S. Yu S. Koo, K. Lee, and N. Park, "Fano-type spectral asymmetry and its control for plasmonic metal-insulator-metal stub structures," Opt. Exp., vol. 19, no. 11, pp. 10907-10912, May. 2011.

[14] K. M. Mayer, and J. H.Hafner, "Localized surface plasmon resonance sensors," *Chem. Rev*. Vol. 111, pp. 3828-3857, Sep. 2011.

[15] A. E. Cetin, A. F. Coskun, B. C. Galarreta, M. Huang, D. Herman, A. Ozcan, and H. Altug, "Handheld High-Throughput Plasmonic Biosensor using Computational On-Chip Imaging", Light: Science & Applications, Vol. 3, pp. e122. Jan. 2014.

[16] A. F. Coskun, A. E. Cetin , B. C. Galarreta, D. A. Alvarez, H. Altug, and A. Ozcan, "Lensfree optofluidic plasmonic sensor for real-time and label-free monitoring of molecular binding events over a wide field-of-view", Scientific Reports, Vol. 4, pp. 6789. July. 2014.

[17] T. Xu, Y. K. Wu, X. G. Luo, and L. J. Guo, "Plasmonic nanoresonators for high-resolution colour filtering and spectral imaging," Nature Commun., vol. 1, pp. 59, Aug. 2010.

[18] Z. Chen, J. J. Chen, L. Yu, and J. H. Xiao, "Sharp Trapped Resonances by Exciting the Anti-symmetric Waveguide Mode in a Metal Insulator Metal Resonator," Plasmonics, Vol.10, no. 1, pp. 131-137, Aug. 2014.

[19] J. J. Chen, Z. Li, M. Lei, X. L. Fu, J. H. Xiao, and Q. H. Gong, "Plasmonic Y-splitters of High Wavelength Resolution Based on Strongly Coupled-Resonator Effects," Plasmonics, vol. 7, no. 3, pp. 441-445, Dec. 2012.

[20] K. H. Wen, L. S. Yan,W. Pan, B. Luo, Z. Guo, Y. H. Guo, and X. G. Luo, "Electromagnetically Induced Transparency-Like Transmission in a Compact Side-Coupled T-Shaped Resonator," J Lightwave Technol., vol. 32, no. 9, pp. 1071-1707, May. 2014.

[21] J. J. Chen, C. Wang, R, Zhang, and J. H. Xiao, "Multiple plasmon-induced transparencies in coupled-resonator systems," Opt. Lett. vol. 37, no. 24, pp. 5133-5135, Dec. 2012.

[22] L. Xu, S. Wang, and L. J. Wu, "Refractive Index Sensing Based on Plasmonic Waveguide Side Coupled With Bilaterally Located Double Cavities," IEEE Trans. Nanotech., Vol. 13, no. 5, pp. 875-880. Sep. 2014.

[23] J. J. Chen, Z. Li, Y. J. Zou, Z. L. Deng, J. H. Xiao, and Q. H. Gong, "Coupled-Resonator-Induced Fano Resonances for Plasmonic Sensing with Ultra-High Figure of Merits," Plasmonics, vol. 8, pp.1627-1632, May. 2013.

[24] Q. Zhang, X. G. Huang, X. S. Lin, J. Tao, and X. P. Jin, "A subwavelength coupler-type MIM optical filter," Opt. Exp., vol. 17, no. 9, pp.7549-7554, Apr. 2009.

[25] F. S. Ma, and C. K. Lee, "Optical Nano filters Based on Meta-Atom Side-Coupled Plasmonics MetalInsulator-Metal Waveguides," J Lightwave Technol., vol. 31, no. 17, pp. 2876-2879, Sep. 2013.

[26] I. Zand, M. S. Abrishamian, and T. Pakizeh, "Nanoplasmonic Loaded Slot Cavities for Wavelength Filtering and Demultiplexing," IEEE J Sel Top Quantum, Vol. 19, no. 3, pp. 4600505. MAY. 2013.

[27] Z. Chen, R. Hu, L. N. Cui, L. Yu, L.L. Wang, and J. H. Xiao, "Plasmonic wavelength demultiplexers based on tunable Fano resonance in coupled-resonator systems," Opt. Comm., Vol. 320, pp. 6-11, Jan. 2014.
[28] G. X. Wang, H. Lu, X. M. Liu, D. Mao, and L. N. Duan, "Tunable multi-channel wavelength demultiplexer based on MIM plasmonic nanodisk resonators at telecommunication regime," Opt. Exp., vol. 19, no. 4, pp.3513-3518, Feb. 2011.
[29] Z. P. Zhou, F. F. Hu, and H. X. Yi, "Wavelength demultiplexing structure based on arrayed plasmonic slot cavities," Opt. Lett. vol. 36, no. 8, pp. 1500-1502, Apr. 2011.
[30] A. Noual, A. Akjouj, Y. Pennec, J. N. Gillet, and B. Djafari-Rouhani, "Modeling of two-dimensional nanoscale Y-bent plasmonic waveguides with cavities for demultiplexing of the telecommunication wavelengths," New J Phys., Vol. 11, pp. 103020, Oct. 2009.
[31] J. J. Chen, Z. Li, J. Li and Q. H. Gong, "Compact and high-resolution plasmonic wavelength demultiplexers based on Fano interference," Opt. Exp., vol. 19, no. 10, pp. 9976-9985, May. 2011.
[32] H. Lu, X. M. Liu, D. Mao, and G. X. Wang, "Plasmonic nanosensor based on Fano resonance in waveguide-coupled resonators," Opt. Lett. vol. 37, no. 18, pp. 3780-3782, Sep. 2012.
[33] N. Liu, L. Langguth, T. Weiss, J. Kastel, M Fleischhauer, T. Pfau, and H. Giessen, "Plasmonic analogue of electromagnetically induced transparency at the Drude damping limit,", Nature Materials, Vol. 8, pp. 758-762, Sep. 2009.
[34] X. S. Lin, and X. G. Huang, "Tooth-shaped plasmonic waveguide filters with nanometeric sizes," Opt. Lett. vol. 33, no. 23, pp. 2874–2876, Dec. 2008.
[35] J. J. Chen, Z. Li, S. Yue, J. H. Xiao, and Q. H. Gong, "Plasmon-Induced Transparency in Asymmetric T-Shape Single Slit," Nano Lett., Vol. 12, no. 5, pp. 2494-2498, Mar, 2012.
[36] N. Liu, T. Weiss, M. Mesch, L. Langguth, U. Eigenthaler, M. Hirscher, C. Sonnichsen, and H. Giessen, "Planar Metamaterial Analogue of Electromagnetically Induced Transparency for Plasmonic Sensing,", Nano Lett., vol. 10, pp. 1103-1107, Sep. 2010.
[37] N. Liu, M. Mesch, T. Weiss, M. Hentschel, and H. Giessen, "Infrared Perfect Absorber and Its Application As Plasmonic Sensor," Nano Lett., vol. 10, pp. 2342-2348, Jun. 2010.
[38] J. Becker, A. Trugler, A. Jakab, U. Hohenester, and C. Sonnichsen, "The Optimal Aspect Ratio of Gold Nanorods for Plasmonic Bio-sensing," Plasmonics, vol. 5, pp. 161-167, Mar. 2010.
[39] R. Ameling, L Langguth, M. Hentschel, M. Mesch, P. Braun, and H. Giessen, "Cavity-enhanced localized plasmon resonance sensing," Appl. Phys. Lett., vol. 97, pp. 253116, Dec. 2010.