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- Rep.*, vol. 6, no. 1, Mar. 2016, Art. no. 22428.
- [29] Y. Chen, et al., "Sensing performance analysis on Fano resonance of metallic double-baffle contained MDM waveguide coupled ring resonator," *Opt. Laser Technol.*, vol. 101, pp. 273-278, May 2018.
 - [30] F. Chen, H. Zhang, L. Sun, J. Li, and C. Yu, "Temperature tunable Fano resonance based on ring resonator side coupled with a MIM waveguide," *Opt. Laser Technol.*, vol. 116, pp. 293-299, Apr. 2019.
 - [31] Y. Chou Chau, C. Chou Chao, H.J. Huang, N.T.R.N. Kumara, C.M. Lim and H. Chiang, "Ultra-High Refractive Index Sensing Structure Based on a Metal-Insulator-Metal Waveguide-Coupled T-Shape Cavity with Metal Nanorod Defects," *Nanomaterials*, vol. 9, no. 10, pp. 1433, Sep. 2019.
 - [32] Z. Li et al., "Manipulation of multiple Fano resonances based on a novel chip-scale MDM structure," *IEEE Access*, vol. 8, pp. 32914-32921, Feb. 2020.
 - [33] J. Zhang, H. Feng and Y. Gao, "Plasmonic Narrowband Filter Based on an Equilateral Triangular Resonator with a Silver Bar," *Photonics*, vol. 8, no. 7, pp. 244, Jun. 2021.
 - [34] Y. Zhang et al., "A graphene based tunable terahertz sensor with double Fano resonances," *Nanoscale*, vol. 7, no. 29, pp. 12682-12688, Jun. 2015.
 - [35] Q. Li et al., "Monolayer graphene sensing enabled by the strong Fano-resonant metasurface," *Nanoscale*, vol. 8, no. 39, pp. 17278-17284, Sep. 2016.
 - [36] Y.K. Srivastava, L. Cong and R. Singh, "Dual-surface flexible THz Fano metasensor," *Appl. Phys. Lett.*, vol. 111, no. 20, Nov. 2017, Art. no. 201101.
 - [37] W. Xu et al., "Terahertz biosensing with a graphene-metamaterial heterostructure platform," *Carbon*, vol. 141, pp. 247-252, Sep. 2019.
 - [38] A. Ahmadvand, B. Gerislioglu, R. Ahuja, and Y. Kumar Mishra, "Terahertz plasmonics: The rise of toroidal metadefects towards immunobiosensings," *Mater. Today*, vol. 32, pp. 108-130, Feb. 2020.
 - [39] S. Jahani and Z. Jacob, "All-dielectric metamaterials," *Nat. Nanotechnol.*, vol. 11, no. 1, pp. 23-36, Jan. 2016.
 - [40] G. Veronis and S. Fan, "Bends and splitters in metal-dielectric-metal subwavelength plasmonic waveguides," *Appl. Phys. Lett.*, vol. 87, no. 13, Sep. 2005, Art. no. 131102.
 - [41] G. Veronis and S. Fan, "Modes of subwavelength plasmonic slot waveguides," *J. Lightw. Technol.*, vol. 25, no. 9, pp. 2511-2521, Sep. 2007.
 - [42] A. Melikyan et al., "High-speed plasmonic phase modulators," *Nat. Photon.*, vol. 8, no. 3, pp. 229-233, Mar. 2014.
 - [43] M. Danaie and A. Shahzadi, "Design of a high-resolution metal-insulator-metal plasmonic refractive index sensor based on a ring-shaped Si resonator," *Plasmonics*, vol. 14, no. 6, pp. 1453-1465, Mar. 2019.
 - [44] M.A. Ordal, R.J. Bell, R.J. Alexander, L.L. Long and M.R. Querry, "Optical properties of Au, Ni, and Pb at submillimeter wavelengths," *Appl Opt.*, vol. 26, no. 4, pp. 744-752, Feb. 1987.
 - [45] H.-J. Hagemann, W. Gudat, C. Kunz, "Optical constants from the far infrared to the x-ray region: Mg, Al, Cu, Ag, Au, Bi, C, and Al₂O₃," *J. Opt. Soc. Amer.*, vol. 65, no. 6, pp. 742-744, Jun. 1975.
 - [46] A.D. Rakic, A.B. Djurisic, J.M. Elazar and M.L. Majewski, "Optical properties of metallic films for vertical-cavity optoelectronic devices," *Appl Opt.*, vol. 37, no. 22, pp. 5271-5283, Aug. 1998.
 - [47] X. Lin and X. Huang, "Tooth-shaped plasmonic waveguide filters with nanometric sizes," *Opt. Lett.*, vol. 33, no. 23, pp. 2874-2876, Dec. 2008.
 - [48] P. Berini, R. Charbonneau, N. Lahoud, and G. Mattiussi, "Characterization of long-range surface-plasmon-polariton waveguides," *J. Appl. Phys.*, vol. 98, no. 4, Aug. 2005, Art. no. 043109.
 - [49] Y. Xu, Y. Li, R.K. Lee, and A. Yariv, "Scattering-theory analysis of waveguide-resonator coupling," *Phys. Rev. E*, vol. 62, no. 5B, pp. 7389-7404, Nov. 2000.
 - [50] S. Fan, "Sharp asymmetric line shapes in side-coupled waveguide-cavity structures," *Appl. Phys. Lett.*, vol. 80, no. 6, pp. 908-910, Feb. 2002.
 - [51] Q. Li, T. Wang, Y. Su, M. Yan, and M. Qiu, "Coupled mode theory analysis of mode-splitting in coupled cavity structure," *Opt. Express*, vol. 18, no. 8, pp. 8367-8382, Apr. 2010.
 - [52] Y. Zhao et al., "Gain enhanced Fano resonance in a coupled photonic crystal cavity-waveguide structure," *Sci. Rep.*, vol. 6, no. 1, Sep. 2016, Art. no. 33645.
 - [53] R. Singh, W. Cao, I. Al-Naib, L. Cong, W. Wu, and W. Zhang, "Ultrasensitive terahertz sensing via Fano resonances in metasurfaces," *Appl. Phys. Lett.*, vol. 105, no. 17, Oct. 2014, Art. no. 171101.
 - [54] L.J. Sherry, S. Chang, G.C. Schatz, R.P. Van Duyne, B.J. Wiley, and Y. Xia, "Localized surface plasmon resonance spectroscopy of single silver nanocubes," *Nano Lett.*, vol. 5, no. 10, pp. 2034-2038, Aug. 2005.
 - [55] R. Mendis and D. Grischkowsky, "Undistorted guided-wave propagation of subpicosecond terahertz pulses," *Opt. Lett.*, vol. 26, no. 11, pp. 846-848, Jun. 2001.
 - [56] R. Mendis, V. Astley, J. Liu and D.M. Mittleman, "Terahertz microfluidic sensor based on a parallel-plate waveguide resonant cavity," *Appl. Phys. Lett.*, vol. 95, no. 17, pp. 171113, Oct. 2009.
 - [57] X. Li, J. Song and J.X.J. Zhang, "Design of terahertz metal-dielectric-metal waveguide with microfluidic sensing stub," *Opt. Commun.*, vol. 361, pp. 130-137, Oct. 2016.
 - [58] C. Ding et al., "Dual-band ultrasensitive THz sensing utilizing high quality Fano and quadrupole resonances in metamaterials," *Opt. Commun.*, vol. 350, pp. 103-107, Mar. 2015.
 - [59] K. Shih, P. Pitchappa, L. Jin, C. Chen, R. Singh, and C. Lee, "Nanofluidic terahertz metasensor for sensing in aqueous environment," *Appl. Phys. Lett.*, vol. 113, no. 7, Aug. 2018, Art. no. 071105.
 - [60] M. Gupta, Y.K. Srivastava, M. Manjappa, and R. Singh, "Sensing with toroidal metamaterial," *Appl. Phys. Lett.*, vol. 110, no. 12, Mar. 2017, Art. no. 121108.
 - [61] S. Karmakar, D. Kumar, R.K. Varshney, and D.R. Chowdhury, "Strong terahertz matter interaction induced ultrasensitive sensing in Fano cavity based stacked metamaterials," *J. Phys. D: Appl. Phys.*, vol. 53, no. 41, Jul. 2020, Art. no. 415101.
 - [62] P. Tang et al., "Ultrasensitive specific terahertz sensor based on tunable plasmon induced transparency of a graphene micro-ribbon array structure," *Opt. Express*, vol. 26, no. 23, pp. 30655-30666, Nov. 2018.
 - [63] M. Chen, L. Singh, N. Xu, R. Singh, W. Zhang, and L. Xie, "Terahertz sensing of highly absorptive water-methanol mixtures with multiple resonances in metamaterials," *Opt. Express*, vol. 25, no. 13, pp. 14089-14097, Jun. 2017.
 - [64] L. Du, J. Li, Q. Liu, J. Zhao, and L. Zhu, "High-Q Fano-like resonance based on a symmetric dimer structure and its terahertz sensing application," *Opt. Mater. Express*, vol. 7, no. 4, pp. 1335-1342, Apr. 2017.

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In the practical detection process, two flat convex cylindrical lenses with appropriate size are placed at the input and output ports and in close contact with the waveguide (see Supporting Information, Fig. S7) [55]. They can prevent analyte overflow and improve the efficiency of optical coupling in and out of the waveguide. Then we can manually inject the analyte into the detection region by using a precision syringe, and a focused HeNe laser beam is used to detect the filling of the analyte in the waveguide [56]. Considering the waveguide gap can serve as a channel for fluid flow, it can combine microfluidics technology to realize real-time monitoring [57].

IV. CONCLUSION

A Fano resonator with subwavelength planar structure has been numerically investigated and theoretically calculated in the THz region, which consists of a metal wall and a stub-coupled MDM waveguide. The numerical results simulated by FDTD are in good agreement with the theoretical results analyzed by SMT. The results indicate that the appearance of Fano resonance is attributed to the interference between the narrow discrete mode and broad continuum mode caused by stub resonator and metal wall, respectively. Maximum transmission of 95.4% is obtained with the propagation loss of $2.836 \times 10^{-4} \text{ dB}/\mu\text{m}$. Fano transmission spectra can be conveniently adjusted by altering geometrical parameters. further, the conversion of transmission spectra from Fano to Lorentzian line shape is realized by controlling the height and width of the stub resonator, as well as the distance between stub resonator and metal wall. Furthermore, the maximum Q-factor can reach up to 225 by optimizing the structural parameters, which is obviously improved about 60 times compared to the single stub-coupled waveguide structure. In sensing application, the results show that the Fano-based MDM waveguide structure can achieve a high sensitivity of 96480 nm/RIU and a satisfactory FOM of 195 in a wide RI range. Therefore, the proposed structure has a good application prospect in THz filtering and sensing, and provides the feasibility for the application of subwavelength plasmonic waveguide device in THz band.

REFERENCES

- [1] U. FANO, "Effects of configuration interaction on intensities and phase shifts," *Phys. Rev.*, vol. 124, no. 6, pp. 1866-1878, Dec. 1961.
- [2] M.F. Limonov, M.V. Rybin, A.N. Poddubny, and Y.S. Kivshar, "Fano resonances in photonics," *Nat. Photon.*, vol. 11, no. 9, pp. 543-554, Sep. 2017.
- [3] Y. Yu, W. Xue, E. Semenova, K. Yvind, and J. Mork, "Demonstration of a self-pulsing photonic crystal Fano laser," *Nat. Photon.*, vol. 11, no. 2, pp. 81-84, Feb. 2017.
- [4] Y. Bao, Z. Hu, Z. Li, X. Zhu, and Z. Fang, "Magnetic plasmonic Fano resonance at optical frequency," *Small*, vol. 11, no. 18, pp. 2177-2181, May 2015.
- [5] Y. Wang, C. Sun, H. Li, Q. Gong, and J. Chen, "Self-reference plasmonic sensors based on double Fano resonances," *Nanoscale*, vol. 9, no. 31, pp. 11085-11092, Jun. 2017.
- [6] Z. Tu, D. Gao, M. Zhang, and D. Zhang, "High-sensitivity complex refractive index sensing based on Fano resonance in the subwavelength grating waveguide micro-ring resonator," *Opt. Express*, vol. 25, no. 17, pp. 20911-20922, Aug. 2017.
- [7] P.P. Vabishchevich, S. Liu, M.B. Sinclair, G.A. Keeler, G.M. Peake, and I. Brener, "Enhanced second-harmonic generation using broken symmetry III-V semiconductor Fano metasurfaces," *ACS Photon.*, vol. 5, no. 5, pp. 1685-1690, May 2018.
- [8] V.A. Nguyen, Q.M. Ngo, and K.Q. Le, "Efficient color filters based on Fano-like guided-mode resonances in photonic crystal slab," *IEEE Photon. J.*, vol. 10, no. 2, pp. 1-8, Feb. 2018.
- [9] Z. Shen, S. Zhou, S. Ge, W. Hu, and Y. Lu, "Liquid crystal induced dynamic cloaking of terahertz Fano resonators," *Appl. Phys. Lett.*, vol. 114, no. 4, Jan. 2019, Art. no. 041106.
- [10] C. Wu *et al.*, "Fano-resonant asymmetric metamaterials for ultrasensitive spectroscopy and identification of molecular monolayers," *Nat. Mater.*, vol. 11, no. 1, pp. 69-75, Jan. 2012.
- [11] B. Li *et al.*, "Sensing application in Fano resonance with T-shape structure," *J. Lightw. Technol.*, vol. 34, no. 14, pp. 3342-3347, Jul. 2016.
- [12] X. Guo, H. Hu, X. Zhu, X. Yang, and Q. Dai, "Higher order Fano graphene metamaterials for nanoscale optical sensing," *Nanoscale*, vol. 9, no. 39, pp. 14998-15004, Oct. 2017.
- [13] C. Wu, A.B. Khanikaev, and G. Shvets, "Broadband slow light metamaterial based on a double-continuum Fano resonance," *Phys. Rev. Lett.*, vol. 106, no. 10, pp. Mar. 2011, Art. no. 107403.
- [14] S. Zhan *et al.*, "Tunable nanoplasmonic sensor based on the asymmetric degree of Fano resonance in MDM waveguide," *Sci. Rep.*, vol. 6, no. 1, Mar. 2016, Art. no. 22428.
- [15] S. Wang, T. Zhao, S. Yu, and W. Ma, "High-performance nano-sensing and slow-light applications based on tunable multiple Fano resonances and EIT-like effects in coupled plasmonic resonator structure," *IEEE Access*, vol. 8, pp. 40599-40611, Mar. 2020.
- [16] N. Dabidian *et al.*, "Electrical switching of infrared light using graphene integration with plasmonic Fano resonant metasurfaces," *ACS Photon.*, vol. 2, no. 2, pp. 216-227, Dec. 2015.
- [17] Y.K. Srivastava *et al.*, "MoS₂ for ultrafast all-optical switching and modulation of THz Fano metaphotonic devices," *Adv. Opt. Mater.*, vol. 5, no. 23, Dec. 2017, Art. no. 1700762.
- [18] M. Song *et al.*, "Nanofocusing beyond the near-field diffraction limit via plasmonic Fano resonance," *Nanoscale*, vol. 8, no. 3, pp. 1635-1641, Dec. 2016.
- [19] N.K. Emani, T. Chung, A.V. Kildishev, V.M. Shalaev, Y.P. Chen, and A. Boltasseva, "Electrical modulation of Fano resonance in plasmonic nanostructures using graphene," *Nano Lett.*, vol. 14, no. 1, pp. 78-82, Dec. 2013.
- [20] S.H. Mousavi *et al.*, "Inductive tuning of Fano-resonant metasurfaces using plasmonic response of graphene in the mid-infrared," *Nano Lett.*, vol. 13, no. 3, pp. 1111-1117, Feb. 2013.
- [21] J. Park, K. Kim, I. Lee, H. Na, S. Lee and B. Lee, "Trapping light in plasmonic waveguides," *Opt. Express*, vol. 18, no. 2, pp. 598-623, Jan. 2010.
- [22] Z. Li, K. Wen, Y. Fang, and Z. Guo, "Refractive index sensing research on multi-Fano-based plasmonic MDM resonant structure with water-based dielectric," *IEEE J. Quantum Electron.*, vol. 56, no. 3, pp. 1-7, Jun. 2020.
- [23] S. Yan, X. Yang, D. Xu, H. Su, X. Wu, and E. Hua, "MIM structure with inverted M-type cavity for sensing applications," *IEEE Sens. J.*, vol. 21, no. 6, pp. 7468-7477, Mar. 2021.
- [24] S. Li, Y. Wang, R. Jiao, L. Wang, G. Duan, and L. Yu, "Fano resonances based on multimode and degenerate mode interference in plasmonic resonator structure," *Opt. Express*, vol. 25, no. 4, pp. 3525-3533, Feb. 2017.
- [25] Z. Guo, K. Wen, Q. Hu, W. Lai, J. Lin, and Y. Fang, "Plasmonic multichannel refractive index sensor based on subwavelength tangent-ring metal-insulator-metal waveguide," *Sensors*, vol. 18, no. 5, Apr. 2018, Art. no. 1348.
- [26] J. Zhu and N. Li, "MIM waveguide structure consisting of a semicircular resonant cavity coupled with a key-shaped resonant cavity," *Opt. Express*, vol. 28, no. 14, pp. 19978-19987, Jul. 2020.
- [27] R. Al Mahmud, M.O. Faruque, and R.H. Sagor, "A highly sensitive plasmonic refractive index sensor based on triangular resonator," *Opt. Commun.*, vol. 483, Nov. 2021, Art. no. 126634.
- [28] S. Zhan, *et al.*, "Tunable nanoplasmonic sensor based on the asymmetric degree of Fano resonance in MDM waveguide," *Sci.*

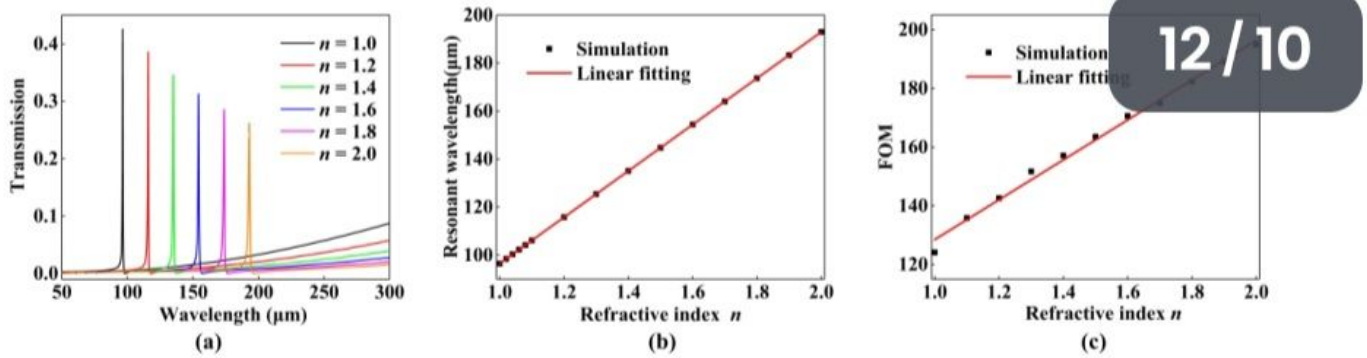


FIGURE 7. The sensing application of the proposed structure with different dielectric RI. (a) Transmission spectra of the Fano resonance when the dielectric RI changes from 1.0 to 2.0 ($L_1 = 20 \mu\text{m}$, $L_2 = 8 \mu\text{m}$, $w = 18 \mu\text{m}$, $t = 2.5 \mu\text{m}$, $a = 0.2 \mu\text{m}$, $d = 25 \mu\text{m}$). (b) The black dots show the numerically simulated resonance wavelength as a function of the dielectric RI. The red straight line is a linear fit to the simulated data, which is used to determine the sensitivity as 96480 nm/RIU. (c) The black dots show the FOM as a function of the dielectric RI. The red straight line is a linear fit to the simulated data.

TABLE I
COMPARISON OF FANO SENSING PERFORMANCE

Reference	Working wavelength range (THz)	Refractive index range (Δn)	S_{max} (nm/RIU)	FOM_{max}	Q-factor
[58]	1.1-1.5	1.0-1.6	20600	4.61	57
[59]	0.4-1.2	1.0-3.0	57000	0.83	5.3
[60]	0.3-0.7	1.0-2.0	103000	4.47	9.6
[61]	0.4-1.0	1.0-2.0	176000	14.05	11.22
[62]	1.0-7.0	1.0-1.8	6750	3.64	19.2
[63]	0.5-2.0	1.0-1.6	70500	1.34	5.34
[64]	0.6-2.0	1.0-2.0	32600	1.79	19.28
This work	1.0-7.0	1.0-2.0	96480	195	225

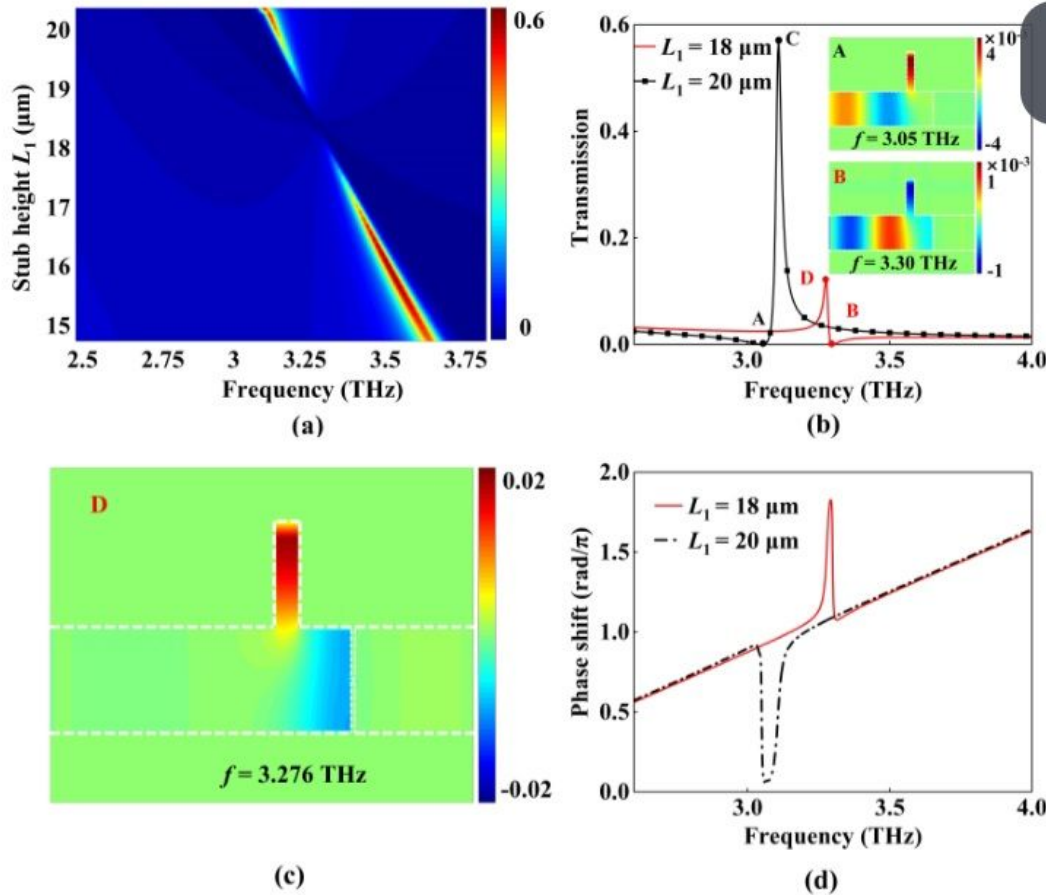
resonance increases due to the strongly enhanced field and interference strength. However, high Q-factor is accompanied by low transmission, thus there is a tradeoff between the maximum transmission and Q-factor of the proposed structure. Fig. 6(b) depicts that as thickness t increases from 0.5 to 4.5 μm , the Fano resonance peak has a slight shift, keeping at around 3.12 THz, which indicates the insensitivity of Fano resonant frequency to t . This property can be used to compensate the error caused by the inaccuracy of the device size and reduce the difficulty during the fabrication process. The transmission sharply decreases from 0.63 to 0.2 due to the increasing A and r shown in the inset of Fig. 6(d). From Fig. 6(d) we can see that the maximum Q-factor is 225 at $t = 2.5 \mu\text{m}$, which is suitable for the highly sensitive THz sensing application.

B. SENSING APPLICATION

Due to the narrow and sharp Fano resonance peak, one interesting application of the proposed structure is THz sensing. The sensitivity (S) is a significant indicator for characterizing the RI sensor, which is defined as $S = \Delta\lambda/\Delta n$ nm/RIU [53], where $\Delta\lambda$ and Δn represent the change of Fano resonant wavelength and the dielectric RI (n), respectively. Fig. 7(a) shows the transmission spectra with RI varying from 1.0 to 2.0 with a step of 0.2. The large

range of RI covers most biomolecules and chemical analytes in the THz region [34]. Here, several representative materials in the RI range of 1-2 are listed, such as, ovalbumin ($n \approx 1.15$), cyclohexane ($n = 1.3$), $\text{C}_8\text{H}_{18}\text{-C}_{16}\text{H}_{34}$ ($n = 1.39\text{-}1.43$), rapeseed oil ($n = 1.44$), 75% ethanol solution ($n = 1.6$), glycerin ($n = 1.77$), and HMX ($n = 1.81$). The Fano transmission spectra present a clear red-shift of the resonant wavelength, which varies from 96.48 to 192.95 μm . The transmission of Fano resonance decreases due to the increasing effective reflection coefficient of the proposed structure. A linear fit of the Fano resonant wavelength shown in Fig. 7(b) leads to a sensitivity of $S = 9.648 \times 10^4$ nm/RIU, which is comparable and higher than other THz Fano-based RI sensors shown in Table I.

Moreover, FOM also plays an important role in characterizing the performance of the sensor, which is defined as $FOM = S/FWHM$ [54]. Here, the FOM of the proposed structure with a dielectric RI sweeping from 1.0 to 2.0 is presented in Fig. 7(c). It indicates that the FOM increases linearly due to the increasing destructive interference and the reduction of Fano linewidth. The maximum FOM is up to 195 at $n = 2.0$. Furthermore, compared to other RI sensors, the sensor based on the proposed structure can achieve a higher FOM, which can be seen in the Table I.



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FIGURE 4. The characteristic analysis of the Fano resonance with different height of the stub resonator. (a) The transmission spectra with height varying from 15 to 20 μm ($L_2 = 8 \mu\text{m}$, $w = 18 \mu\text{m}$, $t = 1 \mu\text{m}$, $a = 0.2 \mu\text{m}$, $d = 25 \mu\text{m}$). (b) The comparison of Fano line shape between $L_1 = 18$ and 20 μm , and H_z field distributions at frequencies of (A) 3.05 THz and (B) 3.3 THz as the insets. (c) H_z field distributions with $L_1 = 18 \mu\text{m}$ at 3.276 THz. (d) The phase shift of the Fano system at $L_1 = 18$ and 20 μm .

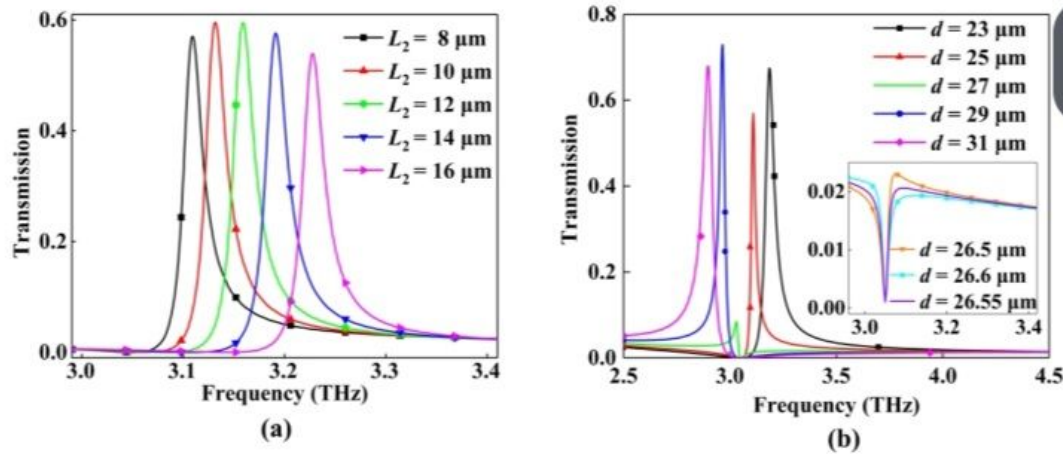
the strong coupling between stub resonator and waveguide, which is consistent with results discussed above. Meanwhile, electric fields mainly distribute in the stub resonator and metal wall at the Fano resonance peak shown in Fig. 2(d). The maximum field strength at the Fano resonance peak is five times larger than that at the Fano resonance dip. This is because that the strong destructive interference between stub resonator and metal wall induces the Fano transmission peak, which generates strong field distribution.

III. RESULTS AND DISCUSSION

A. PARAMETRIC ANALYSIS

Fano resonance is sensitive to the structure size. In order to improve Q-factor of Fano resonance, which is beneficial to achieve better THz sensing performance, we optimize parameters of the proposed structure and investigate the transmission T , reflection R , and loss A of Fano resonance

with three different geometric dimensions. Fig. 3(a) shows the high transmission peak, low reflection dip, and low loss of Fano resonance at $f = 3.915$ THz, where the loss A is defined as $A = 1 - T - R$. Due to the strong confinement of the MDM waveguide, the loss is not the radiative loss but the non-radiative loss caused by the materials. Compared to the result in Fig. 3(a), the transmission spectrum shown in Fig. 3(b) varies rapidly from dip to peak at $f = 3.05$ and 3.11 THz, respectively. A higher Q-factor of 130 is obtained with a transmission peak of 0.58. However, the reflection and loss of the proposed structure at the resonant frequency both increase, which induces the decrease of the Fano transmission peak. Fig. 3(c) shows a sharper Fano resonance with a transmission peak of 0.43 and a Q-factor of 225, which is twenty times larger than that in Fig. 3(a). The reflection at the resonant frequency is only 0.03, while the loss is up to 0.54 due to the enhanced destructive interference between stub resonator and metal wall. Therefore, the decline of transmission peak results from the increasing loss, which



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FIGURE 5. The Transmission spectra of the Fano resonance with (a) different width of stub resonator and (b) different distance between the center of stub resonator and metal wall. Parameters are set as $L_1 = 20 \mu\text{m}$, $L_2 = 8 \mu\text{m}$, $w = 18 \mu\text{m}$, $t = 1 \mu\text{m}$, $a = 0.2 \mu\text{m}$, $d = 25 \mu\text{m}$.

can be compensated by introducing gain mediums into resonators [52]. From the insets of Figs. 3(b) and (c) we can find that H_z field distributions in the stub resonator are in phase with that in the MDM waveguide at points B and C, which is different from the distributions at point A shown in Fig. 1(e). It indicates that there is the weak coupling and constructive interference between the stub resonator and MDM waveguide. Comparing H_z field distributions at three points, it can be seen that the high Q-factor of Fano resonance are attributed to the strong destructive interference between the stub resonator and metal wall, and the weak coupling between the stub resonator and MDM waveguide.

Since the Fano transmission dip is mainly determined by the stub resonator, the variation of dip in the Fano waveguide structure is consistent with that in the single stub-coupled waveguide structure. According to Eq. (1), with the increasing height L_1 of the stub resonator, the transmission dip of the Lorentzian-like line shape is redshift in the single stub-coupled waveguide structure. Similarly, as L_1 increases from 15 to 20 μm , the transmission dip is redshift in the Fano waveguide structure, as shown in Fig. 4(a). At the same time, Fano transmission peak is also redshift due to the increasing effective RI of the proposed structure. Besides, it depicts that the minimum transmission occurs at around $L_1 = 18 \mu\text{m}$. It can be explained that when L_1 is equal to the width w of the MDM waveguide, the coupling strength between stub resonator and MDM waveguide enhances to the maximum, eventually inducing the strong reflection and weak transmission. Since Fano resonance dip is more sensitive to L_1 than the peak, the former changes faster as L_1 increases. Therefore, Fano line shape is reversed at $L_1 = 20 \mu\text{m}$ compared to 18 μm in Fig. 4(b). In order to understand the conversion clearly, H_z field distributions and phase shift of the proposed structure with two different stub heights are investigated in Figs. 4(c) and (d). The stub resonator and metal wall are antiphase (D point) at first and then in-phase

(B point) at $L_1 = 18 \mu\text{m}$ shown in Fig. 4(c) and the lower inset of Fig. 4(b), respectively. The corresponding interference between the stub resonator and metal wall is destructive initially and then constructive, which generates the asymmetric Fano-type transmission spectrum. In addition, the phase shift of the proposed structure at $L_1 = 20 \mu\text{m}$ is different from that at 18 μm , as shown in Fig. 4(d). Therefore, the incident light has different degrees of phase shift after passing through the structure with different stub height, resulting in the conversion of Fano line shape.

Fig. 5(a) shows transmission spectra with the stub resonator width L_2 varying from 8 to 16 μm . Note that the stub resonator width plays an important role on the effective RI (n_{eff}) of the proposed structure and the coupling strength between stub resonator and MDM waveguide, which indirectly affects the variation of Fano transmission spectra. As L_2 increases, the Fano resonance peak shifts from 3.11 to 3.23 THz due to the decreasing n_{eff} . In addition, the transmission first increases owing to the decreasing coupling loss between stub resonator and MDM waveguide. Then it decreases due to the increasing reflection and enhanced coupling strength, where the maximum transmission is 0.6 at $L_2 = 10 \mu\text{m}$. The Fano resonance peak is red-shift and blue-shift with the increasing stub resonator height and width, and peak is more dependent on the stub resonator height than the width, which is demonstrated in Figs. 4(a) and 5(a). This is because that Fano resonant wavelength has a linear relationship with n_{eff} and stub resonator height shown in Eq. (1). Meanwhile, n_{eff} is inversely proportional to stub resonator width and has little correlation with width. Moreover, Fano transmission spectra with L_2 varying from 24 to 32 μm is plotted in Fig. S6(b) of the Supporting Information. It depicts that there is also a conversion from Fano-type to Lorentzian-type transmission spectrum as L_2 increases to 29 μm , which is similar to the conversion with different L_1 .

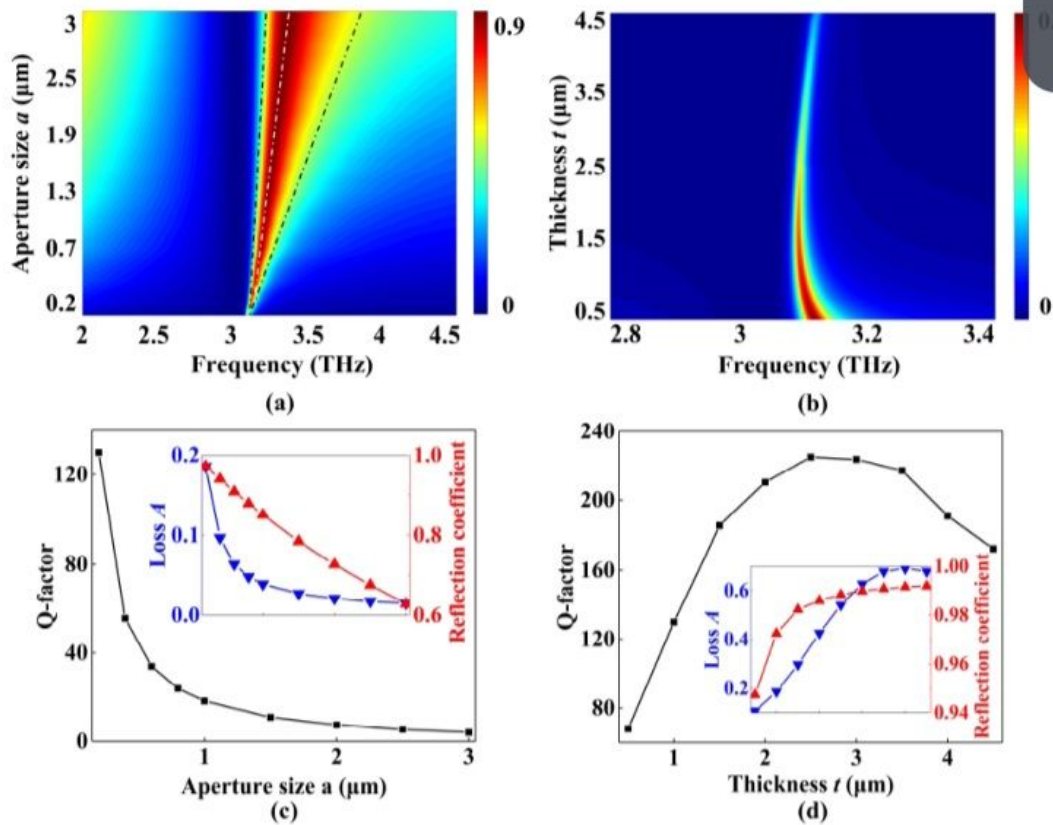


FIGURE 6. The Transmission spectra of the Fano resonance with (a) different aperture size of metal wall and (b) different thickness of metal wall. The calculated Q-factor of the Fano resonance as a function of (c) aperture size a and (d) thickness t . The reflection coefficient r and loss A with different a and t are shown in the insets of Figs. 6(c) and (d), respectively. Parameters are set as $L_1 = 20 \mu\text{m}$, $L_2 = 8 \mu\text{m}$, $w = 18 \mu\text{m}$, $t = 1 \mu\text{m}$, $a = 0.2 \mu\text{m}$, $d = 25 \mu\text{m}$.

Since the metal wall can be placed in an arbitrary position away from the stub resonator, Fano transmission spectra with different distance d are investigated in Fig. 5(b). As d increases from 23 to 31 μm , the resonant frequency shows a red shift from 3.18 to 2.90 THz. This is because that the phase shift δ has a linear relationship with d described in the theoretical analysis, which directly affects the variation of the Fano resonant frequency. Furthermore, the corresponding transmission is fluctuating and has a nonlinear relationship with d . It is due to the factor that d affects the interference strength between stub resonator and metal wall, and further results in the variation of the reflection of this structure, ultimately affecting the transmission. Moreover, as d increases to 26.55 μm , transmission spectra transform from Fano to Lorentzian line shape, as shown in the inset of Fig. 5(b). It can be explained that the strong destructive interference disappears between the stub resonator and metal wall at $d = 26.55 \mu\text{m}$. At the same time, the stub resonator manipulates the Lorentzian-type transmission spectrum independently and the metal wall impacts nothing on it. The conversion between Lorentzian and Fano line shape can be realized by adjusting the stub resonator height and width, as well as the position of the metal wall. Furthermore, from Fig.

S6(c) in the Supporting Information we can see that the metal wall in the left or right side of the stub resonator results in the similar phenomenon.

Considering that the reflection coefficient r is an important factor on Fano transmission spectrum presented in Eq. (5), we investigate the effect of geometric parameters on r by simulation, as shown in Fig. 6. Fig. 6(a) shows the relationship between the transmission and aperture size a which varies from 0.2 to 3 μm . It exhibits that the transmission increases with the increasing a , which is due to the decreasing r and non-radiative loss A , as shown in the inset of Fig. 6(c). It can be found that r and A are highly sensitive to the variation of a . In addition, we can find that the Fano resonance dip remains unchanged due to the factor that it is not determined by the metal wall but the stub resonator. However, Fano resonance peak blue-shifted from 3.11 to 3.35 THz. This is because that r decreases with the increasing a , and the destructive interference between the stub resonator and metal wall gets weaker with smaller r , which ultimately induces the broadening of the FWHM. Due to the invariant Fano resonance dip and increasing FWHM, the peak is far away from the dip and blue-shift. Fig. 6(c) shows that with the decreasing a , Q-factor of Fano

analyzed by SMT [49], [50]. The resonant wavelength of single stub-coupled waveguide structure can be described as [47]:

$$\lambda_m = \frac{4n_{eff}L_1}{2m - \Delta\phi(\lambda)/\pi}, \quad m = 1, 2, 3, \dots \quad (1)$$

where the effective RI n_{eff} is inversely proportional to the width of MDM waveguide and stub resonator, $\Delta\phi(\lambda)$ is the phase change of the incident light, m is the order of the resonance mode. According to Eq. (1), the resonant wavelength of this structure is proportional to the height of stub resonator, which is consistent with simulation results shown in Fig. S3(b) in the Supporting Information.

According to the SMT [49], transmission and reflection spectra of the single stub-coupled waveguide structure can be derived as:

$$T(f) = \frac{(f - f_0)^2 + (1/\tau_0)^2}{(f - f_0)^2 + (1/\tau_0 + 1/\tau_e)^2} \quad (2)$$

$$R(f) = \frac{(1/\tau_e)^2}{(f - f_0)^2 + (1/\tau_0 + 1/\tau_e)^2} \quad (3)$$

where f_0 is the resonant frequency, $1/\tau_0$ and $1/\tau_e$ represent the decay coefficient of the field due to intrinsic loss and coupling loss of the proposed structure, respectively [51]. To simplify the theoretical model, the intrinsic loss is not considered, thus transmission and reflection spectra of the single stub-coupled waveguide structure are obtained by Eqs. (2) and (3) shown in Fig. 2(a). The transmission reaches minimum $T_{min} = 0$ at $f = 3.3$ THz, which matches well with simulation results.

In order to break the symmetry line shape and obtain the sharp and asymmetric Fano transmission spectrum, a metal wall with an aperture is introduced at a certain distance from the center of stub resonator. The metal wall is regarded as a partially reflective element because the light is partly transmitted and partly reflected when passing through it. Transmission spectra of the Fano resonance can be calculated by combining the transfer matrix of stub resonator and metal wall [50]. Thus, the scattering matrix for the Fano structure with the incident wave at a frequency f is expressed as:

$$\begin{aligned} \begin{bmatrix} S_{-3} \\ S_{+3} \end{bmatrix} &= T_{cavity} T_0 T_{wall} \begin{bmatrix} S_{-1} \\ S_{+1} \end{bmatrix} \\ &= \begin{bmatrix} \frac{i(f - f_0) + 2/\tau_e}{i(f - f_0)} & \frac{2/\tau_e}{i(f - f_0)} \\ \frac{-2/\tau_e}{i(f - f_0)} & \frac{i(f - f_0) - 2/\tau_e}{i(f - f_0)} \end{bmatrix} \\ &\quad \begin{bmatrix} e^{i\delta} & 0 \\ 0 & e^{-i\delta} \end{bmatrix} \frac{1}{i\sqrt{1-r^2}} \begin{bmatrix} -1 & -r \\ r & 1 \end{bmatrix} \begin{bmatrix} S_{-1} \\ S_{+1} \end{bmatrix} \end{aligned} \quad (4)$$

where T_{cavity} and T_{wall} are the transfer matrix of stub resonator and metal wall, respectively, T_0 is the phase matching matrix. δ is the phase change of the light

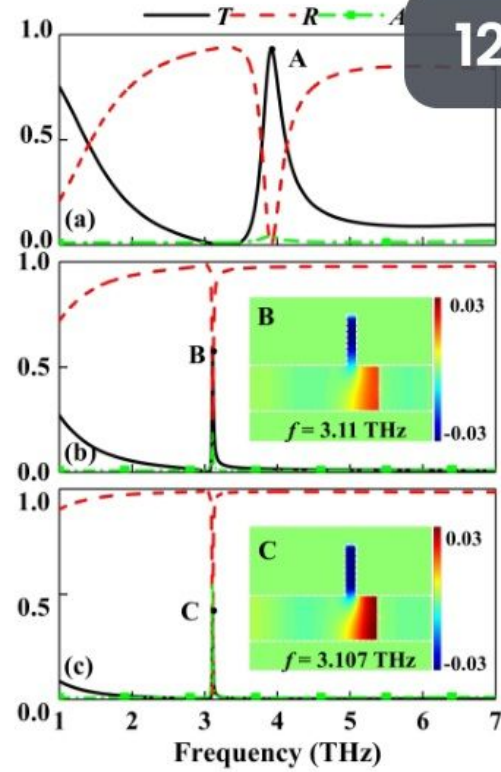


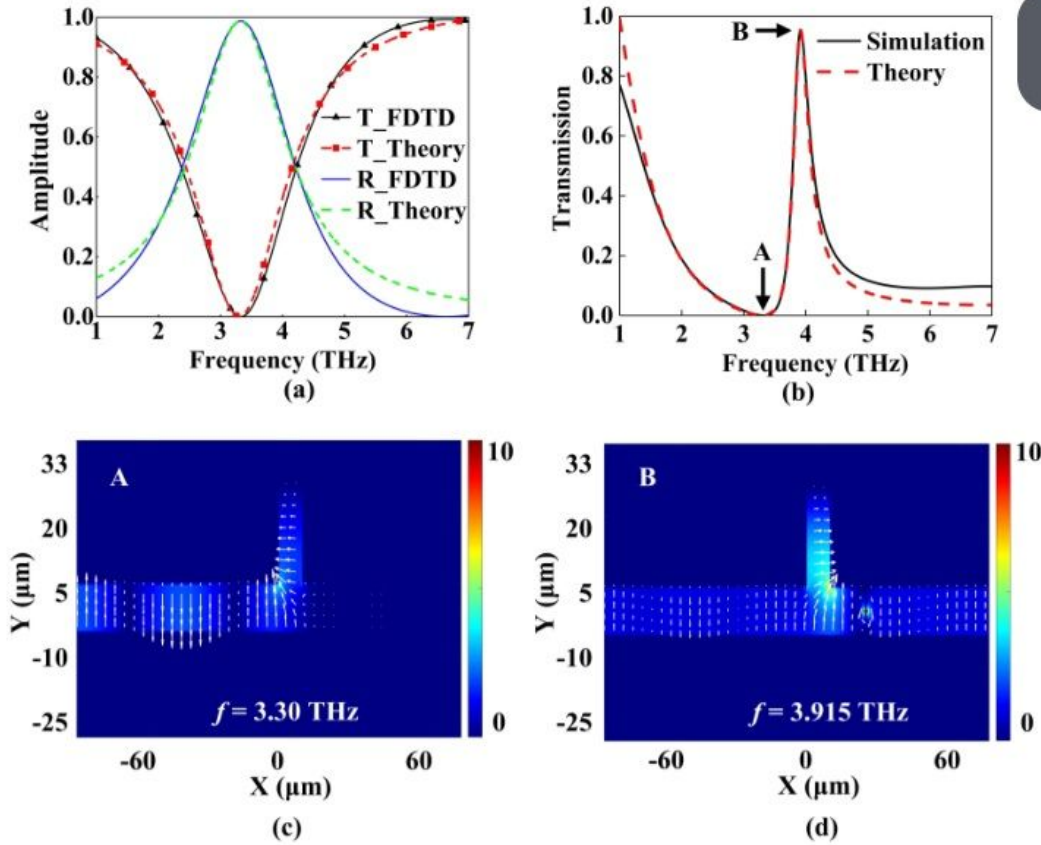
FIGURE 3. Characteristics of the Fano resonance with different structure parameters of the proposed structure. Simulated transmission (black solid curve), reflection (red dotted curve) and loss (green dotted curve) spectra of the proposed system with parameters set as (a) $L_1 = 20 \mu\text{m}$, $L_2 = w = 10 \mu\text{m}$, $t = 1 \mu\text{m}$, $a = 0.4 \mu\text{m}$, $d = 20 \mu\text{m}$, (b) $L_1 = 20 \mu\text{m}$, $L_2 = 8 \mu\text{m}$, $w = 18 \mu\text{m}$, $t = 1 \mu\text{m}$, $a = 0.2 \mu\text{m}$, $d = 25 \mu\text{m}$, and (c) $L_1 = 20 \mu\text{m}$, $L_2 = 8 \mu\text{m}$, $w = 18 \mu\text{m}$, $t = 2.5 \mu\text{m}$, $a = 0.2 \mu\text{m}$, $d = 25 \mu\text{m}$. H_z field distributions at points B and C are shown in the insets.

propagating from stub resonator to metal wall, defined as $\delta = 2\pi fd/c$, c is the velocity of light in vacuum. r is the reflection coefficient of the metal wall shown in Fig. S3(c) in the Supporting Information.

And transmission spectra of the proposed structure can be derived as:

$$T = \left| \frac{S_{-3}}{S_{+1}} \right|^2 = |r^2 - 1| \left| \frac{2\pi i(f - f_0)}{(2\pi(f - f_0) + 2i/\tau_e)e^{-i\delta} - 2ire^{i\delta}/\tau_e} \right|^2 \quad (5)$$

Transmission spectra of Fano resonance calculated by Eq. (5) in theory are shown in Fig. 2(b). It indicates that theoretical results are in accord with simulations, while slight deviation is mainly caused by the intrinsic loss of the structure and additional phase shift introduced by the stub resonator. More comparisons with different parameters can be found in Fig. S5 in the Supporting Information. In addition, strong local electric field can be generated due to the interference effect of the proposed structure, shown in Figs. 2(c) and (d). Fig. 2(c) shows that electric fields mainly focus on the stub resonator at the Fano resonance dip due to



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FIGURE 2. The comparison between theoretical and simulation results. (a) Simulation results (black and blue solid lines) and theoretical results (red and green dotted lines) of transmission and reflection spectra based on the stub-coupled MDM waveguide. Geometrical parameters are set as $L_1 = 20 \mu\text{m}$, $L_2 = w = 10 \mu\text{m}$, with $1/\tau_c = c\Delta\lambda/4\lambda_0^2 = 1 \times 10^{12} (\lambda_0$ and $\Delta\lambda$ are the resonant wavelength and bandwidth of stub resonator, respectively), $f_0 = 3.3$ THz. (b) The simulation result (black solid line) and theoretical result (red dotted line) of transmission spectra based on MDM waveguide coupled with stub resonator and metal wall. Geometrical parameters are set as $L_1 = 20 \mu\text{m}$, $L_2 = w = 10 \mu\text{m}$, $t = 1 \mu\text{m}$, $a = 0.4 \mu\text{m}$, $d = 20 \mu\text{m}$, with $1/\tau_c = c\Delta\lambda/\lambda_0^2 = 4 \times 10^{12}$, $f_0 = 3.3$ THz. Electric field $|E|$ and electric field vector distributions at the Fano resonance (c) dip and (d) peak, and the length and direction of white arrows represent the amplitude and direction of E , respectively.

analyses on propagation loss are presented in Supporting Information.

Fig. 1(c) demonstrates that Fano resonance is induced by the interference between the stub resonator (discrete mode) and metal wall (continuum mode). But it is not clear what kind of interference it is. In order to illustrate the interference mechanism clearly, H_z field distributions at the Fano transmission dip and peak are depicted in Figs. 1(d) and (e), respectively. Fig. 1(d) reveals that the propagation of the incident light is inhibited and reflected at $f = 3.3$ THz due to the strong coupling between MDM waveguide and stub resonator. Meanwhile, due to the in-phase of H_z field distributions in stub resonator and left side of metal wall, the constructive interference between them occurs and further enhances the reflection, leading to the minimum transmission. Therefore, it can be concluded that the stub resonator plays a crucial role in the formation of Fano resonance dip. On the contrary, Fig. 1(e) exhibits that the

incident light can effectively pass through the designed waveguide structure at 3.915 THz. The H_z field distributions in the stub resonator and left side of metal wall are antiphase and induce strong destructive interference between them, which cancels the reflection and results in a sharp transmission peak. Therefore, Fano transmission dip is mainly determined by the strong reflection of stub resonator and assisted by the constructive interference between the stub resonator and metal wall. Fano transmission peak is caused by the destructive interference between them. In addition, the stub resonator and metal wall act as a Fabry-Pérot cavity with the strong $|H_z|^2$ field distributions observed in Fig. 1(f). The dynamic process of H_z field distributions can be found in Supplementary video.

B. THEORETICAL CALCULATION

The characteristics of the proposed structure can be further

dimensions and makes them difficult to integrate into chips. Contrarily, MDM waveguide, due to its deep subwavelength confinement of light, easy fabrication, low propagation loss and long propagation distance [40]-[42], can be used to solve these problems. Moreover, it holds compact size and great promise for THz subwavelength plasmonic device and highly integrated optical circuits. However, high Q-factor Fano-based MDM waveguide structure, which is a suitable platform for sensing application, remains rare explored in THz band.

In this paper, we propose a THz subwavelength MDM waveguide structure composed of a metal wall with an aperture in the center and a stub resonator, which can excite high Q-factor Fano resonance. The formation of Fano resonance is not only investigated numerically by finite-difference time-domain (FDTD) solutions but also analyzed by the scattering matrix theory (SMT). Moreover, the electromagnetic field distribution is exhibited to further explain the mechanism of Fano resonance. Considering the ohmic losses can weak the SPPs in MDM waveguide, the propagation distance of SPPs is also calculated. Furthermore, the effect of structure parameters on Fano transmission spectra, especially on improvement of Q-factor and the conversion between asymmetric Fano and symmetric Lorentzian profile, is clearly demonstrated. Finally, since the resonant frequency of SPPs excited in MDM waveguide is highly sensitive to the change of dielectric environment around metal, a Fano-based THz sensor with a sensitivity of 96480 nm/RIU and a FOM of 195 in the RI range of 1-2 is studied. In brief, the structure provides new routes for THz sensing application and subwavelength plasmonic device.

II. STRUCTURE DESIGN AND THEORETICAL ANALYSIS

A. CONFIGURATION AND NUMERICAL SIMULATION

Figs. 1(a) and (b) exhibit the 3D schematic diagram and the top view of the proposed MDM waveguide structure, which consists of a stub resonator and a metal wall with an aperture in the center. Waveguide-resonator structure is selected because it can create interesting notch effect. The metal wall is introduced to break the symmetric profile of waveguide-resonator structure and realize high-Q Fano resonance. The orange and white areas represent gold and air ($\epsilon_d = 1$). The height L_1 and width L_2 of the stub resonator are 20 and 10 μm , respectively. The thickness of the metal wall t is 1 μm , the aperture size a in the metal wall is 0.4 μm . The distance d between the center of the stub resonator and metal wall is 20 μm , and the width of the MDM waveguide w is 10 μm . Properties of the proposed structure are numerically investigated by the two-dimensional FDTD. Note that 2D simulation results are close to 3D results when structure thickness is larger than the wavelength of incident light [43]. In addition, simulation time and complexity are obviously reduced without weakening the accuracy. The dielectric permittivity of gold is represented by the Drude model [44].

The Gaussian pulse is injected into the waveguide input and excites the fundamental TM mode with magnetic field parallel to the stub resonator. The maximum and minimum mesh step in the x and y directions are set as 1.8 μm and 0.01 μm , respectively. Boundary conditions in the x and y directions are perfect matched layers. Two power monitors are set at the input and output of the waveguide to calculate the incident power T_{in} and transmitted power T_{out} , transmission T of the THz waveguide structure is described as $T = T_{out}/T_{in}$. Moreover, high frequency structure simulator (HFSS) are also used to obtain the simulation result of the proposed structure, which is similar to the result simulated by FDTD (see Supporting Information, Fig. S1). The proposed structure can be fabricated by focused-ion-beam (FIB) and E-beam. First, we use FIB to etch a certain depth of stub-wall-coupled waveguide structure on Si substrate. Then we deposit titanium (Ti) film on the surface of the structure to increase adhesion between gold and Si. In the end, we can use E-beam to deposit gold on the surface of this structure. In fact, the simulation results of Al and Ag are consistent with gold, as shown in Fig. S2 in the Supporting Information. Characteristics of Al and Ag are obtained by Lorentz-Drude mode [46] and the experimental optical constant of Hagemann et al. [45], respectively. Therefore, the proposed structure shows strong universality and feasibility. Several metal materials, such as gold, Al, and Ag, can be selected in practical application.

To better understand the interaction between the stub resonator and metal wall, the MDM waveguide with only a stub resonator and with only a metal wall is calculated, respectively. The transmission spectrum for the single stub-coupled waveguide structure is shown as the black line in Fig. 1(c), which is a symmetric Lorentzian-like line shape for notching filter [47]. The transmission spectrum of a single metal wall with an aperture in MDM waveguide exhibits continuous broadband line shape shown in the Fig. 1(c) (red line). For waveguide with a stub resonator and a metal wall, the transmission spectrum exhibits an asymmetric Fano line shape, which is the green line in Fig. 1(c). It is worth noting that the maximum transmittance is not 100% but $\sim 95.4\%$ at the Fano resonance peak mainly due to the ohmic loss of Au and the coupling loss of the proposed structure. A return loss of 23 dB and a transmission loss of ~ 0 dB also exist (see Fig. S3(a) in the Supporting Information). Furthermore, the full width half maximum (FWHM) of Fano resonance is 0.348 THz, thus Q-factor is ~ 11.25 with the definition of $Q = f_0/\text{FWHM}$, where f_0 is the resonant frequency. The minimum transmittance is 0 at the notch frequency of 3.3 THz, which corresponds to a return loss of 0 dB and a transmission loss of 60 dB shown in Fig. S3(a) of the Supporting Information. Meanwhile, the propagation loss per unit distance of $2.836 \times 10^{-4} \text{ dB}/\mu\text{m}$ is calculated by FDTD shown in Fig. S4 in the Supporting Information, corresponding to propagation length of $\sim 1.47 \text{ cm}$ [48]. More detailed

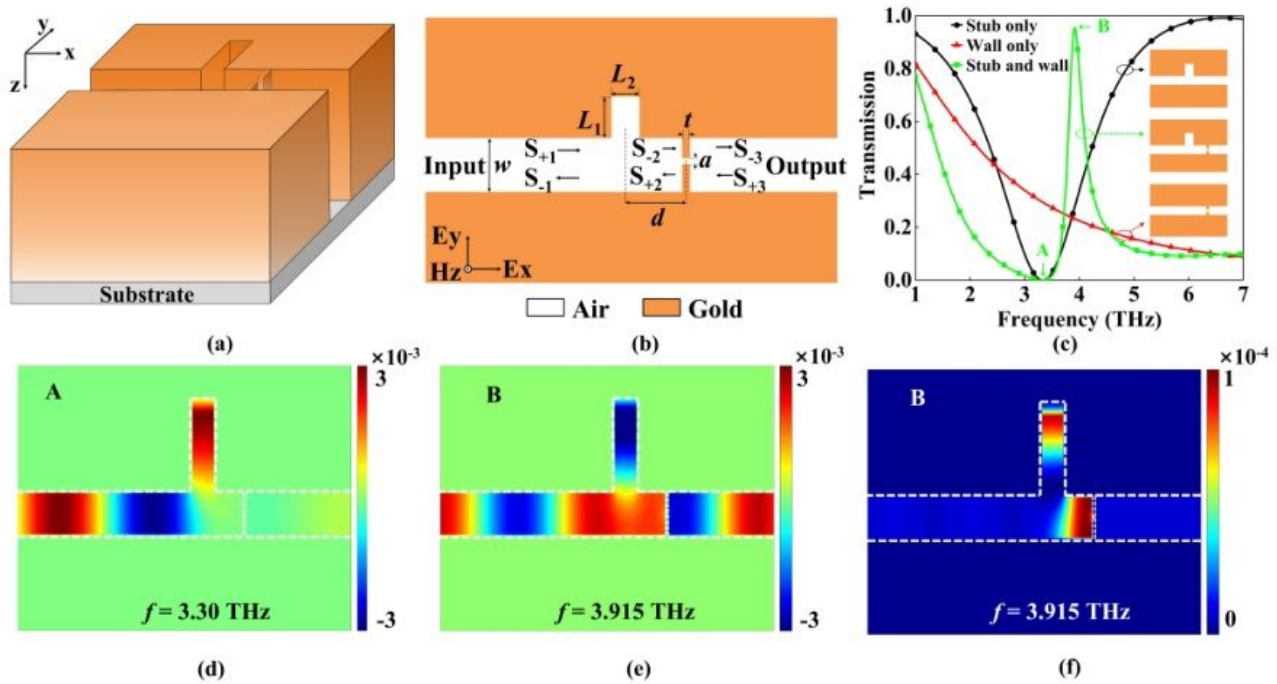


FIGURE 1. Structure design and properties of Fano resonance. (a) 3D diagram of the proposed structure. (b) 2D cross section of the proposed structure. (c) Transmission spectra of MDM waveguide structure with only a stub resonator (black curve), only a metal wall (red curve), and both stub resonator and metal wall (green curve). Geometrical parameters are set as $L_1 = 20 \mu\text{m}$, $L_2 = w = 10 \mu\text{m}$, $t = 1 \mu\text{m}$, $a = 0.4 \mu\text{m}$, $d = 20 \mu\text{m}$. (d) H_z field distributions at 3.3 THz. (e) H_z and (f) $|H_z|^2$ field distributions at 3.915 THz.

and infrared band, such as rectangular resonators [22], [23], multiple ring or disk resonators [24], [25], stub resonators combined with ring or disk resonators [15], [26], and triangular resonators [27]. Furthermore, due to the sensitivity of Fano resonance to the dielectric region, Fano-based MDM waveguide has great potential for refractive index (RI) sensing application. Many related studies devoted to improving the sensing performance have been reported in visible and infrared band. In 2016, Zhan et al. found that adjusting the asymmetry factor of Fano in MDM waveguide structure can improve the performance of the RI sensor and achieve a sensitivity of 780nm/RIU, which can also be used for slow light sensing [28]. In order to investigate the coupling of different wave modes and break the traditional method of coupling between cavities, Chen et al. introduced metallic double-baffle into ring-coupled MDM waveguide to realize Fano resonance, and obtained a RI sensor with sensitivity of 825nm/RIU [29]. In 2019, Chen et al. tuned the transmission spectrum of Fano resonance after the structure size was fixed, and achieved temperature adjustable Fano-based sensor with sensitivity of 0.31nm/°C [30]. Zhou et al. achieved a RI sensor with the sensitivity of 8280nm/RIU in MDM waveguide structure by introducing metal nanorods into the T-cavity, which was the highest sensitivity reported in cavity-MDM waveguide structure [31]. Due to the development of highly integrated circuits, multiple Fano resonances achieved in single MDM waveguide are of practical significance. In 2020, eight Fano peaks were

generated from the visible to near-infrared band by introducing two metal barriers into ring-stub-coupled MDM waveguide structure, and a RI sensor with sensitivity of 1062nm/RIU was obtained [32]. Considering figure of merit (FOM) is also an important indicator of sensor, Zhang et al. proposed a Fano-based RI sensor with sensitivity of 923nm/RIU and FOM of 710 in MDM waveguide coupled with an equilateral triangle-shaped cavity, which significantly improved FOM [33]. These studies show that the sensing performance of RI sensor realized by Fano-based MDM waveguide structure has been improved in visible and infrared band. However, compared with terahertz (THz) Fano-based sensors, the sensitivity still needs to be improved.

In the THz region, Fano resonance is mainly achieved by the periodic array in metamaterials/metasurfaces and possesses high sensitivity in sensing applications [34]–[37]. Realizing high quality factor (Q-factor) Fano resonance is of particular significance to improve the resolution of THz sensor. However, the plasmonic metamaterials are strongly coupled to free space and have thin thickness, which leads to the limitation of possessing high electromagnetic field confinement. Thus, Q-factors of Fano resonance based on them need to be further improved and radiation losses need to be reduced [38]. All-dielectric metamaterials can overcome these shortcomings of plasmonic metamaterials to some extent, but they have the problems of diffraction limit and low field enhancement [39]. Furthermore, the dependence on periodic structures leads to inevitably large

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High-Q Fano Resonance in Subwavelength Stub-Wall-Coupled MDM Waveguide Structure and Its Terahertz Sensing Application

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ABSTRACT Waveguide structures effectively controlling and guiding terahertz (THz) waves can achieve interesting resonance effects when combined with resonators. At present, achieving high quality factor (Q-factor) resonance in THz resonator-coupled waveguide structure is still a critical consideration to expand its practical application. Here, a high Q-factor Fano resonance based on a metal-dielectric-metal (MDM) waveguide consisting of a stub resonator and a metal wall with an aperture in the center is investigated theoretically and numerically in the THz region. The results show that the sharp and asymmetric Fano resonance peak is induced by the destructive interference between the stub resonator and metal wall which act as a Fabry-Pérot cavity. Q-factor is obviously improved about 60 times (3.72 to ~225) by introducing the metal wall into the stub-coupled MDM waveguide. Moreover, Fano resonance can be effectively tuned by varying different structure parameters. Owing to the high sensitivity of Fano resonance peak to dielectric surroundings, a large-range refractive index (RI) sensor based on the proposed structure with a high sensitivity of 96480 nm/RIU is obtained. The figure of merit (FOM) of 195 is greatly improved compared to other THz Fano-based RI sensors. These results provide possibilities for subwavelength MDM waveguide structure to apply for THz bio/chemical sensing, bandpass filters, and on-chip highly integrated plasmonic device.

INDEX TERMS Fano resonance, MDM waveguide, high Q-factor, THz sensing

I. INTRODUCTION

Fano resonance was firstly discovered in the autoionizing states of atoms by Ugo Fano, caused by the constructive and destructive interference between a discrete excited state and a broad continuum resonant scattering process [1], [2]. It not only exists in quantum systems, but also can be realized in symmetry-breaking classical systems, such as photonic crystals, plasmonic nanostructures, gratings, resonator-coupled waveguide structures, and metamaterials [3]-[7]. Compared to the symmetric Lorentzian profile, Fano resonance presents a sharp asymmetric line shape and a dramatic variation from dip to peak with only a small frequency shift, resulting in characteristics of easy identification and tracking of resonance peak. And it can also

generate strong local electric field due to the interference effect. In addition, it is highly sensitive to the variation of geometric parameters and surroundings environment, leading to great advantages in tunability of Fano transmission spectra. These properties allow Fano resonance to be widely studied for these applications, including filters [8], [9], sensing [10]-[12], slow-light effect [13]-[15], optical switching [16], [17], nanofocusing [18] and modulator [19], [20].

In recent years, metal-dielectric-metal (MDM) waveguide structure supporting surface plasmon polaritons (SPPs) has attracted much attentions because of its strong field enhancement and deep subwavelength confinement [21]. Meanwhile, Fano-based MDM waveguide structure coupled with different shapes of resonators can be found in visible