

Tunable Fano resonance based on plasma-dielectric-plasma waveguide coupled resonator system

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A plasma-dielectric-plasma (PDP) waveguide structure consisting of a bus waveguide, a stub cavity, and a U-shaped coupling cavity is designed, and the two-dimensional finite-difference time-domain (FDTD) method is adopted for simulation. Transmission spectra show that the stub cavity structure corresponds to a continuous spectrum, the coupling cavity structure corresponds to a discrete state, and the coupling of the two resonators can produce a significant Fano resonance. Magnetic field distribution confirms that energy localization and destructive interference determine the transmission dips, while dual-cavity coupling enhances transmission at the Fano peak. The geometric parameters of the structure (coupling cavity side length, stub cavity length, and cavity spacing) can effectively regulate the position, transmittance, and line shape of the Fano resonance. In the present work, a Fano interference model is constructed to fit the transmission spectra, and the theoretical calculation results are in excellent consistency with the FDTD simulation results. In the frequency band of 0.3–1.3 GHz, the dielectric constant of the gaseous discharge plasma is determined by the plasma frequency, thus enabling the PDP structure to break the limitation that traditional waveguides cannot be dynamically modulated after fabrication. Dynamic tuning of the resonance frequency and transmittance can be realized by changing the plasma electron density. In this work, the designed PDP structure can be prepared using electron beam lithography (EBL), focused ion beam (FIB) lithography, and nano-imprinting technology. This provides a feasible solution for dynamic tunable plasma devices in the microwave frequency band.

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1. Introduction

The interaction between incident electromagnetic waves and the surface can generate surface plasmon polaritons (SPPs), and these oscillations will propagate along the interface [1–3]. Because SPPs possess numerous unique optical properties, they are widely applied in the field of nanophotonics, such as in temperature sensors and antioxidant devices, etc [4–6]. The mechanism of SPPs is as follows: Electromagnetic waves within a specific frequency range can excite collective electron oscillations within the metal layer, which is known as electron plasma resonance [7–9]. Fano resonance is an important phenomenon in the fields of quantum physics and optics [10,11]. Its essence is the coupled resonance of continuous states and discrete states. This resonance will result in asymmetric peaks or valleys [12]. Fano resonance can further enhance the performance of SPPs devices [13–15]. Fano resonance is also widely applied in cutting-edge fields such as sensors [16–18], slow light [19–21], absorbers [22,23] and optical switches [24–26].

In traditional waveguide structures, Fano resonance also has extensive applications. However, the traditional metal-dielectric-metal (MDM) waveguide structure is limited by the fact that once it is fabricated, its properties

are difficult to change [27–29]. Therefore, it is necessary to develop a waveguide structure with a simple design and the ability to be dynamically adjustable. Gaseous discharge plasma, a special type of electromagnetic material, has a dielectric constant with wide-spectrum continuous tunability within a specific frequency range [30–32]. When the real part of the plasma dielectric constant is negative, SPPs can be excited at the plasma-dielectric interface [33–35].

Therefore, based on the characteristics of plasma, this paper proposes a plasma-dielectric-plasma (PDP) waveguide structure. The two-dimensional time-domain finite difference (FDTD) method was employed to conduct a systematic simulation of this structure. The key parameters, such as the boundary conditions of the simulation area, the grid step size, and the simulation time, were clearly defined to ensure the accuracy and reliability of the simulation results. During the research process, the structural parameters of the PDP structure were first introduced. Subsequently, through the transmission spectroscopy test, the coupling mechanism between the short column cavity and the coupled cavity was explored, clarifying that the short column cavity corresponds to the continuous spectrum, while the coupled cavity corresponds to the discrete state. The coupling of the two

can generate a significant Fano resonance. Through the analysis of the magnetic field distribution, the role of energy localization and destructive interference in determining the transmission valleys was verified, as well as the transmission enhancement effect of the double-cavity coupling at the Fano peak. At the same time, the governing laws of the geometric parameters, such as the length of the coupled cavity, the length of the short cavity, and the cavity spacing on the Fano resonance position, transmission rate, and line shape were systematically studied. The transmission spectrum was fitted using the Fano interference model to verify the good consistency between the theoretical calculation and the FDTD simulation results. Additionally, by utilizing the tunable property of the plasma dielectric constant, the dynamic tuning of the structural resonance frequency and transmission rate through changing the plasma electron density was achieved. Finally, the fabrication method of the structure was proposed, providing a possibility for the preparation of this structure.

2. Design and simulation

The proposed PDP plasmonic structure is shown in Fig. 1. (a). The structure is composed of a bus waveguide, a stub cavity, and a U-shaped coupling cavity. According to the SPPs' theory of the PDP waveguide, this waveguide system can excite and propagate a TM mode. In this case,

the TM mode refers to the type of mode that has a magnetic field component only in the transverse direction and no such component in the propagation direction. Fig. 1 (b) shows the indications of the geometric parameters of the proposed structure. The meanings of the corresponding parameters and their specific values are presented in Table 1. The refractive index of SiO_2 is 1.478. Here, the dielectric constant of the gaseous discharge plasma is calculated based on the two-fluid or kinetic models proposed in the relevant literature [36–38]. In the frequency band of 0.3 - 1.3 GHz discussed in this article,

where $\omega \geq \omega_{pi}$ ($= \sqrt{n e^2 / \epsilon_0 m_i} \leq \omega_{pe}$) and $\omega \geq k v_e$ ($= k \sqrt{T_e / m_e}$),

both ion reactions and thermal effects can be disregarded. Therefore, its dielectric constant can be expressed as follows [39,40]:

$$\epsilon_p = 1 - \frac{\omega_{pe}^2}{\omega(\omega + i\nu)} \quad (1)$$

where ω represents the angular frequency of electromagnetic waves. ν is the collision rate of electrons and neutral particles. f_{pe} is the plasma frequency. $f_{pe} = \omega_{pe} / 2\pi$, where $\omega_{pe} = \sqrt{n_e e^2 / \epsilon_0 m_e}$. n_e is the electron density and m_e is the electron mass.

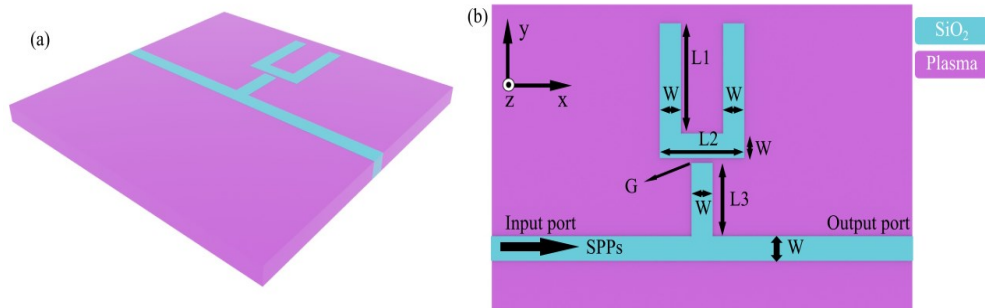


Fig. 1. (a) The 3D view of the proposed PDP structure. (b) The top view of the proposed structure (colour online)

Table. 1. The table of structural parameters

Parameter	Symbol	Value	Unit
Plasma frequency	f_{pe}	8	GHz
Collision rate	ν	$0.01 \times 10^9 \times 2\pi$	s^{-1}
Dielectric region width	W	5	mm
Side length of the coupled cavity	L1	45	mm
Bottom edge length of coupling cavity	L2	40	mm
The resonant cavity length	L3	30	mm
The distance between the coupled cavity and the resonant cavity	G	2	mm

In this article, we employ the FDTD. The simulation area is set to 2D mode. The boundary condition in the x-direction is set as a perfectly matched layer (PML), and the boundary condition in the y-direction is set as the metal. The simulation time is 1010 fs. The simulation temperature is 300 K. The light source enters along the x-direction from the bus waveguide.

3. Result and discussion

Fig. 2 (a) illustrates the transmission spectra of the whole structure (WS), the bus waveguide with stub cavity (WSC), and the bus waveguide with coupling cavity (WCC), respectively. When the electromagnetic waves are incident from the bus waveguide, the spectral lines of WCC are relatively smooth, the overall transmittance is almost 1, and the spectral lines of WCC can be considered

as discrete spectra. While, for WSC, there is a transmission valley appearing at 0.875 GHz, therefore, the spectral lines of WSC can be regarded as discrete spectra, while the spectral lines of WCC can be considered as continuous spectra. When two resonators are simultaneously excited, an obvious asymmetric Fano line appears. The coupled surface waves will alter the resonant conditions, resulting in the formation of a distinct Fano line within the two resonant cavities. For the convenience of subsequent description, we have marked several key points in the figure (dip1, dip 2, dip 3, peak). Fig. 2 (b) shows the magnetic field ($|H_z|$) diagram at the frequency corresponding to the peak. It can be clearly seen that most of the energy is concentrated in the short cavity and at the top of the coupled cavity. This indicates that it is the mutual coupling between two resonant cavities that results in a higher transmission rate for this structure at specific frequencies.

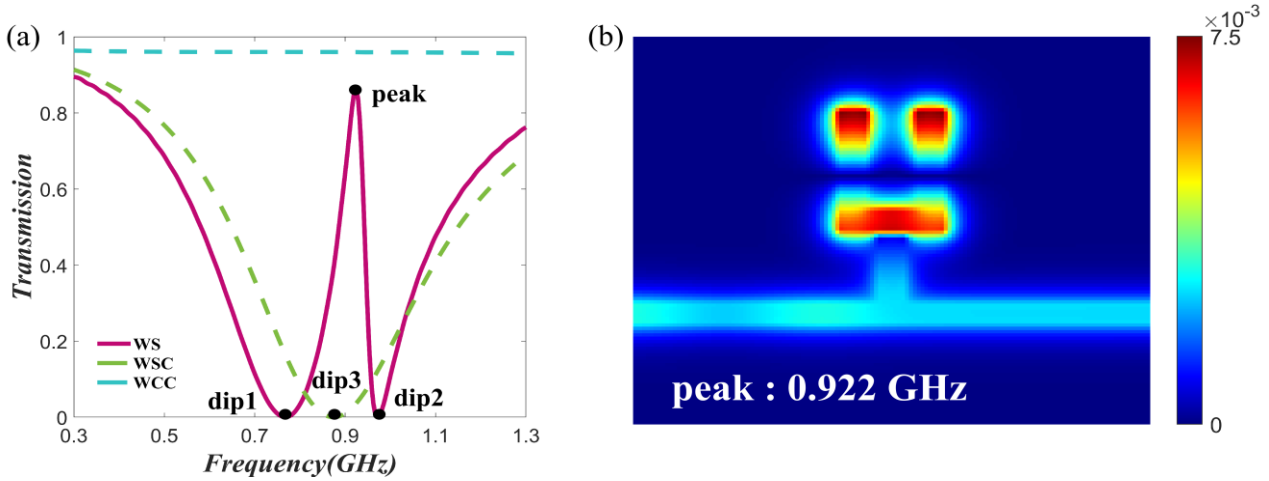


Fig. 2. (a) The transmission spectra of the whole structure and individual structures. (b) The magnetic field map with the frequency of 0.922 GHz (colour online)

To further explain the physical laws governing the Fano phenomenon, we presented magnetic field ($|H_z|$) diagrams at several specific frequency points. Fig. 3 (a) is the magnetic field ($|H_z|$) map at dip1. The energy is coupled into the stub cavity. The stub cavity is effectively activated through strong destructive interference, preventing the transmission of magnetic field energy to the right side. In the magnetic field distribution map of dip2, the energy is concentrated in the coupling cavity and the stub cavity. This is because the coupling cavity and the stub cavity are mutually coupled, causing destructive interference to the propagation of the magnetic field, resulting in a relatively low transmission rate. In Fig. 3 (c), the magnetic field ($|H_z|$) diagram of dip3 is shown under the structure with only the bus waveguide and the stub cavity. The energy is mainly concentrated within the stub cavity and undergoes destructive interference with the electromagnetic waves in the bus waveguide. This makes

WSC be regarded as a discrete state. While in Fig. 3 (d), the magnetic field diagram ($|H_z|$) at a frequency of 0.875 GHz is shown under the structure with only the bus waveguide and the coupled cavity. The coupled cavity cannot be effectively activated, and the propagation of electromagnetic waves is not affected. Thus, the spectral line has the characteristic of high transmittance. Therefore, it can be regarded as a continuous state. At a specific frequency, the discrete state and the continuous state are coupled with each other, resulting in destructive interference, allowing some of the magnetic field to propagate. As shown in Fig. 2 (b), the significant Fano effect is produced by the mutual coupling of the two states.

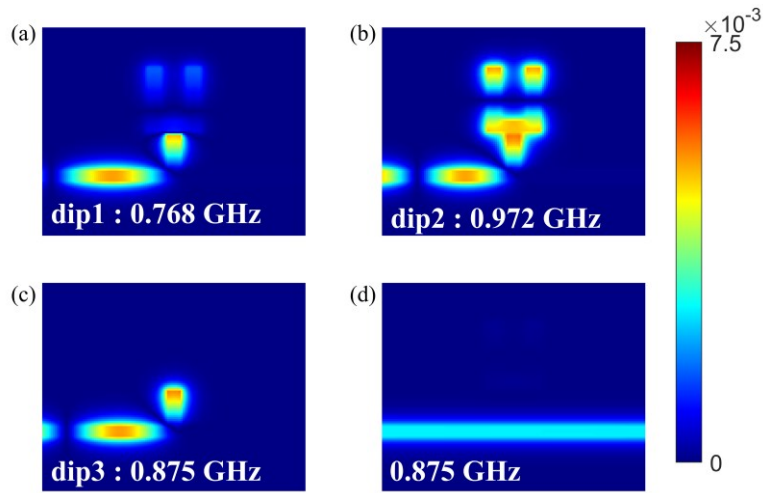


Fig. 3. (a) The magnetic field map at the dip1 position. (b) The magnetic field map at the dip2 position. (c) The magnetic field map at the dip3 position. (d) The magnetic field map with the frequency of 0.875 GHz (colour online)

Next, the influence of geometric parameters on the Fano spectrum was studied. In Fig. 4 (a), the influence of the coupling cavity's side length on the Fano spectrum was studied. As the side length changes from 43 mm to 47 mm, the frequencies of peak and dip2 undergo a redshift. This is because the resonant wavelength is proportional to the side length of the coupling cavity $\lambda_m = n_{eff} L_{eff} / m$ [41]. The

variation of the bottom edge of the coupling cavity is shown in Fig. 4. (b). As the value of L2 increases, the anti-symmetry degree of transmission spectral lines changes because the change in the length of the U-shaped cavity bottom affects the phase matching with the stub mode.

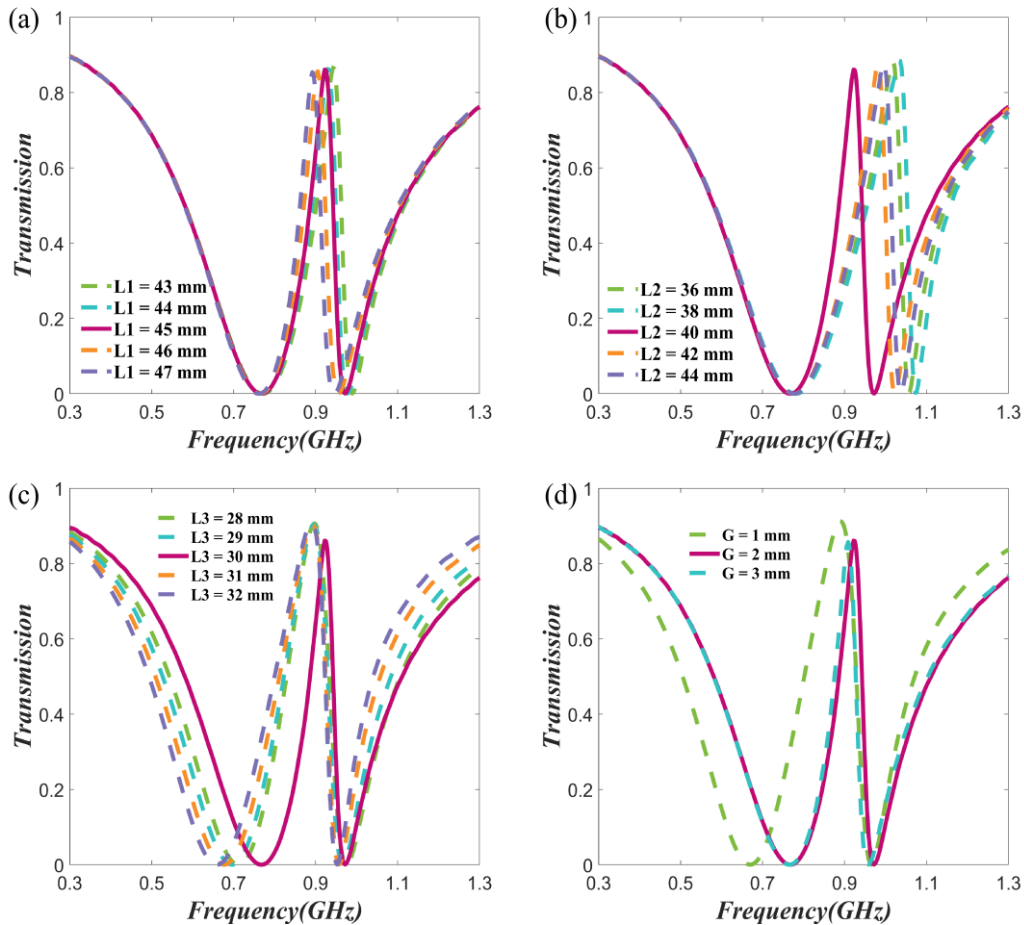


Fig. 4. (a) The transmission spectrum for different L1 (b) The transmission spectrum for different L2. (c) The transmission spectrum for different L3. (d) The transmission spectrum for different G (colour online)

Fig. 4 (c) shows the variation of the short cavity side length L_3 . As L_3 increases, the full width at half maximum of the transmission spectral line varies because L_3 will adjust the Q value of the discrete spectral line, thereby affecting the line shape of the coupled Fano spectral line. At the same time, the influence of the distance G between the short cavity and the coupled cavity on the transmission spectrum was also studied. In Fig. 4 (d), as G increases from 1 mm to 3 mm, the transmission rate corresponding to the peak decreases. This is because the coupling strength between discrete and continuous states decreases with increasing coupling distance.

To further explain the physical mechanism of the coupling between the modes, the Fano interference model was adopted. As shown in Fig. 5 (a-d). The simulation results of FDTD under different f_{pe} are presented in the form of implementation. The dotted lines represent the results of theoretical quantitative calculations. The transmission function T can be expressed as: $T = 1 - |t|^2$. Here, t can be expressed as [42,43]:

$$t = A + \sum_{i=1}^{\infty} \frac{a_i \Gamma_i e^{j\varphi_i}}{\omega - \omega_i + j\Gamma_i} \quad (2)$$

where A represents the modulation amplitude. ω is the incident angular frequency. a_i indicates the amplitude of the i -th oscillator. Γ_i represents the radiation damping of the i -th oscillator. φ_i indicates the phase of the i -th oscillator. ω_i indicates the angular resonant frequency of the i -th oscillator. In our structure, there are only two resonators: the stub cavity and the coupled cavity ($i=1,2$). In Fig. 5 (a-d), the theoretical calculations are represented by dotted lines. The fitting parameters are shown in Table 2. In Fig. 5 (a-d), the theoretical calculations are represented by dotted lines. The fitting parameters are shown in Table 2. The simulation calculation results have a good fit with the theoretical calculation results. In Fig. 5 (a-d), the theoretical calculations are represented by dotted lines. It can be found that the Fano spectra totally shift toward higher frequency region as f_{pe} increases, moreover, the transmittance of the Fano Peak is gradually decreasing, therefore, we can adjust the shape and position of the Fano resonance spectral lines by changing f_{pe} .

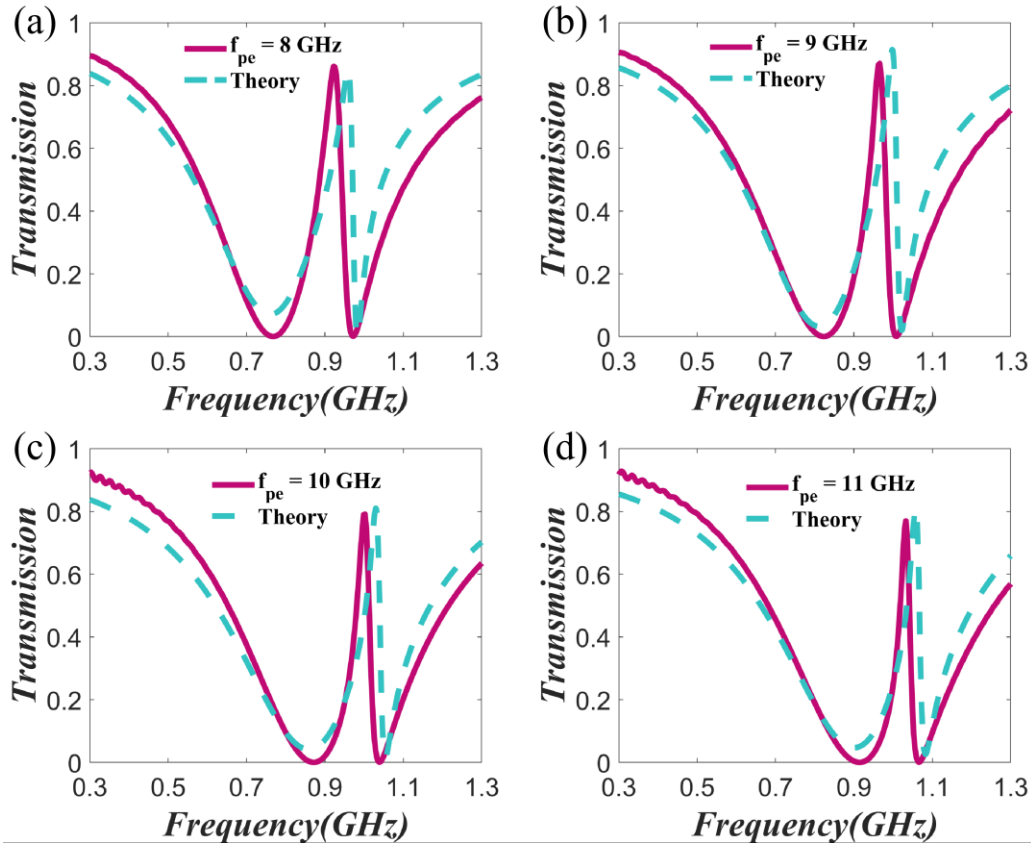


Fig. 5. (a-d) Fano interference model fitting graphs under different f_{pe} conditions (colour online)

Table 2. The table of fitting parameters

f_{pe} (GHz)	8	9	10	11
ω_1 (rad/s)	4.8269×10^{-9}	5.1631×10^{-9}	5.4783×10^{-9}	5.7515×10^{-9}
ω_2 (rad/s)	6.1088×10^{-9}	6.3399×10^{-9}	6.5290×10^{-9}	6.6972×10^{-9}
A	-0.03	-0.02	-0.02	-0.02
a_1	1.02	1.05	1.05	1.05
a_2	1.44	1.35	1.5	1.5
Γ_1 (THz)	1.3409×10^{-9}	1.3409×10^{-9}	1.6×10^{-9}	1.6×10^{-9}
Γ_2 (THz)	8×10^{-11}	8×10^{-11}	8×10^{-11}	8×10^{-11}
φ_1	4.2197	4.2197	4.2197	4.4
φ_2	2.2361	2.2361	1.96	2.07

Compared with the traditional waveguide structure, the PDP structure we proposed breaks the limitation of the traditional waveguide structure that once fabricated, it cannot be dynamically modulated. Because as the plasma's f_{pe} changes, the dielectric constant will also change, thereby causing the resonance frequency of the transmission spectrum to shift. According to formula (1), we plotted the real and imaginary parts of the plasma dielectric constant under different f_{pe} values. In Fig. 6 (a), the real part of the plasma dielectric constant decreases as f_{pe} increases. In Fig. 6 (b), the imaginary part increases as f_{pe} increases. In Fig. 7 (a), the transmission spectra of

the structure under different f_{pe} conditions are plotted. It can be observed that as the f_{pe} value increases, the transmission spectrum undergoes a blue shift. This is because as the f_{pe} increases, the real part of the plasma dielectric constant decreases, and the dielectric polarization intensifies, thereby causing the transmission spectrum blue shift. At the same time, the imaginary part increases and the structural absorption enhances, thereby causing the transmittance to decrease. Fig. 7 (b) shows the changes in the corresponding frequencies of dip1, dip2, and peak as f_{pe} increases. This indicates that our PDP structure can achieve wide-range dynamic modulation.

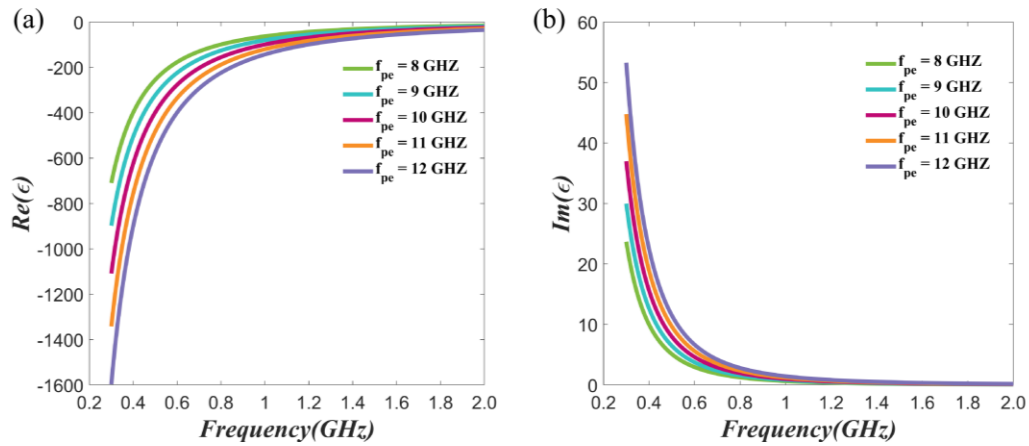


Fig. 6. (a) The real part of the plasma dielectric constant under different f_{pe} . (b) The imaginary part of the plasma dielectric constant under different f_{pe} (colour online)

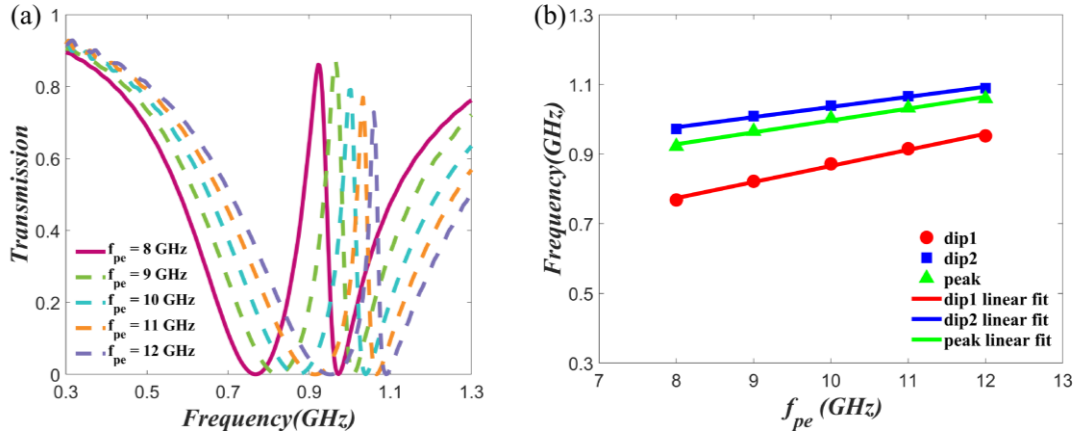


Fig. 7. (a) Transmission spectrum with varying f_{pe} . (b) The frequencies of dip1, dip2, and peak change along with the variation of f_{pe} (colour online)

Fig. 8 shows the manufacturing flowchart of the proposed structure. The most important aspect in these processes is the nano-imprinting technology. The proposed PDP waveguide structure can be fabricated using either electron beam lithography (EBL) technology or focused ion beam (FIB) lithography technology [44,45]. Provides flexible production of precise millimeter-level patterns. The specific process is as follows: Firstly, SiO_2 is evaporated on the substrate. Secondly, a layer of photomask is coated on the SiO_2 . Then, to create an imprint template, reactive ion etching (RIE) is used to replicate the proposed structure into the mold material. Based on this template, the desired structure is pressed into

the photomask layer by controlling the pressure and temperature. Then, the photomask layer is removed through etching techniques. After this, the remaining area serves as a mask for the subsequent material stripping process (such as RIE), for example, etching out the exposed SiO_2 . Finally, the photomask stripping technique can be used to obtain the final structure. With excellent dynamic tunability and clear Fano resonance characteristics, this PDP waveguide is suitable for applications such as switches, filters, sensors, and modulators in the microwave and plasmonic integrated systems.

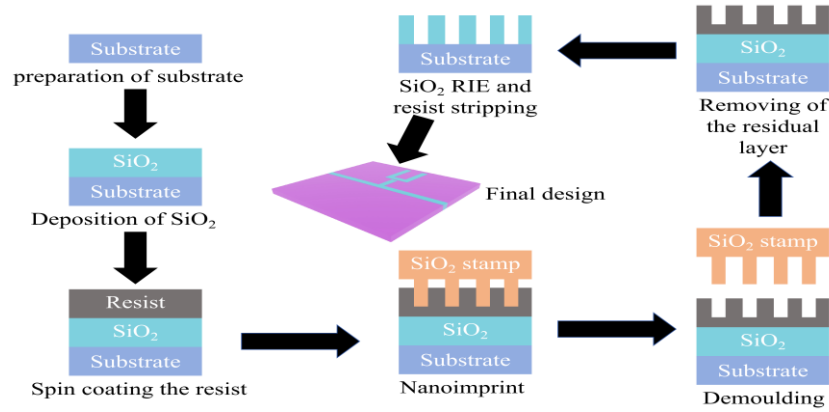


Fig. 8. The flowchart of the proposed structure's manufacturing process (colour online)

Our PDP structure demonstrates a continuous blue-shift of the Fano resonance frequency from 0.85 GHz to 1.15 GHz (approximately 30% relative tuning) when the plasma frequency f_{pe} is varied from 8 GHz to 11 GHz, achieving a modulation range competitive with or superior to many existing designs based on liquid crystals or nonlinear materials. The Q-factor of the Fano resonance, estimated from the full width at half maximum (FWHM) of the transmission dip/peak for the typical geometry ($L_1 = 45$ mm, $L_3 = 30$ mm, $G = 2$ mm), ranges from 80 to 120, which is comparable to other subwavelength Fano

structures in the microwave regime. Regarding insertion loss, the transmittance at the Fano peak reaches approximately 0.75–0.85 depending on the plasma frequency, indicating moderate loss; this is explicitly attributed to the intrinsic absorption of the plasma (imaginary part of permittivity), and we note that the insertion loss can be further reduced by optimizing the collision rate. Finally, the overall lateral dimensions of our PDP structure are about 50 mm $\times$ 60 mm (at an operating wavelength $\lambda < 350$ mm), which is compact relative to conventional microwave waveguide components, and

unlike metallic-dielectric structures, our design eliminates the need for post-fabrication tuning mechanisms. The typical formation and decay time constants of low-pressure gas discharge plasmas are on the order of 0.1–10 μs , suggesting that the proposed structure is suitable for moderate-speed switching and modulation (up to MHz-level repetition rates). The modulation depth—defined as the transmittance difference between the Fano peak and the adjacent dip—ranges from approximately 0.65 to 0.82 across the plasma frequency sweep, corresponding to an extinction ratio of roughly 8–12 dB for filtering applications. For sensing applications, the steep slope of the Fano lineshape yields a sensitivity of approximately 0.5 GHz per unit change in refractive index, and with a linewidth of ~ 10 MHz, the figure of merit (FOM = sensitivity / linewidth) exceeds 50, which is attractive for label-free detection. It should be noted that the present work adopts an ideal uniform gaseous plasma model with freely adjustable electron density as a first-order approximation to demonstrate the fundamental tunability of the proposed PDP waveguide. Several real-world engineering limitations are not addressed in this proof-of-concept study. In practice, plasma non-uniformity arising from skin effects or electrode geometries may introduce spatial variations in the dielectric constant, potentially affecting the Fano resonance lineshape. The collision rate used in our simulations is relatively low, whereas actual gas discharge plasmas at GHz frequencies may exhibit higher collision losses, which could increase insertion loss beyond the levels reported here; optimization of gas pressure and species may help mitigate this issue. Moreover, sustaining the required electron densities (corresponding to $f_{\text{pe}}=8\text{--}11$ GHz) demands electric fields above the breakdown threshold, and the associated power consumption must be carefully evaluated for practical device feasibility. Future work should incorporate non-uniform plasma modeling, loss mitigation strategies, and power efficiency analysis to bridge the gap between theoretical demonstration and practical application.

4. Conclusion

Overall, a dynamically tunable PDP plasmonic waveguide structure with a bus waveguide, stub cavity, and U-shaped coupling cavity is proposed and numerically investigated. The combined excitation of the two resonators produces a distinct Fano resonance via the coupling between continuous and discrete states. Magnetic field distributions reveal that energy concentration and coherent interference in the two cavities determine the transmission dips and peak. Geometric parameters can precisely regulate the Fano spectrum, and the established Fano interference model yields consistent results with FDTD simulations. Benefiting from the tunable dielectric constant of plasma, the structure realizes dynamic modulation of resonance frequency and transmittance by changing the plasma electron density, breaking the fixed-performance constraint of traditional photonic structures. The proposed structure can be manufactured by mature nanofabrication techniques including nanoimprinting, EBL, and FIB. With excellent dynamic

tunability and clear Fano resonance characteristics, this PDP waveguide is suitable for applications such as switches, filters, sensors, and modulators in the microwave and plasmonic integrated systems.

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Authorship contribution statement

Zhongwan Dun: Methodology, Investigation, Writing – review & editing.

Bowen Liu: Software.

Fang Chen: Software, Formal analysis, Conceptualization.

References

- [1] Z. Fei, A. S. Rodin, G. O. Andreev, W. Bao, A. S. McLeod, M. Wagner, L. M. Zhang, Z. Zhao, M. Thiemens, G. Dominguez, M. M. Fogler, A. H. C. Neto, C. N. Lau, F. Keilmann, D. N. Basov, *Nature* **487**, 82 (2012).
- [2] S. Y. Yin, Q. Guo, S. R. Liu, J. W. He, Y. S. Yu, Z. N. Tian, Q. D. Chen, *Opto-Electronic Science* **3**, 240003-1 (2024).
- [3] Y. Pan, F. Chen, Y. Li, W. Yang, L. Sun, Z. Yi, *Phys. Chem. Chem. Phys.* **26**, 16096 (2024).
- [4] Y. Qi, G. Yue, T. Hao, Y. Li, *Opto-Electronic Advances* **8**, 250056-1 (2025).
- [5] Q. Ding, X. Chen, Y. Jia, H. Liu, X. Zhang, N. Cheng, S. Yang, *Opto-Electronic Advances* **9**, 250269 (2026).
- [6] Y. Pan, F. Chen, Y. Li, C. Li, Y. Gao, W. Yang, *Phys. Scripta* **99**, 085560 (2024).
- [7] X. Cao, Y. Shen, L. Yang, Y. Cheng, *Physica B: Condensed Matter* **737**, 418729 (2026).
- [8] J. Lyu, L. Huang, L. Chen, Y. Zhu, S. Zhuang, *Photonics Research* **12**, 194 (2024).
- [9] A. Taharat, M. A. Kabir, A. I. Keats, A. K. M. Rakib, R. H. Sagor, *Optics Communications* **578**, 131495 (2025).
- [10] W. Li, S. Cheng, Z. Yi, H. Zhang, Q. Song, Z. Hao, T. Sun, P. Wu, P. Zeng, R. Raza, *Applied Physics Letters* **126**, 3 (2025).
- [11] A. E. Miroshnichenko, S. Flach, Y. S. Kivshar, *Reviews of Modern Physics* **82**, 2257 (2010).
- [12] U. Fano, *Phys. Rev.* **124**, 1866 (1961).
- [13] B. Peng, Ş. K. Özdemir, W. Chen, F. Nori, L. Yang, *Nat. Commun.* **5**, 5082 (2014).
- [14] F. Hao, Y. Sonnefraud, P. V. Dorpe, S. A. Maier, N. J. Halas, P. Nordlander, *Nano Lett.* **8**, 3983 (2008).
- [15] Z. Li, F. Chen, W. Yang, *Phys. Scripta* **99**, 125527 (2024).
- [16] Z. Zeng, H. Liu, H. Zhang, S. Cheng, Y. Yi, Z. Yi,

- J. Wang, J. Zhang, *Photonics and Nanostructures - Fundamentals and Applications* **63**, 101347 (2025).
- [17] Z. Chen, S. Cheng, H. Zhang, Z. Yi, B. Tang, J. Chen, J. Zhang, C. Tang, *Physics Letters A* **517**, 129675 (2024).
- [18] W. Gao, F. Chen, W. Yang, *Photonics and Nanostructures - Fundamentals and Applications* **63**, 101366 (2025).
- [19] Z. Chen, Y. Xu, L. Ren, F. Chen, S. Cheng, Z. Yi, G. Xiao, X. Huang, X. Zeng, *Opt. Quant. Electron.* **56**, 631 (2024).
- [20] Z. Vafapour, *Integrated Optics: Devices, Materials, and Technologies XXII*, edited by S. M. García-Blanco and P. Cheben (SPIE, San Francisco, United States), p. 82, 2018.
- [21] S. Xiao, T. Liu, C. Zhou, X. Jiang, L. Cheng, C. Xu, *J. Opt. Soc. Am. B* **36**, E48 (2019).
- [22] S. Zhang, F. Wen, M. Zhai, Z. Li, H. Ye, H. Zhang, Y. Gu, Y. Lei, W. Wang, Y. Zhang, H. Wang, *Phys. Rev. Appl.* **22**, 024004 (2024).
- [23] C. Liu, H. Li, H. Xu, M. Zhao, C. Xiong, M. Li, B. Ruan, B. Zhang, K. Wu, *Journal of Applied Physics* **127**, 163301 (2020).
- [24] M. Amin, M. Farhat, H. Bağcı, *Scientific Reports* **3**, 2105 (2013).
- [25] L. Da, L. Jiu-Sheng, *Optics Communications* **472**, 125862 (2020).
- [26] H. Li, X. Li, Y. Luo, E. Gao, *Phys. Scripta* **99**, 085613 (2024).
- [27] X.-S. Lin, X.-G. Huang, *Opt. Lett.* **33**, 2874 (2008).
- [28] H. Li, R. Jiao, *Optics Communications* **439**, 201 (2019).
- [29] X. Tang, F. Chen, *Micro and Nanostructures* **207**, 208265 (2025).
- [30] X. Xu, F. Liu, Q. Zhou, B. Liang, Y. Liang, R. Liang, *Applied Physics Letters* **92**, 011501 (2008).
- [31] X. Tang, Y. Li, F. Chen, W. Yang, *Phys. Scripta* **99**, 065561 (2024).
- [32] Z. Li, Y. Pan, F. Chen, W. Yang, *Micro and Nanostructures* **204**, 208156 (2025).
- [33] Q. Wang, L. Ma, *Plasma Sci. Technol.* **21**, 105001 (2019).
- [34] B. Qu, X. Wang, B. Li, P. Chen, Q. Nie, *Plasmonics* **15**, 1591 (2020).
- [35] Y. Li, Y. Pan, F. Chen, S. Cheng, W. Yang, B. Wang, Z. Yi, *Plasmonics* **19**, 711 (2024).
- [36] C. S. Liu, V. K. Tripathi, Y.-Y. Lau, *Physics Today* **48**, 70 (1995).
- [37] T. Fu, T. Yang, Y. An, Q. Li, Z. Deng, *Plasma Sci. Technol.* **23**, 075502 (2021).
- [38] L. Qi, C. Li, G. Fang, X. Gao, *Plasma Sci. Technol.* **17**, 4 (2015).
- [39] G. Wei, Q. Nie, Z. Zhang, P. Chen, C. Yan, *Physics of Plasmas* **29**, 083505 (2022).
- [40] G. Wei, Q. Nie, Z. Zhang, P. Chen, C. Yan, T. Huang, Z. Zhang, *Journal of Physics D: Applied Physics* **58**, 315202 (2025).
- [41] S. Xiong, X. Tang, F. Chen, *Plasmonics* **20**, 6539 (2025).
- [42] B. Wei and S. Jian, *Appl. Phys. B* **124**, 137 (2018).
- [43] Y. Binfeng, H. Guohua, C. Jiawei, C. Yiping, *Plasmonics* **9**, 691 (2014).
- [44] H. T. Miyazaki, Y. Kurokawa, *Physical Review Letter* **96**, 097401 (2006).
- [45] A. K. M. Rakib, Md. R. Muttaqi, A. T. B. Siddique, Mohd. A. B. Siddique, R. H. Sagor, *Results in Physics* **53**, 106956 (2023).

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