Hybridization-induced resonances with high-quality factor in a plasmonic chipscale ring-disk nanocavity

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**ABSTRACT**

Plasmonic resonators have drawn more attention due to the ability to confine light into subwavelength scale. However, they always suffer from a low-quality (Q) factor owing to the intrinsic loss of metal. Here, we numerically propose a plasmonic resonator with ultra-high Q factor based on plasmonic metal–insulator-metal (MIM) waveguide structures. The resonator consists of a disk cavity surrounded by a concentric ring cavity, possessing an ultra-small volume. Arising from the plasmon hybridization between plasmon modes in the disk and ring cavity, the induced bonding hybridized modes have an ultra-narrow full width at half maximum (FWHM) as well as ultra-high Q factors. The FWHM can be nearly 1 nm and Q factor can be more than 400. Furthermore, such a device can act as a refractive index sensor with an ultra-high figure of merit (FOM). This work provides a novel approach to design plasmonic high-Q-factor resonators and has potential on-chip applications such as filters, multi-spectral sensors and nanolasers.

**1. Introduction**

In the past few decades, optical resonators have been playing an important role in photonic research. For fundamental research, they provide ideal platforms to study light-matter interaction [1], chaos [2], and nonlinear effects [3]. For applied research, they promote a series of significant applications, including sensors [4], lasers [5], delay lines [6], and frequency comb [7]. In these applications, quality (Q) factor (which is proportional to the photon confinement time) and volume of the cavity figure prominently, since higher Q factors and smaller cavity volumes will enhance the performances of these devices [1]. However, the volumes of conventional dielectric and semiconductor cavities are limited to micron scales due to the diffraction limit [8].

Toward ultra-small volume devices, plasmonics is introduced to optical systems. Surface plasmons can confine visible and near-infrared light on subwavelength scales, thus bringing plasmonic resonators into nanoscales to achieve various applications, such as...
modulators [9–11] and sensors [12–15]. However, the Q factors of plasmonic resonators have been less than 100 both for visible and near-infrared wavelengths due to the ohmic loss of the metal [16–18]. Plasmonic dielectric–metal hybrid resonators are introduced to increase the Q factor, but still possess footprints as large as several micrometers [19–20]. Recently, as a strong candidate to build high-compact optical circuits on chips, plasmonic metal–insulator-metal (MIM) waveguides are utilized to construct plasmonic resonators with ultra-small footprint [21]. For example, a rectangle resonator is introduced based on MIM waveguides with a Q factor of 20 [22]. Utilizing the Fano resonance, MIM-based resonator can reach a Q factor of 120 and 145 [23–24]. It has also been reported that a fillet cavity has a Q factor of nearly 190 [25]. Therefore, MIM waveguides have the potential to support high-Q-factor resonances in plasmonic nanocavities.

In this work, we introduce a resonator comprised of a concentric ring and disk cavity based on MIM waveguides. Due to the plasmon hybridization, there is an interaction between plasmon modes in both ring and disk cavity. As a result, the induced bonding hybridized modes possess ultra-narrow full width at half maximum (FWHM) and ultra-high Q factors in a visible band. The influences of gap widths are also studied. After structural optimization, this resonator can obtain an FWHM nearly 1 nm and a Q factor of more than 400. As a sensor, this device has considerable sensitivity and ultra-high figure of merit (FOM). Besides, such a hybridization strategy can also produce a multi-spectral response meanwhile meets the ultra-compact requirement [26]. Such resonator has an ultra-small volume and can find on-chip applications on sensing, filtering, lasing, and nonlinear enhancement.

2. Results and discussion

The 3D schematic of the proposed structure is shown in Figure 1(a), which consists of a layer of silver (Ag) and a substrate. The waveguide, as well as the ring-disk nanocavity, is etched on the metal surface, which can be realized by focused ion beam (FIB), and the substrate is usually chosen as silica [27]. The top view of this structure is shown in Figure 1(d). Here, the gray color represents Ag, and the white color represents air. The geometric parameters are provided in the caption of Figure 1. The dispersive permittivity of Ag is adapted following the Drude model [28]:

\[ \varepsilon_m = \varepsilon_\infty - \frac{\omega_p^2}{\omega(\omega + i\gamma)} \tag{1} \]

where \( \varepsilon_\infty \) is the permittivity of infinite frequency, \( \omega_p \) is the bulk plasma frequency, \( \gamma \) is the electron oscillation damping frequency, and \( \omega \) is the angular frequency of incident light. The parameters of Ag are as follows: \( \varepsilon_\infty = 3.7 \), \( \omega_p = 1.38 \times 10^{16} \text{ Hz} \), and \( \gamma = 2.73 \times 10^{13} \text{ Hz} \).

There is only a transverse-magnetic (TM) mode in the MIM waveguide [29]. Since the waveguide width \( w \) is much smaller than input wavelengths, only fundamental TM mode can be supported. The dispersion of this mode is as follows [30]:

\[ \frac{\varepsilon_{ip}}{\varepsilon_{mk}} = \frac{1 - e^{kw}}{1 + e^{kw}} \tag{2} \]
Figure 1. (a) The 3D schematic of the proposed structure. (b–d) The 2D schematic of the disk, ring, and ring-disk nanocavity, geometric parameters are as follows: the width of the waveguide $w = 50$ nm, $g = 10$ nm, $G = 34$ nm, $R = 325$ nm, and $r = 241$ nm. (e–f) The real and imaginary parts of $n_{eff}$ corresponding to different $w$.

$$k = k_0 \sqrt{\left(\frac{\beta_{spp}}{k_0}\right)^2 - \varepsilon_i}$$

$$p = k_0 \sqrt{\left(\frac{\beta_{spp}}{k_0}\right)^2 - \varepsilon_m}$$

(3)

$$\beta_{spp} = n_{eff} k_0 = \frac{2\pi}{\lambda}$$

(4)

Here $\lambda$ is the incident wavelength in vacuum, $\varepsilon_i$ and $\varepsilon_m$ are dielectric constant and metal constant, respectively. $\beta_{spp}$ is the propagation constant of surface plasmons, $n_{eff}$ is an effective refractive index of MIM waveguide, and $k_0 = 2\pi / \lambda$ is the wave number. The calculated real and imaginary parts of $n_{eff}$ corresponding to different $w$ are shown in Figure 1(e–f). It is shown that wider waveguide will possess smaller $Re(n_{eff})$ and $Im(n_{eff})$. Smaller $Re(n_{eff})$ will lead to the blue shift of resonant wavelengths, while smaller $Im(n_{eff})$ means less propagating loss inside the waveguide. Considering the trade-off between the device footprint and loss, the width is chosen as 50 nm [21]. 2D Finite-Difference Time-Domain (FDTD) method is adapted to do the simulation, which has been mostly utilized in previous works [21–25]. And it has been reported that 2D simulation has the same result as 3D simulation when the height (the scale in the $z$-direction) of the metal is high sufficiently [31]. The mesh size is 2.5 nm; the boundary condition is perfectly matched layers (PML). As depicted in Figure 1(d), light source and power monitor is placed at $P_{in}$, while another power monitor is placed at $P_{out}$. The transmission is defined as $T = P_{out}/P_{in}$. 
We start with the simple structure, including an input waveguide side-coupled with a single disk resonator, as shown in Figure 1(b), or a single ring resonator, as shown in Figure 1(c). The resonance conditions are as follows [25,32]:

\[
\begin{align*}
\text{Disk} : & \quad k_d H_m^{(1)}(k_d r) = k_e J_m'(k_e r), m = 1, 2 \ldots \\
\text{Ring} : & \quad n \lambda = L_{eff} \Re(n_{eff}), n = 1, 2 \ldots 
\end{align*}
\]

For the disk, \( r \) is the disk radius, \( k_d \) and \( k_e \) are the wave vectors in the disk and metal, \( H_m^{(1)} \) and \( H_m^{(1)'} \) are the first kind Hankle function with order \( m \) and its derivative, \( J_m \) and \( J_m' \) are the first kind Bessel function with order \( m \) and its derivative, respectively. For the ring, \( L_{eff} \) is the effective perimeter of the ring, which is the average of the inner and outer perimeters, \( \lambda \) is the resonant wavelength. Both \( m \) and \( n \) are integer mode numbers. The corresponding transmission spectra are shown in Figure 2(a). For the disk resonator, there are two resonances at 446.3 and 586.5 nm, FWHM of each is 1.7 and 1.9 nm, and Q factor, defined as \( Q = \lambda / \text{FWHM} \), is 262.5 and 308.7, respectively. According to the \( H_x \) field distributions in insets of Figure 2(a), \( m = 3 \) and 2 for disk modes at 446.3 and 586.5 nm, respectively. For the two ring modes at 466 and 546.7 nm, \( n = 6 \) and 5, respectively.

Figure 2(b) shows the transmission spectrum of the concentric ring-disk resonator given in Figure 1(d), the mode numbers and field distributions are provided in insets of Figure 2(b). Basically, this spectrum is a combination of disk and ring spectrum. However, there are two interesting phenomena. Firstly, there are two types of plasmon modes in such a hybrid resonator: antisymmetrically coupled (antibonding) modes (mode III at 472.6 nm and mode IV at 554.1 nm), and symmetrically coupled (bonding) modes (mode I at 450.7 nm and mode II at 590.7 nm). Interestingly, the energy is mainly confined in the outer ring for antibonding modes and inner disk for bonding modes. Such plasmon mode distributions can be described by the plasmon hybridization [33–35], the corresponding energy diagram is shown in Figure 3. According to this model, the plasmon hybridization between two plasmon sub-modes will give rise to two hybridized plasmon modes: the antibonding mode and bonding mode. Therefore, such hybridization process will happen via the coupling between the disk and ring nanocavity, leading to antibonding hybridized modes with lower energy (mode III and IV) and bonding hybridized modes with higher energy (mode I and II) in this system.

Secondly, bonding modes have ultra-narrow FWHM and ultra-high Q factors. We believe this is due to the special mode distributions of bonding modes. The energy of such modes is mainly trapped in the inner disk nanocavity, so the outer ring nanocavity can suppress the dissipation rate of photons confined to the disk nanocavity. In this case, FWHM and Q factor for mode I are 1.1 nm and 417.3, and for mode II are 1.4 nm and 418.9, respectively. Such values are better than those of previous similar works [21–25].

Next, the influence of gap width will be studied, including the \( g \), which is the gap width between the input waveguide and ring-disk resonator, and \( G \), which is the gap width between the ring and disk nanocavity, as shown in Figure 4. As \( g \) increases (keep \( G \) unchanged at 34 nm), the transmission at bonding modes will increase while that at antibonding modes will decrease, indicating that increasing \( g \) from 6 to 14 nm goes away from the critical coupling distance of the disk nanocavity while approaches that of the ring nanocavity [36]. When \( G \) increases (keep \( g \) unchanged at 10 nm and reduce \( r \), the
transmission at each hybridized mode increases, because a wider metal gap will lead to more intrinsic loss into the whole resonator. Furthermore, increasing $g$ will cause a resonant wavelength blueshift of mode III and IV, but will not for mode I and II, as presented in Figure 4(a). This is because, altering coupling distance will bring about the phase change in the coupling process, leading to the coupling-induced resonant frequency shift (CIFS) [37]. Resonant wavelengths of antibonding/bonding modes are mainly decided by ring/disk nanocavity, so $g$ will directly influence resonant wavelengths of antibonding modes and will not for bonding modes. From the same fact, $G$ will affect the resonant wavelengths of both hybridized modes, as shown in Figure 4(b).

Due to the superior energy storage capacity, bonding modes will be focused next, and two important factors of which will be investigated under different gap widths: Q factor, which represents energy storage time, and contraction ratio, defined as $T_c = T_{\text{max}} / T_{\text{min}}$ ($T_{\text{max}}$ and $T_{\text{min}}$ are the transmission at the highest and lowest point of resonance dips, respectively), indicating the amount of stored energy inside. The relationship diagrams are
Figure 3. The energy diagram of plasmon hybridization in this system.

given in Figure 5. From both diagrams, we can see that increasing gap widths will lead to a decline of contraction ratio, while Q factor will rise on the main trend because the wider gap will promote photon confinement time [1]. Therefore, there is a trade-off between Q factor and the contraction ratio.

3. Sensing performance

In consideration of the balance between Q factor and contraction ratio, we adopt the structure with $g = 10$ nm and $G = 34$ nm to investigate the corresponding sensing performance. A sensor can be assessed by two factors, sensitivity ($S$) and FOM [25]:

$$S = \frac{\Delta \lambda}{\Delta n}$$

$$\text{FOM} = \frac{S}{\text{FWHM}}$$

Here, $S$ represents the wavelength shift induced by a unit change of surrounding refractive index, FOM indicates the optical resolution of the sensor. The resonant wavelengths and FWHM of mode I and II under different surrounding refractive index are shown in Figure 6 (a) and (b), respectively, from which we can see that the resonant wavelengths of both modes have linear relationships with surrounding refractive index. Therefore, $S$ of mode I is 429 nm/RIU, and of mode II is 579 nm/RIU. The average FWHM of mode I and II under surrounding refractive index from 1 to 1.1 is 1.1 and 1.5 nm respectively, so FOM of mode I is 376.2/RIU, and of mode II is 378/RIU. Compared with other MIM-based sensors, this sensor has moderate sensitivity since the working wavelength is in the visible band, which is due to the ultra-small footprint of this sensor. However, this sensor has much higher FOM.
Figure 4. (a) The transmission spectra under different $g$. (b) The transmission spectra under different $G$.

Figure 5. (a) The relationship diagram between $g$ and Q factor/contraction ratio of mode I and II. (b) The relationship diagram between $G$ and Q factor/contraction ratio of mode I and II.
than other similar previous works [24–25,38–40], therefore possessing ultra-high optical resolution.

4. Conclusion

In summary, we propose a plasmonic hybrid ring-disk nano-resonator with high Q factors and small footprint based on MIM waveguides. Due to plasmon hybridization, bonding and antibonding hybridized plasmon modes are generated and ultra-narrow FWHM and ultra-high Q factors can be supported by bonding modes. The performance as a sensor with ultra-high FOM is also investigated. This work provides a way to improve the Q factor by using hybridized modes and can be applied on light–matter interaction, multi-spectral sensing, and nanolasers on chipscales.

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Disclosure statement

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References

[1] Vahala KJ. Optical microcavities. Nature. 2003;424(6950):839.
[2] Cao H, Wiersig J. Dielectric microcavities: model systems for wave chaos and non-hermitian physics. Rev Mod Phys. 2015;87(1):61–111.
[3] Bravo-Abad J, Rodriguez A, Bermel P, et al. Enhanced nonlinear optics in photonic-crystal microcavities. Opt Express. 2007;15(24):16161–16176.
[4] Foreman MR, Swaim JD, Vollmer F. Whispering gallery mode sensors. Adv Opt Photonics. 2015;7(2):168–240.
[5] Spillane SM, Kippenberg TJ, Vahala KJ. Ultralow-threshold Raman laser using a spherical dielectric microcavity. Nature. 2002;415(6872):621–623.
[6] Maleki L, Matsko AB, Savchenkov AA, et al. Tunable delay line with interacting whispering-gallery-mode resonators. Opt Lett. 2004;29(6):626–628.
[7] Del'Haye P, Schliesser A, Arcizet O, et al. Optical frequency comb generation from a monolithic microresonator. Nature. 2007;450(7173):1214–1217.
[8] Min B, Ostby E, Sørger V, et al. High-Q surface-plasmon-polariton whispering-gallery microcavity. Nature. 2009;457(7228):455.
[9] Dionne JA, Diest K, Sweatlock LA, et al. PlasMOStor: a metal-oxide-Si field effect plasmonic modulator. Nano Lett. 2009;9(2):897–902.
[10] Melikyan A, Alloatti L, Muslija A, et al. High-speed plasmonic phase modulators. Nat Photonics. 2014;8(3):229–233.
[11] Zhang Z, Yang J, Bai W, et al. Chipscale plasmonic modulators and switches based on metal–insulator–metal waveguides with Ge2Sb2Te5. J Nanophotonics. 2019;13(4):046009.
[12] Liu N, Mesch M, Weiss T, et al. Infrared perfect absorber and its application as plasmonic sensor. Nano Lett. 2010;10(7):2342–2348.
[13] Shi L, Tang Q, Liu Z, et al. Tunable dual-band plasmonic perfect absorber and its sensing applications. JOSA B. 2019;36(10):2750–2756.
[14] Li Y, Liu Y, Liu Z, et al. Grating-assisted ultra-narrow multispectral plasmonic resonances for sensing application. Appl Phys Express. 2019;12(7):072002.
[15] Zhang Z, Yang J, Xu H, et al. A plasmonic ellipse resonator possessing hybrid modes for ultracompact chipscale application. Phys Scr. 2019;94(12):125511.
[16] Kuttge M, Javier GDAF, Polman A. Ultrasmall mode volume plasmonic nanodisk resonators. Nano Lett. 2010;10(5):1537–1541.
[17] Weeber JC, Bouhelier A, Colas DFG, et al. Submicrometer in-plane integrated surface plasmon cavities. Nano Lett. 2007;7(5):1352–1359.
[18] Vesseur EJR, De Waele R, Lezec HJ, et al. Surface plasmon polariton modes in a single-crystal Au nanostructure patterned using focused-ion-beam milling. Appl Phys Lett. 2008;92(8):083110.
[19] Song Y, Wang J, Yan M, et al. Subwavelength hybrid plasmonic nanodisk with high Q factor and Purcell factor. J Opt. 2011;13(10):075001.
[20] Xiao YF, Li BB, Jiang X, et al. High quality factor, small mode volume, ring-type plasmonic microresonator on a silver chip. J Phys B: At, Mol Opt Phys. 2010;43(3):035402.
[21] Lu H, Wang G, Liu X. Manipulation of light in MIM plasmonic waveguide systems. Chin Sci Bull. 2013;58(30):3606–3616.
[22] Zhang Q, Huang XG, Lin XS, et al. A subwavelength coupler-type MIM optical filter. Opt Express. 2009;17(9):7533–7539.
[23] Binfeng Y, Ruohu Z, Guohua H, et al. Ultra sharp Fano resonances induced by coupling between plasmonic stub and circular cavity resonators. Plasmonics. 2016;11(4):1157–1162.
[24] Zafar R, Salim M. Enhanced figure of merit in Fano resonance-based plasmonic refractive index sensor. IEEE Sens J. 2015;15(11):6313–6317.
[25] Chen L, Liu Y, Yu Z, et al. Numerical analysis of a near-infrared plasmonic refractive index sensor with high figure of merit based on a fillet cavity. Opt Express. 2016;24(9):9975–9983.

[26] Liu Z, Liu G, Liu X, et al. Multispectral sharp plasmon resonances for polarization-manipulated subtractive polychromatic filtering and sensing. Plasmonics. 2015;10(4):821–830.

[27] Chai Z, Hu X, Yang H, et al. All-optical tunable on-chip plasmon-induced transparency based on two surface-plasmon-polaritons absorption. Appl Phys Lett. 2016;108(15):151104.

[28] Johnson PB, Christy RW. Optical constants of the noble metals. Phys Rev B (Solid State). 1972;6(12):4370–4379.

[29] Dionne J, Sweatlock L, Atwater H, et al. Plasmon slot waveguides: towards chip-scale propagation with subwavelength-scale localization. Phys Rev B. 2006;73(3):035407.

[30] Economou EN. Surface plasmons in thin films. Phys Rev. 1969;182(2):539–554.

[31] He Z, Li H, Li B, et al. Theoretical analysis of ultrahigh figure of merit sensing in plasmonic waveguides with a multimode stub. Opt Lett. 2016;41(22):5206.

[32] Luo S, Li B, Xiong D, et al. A high performance plasmonic sensor based on metal-insulator-metal waveguide coupled with a double-cavity structure. Plasmonics; 2016;12(2):1–5.

[33] Prodan E. A hybridization model for the plasmon response of complex nanostructures. Science. 2003;302(5644):419–422.

[34] Kandil SM, Eshrah IA, El BIS, et al. Plasmon hybridization in split ring nanosandwich for refractive index sensing—numerical investigation. Opt Express. 2016;24(26):30201.

[35] Nanli M, Shulin S, Hongxing D, et al. Hybridization-induced broadband terahertz wave absorption with graphene metasurfaces. Opt Express. 2018;26(9):11728–11736.

[36] Cai M, Painter O, Vahala KJ. Observation of critical coupling in a fiber taper to a silica-microsphere whispering-gallery mode system. Phys Rev Lett. 2000;85(1):74.

[37] Li Q, Soltani M, Atabaki AH, et al. Quantitative modeling of coupling-induced resonance frequency shift in microring resonators. Opt Express. 2009;17(26):23474–23487.

[38] Wu C, Ding H, Huang T, et al. Plasmon-induced transparency and refractive index sensing in side-coupled stub-hexagon resonators. Plasmonics. 2018;13(1):251–257.

[39] Zhang Z, Luo L, Xue C, et al. Fano resonance based on metal-insulator-metal waveguide-coupled double rectangular cavities for plasmonic nanosensors. Sensors. 2016;16(5):642.

[40] Ren X, Ren K, Cai Y. Tunable compact nanosensor based on Fano resonance in a plasmonic waveguide system. Appl Opt. 2017;56(31):H1–H9.

[41] Zhang Z, Yang J, Xu H, et al. (2019). Hybridization-induced resonances with high quality factor in a plasmonic concentric ring-disk nanocavity. arXiv preprint arXiv:1904.09437.