Hybrid photonic-plasmonic molecule based on metal/Si disks

Qing Wang, 1 Hang Zhao, 1 Xu Du, 1 Weichun Zhang, 1 Min Qiu, 1, 2 and Qiang Li 1, *

1 State Key Laboratory of Modern Optical Instrumentation, Department of Optical Engineering, Zhejiang University, 310027, Hangzhou, China
2 School of Information and Communication Technology, KTH Royal Institute of Technology, Electrum 229, 16440, Kista, Sweden

* qiangli@zju.edu.cn

Abstract: Optical properties of two identical coupled disks forming a “hybrid photonic-plasmonic molecule” are investigated. Each disk is a metal-dielectric structure supporting hybrid plasmonic-photonic whispering-gallery (WG) modes. The WG modes of a molecule split into two groups of nearly-degenerate modes, i.e., bonding and anti-bonding modes. The oscillation of quality factor (Q) with the inter-disk gap (d) and significant enhancement at certain inter-disk gaps can be observed. An enhanced Q factor of 1821 for a hybrid photonic-plasmonic molecule composed of two 1.2 μm-diameter disks, compared with that for a single disk, is achieved. The corresponding Purcell factor is 191, making the hybrid photonic-plasmonic molecule an optimal choice for subwavelength-scale device miniaturization and light-matter interactions. Moreover, the far-field emission pattern of the hybrid photonic-plasmonic molecule exhibits an enhanced directional light output by tuning the azimuthal mode number for both bonding and anti-bonding modes.

© 2013 Optical Society of America

OCIS codes: (250.5403) Plasmonics; (230.4555) Coupled resonators; (310.6628) Subwavelength structures, nanostructures.

References and links
12. S. V. Boriskina, T. M. Benson, and P. Sewell, “Photonic molecules made of matched and mismatched
2. S. V. Boriskina and B. M. Reinhard, “Spectrally and spatially configurable superlenses for optoplasmonic...”
1. Introduction

Photonic molecules composed of a cluster of mutually-coupled optical microcavities have aroused keen interest in the last decade [1]. Conventional configurations of photonic molecules include two or more optical resonators, such as microdisks, microrings, microspheres and point-defect cavities in photonic crystals, etc [2–12]. By playing with the structures and the compositions of the microcavities, photonic molecules can be optimized to exhibit many unique optical properties including light confinements in the wavelength-scale. Therefore, the photonic molecule is regarded as one of key components for a variety of optical applications, such as low-threshold semiconductor microlasers [3, 12, 13], optical filters and switches [7, 14, 15], information processing [16], biochemical sensing [17, 18], etc.

Most optical microcavities designed so far are based on dielectric materials. Hence a further size reduction is hindered by the diffraction [19–21]. Moreover, as the size of a disk cavity decreases, the total internal reflection of the microcavity becomes weak, resulting into an increase in the mode radiation loss and an exponential decrease in the quality factor \(Q\) [20]. Thus the desire for a high \(Q\) and that for device miniaturization seem contradictory. Recently the plasmonic cavities, which are capable of further reducing the mode volume to subwavelength scale while maintaining a relatively high \(Q\) due to the effect of surface plasmon polaritons (SPPs), are proposed as an alternative [22–27].

Earlier efforts dedicated to the plasmonic microcavities mainly focused on a single disk [22–27]. Few of them have investigated the coupling between plasmonic disks. Previous studies on the hybrid photonic-plasmonic geometry have shown many functionalities [28–32]. Ref [28] has shown cascaded nanoscale hot-spot intensity enhancement in a hybrid photonic-plasmonic structure composed of an Au nanoparticle dimer and a dielectric microcavity. Ref [29] has demonstrated significant enhancement and redistribution of the magnetic field in the hybrid metallo-dielectric clusters. Ref [30] has shown a whispering-gallery-mode biosensor based on wavelength shifts of a hybrid photonic-plasmonic structure composed of a gold nanoparticle and a silica microsphere. Ref [31] has demonstrated a spectrally and spatially configurable hybrid photonic-plasmonic superlens composed of a polystyrene microsphere and two Au nanodimers. In this paper, a hybrid photonic-plasmonic molecule consisting of two identical metal/Si microdisks is investigated. Unlike previous hybrid metallo-dielectric structures composed of nanoparticles and microcavities [28–32], the hybrid photonic-plasmonic molecule reported here can achieve a good field confinement and enhancement [27, 33, 34]. Moreover, the characteristics of whispering gallery (WG) mode splitting can be observed in the hybrid photonic-plasmonic molecule. The single-disk mode splits into red-shifted bonding modes and blue-shifted anti-bonding modes. The shift of resonant wavelength decreases with inter-disk gap \(d\) varying from 0 to 1200 nm. Meanwhile, a highly enhanced \(Q\) factor of 1821 corresponding to a high Purcell factor of 191 can be achieved at the resonant wavelength of 1025 nm. This is an extremely large improvement over conventional photonic molecules in terms of reducing the mode volume while maintaining a relatively high \(Q\) factor [4, 19, 20]. In addition, the far-field emission patterns in the H-plane and the E-plane for the bonding modes and the anti-bonding modes are studied. The possibility of manipulating the emission pattern by tuning the azimuthal mode number is demonstrated.
2. The structure of the hybrid photonic-plasmonic molecule

The hybrid photonic-plasmonic molecule consists of two identical 1.2 μm-diameter disks on a silica substrate. As shown in Fig. 1, the disk is a sandwich-like geometry, which is composed of the top silver layer, the middle alumina and the bottom silicon. Numerical simulation based on our home-made three-dimensional finite-difference time-domain (FDTD) code is conducted to model the hybrid photonic-plasmonic molecule [35, 36]. The total computation domain is 4.4 μm × 4 μm × 1.2 μm along the x, y and z directions. The spatial resolution is 15 nm in the x and y direction and 10 nm in the z direction. The absorbing boundary condition used in the simulation is perfectly matched layers (PMLs). The permittivities of the silica substrate and the silicon layer are ε_{SiO_2} = 2.1 and ε_{Si} = 11.9, respectively. The lower index layer is alumina with a permittivity of ε_{Al_2O_3} = 3. The dispersive permittivity of silver is modeled according to the Drude model which is fitted with experimental data [37]. The heights of each layer are h_{Si} = 250 nm, h_{Ag} = 100 nm and h_{Al_2O_3} = 50 nm, respectively. For a practical device, a layer of silica is usually deposited atop to prevent it from oxidizing.

![Fig. 1. Schematic diagram of the hybrid photonic-plasmonic molecule consisting of two disks.](image)

Two kinds of modes can be excited in the proposed structure, i.e., transverse electric (TE) mode and transverse magnetic (TM) mode. For the hybrid photonic-plasmonic TM mode, most portion of energy is confined in the low-index layer. While for the dielectric TE mode, most portion of energy is stored in the silicon layer. Therefore, the TM mode is more promising for achieving subwavelength application than the TE mode and we only discuss the TM mode in this paper. Resonant WG modes in individual microdisk are double degenerate and characterized by two mode numbers, corresponding to the radial mode number (n) and the azimuthal mode number (m) [20]. The fundamental modes (with n = 1) are mostly related to practical applications because of their high Q factors and small mode volumes. So we only classify the modes of the hybrid photonic-plasmonic disks in terms of the azimuthal mode number m.

3. Mode splitting in the hybrid photonic-plasmonic molecule

Similar to the photonic molecules, when two hybrid photonic-plasmonic atoms (disks) are brought into proximity, their WG modes will couple and split into two double-degenerate WG modes, i.e., bonding (even) and anti-bonding (odd) modes, depending on symmetry of the mode with respect to the y-axis. If we consider the mode symmetry with respect to the x-axis further, the bonding (even) mode includes x-even/y-even (EE) mode and x-odd/y-even...
(OE) mode. While for the anti-bonding (odd) mode, it includes x-even/y-odd (EO) mode and x-odd/y-odd (OO) mode. Figure 2 illustrates the mode-splitting behavior in a hybrid photonic-plasmonic molecule composed of two 1.2 μm diameter disks. For a single disk, there is a resonant mode with the azimuthal number \( m = 8 \) at the wavelength \( \lambda = 1025 \) nm. When the two disks are brought together with an inter-disk gap of \( d = 120 \) nm, the single-disk mode splits into red-shifted bonding modes (resonant wavelength \( \lambda = 1028 \) nm (OE) and \( \lambda = 1026 \) nm (EE)) and blue-shifted anti-bonding modes (resonant wavelength \( \lambda = 1023 \) nm (OO) and \( \lambda = 1022 \) nm (EO)). The profile of the dominant electric field component \( E_z \) over the \( x-y \) plane in the center of the alumina layer is shown in Fig. 2(a). Figure 2(b) shows the profile of the electric field \( E_z \) in the \( x-z \) plane for EE mode. Most of the electric field is confined within the disk edge of the middle layer, yielding a rather small mode volume.

To gain more insight into the mode splitting, the resonant wavelength against the inter-disk gap is plotted in Fig. 3(a). The resonant wavelength differences decrease when the distance increases from 0 to 320 nm due to an increasingly weakened coupling strength. When the distance increases further from 320 nm to 1200 nm, oscillations of the resonant wavelengths can be observed. The oscillations can be attributed to oscillatory behavior of the evanescent field. This oscillatory behavior has also been shown in Refs [3, 4, 18, 19]. When the inter-disk separation is large enough, the four split molecule modes converge to a single resonant wavelength. The coupling strength between the WG modes of disks (which is represented by the difference between the resonant wavelengths of the bonding and the anti-bonding modes) decreases with the increasing distance. The difference of the resonant wavelength \( \Delta \lambda \) is also related to the azimuthal mode number. For increasing azimuthal mode number, the resonant wavelengths of WG modes shift to short wavelengths, similar to the case of photonic molecules demonstrated by previous study [3]. The hybrid photonic-plasmonic molecule shows excellent ability to bind the short wavelength modes; therefore, the coupling strength decreases as the azimuthal mode number increases. As shown in Fig. 3(b), the difference of the resonant wavelengths \( \lambda_{OE} - \lambda_{OO} \) decreases from 22 nm to 5 nm with the azimuthal mode ranging from 4 to 8, while the \( \lambda_{EE} - \lambda_{EO} \) decreases from 20 nm to 4 nm.
4. Q factor enhancement of hybrid photonic-plasmonic molecule modes

Optical performance of a resonator cavity is evaluated by three major parameters: 1) the quality factor $Q$, which represents the power of the optical disks to enhance light-matter interactions, is calculated using a combination of FDTD techniques and Padé approximation with Baker's algorithm [35, 36]. 2) the effective mode volume $V_{eff}$ which is vital for the size-reduction of optical devices and 3) the Purcell factor $F_p$, which is related to the ratio of the $Q$ factor and mode volume as [27]:

$$F_p = \frac{3}{4\pi^2} \left( \frac{\lambda_0}{n} \right)^3 \left( \frac{Q}{V_{eff}} \right)$$

where $\lambda_0$ is the resonant wavelength in free space and $n$ is the refractive index of the lower-index layer. The effective mode volume is calculated as [27]:

$$V_{eff} = \frac{\int \epsilon(x, y, z) |E(x, y, z)|^2 \, dx \, dy \, dz}{\max \{\epsilon(x, y, z) |E(x, y, z)|^2 \}}$$

A cavity system with a high $Q$ factor and a small mode volume and thus a high Purcell factor is in favor of practical applications. Previous studies have shown that a resonator of a larger size can achieve a higher $Q$ factor and the $Q$ factor increases with the azimuthal mode number $m$ [4, 27]. Here we investigate the case of a high-azimuthal-order ($m = 8$) in the coupling system. The dependencies of the $Q$ factors for the OE, OO, EE, and EO modes on the distance between disks $d$ are plotted in Fig. 4 and $Q$ factors are found to oscillate with respect to $d$, which can be explained by “loss splitting” due to an imperfect destructive interference between the WG modes referred in [38]. The highest $Q$ factor of 1821 is obtained for the anti-bonding mode (OO) at $d = 540$ nm. This is a three times enhancement with respect to that of an isolated hybrid photonic-plasmonic atom ($Q = 608$). We also plot effective mode volume $V_{eff}$ against the azimuthal mode number ranging from 4 to 8 for all modes at $d = 120$ nm and $d = 540$ nm. Figure 5 shows that the increase of effective mode volume is nearly linear with respect to the increasing azimuthal number $m$. For the same azimuthal mode, $V_{eff}$ keeps almost the same for different modes (OE, OO, EE, and EO modes) at different inter-disk distances (120 nm and 540 nm). The effective mode volume of the hybrid photonic-plasmonic molecule is approximately two times of that of the single disk. So the effect of coupling between the two atoms in the hybrid photonic-plasmonic
molecule on the mode volume is not significant. The mode volume is predominantly determined by the azimuthal mode number and the number of disks in the coupling system.

![Fig. 4. The Q factor as functions of the distance between disks for bonding modes (OE, EE) and anti-bonding modes (OO, EO). The azimuthal-order \( m \) is 8. For comparison, the Q factor of an isolated disk \((m = 8)\) is also plotted (dash dot line).](image)

![Fig. 5. The effective mode volume \( V_{\text{eff}} \) against the azimuthal mode number for the bonding modes (OE, EE) and the anti-bonding modes (OO, EO) at \( d = 120 \text{ nm} \) and 540 nm. For comparison, the mode volume of a single disk is also plotted (triangle).](image)

As shown in Fig. 4, the highest Q factor of the hybrid photonic-plasmonic molecule is \( Q = 1821 \) at \( d = 540 \text{ nm} \). Correspondingly, a large Purcell factor \( F_P = 191 \) can be realized for the hybrid photonic-plasmonic molecule at 1025 nm resonant wavelength. Those properties offered by the hybrid photonic-plasmonic molecule demonstrate a way of reducing the microcavity size to the order of subwavelength scale while maintaining a relatively high Q factor.
5. The far-field pattern from hybrid photonic-plasmonic molecule

High directional radiation and selective mode enhancement are desirable for the applications of microcavities [39–42]. For a single microcavity, the disadvantage of multi-beam emission pattern hinders its further optical applications. When two identical disks are brought into proximity, the far-field emission properties of the hybrid photonic-plasmonic molecule are modified by near-field coupling. The exact emission patterns of the hybrid photonic-plasmonic molecule can be quite different among different WG modes. Appropriate control of the mutual coupling between individual cavities forming the hybrid photonic-plasmonic molecule enables enhancement of the directional emission.

In our FDTD calculation, the whole structure is first enclosed in a cube to collect near-field electromagnetic components at resonant wavelengths. Then the far-field patterns are calculated from the Fourier transformed near-field electromagnetic components based on the Green’s theorem [43]. The observed near-field distributions of the hybrid photonic-plasmonic molecule are analogous to those of multi-dipoles \((m = 7 \text{ and } 8)\) arranged along the edge of circle disks. Their far-field emission patterns result from the multi-dipoles \((m = 7 \text{ and } 8)\) of individual disk and the interactions between coupled disks. The radiations from multi-dipoles of individual disk for \(m = 7 \text{ and } 8\) are different. The interactions between coupled disks further complicate the radiation patterns, leading to a substantial difference between the patterns for \(m = 7 \text{ and } m = 8\).

Figure 6 shows the normalized H-plane emission patterns of the WG modes of \(m = 7\) for individual atom and a hybrid photonic-plasmonic molecule. As for a single disk, there exists multi-beam emission (Fig. 6(a)), while the number of main emission beams decreases in the hybrid photonic-plasmonic molecule. There are main emission beams in the direction of \(\phi = 90^\circ \text{ and } 270^\circ\) for OE and EE modes, while these beams disappear for OO and EO modes. Meanwhile, there are negligible emission beams in the direction of \(\phi = 0^\circ \text{ and } 180^\circ\) for OE and OO modes. The far-field emission patterns of the hybrid photonic-plasmonic molecule for \(m = 8\) are shown in Fig. 7. The emission pattern for a single disk is similar to that of \(m = 7\). In contrast to the case of bonding modes (OE and EE), the anti-bonding modes (OO and EO) have a better directional emission with four main beams of emission shown in Fig. 7(c) and 7(e).

![Fig. 6. The far-field emission patterns of H-plane (a) for the individual disk of WG modes of \(m = 7\), (b), (d) the bonding modes (OE and EE) and (c), (e) the anti-bonding modes (OO and EO) for hybrid photonic-plasmonic molecule.](image-url)
Fig. 7. The far-field emission patterns of H-plane (a) for the individual disk of WG modes of $m = 8$, (b), (d) the bonding modes (OE and EE) and (c), (e) the anti-bonding modes (OO and EO) for hybrid photonic-plasmonic molecule.

Figure 8 shows the normalized E-plane emission patterns of the WG modes of $m = 7$ for individual hybrid photonic-plasmonic atom and a hybrid photonic-plasmonic molecule. From Fig. 8, the E-plane emission concentrates mainly in the direction of $\phi = 0^\circ$ and $180^\circ$ for the individual disk, OE and EE modes, whereas the electric field emit downward for OO and EO modes. The E-plane emission patterns of $m = 8$ are shown in Fig. 9, which shows that the directions of main emission beam slope are unique for the four modes. However, there is no emission energy in the direction of $\phi = 90^\circ$ and $270^\circ$ for both a single disk and a hybrid photonic-plasmonic molecule owing to the top silver layer.

Fig. 8. The far-field emission patterns of E-plane (a) for the individual disk of WG modes of $m = 7$, (b), (d) the bonding modes (OE and EE) and (c), (e) the anti-bonding modes (OO and EO) for hybrid photonic-plasmonic molecule.
Fig. 9. The far-field emission patterns of E-plane (a) for the individual disk of WG modes of $m = 8$, (b), (d) the bonding modes (OE and EE) and (c), (e) the anti-bonding modes (OO and EO) for hybrid photonic-plasmonic molecule.

The far-field emission patterns of the hybrid photonic-plasmonic molecule can be efficiently manipulated by varying the azimuthal mode number. Furthermore, the emission pattern of OE mode $m = 7$ shows enhanced directivity in the H-plane.

6. Conclusions

A new type of coupled resonator named “hybrid photonic-plasmonic molecule” comprising of two identical disks is studied. For the molecule, each azimuthal mode can split into two groups of nearly-degenerate modes, i.e., the bonding (OE, EE) and anti-bonding (EO, OO) modes. The coupling strength and shifted resonant wavelength of the two modes decrease with the inter-disk distance. Compared with the photonic molecule, the hybrid photonic-plasmonic molecule can acquire a high Purcell factor 191 accompanied by a Q factor of 1821. Moreover, the far-field emission patterns of the coupling WG modes are investigated. The emission patterns of the hybrid photonic-plasmonic molecule show an enhanced directivity in the H-plane with fewer main beams of emission for both bonding and anti-bonding coupling modes by varying the azimuthal mode number. Compared with photonic molecule geometries, the hybrid photonic-plasmonic molecule cannot only further reduce the cavity size to the subwavelength dimension but also lower the threshold of WG modes lasers, while a high Q factor and a small mode volume are maintained. These capabilities drive its potential applications in a single photon source, laser, optical memory, etc [20, 44]. For example, when a quantum dot is embedded in the hybrid photonic-plasmonic molecule, the optical cavities with increased local density of optical states can enhance the emission rate, which is beneficial for single photon sources [45].

Acknowledgments

This work is supported by the National Natural Science Foundation of China (Grant Nos. 61205030, 61275030 and 61235007), the Opened Fund of State Key Laboratory of Advanced Optical Communication Systems and Networks, the Opened Fund of State Key Laboratory on Integrated Optoelectronics, the Fundamental Research Funds for the Central
Universities (2012QNA5003), Doctoral Fund of Ministry of Education of China (Grant No 20120101120128), the Swedish Foundation for Strategic Research (SSF) and the Swedish Research Council (VR).