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Optical absorption tunability and local electric field distribution of gold-dielectric-silver three-layered cylindrical nanotube*

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The effects of inner nanowire radius, shell thickness, the dielectric functions of middle layer and surrounding medium on localized surface plasmon resonance (LSPR) of gold-dielectric-silver nanotube are studied based on the quasi-static approximation. Theoretical calculation results show that LSPR of gold-dielectric-silver nanotube and LSPR numbers can be well optimized by adjusting its geometrical parameters. The longer wavelength of $|\omega_{-}\rangle$ mode takes place a distinct red-shift with increasing the inner nanowire radius and the thickness of middle dielectric layer, while a blue-shift with increasing outer nanotube thickness. The physical mechanisms are explained based on the plasmon hybridization theory, induced charges and phase retardation. In addition, the effects of middle dielectric function and surrounding medium on LSPR, and the local electric field factor are also reported. Our study provides the potential applications of gold-dielectric-silver nanotube in biological tissues, sensor and related regions.

Keywords: localized surface plasmon resonance, gold-dielectric-silver nanotube, quasi-static approximation, plasmon hybridization theory

PACS: 42.25.−p, 42.70.−a, 77.84.Lf, 78.67.−n **DOI:** 10.1088/1674-1056/ac0785

1. Introduction

Special optical properties of noble metal nano-structures (i.e., gold and silver) demonstrate different optical properties in comparison with bulk metal materials, thus optical properties of nobel metal nano-structures have attractive interests due to the intense light absorption of localized surface plasmon resonance (LSPR). LSPR originates from the collective oscillation of conduction electrons in accordance with the incident wave frequency,[1,2] and the results show that both the intensity and LSPR peak position can be well tuned by varying the nano-structure size, shape, structure and surrounding medium function.[3] Therefore, the LSPR can be well tuned by adjusting the parameters of the particle size, shape, component and surrounding medium function. LSPR has been widely used in chemical and biological sensing,[4] tunabilty of Fano resonance[5] and surface-enhanced Raman spectroscopy (SERS).[6] The studies show that core-shell nano-particle is one of the most efficient methods to vary the LSPR wavelength from ultraviolet to infrared region. Xia *et al.* have synthesized three-layered gold-silica-gold nanoshell with a size sub-100 nm, and the results shows that gold-silica-gold nanoshell can generate a strong surface plasmon resonance.[7] Halas *et al.* have studied the optical properties of concentric nanoshell structures using the plasmon hybridization theory, and suggested the complex structure of nanoshell can be viewed as a sum of the contributions of the dipolar and higher order hybrid multipolar plasmon modes,[8,9] which provides a new approach to well analyze the optical properties of nanoshell. Wang *et al.* have studied a novel plasmonic refractive index sensor based on gold/silicon structure and used it as a sensor in biochemistry.[10] Debelaa *et al.* have reported surface plasmon resonances in ellipsoidal bimetallic nanoparticles using the Laplace equation, and the results show that the LSPR depends on surrounding dielectric function.[11] Wu *et al.* have studied optical properties of bimetallic gold and silver alloy nanoshell for biomedical applications *in vivo* with Mie scattering theory and plasmon hybridization theory, and the result indicates that the lower energy mode has a distinct red-shift with increasing core radius.[12] Schiditabar *et al.* have investigated the resonance light scattering properties of silver-dielectric-silver nanoshell based on quasi-static approach, and the results show that LSPR are optimized by tuning the geometrical dimensions.[13] Based on the light absorption spectra properties of a bimetallic multilayer nanoshell (silver-dielectric-silver, gold-dielectric-silver and silver-dielectric-gold), the results show that relatively small thickness of outer silver shell and large dielectric constants of middle dielectric layer of gold-dielectric-silver nanoshell are suitable to obtain the triple plasmon resonance.[14]

Recently, the optical properties of nanotube have also

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been widely investigated and applied in biological tissues, nanosensors, optical devices, optical data storage and some regions. Bahari *et al.* have studied metal-air-metal cylinder theoretically, and given the effect of increasing the interwall spacing between two metals on plasmon dispersion relation.[15] Wang have reported that cylindrical core-shell nanorods can obtain Fano resonance by adjusting the field coupling between cavity and gold surface, which could be applied in optical devices.[6] Zhu *et al.* have investigated the effect of local dielectric environment on the resonance light scattering of Au-Ag bimetallic nanotube, and the result presents a potential for design and fabrication of optical refractive index nanosensors.[16] Gao *et al.* have investigated the geometrical parameters focusing and enhancing near field in infinite circular silver-dielectric-silver cylinder with quasi-static approach, what is more, the study shows that local electric field enhancement provides the potential applications for optical data storage.[17] A stronger local field enhancement can be obtained in the middle dielectric wall between inner silver and outer tube at the resonance wavelength.[18] Moradi has theoretically studied how the plasmon excitations of the system depend on the dielectric difference between the core and shell in coated metallic nanowires.[19] Zhu *et al.* have reported the local dielectric environment dependent local field enhancement properties in double concentric silver nanotube using plasmon hybridization method and quasi-static calculation.[20] Daneshfar *et al.* have studied optical and spectral tunability of multilayer spherical and cylindrical nanoshell with quasi-static theory.[21] Wu *et al.* have studied the multiple Fano resonance of nanrod and nanoring, which has been applied in refractive index sensing and high-sensitivity biosensors.[22] The optical absorption of three-layered nanoshell shows that the LSPR can be well adjusted the parameters of nanoshell.[23]

Most of previous studies have mainly focused on gold-dielectric-gold nanotube, where the core and outer shell have the same nobel metal, while the core and outer shell with different nobel metals are less reported. In this paper, we theoretically investigate the effects of inner gold nanowire radius, the dielectric functions of inner core and surrounding medium on gold-dielectric-silver nanotube. In addition, its sensor and local electric field factor are also reported. Local electric field factor is one of the important parameters to affect the surface enhanced Raman scattering, nonlinear optical response and optical data storage. Our study provides a method to broaden the potential applications of gold-dielectric-silver nanotube in biological tissues, sensor, optical data storage and other regions.

2. Model and theoretical method

In this paper, we study the absorption properties of gold-dielectric-silver three-layered nanotube. The geometry of an infinite three-layered gold-dielectric-silver nanotube is given in Fig. 1. The geometry consists of an infinite length gold nanowire with a radius r_1 and dielectric function ε_1, the outer silver nanotube with a thickness $r_3 - r_2$ and dielectric function ε_3. The nanowire and nanotube are separated by a middle dielectric layer with a thickness $r_2 - r_1$ and dielectric function ε_2, and the total nanotube is suspended in the surrounding medium with dielectric function ε_4. The total diameter of gold-dielectric-silver nanotube is much smaller than the incident wavelength, thus the surface charges in gold-dielectric-silver nanotube oscillate like a simple electric dipole and then the quasi-static approximation can be used to calculate the optical property of absorption cross section.[24] The diameter of gold-dielectric-silver nanotube is much smaller than the incident wavelength, thus the induced field in the region outside the shell likes a dipole. The absorption cross section can be gotten from polarizability by using the scattering theory $C_{\text{abs}} = k\,\text{Im}(\alpha)$,[25] where α is the polarizability.

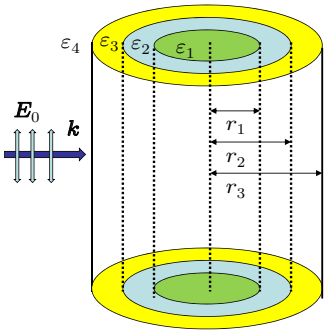


Fig. 1. The geometry of gold-dielectric-silver nanotube.

In Drude model,[26] the frequency-dependent inner gold nanowire ε_1 and outer silver shell ε_3 have real and imaginary components. The dielectric functions of gold and silver could be written as follows:

$$\varepsilon(\omega) = \varepsilon_{\text{exp}}(\omega) + \frac{{\omega_{\text{p}}}^2}{\omega^2 + \text{i}\omega\gamma_{\text{bulk}}} - \frac{{\omega_{\text{p}}}^2}{\omega^2 + \text{i}\omega(\gamma_{\text{bulk}} + \frac{V_{\text{F}}}{R})}, \quad (1)$$

where $\varepsilon_{\text{exp}}(\omega)$ is the experimental bulk dielectric function.[27] $\omega_{\text{p}} = 1.37 \times 10^{16}$ Hz denotes the plasma frequency of bulk gold and $\omega_{\text{p}} = 1.364 \times 10^{16}$ Hz for silver, $\gamma_{\text{bulk}} = 1.07 \times 10^{13}$ Hz is electron collision damping in the gold and $\gamma_{\text{bulk}} = 3.23 \times 10^{13}$ Hz for silver. $V_{\text{F}} = 1.4 \times 10^6$ m/s is the Fermi velocity, $R = r_3 - r_2$ for silver nanotube and $R = 2r_1$ for inner gold nanowire.

3. Results and discussion

According to plasmon hybridization theory,[8,28] gold-dielectric-silver nanotube can be viewed as the coupling between the plasmon response of a gold nanowire with its energy mode $|\omega_{\text{s}}\rangle$ and outer silver nanotube ($|\omega_{-}\rangle$ and $|\omega_{+}\rangle$), which results in four new plasmon modes $|\omega_{+}^{+}\rangle$, $|\omega_{+}^{-}\rangle$, $|\omega_{-}^{+}\rangle$

and $|\omega_-^-\rangle$. The higher energy $|\omega_+^+\rangle$ ($|\omega_-^+\rangle$) mode corresponds to anti-symmetric (symmetric) coupling between anti-symmetric plasmon mode $|\omega_+\rangle$ and the inner gold nanowire plasmon $|\omega_s\rangle$. And the lower energy $|\omega_-^-\rangle$ ($|\omega_+^-\rangle$) mode corresponds to anti-symmetric (symmetric) coupling between symmetric plasmon mode $|\omega_-\rangle$ and $|\omega_s\rangle$. The highest energy $|\omega_+^+\rangle$ mode is usually too weak to be observed in experiments due to the induced charges of inner nanowire plasmon oppositely aligned with that of outer nanotube plasmon, which weakens the dipole moment. The coupling between inner gold nanowire and outer nanotube is given in Fig. 2. As shown in Fig. 2(a), one can find that $|\omega_-\rangle$ plays a more role to $|\omega_-^-\rangle$ than that of $|\omega_s\rangle$, where the higher energy $|\omega_-^+\rangle$ is mainly dominated by $|\omega_s\rangle$. In order to fully understand the physical mechanism of plasmon coupling, Figs. 2(b)–2(d) give the local electric field intensity distribution of gold-dielectric-silver nanotube at LSPR wavelength $\lambda = 318$ nm, 484 nm and 750 nm, respectively. As shown in Fig. 2(b), the intense local electric field appears in the middle dielectric layer and outer silver nanotube at wavelength $\lambda = 318$ nm, where the electric field is very weak in the inner gold nanowire and surrounding medium. The distribution of local electric field intensity indicates that the opposite charges distribute on the surface of inner dielectric layer and outer nanotube, which get strong attractive force,[28] thus we think $\lambda = 318$ nm is the $|\omega_+^-\rangle$ mode. Figure 2(c) shows the intense local electric field appearing in the region of inner gold nanowire and outer silver nanotube at wavelength $\lambda = 484$ nm, where the electric field is much stronger in the inner gold nanowire, while the electric field is much weaker in the middle dielectric layer. The induced charges are opposite on the surface of inner gold nanowire, while the same sign of induced charges distribute on the inner and outer surface of outer silver nanotube, thus $\lambda = 484$ nm is $|\omega_-^+\rangle$ mode. In addition, one can find that the intense local electric field enhancement appears in the middle dielectric layer due to the opposite charges distribution on the inner and outer surface of middle dielectric layer in Fig. 2(d) at wavelength $\lambda = 750$ nm, therefore, $\lambda = 750$ nm is $|\omega_-^-\rangle$ mode. Normally, both the lower energies of $|\omega_-^-\rangle$ mode and $|\omega_-^+\rangle$ mode can be easily visible in the infrared region. In this paper, the absorption optical properties of $|\omega_-^+\rangle$ mode and $|\omega_-^-\rangle$ mode are studied in detail.

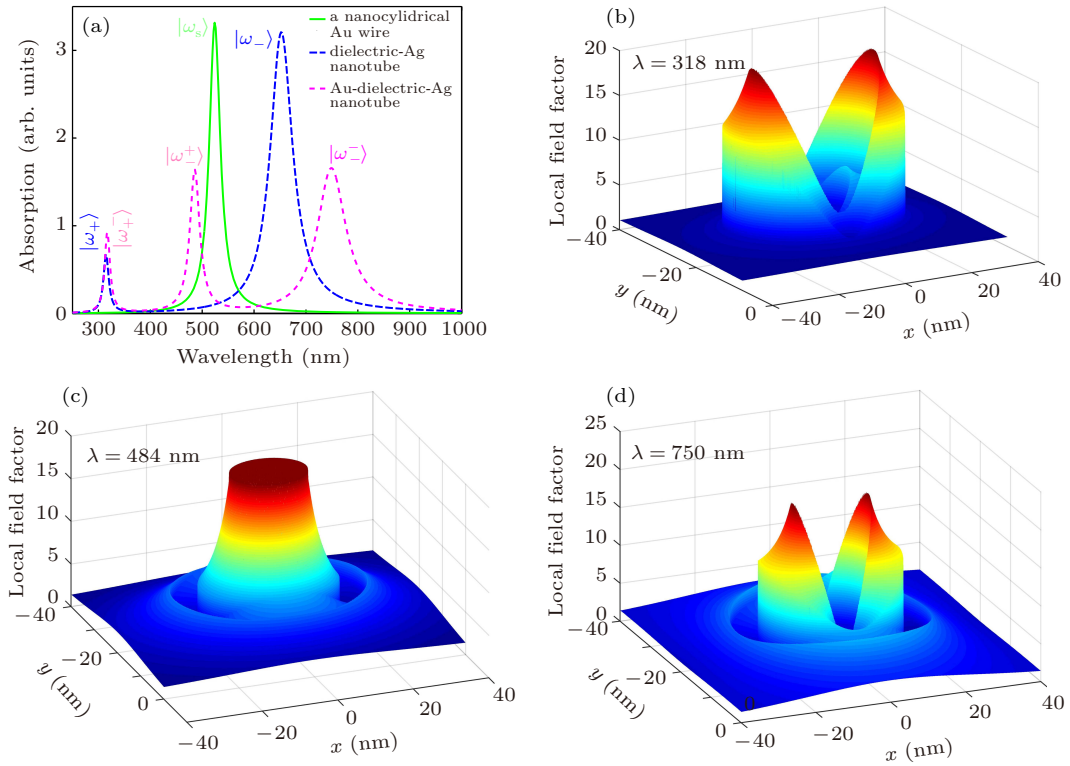


Fig. 2. (a) Absorption spectra of gold-dielectric-silver nanotube calculated for a single cylindrical gold nanowire, dielectric-silver nanotube and gold-dielectric-silver nanotube, (b)–(d) the local electric field factor of gold-dielectric-silver nanotube at each LSPR wavelength $\lambda = 318$ nm, $\lambda = 484$ nm and $\lambda = 750$ nm, respectively.

3.1. The effect of inner nanowire radius with different middle dielectric functions on LSPR of gold-dielectric-silver nanotube

The absorption spectra of gold-dielectric-silver nanotube with different inner nanowire radius and the middle dielectric function are plotted in Fig. 3, where the radii of the middle dielectric layer r_2 and the outer silver nanotube r_3 are fixed at 15 nm and 25 nm, respectively. The gold-dielectric-silver nanotube is suspended in surrounding medium $\varepsilon_4 = 4.0$. The results show that the intensity, LSPR position and LSPR peak number are sensitive to the inner nanowire radius and middle dielectric functions. $|\omega_-^-\rangle$ mode shows a distinct red-shift

($\Delta\lambda = 198$ nm from $\lambda = 652$ nm to $\lambda = 854$ nm) with increasing inner nanowire radius from $r_1 = 2$ nm to 12 nm, while $|\omega_-^+\rangle$ mode shows a little blue-shift, and its full widths at half maxium (FWHMs) narrows.[13,14] The near infrared region is well suitable for biomedical applications due to minimal absorption of biological tissues and provides a transparent window for biological tissues.[29] The nanotube plasmon of $|\omega_-\rangle$ and $|\omega_+\rangle$ can be considered as a constant when the radii of r_2 and r_3 are fixed, and in this case the LSPRs are mainly affected by that of inner gold nanowire $|\omega_s\rangle$ mode.[8] As the inner gold nanowire radius increases, the separation between inner gold nanowire and outer nanotube reduces, and then the coupling between inner nanowire and nanotube is enhanced. Therefore, the energy of $|\omega_-^-\rangle$ mode reduces (a red-shift) and $|\omega_-^+\rangle$ mode enhances (a blue-shift). However, the intensity of $|\omega_-^+\rangle$ mode shows a contrary behavior to that of $|\omega_-^-\rangle$ mode, and $|\omega_-^+\rangle$ mode intensity enhances with increasing inner nanowire radius. The physical mechanism of this property could be explained as that the intensity of $|\omega_-^+\rangle$ mode is mainly dominated by inner gold nanowire $|\omega_s\rangle$. There are more electrons to oscillate with increasing the inner gold nanowire radius and then the intensity of $|\omega_-^+\rangle$ mode enhances. It is also found that both the intensity and the peak position of LSPR are sensitive to middle dielectric function. Compared with Figs. 3(a)–3(c), the characteristic of $\Delta\lambda$ has a red-shift and the intensity reduces quickly with increasing $\varepsilon_2 = 2.0$ to 6.0. The induced charges reduce with increasing middle dielectric function,[28] and then $|\omega_-^-\rangle$ mode shows a red-shift and its intensity also reduces. In addition, one can find that $|\omega_+^-\rangle$ mode becomes to appear when the inner gold nanowire radius is bigger enough ($r_1 \geq 4$ nm), and its intensity enhances with increasing inner gold nanowire radius. In summary, LSPR numbers and its intensity can be well tuned by varying the inner gold nanowire radius and middle dielectric function.

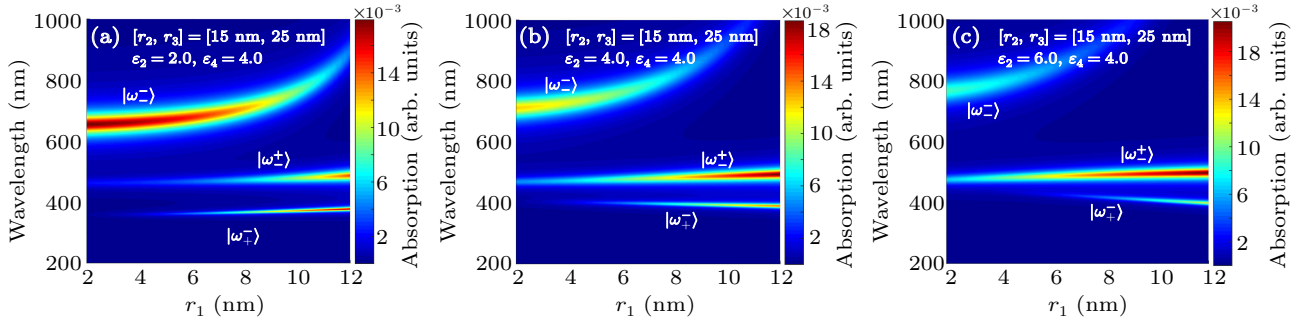


Fig. 3. The effect of inner gold nanowire radius r_1 on absorption spectra of gold-dielectric-silver nanotube with $[r_2, r_3] = [15\text{ nm}, 25\text{ nm}]$ and $\varepsilon_4 = 4.0$. (a) $\varepsilon_2 = 2.0$, (b) $\varepsilon_2 = 4.0$ and (c) $\varepsilon_2 = 6.0$, respectively.

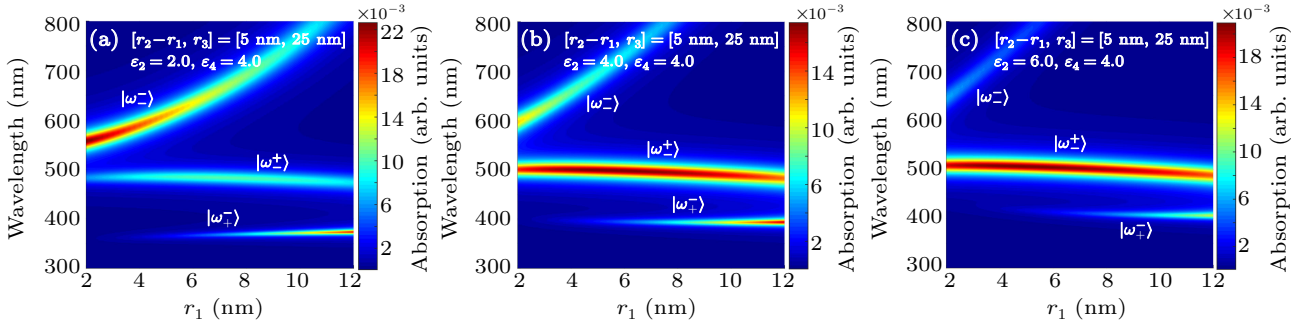


Fig. 4. The effect of inner gold nanowire radius r_1 on absorption spectra of gold-dielectric-silver nanotube with $[r_2 - r_1, r_3] = [5\text{ nm}, 25\text{ nm}]$ and $\varepsilon_4 = 4.0$. (a) $\varepsilon_2 = 2.0$, (b) $\varepsilon_2 = 4.0$ and (c) $\varepsilon_2 = 6.0$, respectively.

To fully understand the influence of inner gold nanowire radius on LSPR, the absorption spectra of LSPR with middle dielectric thickness fixed at $r_2 - r_1 = 5$ nm are given in Fig. 4, where the inner gold nanowire radius r_1 is varied from $r_1 = 2$ nm to 12 nm and the outer nanotube radius r_3 is fixed at $r_3 = 25$ nm. Compared with Figs. 3(a)–3(c), the results show that $|\omega_-^-\rangle$ mode shows a red-shift much more quickly than that of Figs. 3(a)–3(c), and its intensity also reduces rapidly.[17] $|\omega_-^+\rangle$ mode shows a little blue-shift, and its intensity enhances firstly and then reduces. The physical mechanism could be attributed to plasmon hybridization, the coupling of outer nanotube is affected by the ratio of r_2/r_3.[19] The coupling is enhanced with increasing the ratio r_2/r_3 ($r_2/r_3 = 0.28$ for $r_2 = 7$ nm and $r_2/r_3 = 0.68$ for $r_2 = 17$ nm), and then $|\omega_-^-\rangle$ mode shows a red-shift and $|\omega_-^+\rangle$ mode has a blue-shift. An increase in middle dielectric layer will reduces outer nanotube thickness, the increasing middle dielectric radius leads to interface curvatures of the middle dielectric thickness reduce, and then the surface charges concentrated at both inner gold nanowire and outer silver nanotube of the middle dielectric thickness reduces. Thus the surface charges induced electrostatic attraction lead to the local electric field intensity reduce.

On the other hand, there are less effective electrons to oscillate, and then the energy of $|\omega_-^-\rangle$ mode and $|\omega_-^+\rangle$ mode reduce. It means that the intensities of LSPR are controlled by two factors, one is the coupling, and the other is the induced charges. In addition, compared with Figs. 4(a)–4(c), one can find that the LSPR of $|\omega_-^-\rangle$ mode shows a red-shift quickly with increasing middle dielectric function and its intensity also fades down quickly.[28] The third peak $|\omega_+^-\rangle$ mode becomes to appear when r_1 is bigger enough, i.e., $r_1 \geq 5$ nm, which is similar to that of Fig. 3.

3.2. The effect of middle dielectric layer radius on LSPR of gold-dielectric-silver nanotube

Figure 5 shows the effects of the middle dielectric radius varied from $r_2 = 8$ nm to 23 nm on LSPR, where the radii of inner gold nanowire r_1 and the outer silver nanotube r_3 are fixed at 5 nm and 25 nm, respectively. Figure 5(a) shows that $|\omega_-^-\rangle$ mode takes place a blue-shift firstly and then a red-shift rapidly with increasing middle dielectric radius, its enhanced intensity only appears when the middle dielectric layer has a thin thickness (about $r_2 = 12$ nm) and then fades down rapidly as the thickness of middle dielectric layer is further increased. It is known that the plasmon coupling is controlled by the thickness of nanotube according to plasmon hybridization theory.[8] The plasmon responses of a gold wire with its energy mode $|\omega_s\rangle$ could be considered as a constant when the inner gold wire radius is fixed. Thus the LSPR is mainly effected by the outer nanotube ($|\omega_+\rangle$ and $|\omega_-\rangle$).[19,22,23] The ratio (r_2/r_3) is increased from $r_2/r_3 = 0.67$ for $r_2 = 10$ nm to 0.8 for $r_2 = 20$ nm, and then the coupling of nanotube enhances. Therefore, $|\omega_-\rangle$ mode reduces and $|\omega_+\rangle$ mode increases. $|\omega_-^-\rangle$ mode shows a red-shift and $|\omega_-^+\rangle$ mode has a blue-shift. On the other hand, the thickness of middle dielectric layer also increases when the middle layer radius increases, and then the separation between the inner gold nanowire and outer nanotube is increased. The attractive strengthen between the inner gold nanowire and outer silver nanotube will be reduced, thus the LSPR peak of $|\omega_-^-\rangle$ mode shows a red-shift. In addition, the intensity of LSPR increases firstly and then reduces rapidly as the middle dielectric radius increases. This behavior could be explained as that although the coupling is stronger with thinner thickness, there are less electrons to participant in oscillating when thickness of outer nanotube become much thinner, thus the resonance decreases and absorption gets less intensity. In addition, one can find that an increase in middle dielectric function will leads to the LSPR of $|\omega_-^-\rangle$ mode a red-shift and its intensity fades down quickly.[28] The optical property of $|\omega_+^-\rangle$ mode is contrary to that of Figs. 3 and 4, its intensity fades down and becomes to disappear with increasing middle dielectric layer radius r_2, and this phenomenon agrees with the previous study.[20] The effect of middle dielectric function ε_2 on $|\omega_+^-\rangle$ mode is similar to that of Figs. 3 and 4.

Our next goal is to study the effect of outer middle dielectric thickness on LSPR, where the inner gold nanowire radius r_1 and outer nanotube thickness $r_3 - r_2$ are fixed at $r_1 = 5$ nm and $r_3 - r_2 = 5$ nm, while the middle dielectric radius r_2 is varied from $r_2 = 10$ nm to 20 nm, which is given in Fig. 6.

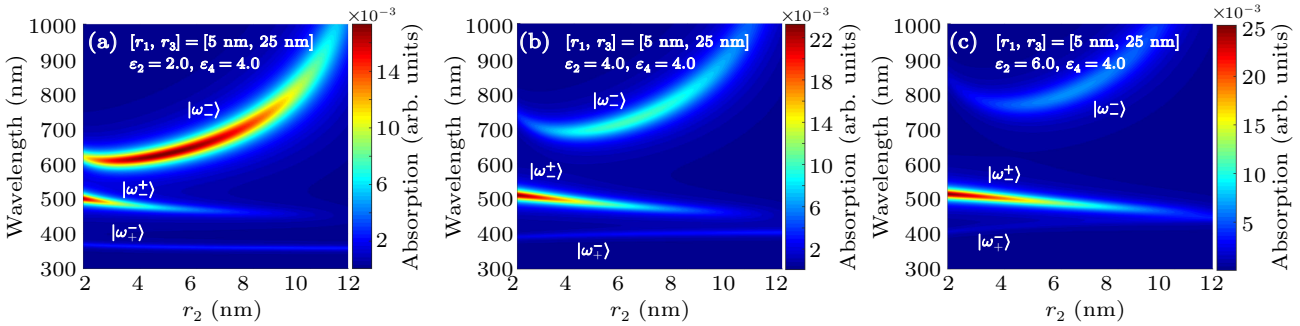


Fig. 5. The effect of middle dielectric radius r_2 on absorption spectra of gold-dielectric-silver nanotube with $[r_1, r_3] = [5\,\text{nm}, 25\,\text{nm}]$ and $\varepsilon_4 = 4.0$: (a) $\varepsilon_2 = 2.0$, (b) $\varepsilon_2 = 4.0$ and (c) $\varepsilon_2 = 6.0$, respectively.

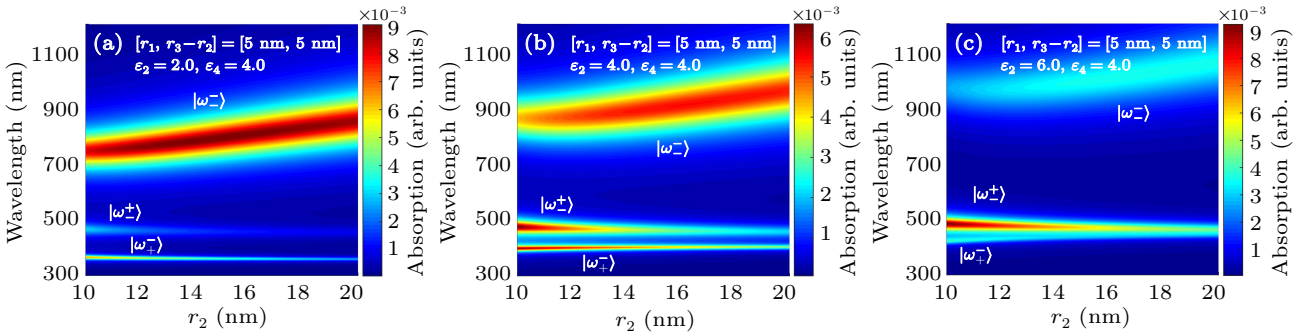


Fig. 6. The effect of middle dielectric radius r_2 on absorption spectra of gold-dielectric-silver nanotube with $[r_1, r_3 - r_2] = [5\,\text{nm}, 5\,\text{nm}]$ and $\varepsilon_4 = 4.0$: (a) $\varepsilon_2 = 2.0$, (b) $\varepsilon_2 = 4.0$ and (c) $\varepsilon_2 = 6.0$, respectively.

Figure 6 shows that $|\omega_-^-\rangle$ mode shows a red-shift and $|\omega_-^+\rangle$ mode has a little blue-shift. The coupling of nanotube ($|\omega_-\rangle$ mode and $|\omega_+\rangle$ mode) is enhanced with increasing the ratio of r_2/r_3.[9] On the other hand, the total size of gold-dielectric-silver nanotube is also increased, thus the phase retardation will leads to the intensity of LSPR reduce, and then both $|\omega_-^-\rangle$ mode and $|\omega_-^+\rangle$ are reduced,[12] thus $|\omega_-^-\rangle$ mode shows a red-shift. It means that $|\omega_-^-\rangle$ mode is controlled by two factors, one is the coupling between gold wire and silver nanotube, and the other is the phase retardation. $|\omega_-^-\rangle$ mode shows a blue-shift when the coupling plays a dominate role than phase retardation, otherwise, $|\omega_-^-\rangle$ mode has a red-shift. Figure 6 means that phase retardation plays a dominate role than the coupling, and then $|\omega_-^-\rangle$ mode shows a red-shift. In addition, the intensity reduces with increasing middle dielectric function, which is similar to that of Fig. 5.

3.3. The effect of outer silver radius on LSPR of gold-dielectric-silver nanotube

We further investigate the effects of outer nanotube radius r_3 on LSPRs, and the results are shown in Fig. 7, where the radii of inner gold nanowire r_1 and the middle dielectric layer r_2 are fixed at 5 nm and 12 nm, respectively, while the outer radius r_3 is varied from $r_3 = 15$ nm to 25 nm. One can find that the $|\omega_-^-\rangle$ mode has a distinct blue-shift with increasing the outer radius from $r_3 = 15$ nm to 25 nm, and the intensity of LSPR enhances. $|\omega_-^+\rangle$ mode shows a little red-shift. The ratio of r_2/r_3 is reduced with increasing outer nanotube radius r_3, and then ω_+ reduces and ω_- enhances.[20,22] Thus the coupling between the gold wire and nanotube is reduced, in this case the intensity of $|\omega_-^-\rangle$ mode is increased and $|\omega_-^+\rangle$ mode is reduced. On the other hand, the total size is also increased with increasing outer nanotube radius r_3, which reduces the LSPR intensity due to phase retardation effect, thus both $|\omega_-^-\rangle$ mode and $|\omega_-^+\rangle$ mode reduce. Figure 7 shows that the coupling is more dominate than that of phase retardation. It is also found that the absorption gets more intensity with increasing outer shell thickness due to more electrons to participant in oscillating when thickness becomes much thicker. In addition, Fig. 7 shows the intensity reduces with increasing middle dielectric function.[22] Figure 8 shows the effects of the ratio of $r_1/r_2/r_3 =$ constant on LSPR, and the results show that the peak is no-shift and its intensity enhances with increasing the inner gold wire radius, which agrees well with theoretical studies,[19] where the LSPR shows no-shift when $r_1/r_2 =$ constant, $r_2/r_3 =$ constant and $r_1/r_3 =$ constant.

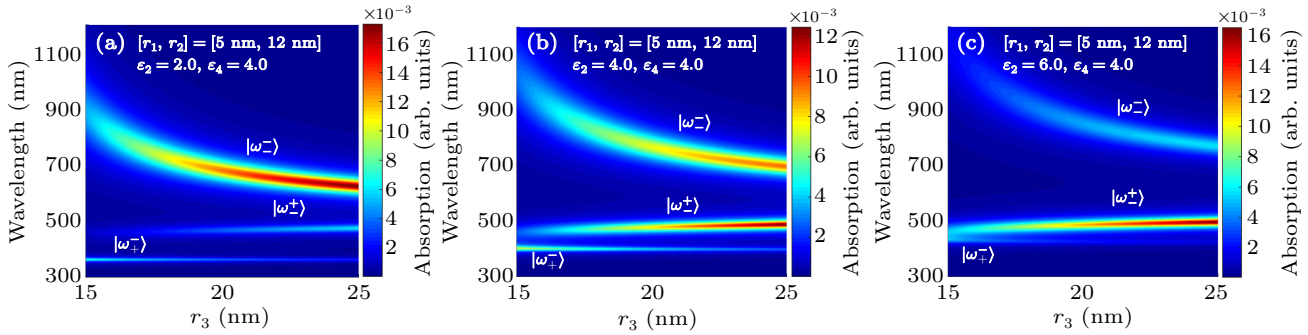


Fig. 7. The effect of outer nanotube radius r_3 on absorption spectra of gold-dielectric-silver nanotube with $[r_1, r_2] = [5\text{ nm}, 10\text{ nm}]$ and $\varepsilon_4 = 4.0$: (a) $\varepsilon_2 = 2.0$, (b) $\varepsilon_2 = 4.0$ and (c) $\varepsilon_2 = 6.0$, respectively.

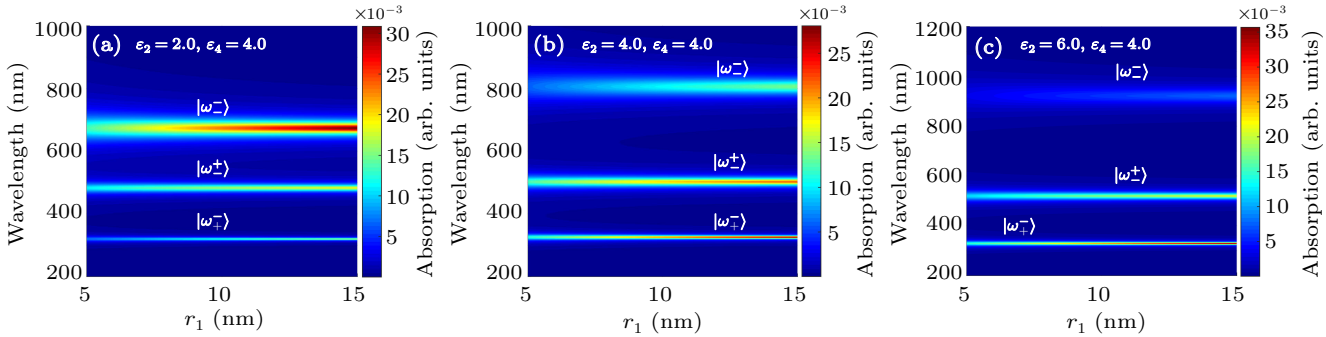


Fig. 8. The effect of the ratio of $r_1/r_2/r_3 =$ constant on absorption spectra of gold-dielectric-silver nanotube with $r_1 = 5$ nm and $\varepsilon_4 = 4.0$: (a) $\varepsilon_2 = 2.0$, (b) $\varepsilon_2 = 4.0$ and (c) $\varepsilon_2 = 6.0$, respectively.

3.4. The effect of surrounding medium dielectric function on LSPR of gold-dielectric-silver nanotube

In order to understand the absorption spectra of gold-dielectric-silver nanotube, we also gain an insight into the effects of surrounding medium dielectric functions ε_4 on LSPR in Fig. 9. Figure 9(a) shows that the LSPR of $|\omega_-^-\rangle$ mode is sensitive to the surrounding medium ε_4, which shows a distinct red-shift and its intensity enhances quickly with increasing the

surrounding medium ε_4, while the LSPR of $|\omega_-^+\rangle$ mode is not sensitive to the surrounding medium ε_4, and LSPR position almost keeps at a constant and its intensity fades down. In the reports of Deeb[30] and Zhu,[31] both the induced surface charges and the absorption intensities are related to the electric field discontinuity at the particle interface. According to plasmon hybridization theory, the inside and outside surface of middle dielectric layer have the opposite induced surface charges (positive and negative charges) in $|\omega_-^-\rangle$ mode. And then the local field in the dielectric layer is polarized in the direction of the depolarization field around the surrounding media. The attractive force between the inside and outside of the middle dielectric layer leads to an increase in the induced charges density of the dielectric layer, and then the absorption is increased. Therefore, $|\omega_-^-\rangle$ mode is sensitive to the surrounding medium function ε_4. However, in $|\omega_-^+\rangle$ mode, the surfaces of the dielectric layer (inside and outside) have the same sign charge, the local field in the dielectric layer is perpendicular to the depolarization field around the surrounding medium, and then the surface density of induced charges is proportional to the change of the local electric field inside and outside of the particle. Thus the absorption intensity of $|\omega_-^+\rangle$ mode is not very sensitive to the surrounding dielectric function. The intensity difference between $|\omega_-^-\rangle$ mode and $|\omega_-^+\rangle$ mode is increased with increasing the surrounding media functions ε_4. In other words, the intensity difference is sensitive to the surrounding medium functions ε_4. Recent studies have shown that the plasmon absorption intensity difference between $|\omega_-^-\rangle$ mode and $|\omega_-^+\rangle$ mode has been used for refractive index sensitivity,[3,6,22,31] the effects of the thickness of inner nanowire and middle dielectric layer, and middle dielectric function on LSPR are also studied, which are given in Figs. 9(b)–9(d). Compared with Fig. 9(a), Fig. 9(b) shows that the intensity of $|\omega_-^-\rangle$ mode enhances quickly with increasing inner gold wire radius, while the intensity of $|\omega_-^+\rangle$ mode almost remains at a constant, which is contrary to that of sphere nanoshell.[23,32] As an increase in surrounding medium function, the intensity difference between $|\omega_-^-\rangle$ mode and $|\omega_-^+\rangle$ mode is slower than that of Fig. 9(a) with smaller inner radius. In other words, the thinner gold wire radius is more superior than that of thicker gold wire to be used in refractive index sensitivity. Compared with Figs. 9(a) and 9(b), Fig. 9(c) shows that the intensity of $|\omega_-^+\rangle$ mode enhances slower with thinner thickness of outer nanotube than that of Figs. 9(a) and 9(b) with thicker thickness of outer nanotube. Finally, the effect of middle dielectric function is also investigated. Figure 9(d) shows that the LSPR of $|\omega_-^+\rangle$ mode is mainly effected by the middle dielectric function ε_2, and the intensity of $|\omega_-^+\rangle$ mode enhances quickly. In this case, the intensity difference is reduced, which is not suitable for refractive index sensitivity. In summary, a higher refractive index sensitivity can be improved by thinner nanowire radius r_1, thicker outer nanoshell (smaller middle layer radius r_2 or bigger outer shell radius r_3) and smaller dielectric function of middle layer ε_2. This behavior can be used to detect the local dielectric environment, the red blood cells and applied in some regions, when blood cells or molecules are near the nanotube surface, and the refractive index of surrounding medium will change, which influences LSPR.[3]

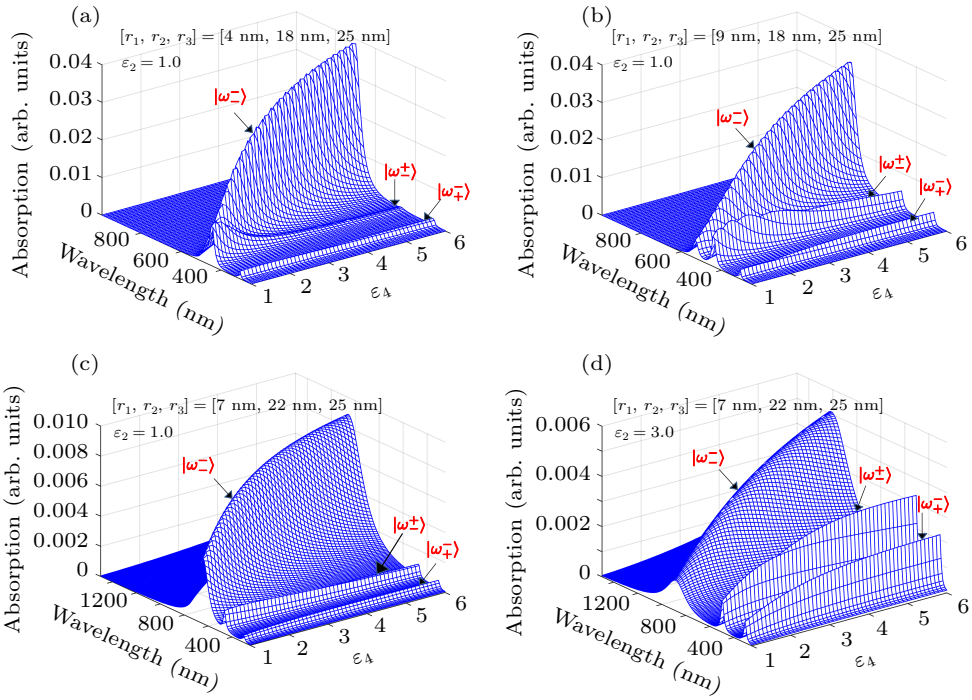


Fig. 9. The effect of surrounding medium ε_4 on gold-dielectric-silver nanotube. (a) $[r_1, r_2, r_3] = [4\,\text{nm}, 18\,\text{nm}, 25\,\text{nm}]$ and $\varepsilon_2 = 1.0$, (b) $[r_1, r_2, r_3] = [9\,\text{nm}, 18\,\text{nm}, 25\,\text{nm}]$ and $\varepsilon_2 = 1.0$, (c) $[r_1, r_2, r_3] = [7\,\text{nm}, 22\,\text{nm}, 25\,\text{nm}]$ and $\varepsilon_2 = 1.0$, and (d) $[r_1, r_2, r_3] = [7\,\text{nm}, 22\,\text{nm}, 25\,\text{nm}]$ and $\varepsilon_2 = 3.0$.

3.5. The local electric field factor of gold-dielectric-silver nanotube

In order to find the physical mechanism of gold-dielectric-silver nanotube, we calculate local electric field factor at the resonance wavelength corresponding to $|\omega_-^-\rangle$ mode with different inner gold nanowire radius r_1, middle dielectric layer radius r_2 and middle dielectric functions ε_2, which are given in Fig. 10. Local electric field enhancement is one of the important parameters to affect the surface enhanced Raman scattering,[3,6] optical storage and nonlinear optical response.[17] As shown in Fig. 10(a), one can find that the electric field intensity is concentrated in the middle dielectric layer, where the inner gold nanowire and outer silver nanotube is very weak.[15] Compared with Fig. 10(a), Fig. 10(b) shows that the local electric field intensity reduces with increasing inner gold wire radius r_1. The coupling between inner gold wire and outer nanotube is enhanced when the separation between inner gold wire and outer nanotube is reduced with increasing inner gold nanowire radius r_1. Therefore, the electric field intensity is concentrated with smaller inner gold nanowire in middle dielectric layer, which is similar to that of silver-dielectric-silver nanotube.[17] Compared with Fig. 10, one can find that the local field intensity reduces quickly as the thickness of middle dielectric layer is increased. Meanwhile, the electric field in the outer nanotube and outer surrounding enhances, whereas the electric field becomes weak with increasing the radius of middle dielectric layer. The physical mechanisms of these phenomena can be explained as follows. The gap between the inner gold nanowire and outer nanotube is increased with an increase in the radius of middle dielectric layer, and then the attraction between the inner gold nanowire and outer nanotube is reduced. In other words, the weakened attraction results in a decrease in the local electric field in middle dielectric layer. In addition, the local electric field intensity in the middle dielectric layer reduces with increasing the middle dielectric function ε_2.[19,20,28] The bigger dielectric function will reduces the surface charges, and then the restoring force of the collective oscillation is reduced due to dielectric screening, which results in the decrease of plasmon energy. Therefore, a better electric field enhancement can be obtained with smaller inner gold nanowire radius and smaller middle dielectric function.[28]

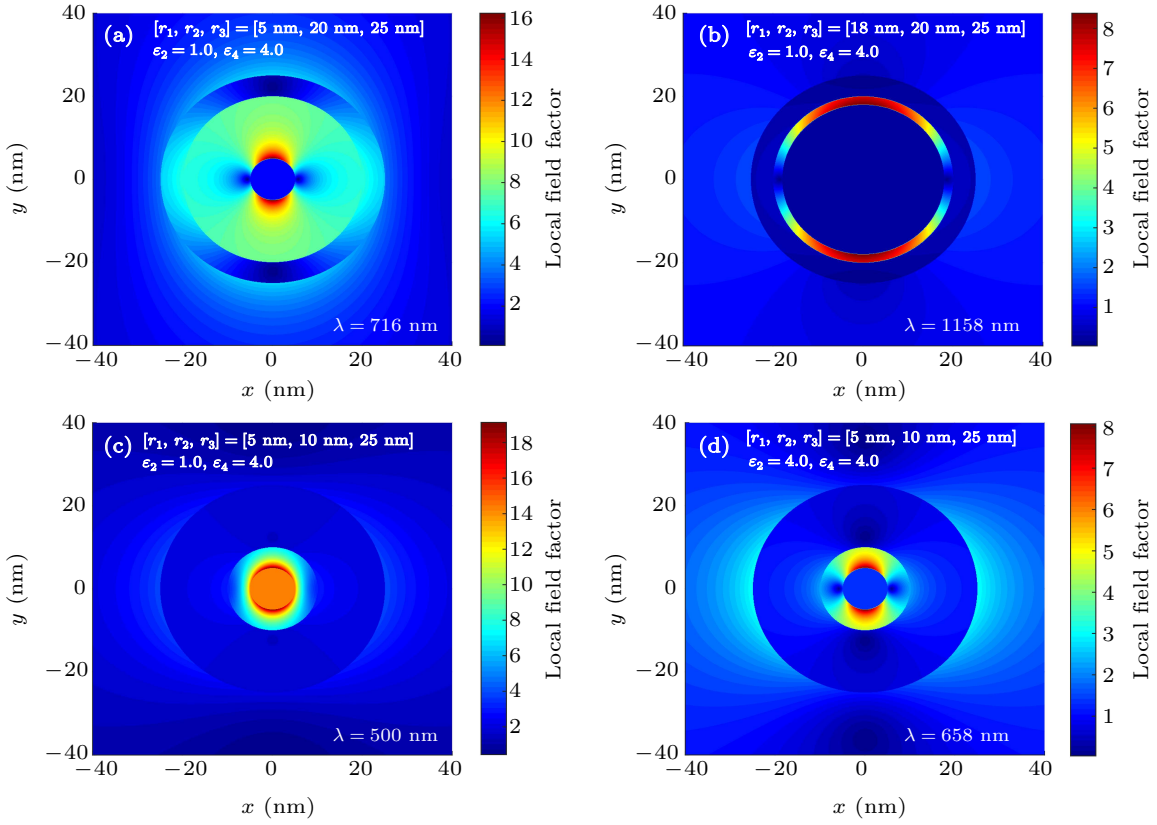


Fig. 10. The local electrical field factor of gold-dielectric-silver nanotube at the resonance wavelength corresponding to $|\omega_-^-\rangle$ mode with different middle dielectric radii and middle dielectric functions. (a) $[r_1, r_2] = [5\ \text{nm}, 20\ \text{nm}]$, $[\varepsilon_2, \varepsilon_4] = [1.0, 4.0]$ and $\lambda = 716$ nm, (b) $[r_1, r_2] = [18\ \text{nm}, 20\ \text{nm}]$, $[\varepsilon_2, \varepsilon_4] = [1.0, 4.0]$ and $\lambda = 1158$ nm, (c) $[r_1, r_2] = [5\ \text{nm}, 10\ \text{nm}]$, $[\varepsilon_2, \varepsilon_4] = [1.0, 4.0]$ and $\lambda = 500$ nm, (d) $[r_1, r_2] = [5\ \text{nm}, 10\ \text{nm}]$, $[\varepsilon_2, \varepsilon_4] = [4.0, 4.0]$ and $\lambda = 658$ nm.

4. Conclusions

In conclusion, the absorption optical properties of gold-dielectric-silver nanotube have been studied by using the quasi-static approximation. The results show that LSPR and its LSPR numbers can be well tuned by adjusting the radius of inner gold nanowire, the thickness of middle dielectric layer and outer nanotube. $|\omega_-^-\rangle$ mode shows a distinct red-shift with

increasing the thickness of inner gold nanowire and middle dielectric layer, while a blue-shift with increasing the thickness of outer nanotube. $\left|\omega_{-}^{-}\right\rangle$ mode is sensitive to middle layer dielectric function and surrounding medium dielectric function. The intensity difference is enhanced with thinner nanowire radius and smaller middle layer dielectric function. A better refractive index sensitivity can be obtained by adjusting the geometrical parameters. In addition, the local electric field factor of nanotube is also reported.

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