Investigation of the fano lineshapes in plasmonic asymmetric silver nanosphere dimer

Jiexuan Gu\textsuperscript{1} · Dandan Dong\textsuperscript{1} · Tao Xiong\textsuperscript{1,2} · Wei Wang\textsuperscript{1} · Cheng Sun\textsuperscript{1,2}\textsuperscript{©}

Received: 23 October 2021 / Accepted: 28 May 2022 / Published online: 22 June 2022
© The Author(s), under exclusive licence to Springer Science+Business Media, LLC, part of Springer Nature 2022

Abstract
The plasmonic properties of an asymmetric dimer, comprising of two silver nanospheres with different radii, are studied by the finite difference time domain method. The extinction efficiencies of the plasmonic dimer are numerically calculated in the visible and near-infrared regime, i.e., from 950 to 150 THz. Two distinguishable Fano resonances are observed when the separation between the nanospheres is narrowed within a certain value, e.g., less than 10 nm. The extinction spectrum that presents two Fano resonances, associated with two electromagnetic modes, is well fitted using a model consisting of two Fano lineshape functions. The resonance frequencies, the spectral widths, and the characteristic $q$ values are obtained via the best fit parameters, and their trends are revealed with varying the radii of the nanospheres. The fitting scheme proposed in this work may be useful in the study of other plasmonic nanostructures with multiple Fano resonances.

Keywords Fano resonance · Asymmetric dimer · Silver nanosphere · Extinction efficiency

1 Introduction

Fano resonance has attracted much attention since it exhibits interesting quantum physics including the characteristic asymmetric lineshape. In 1961, U. Fano derived a theoretical formula to successfully fit the lineshape of the He spectrum obtained from the electron inelastic scattering experiment (Fano 1961). The Fano model was later extended to several other quantum systems with resonance scattering effects, and the Fano lineshape function was employed in many cases (Brown et al. 2001; Jiang and Sun 2018; Sun 2018; Johnson et al. 2004; Kobayashi et al. 2004; Genet et al. 2003). In general quantum systems, Fano resonance occurs when interference between a discrete state and a continuum is established, accompanied with asymmetric peaks in excitation spectra (Kumar et al. 2020; Tan et al. 2020; Srivastava et al. 2019). In plasmonic nanostructures, Fano resonance is also observed, which is interpreted as the strong interaction of a discrete (localized) mode with...
a continuum of propagation modes, manifesting itself into asymmetric lineshapes in extinction spectra (Miroshnichenko et al. 2010; Luk’yanchuk et al. 2010).

Among plasmonic nanostructures, the nanoparticle dimer provides an effective and simple platform to study the Fano resonance effects. For example, multiple plasmonic Fano-like resonances, arising from interference of dimer plasmon modes, were created in a split nanoring dimer resonator (Khan et al. 2014). The extinction spectra of gold nanoparticle dimers, and the electromagnetic contributions to surface-enhanced Raman spectroscopy were calculated by finite element method (McMahon et al. 2009). The plasmonic effect of a nanoshell dimer, with its core filled with different gain materials, was reported (Wang et al. 2014). The plasmonic properties of gold supershape nanoparticle dimers were studied using finite difference time domain simulations, and the resonance wavelength was obtained from extinction spectra for all plasmonic bands (Babaei et al. 2019). Besides, the optical absorption spectrum of a periodic array of silver nanoparticle dimer on a thin silver film was investigated using multiple scattering formalism (Chang et al. 2013). Arrays of metallic nanoparticle dimers with nanometer separation were fabricated using electron beam lithography and angle evaporation, and a strong polarization dependence with two dominant scattering peaks in spectra was observed (Theiss et al. 2014). Recently, the physics models of plasmonics for nanodimer was reviewed in Ref. Li (2018).

In this work, an asymmetric dimer that consists of two silver nanospheres with different radii is investigated. It is found that a two-peak feature is revealed in the frequency dependent extinction spectrum, which is accounted for by two Fano resonances. Further, the extinction spectrum is fitted to a model that is composed of two Fano lineshape functions, and the best fit values for the key parameters are extracted to quantitatively probe the Fano resonances in the plasmonic dimer.

2 Structure and method

The structure of the asymmetric dimer that consists of two silver nanospheres with different radii is illustrated in Fig. 1. In the figure, the radii of the smaller sphere and the bigger one are labeled ’r’ and ’R’, respectively. The spheres are placed along the x-axis in this work.

Fig. 1 Schematic of the asymmetric silver nanosphere dimer. The radius of the smaller nanosphere is denoted as r, and the larger one is labeled R. The separation between the nanospheres is indicated in Δ. A plane-wave light was normally incident along the z-axis.
while the spheres’ centers are fixed to be the same in both the y- and z-axes. In the x-direction, the separation between the spheres is indicated in $\Delta$. Numerical simulations of the dimer were achieved by employing the Finite Difference Time Domain (FDTD) method for solving the Maxwell equations (Lumerical software) (FDTD FDTD). In this work a plane-wave light in the frequency range of 150–950 THz was normally incident along the z-axis, and the electric vector of the light was kept to be x-polarized. Perfect Match Layer (PML) boundary conditions were used in all the directions. In the simulations the optical constants for silver were from Palik’s experimental data, which were given in Ref. Palik (1998).

3 Results and discussions

Based on the configuration shown in Fig. 1, the scattering and absorption cross sections (labeled $C_{scat}$ and $C_{abs}$, respectively) were first simulated, before the corresponding extinction efficiency (indicated in $Q_{ext}$) was calculated by

$$Q_{ext} = (C_{scat} + C_{abs})/S$$

where $S$ is the projected cross sectional area of the dimer in the x-y plane, i.e., $S = \pi(r^2+R^2)$.

As an example, Fig. 2 presents the results of the case when the radii of the spheres were $r = 30$ nm and $R = 40$ nm, respectively, and the separation was $\Delta = 150$ nm. In Fig. 2a, the normalized scattering and absorption cross sections were obtained by scaling the simulated scattering and absorption cross sections to the value of $S$. According to Eq. 1 the extinction efficiency of the dimer is the sum of the normalized scattering and absorption cross sections (i.e., $C_{scat}/S$ and $C_{abs}/S$), which is shown in Fig. 2b.

Fig. 2 a normalized scattering and absorption cross sections of the dimer shown in Fig. 1, and b extinction efficiency determined from Eq. 1, as a function of the incident light’s frequency, $f$. The radii of the silver nanospheres were $r = 30$ nm and $R = 40$ nm, respectively. The separation between the nanospheres was $\Delta = 150$ nm.
Following the same procedure, with varying the separation, $\Delta$, from 70 to 4 nm, the frequency dependent extinction efficiencies were calculated, and the resultant extinction spectra are plotted in Fig. 3. In Fig. 3 the radii of the dimer were the same to that in Fig. 2, that is, $r = 30$ nm and $R = 40$ nm, respectively.

Regarding Fig. 3, as $\Delta$ is decreased, the one-peak extinction spectrum is gradually changed into a two-peak pattern. Specifically, the two peaks become distinguishable when the separation is as narrow as 10 nm. As known to the community, the strength of the plasmonic coupling between adjacent nanoparticles may be increased with decreasing the nanoparticles’ separation, which may in turn cause multiple resonances in certain circumstances. Similar effects were previously reported and addressed in Ref. Singh et al. (2014) where the transition from an uncoupled to a strong near-field coupled regime in split-ring-resonators was studied. To further study the underlying physics for the feature revealed in Fig. 3, the electric field distributions at the peak frequencies were also simulated, and the results are shown in Fig. 4.

In Fig. 4, the radii of the dimer were kept to be $r = 30$ nm and $R = 40$ nm. The electric fields in the scenarios with four different separations (i.e., $\Delta = 150$ nm, 70 nm, 10 nm, and 4 nm) are highlighted. Referring to Fig. 4a, the plasmonic behavior of two individual nanospheres, accompanied by very little plasmonic coupling between the two, is observed in the case when they are quite far apart (i.e., $\Delta = 150$ nm). It is revealed in Fig. 4e and 4f, however, that the electromagnetic hot spots with great intensities are confined in the space between the two nanospheres. This is a manifestation of the strong plasmonic coupling between the silver spheres when they are very close to each other (i.e., $\Delta = 4$ nm).

Fig. 4b–d illustrate the electric fields with the separation being in the transition regime from the very far to the very close. Although there is a subtle deviation of the field distributions with comparing Fig. 4b to a, the one-peak pattern is clear in both extinction spectra of $\Delta = 70$ nm in Fig. 3 and of $\Delta = 150$ nm in Fig. 2b. This similarity is consistent with the fact that the plasmonic coupling is weak once the separation is large.

![Fig. 3 Extinction spectrum of the dimer shown in Fig. 1. The radii of the silver nanospheres were $r = 30$ nm and $R = 40$ nm, respectively. The separation between the nanospheres, $\Delta$, was varied from 70 to 4 nm.](image-url)
Fig. 4 Electric field in the x-y plane for the dimer with \( r = 30 \text{ nm} \) and \( R = 40 \text{ nm} \). The electric fields were determined from a the peak in Fig. 2b (i.e., \( f = 792 \text{ THz} \)), b the peak of \( \Delta = 70 \text{ nm} \) in Fig. 3 (i.e., 774 THz), c and d the peaks of \( \Delta = 10 \text{ nm} \) in Fig. 3 (679 THz and 814 THz, respectively), and e and f the peaks of \( \Delta = 4 \text{ nm} \) in Fig. 3 (629 THz and 799 THz, respectively). In the \( z \) direction, the x-y plane was through the centers of the silver nanospheres. Note that the maximum intensity of the color bar, indicating the field intensity, is different for each figure. To guide the eye, the black circles are added in each case to highlight the boundaries of the nanospheres.

By comparing the fields in Fig. 4c and d to that in Fig. 4e and f, although the intensities are not as great, the confined hot spots are still evident, indicating a relatively strong plasmonic coupling of the dimer with a narrow separation of \( \Delta = 10 \text{ nm} \). Note that this field enhancement effect was previously studied by a rigorous analytical approach in complex systems of coupled metallic nanoparticles (Sun et al. 2011); a dipole-dipole interaction model was also employed to investigate the field enhancement in Ref. (Toroghi and Kik 2012) where the nanosphere was modeled as a point dipole. Referring to the spectrum of \( \Delta = 10 \text{ nm} \) in Fig. 3, although a plateau instead of a obvious peak is observed in the higher frequency region (about 814 THz), the plateau is well separated from the peak at the lower frequency (679 THz). This implies that a model that consists of two lineshapes, characteristic of two resonances, may be utilized to quantify the plasmonic dimer, once the separation is as narrow as 10 nm.

To further probe the two-peak feature, the investigation below is focused on the narrow separations, i.e., \( \Delta = 10 \text{ nm} \), and 4 nm. First, with the radius of the smaller nanosphere being fixed at \( r = 20 \text{ nm} \), the extinction spectra were computed for a variety of
the larger nanosphere’s radii. The results are given in Fig. 5, where the cases of the two small separations are both shown.

Generally, Fano resonance may occur when the interference between a continuum and a discrete state of a quantum system is established, and the corresponding asymmetric Fano lineshape is governed by the following function (Fano 1961),

$$\frac{(\epsilon + q)^2}{\epsilon^2 + 1}$$

(2)

It should be noted that the Fano resonance can appear in Mie theory for light scattering from a single spherical plasmonic particle, such as a single silver nanosphere (Luk’yanchuk et al. 2010). Although Fano resonances occur in simple spherical particles, the damping of typical metals is usually too large for the Fano resonance to be clearly witnessed. The condition for a Fano resonance to be clearly observed is the establishment of the interference between a spectrally overlapping broad resonance or continuum and a narrow discrete resonance, which can be satisfied using tunable coupled plasmonic structures, such as the asymmetric silver spherical dimers proposed in this work. Once the above condition is established, the lineshape may be explained by Eq. 2 that was derived by Fano using a perturbation approach, where it describes only the resonant contribution, whereas the non-resonant (potential scattering) was omitted (Miroshnichenko et al. 2010).

In Eq. 2 the reduced energy variable may be written as $\epsilon = (f - f_0)/f_s$, where $f_0$ indicates the resonance frequency, and $f_s$ is the spectral width of the discrete state. $q$ is the characteristic parameter in the Fano lineshape function, depending on both the continuum and the discrete state of the quantum system.

As mentioned above, multiple resonances may be induced by strong plasmonic coupling between adjacent nanoparticles in plasmonic systems. Correlating to the multiple resonances, multiple discrete states are created, and thus multiple Fano resonances may occur.

Fig. 5 Extinction spectrum of the dimer shown in Fig. 1. The radius of the smaller silver nanosphere was $r = 20$ nm. The larger one’s radius was varied from $R = 60$ nm to 78 nm. a $\Delta = 10$ nm, and b $\Delta = 4$ nm. The solid lines are a best fit to Eq. 3.
Regarding Fig. 5, in this work two Fano lineshapes in the extinction spectra, associated with two Fano resonances, are observed in the dimer with a narrow separation. Therefore, the simulated extinction efficiencies were fitted to the following equation comprised of two Fano lineshape functions,

\[ Q_{\text{ext}} = A_a \frac{(\epsilon_a + q_a)^2}{\epsilon_a^2 + 1} + A_\beta \frac{(\epsilon_\beta + q_\alpha)^2}{\epsilon_\beta^2 + 1} \]  \hspace{1cm} (3)

where \( A_a \) and \( A_\beta \) are coefficients. It is clear from Fig. 5 that the best fit curves (denoted by solid lines) are all in good agreements with the simulated data for both \( \Delta = 10 \text{nm} \) and \( 4 \text{nm} \). This consistency strongly indicates that the plasmonic properties of the asymmetric silver nanosphere dimer are characteristic of two Fano resonances, under the condition of a small separation.

Note that strictly speaking, the effects of overlapping resonances may not be negligible if the interaction of resonances for two nanospheres was strong, and the Fano theory may also need to be modified, which was discussed in literatures (Mies 1968). It was demonstrated that without prior knowledge of the overlap matrix between the continua to which neighboring resonances are coupled, it is impossible to uniquely characterize a resonance from limited experimental observations. Besides, the interaction between the resonances may be complex in certain circumstances if the separation between the nanospheres was varied (Joe et al. 2005). Given above reasons, it is clear that Eq. 3 is a simplified model, and the scheme proposed in this work can only be implemented in the condition of two well-resolved peaks, and it may also need to be justified by the agreement between the fit and the experimental data. Further, the extracted parameters must be used afterwards with reservations, unless the effects of overlapping resonances are well known. Therefore, the semi-empirical model proposed in this work only provides us with a simple way to interpret the lineshape in some practical cases where the interaction of resonances is not dominant.

Based on Fig. 5, the electric fields at two peak frequencies were calculated, and the results of \( R = 60 \text{ nm} \) and \( 74 \text{ nm} \) are summarized in Fig. 6 as an example. The figures in the left column (i.e., a, c, e, and g) correspond to Peak \( \alpha \) in the extinction spectra, as indicated in Fig. 5. The frequency values for Peak \( \alpha \) and Peak \( \beta \) were determined by fitting to Eq. 3 as aforementioned, and the best fit resonance frequencies, \( f_0 \), are plotted in Fig. 7a. Regarding Fig. 6, by carefully examining the fields between the left column and the right, two different electromagnetic modes, correlating to two Fano resonances, are witnessed, which are attributed to Peak \( \alpha \) and Peak \( \beta \), respectively.

Referring to Fig. 5 again, in addition to \( f_0 \), the best fit values for the spectral widths and the \( q \) parameters are also plotted in Fig. 7. It is clear from Fig. 7 that the key parameters that are accompanied with the Fano resonances can be quantitatively presented and analyzed. For both separations, the trends in the three parameters are pronounced, with increasing the value of \( R \). Take \( \Delta = 10 \text{ nm} \) for example, Fig. 7a shows that the resonance frequency of Peak \( \alpha \) is decreased from 650THz to 580THz, and Peak \( \beta \) is also downside shifted from 820THz to 800THz. Fig. 7b presents that the spectral width of Peak \( \alpha \) is increased from 108 to 155 THz, and Peak \( \beta \) is also broadened from 39 to 57 THz. Fig. 7c gives that the \( q \) parameter of Peak \( \alpha \) is slightly decreased from 8.7 to 7.2, while Peak \( \beta \) is dramatically reduced from 46.3 to 25.8.

To further confirm the fitting approach, another set of simulations were performed on the dimer, with the radius of the smaller nanosphere being varied, while the larger one being kept the same. The corresponding extinction spectra are given in Fig. 8, and the
best fits to Eq. 3 are also shown as solid lines. In Fig. 8, \( R \) was always 60 nm, while \( r \) was changed from 55 to 30 nm. Similar to Fig. 5, the simulated extinction efficiencies in Fig. 8 were also well fitted to Eq. 3, which implies again that two Fano resonances take place in the plasmonic dimer when the separation is as narrow as 10 nm.

As with the scenario in Fig. 5, the electric fields relating to Peak \( \alpha \) and Peak \( \beta \) in Fig. 8 were also computed, and the results are illustrated in Fig. 9. For brevity, only the fields of \( r = 50 \) nm, 40 nm, and 30 nm are presented in the figure. Similar to the fashion witnessed in Fig. 6, by carefully comparing the fields at Peak \( \alpha \) and Peak \( \beta \) in
Fig. 7  Best fit values for a resonance frequencies, $f_0$, b spectral widths, $f_s$, and c $q$ parameters, as a function of the larger nanosphere’s radius, $R$, determined by fitting the extinction spectra in Fig. 5 to Eq. 3. In all figures, the dashed lines are intended to guide the eye, and do not represent or intend to be a fit to the data.

Fig. 8  Extinction spectrum of the dimer shown in Fig. 1. The radius of the larger silver nanosphere was $R = 60$ nm, and the separation was $\Delta = 10$ nm. The smaller one’s radius was varied from $r = 55$ to 30 nm. The solid lines are a best fit to Eq. 3.
Fig. 9, two types of electromagnetic modes, associated with two Fano resonances, are also manifested.

Lastly, the best fit parameters including the resonance frequencies, the spectral widths, and the $q$ were also derived for the case of Fig. 8, and the values are given in Fig. 10. According to Fig. 10a, the resonance frequency of Peak $\alpha$ is increased from 530 to 610 THz, as $r$ is decreased from 55 to 30 nm. While Peak $\beta$ exhibits similar resonance frequencies of about 803 THz. Regarding Fig. 10b, the spectral width of Peak $\alpha$ is reduced from 110 to 98 THz, whereas Peak $\beta$ has similar spectral widths of about 32 THz. Referring to Fig. 10c, the $q$ parameter of Peak $\alpha$ shows a variation between 3.9 and 6.7, and Peak $\beta$ gives a subtle change around the value of 7.2.

Note that the plasmonic systems of silver dimers with similar configurations were previously studied, and the observations regarding Fano resonances were discussed in terms of its figure of merit (FOM) (Das et al. 2020). In this work, however, the lineshape of the Fano resonance is fitted to a two-peak model, from which the resonance frequencies, the spectral widths, as well as the characteristic $q$ parameters are determined. Therefore, the purpose of the paper is to demonstrate that the fitting scheme may be implemented for simplicity in some practical cases where a two well-resolved peak pattern can be observed.
4 Conclusions

In this work, the plasmonic properties of an asymmetric silver nanosphere dimer have been investigated, with the incident light being in the visible and near-infrared region. The frequency dependent extinction spectra have been numerically simulated by the FDTD method. With decreasing the separation of the dimer, the effect of plasmonic coupling between the nanospheres becomes evident, resulting in a two-peak lineshape that correlates to two Fano resonances. The electric fields at peak frequencies have also been computed, and two different electromagnetic modes that account for the two Fano resonances have been observed. The calculated extinction efficiencies have been fitted to a model that consists of two Fano lineshape functions, and a good agreement has been achieved. The best fit parameters including the resonance frequencies, the spectral widths, and the $q$ parameters, as a function of the smaller nanosphere’s radius, $r$, determined by fitting the extinction efficiency spectra in Fig. 8 to Eq. 3. In all figures, the dashed lines are intended to guide the eye, and do not represent or intend to be a fit to the data.

Fig. 10  Best fit values for a resonance frequencies, $f_0$, b spectral widths, $f_s$, and c $q$ parameters, as a function of the smaller nanosphere’s radius, $r$, determined by fitting the extinction efficiency spectra in Fig. 8 to Eq. 3. In all figures, the dashed lines are intended to guide the eye, and do not represent or intend to be a fit to the data.
Declarations

Conflict of interest  The authors declare no competing interests.

References

Babaei, F., Javidnasab, M., Rezaei, A.: Localized surface plasmons of supershape nanoparticle dimers. Plasmonics 14, 285–291 (2019)
Brown, S.D.M., Jorio, A., Corio, P., Dresselhaus, M.S., Saito, R., Kneipp, K.: Origin of the breitwigner-fano lineshape of the tangential G-band feature of metallic carbon nanotubes. Phys. Rev. B 63, 155413 (2001)
Chang, Y., Jiang, Y., Sun, X.: Plasmonic coupling from silver nanoparticle dimer array mediating surface plasmon resonant enhancement on the thin silver film. Appl. Phys. B 113, 503–509 (2013)
Das, A., Ahmed, A., Hasan, M.M.: Observation of Fano resonance in silver nanocube-nanosphere dimer. Pramana 94, 128 (2020)
Fano, U.: Effects of configuration interaction on intensities and phase shifts. Phys. Rev. 124, 1866–1878 (1961)
Genet, C., van Exter, M.P., Woerdman, J.P.: Fano-type interpretation of red shifts and red tails in hole array transmission spectra. Opt. Commun. 255, 331–336 (2003)
Jiang, B.Z., Sun, C.: On the plasmonic properties of a symmetry-breaking silver nanoring structure. Phys. E 101, 62–70 (2018)
Joe, Y.S., Satanin, A.M., Klimeck, G.: Interactions of Fano resonances in the transmission of an Aharonov-Bohm ring with two embedded quantum dots in the presence of a magnetic field. Phys. Rev. B 72, 115310 (2005)
Johnson, A.C., Marcus, C.M., Hanson, M.P., Gossard, A.C.: Coulomb-modified fano resonance in a one-lead quantum dot. Phys. Rev. Lett. 93, 106803 (2004)
Khan, A.D., Khan, S.D., Khan, R.U., Ahmad, N., Ali, A., Khalil, A., Khan, F.A.: Generation of multiple fano resonances in plasmonic split nanoring dimer. Plasmonics 9, 1091–1102 (2014)
Kobayashi, K., Aikawa, H., Sano, A., Katsumoto, S., Iye, Y.: Fano resonance in a quantum wire with a side-coupled quantum dot. Phys. Rev. B 70, 035319 (2004)
Kumar, A., Solanki, A., Manjappa, M., Ramesh, S., Srivastava, Y.K., Agarwal, P., Sum, T.C., Singh, R.: Excitons in 2D perovskites for ultrafast terahertz photonic devices. Sci. Adv. 6, eaax8821 (2020)
Li, W.: Physics models of plasmonics: single nanoparticle, complex single nanoparticle, nanodimer, and single nanoparticle over metallic thin film. Plasmonics 13, 997–1014 (2018)
Luk’yanchuk, B., Zheludev, N.I., Maier, S.A., Halas, N.J., Nordlander, P., Giessen, H., Chong, C.T.: The fano resonance in plasmonic nanosystems and metamaterials. Nat. Mater. 9, 707–715 (2010)
McMahon, J.M., Henry, A.I., Wustholz, K.L., Natan, M.J., Freeman, R.G., Duyne, R.P.V., Schatz, G.C.: Gold nanoparticle dimer plasmonics: finite element method calculations of the electromagnetic enhancement to surface-enhanced raman spectroscopy. Anal. Bioanal. Chem. 394, 1819–1825 (2009)
Mies, F.H.: Configuration interaction theory effects of overlapping resonances. Phys. Rev. 175, 164 (1968)
Miroshnichenko, A.E., Flach, S., Kivshar, Y.S.: Fano resonances in nanoscale structures. Rev. Mod. Phys. 82, 2257–2298 (2010)
Palik, E.D.: Handbook of optical constants of solids, vol. 3. Academic press, Cambridge (1998)
Singh, R., Al-Naib, I., Chowdhury, D.R., Cong, L., Rockstuhl, C., Zhang, W.: Probing the transition from an uncoupled to a strong near-field coupled regime between bright and dark mode resonators in metasurfaces. Appl. Phys. Lett. 105, 081108 (2014)
FDTD Solutions, www.lumerical.com
Srivastava, Y.K., Ako, R.T., Gupta, M., Bhaskaran, M., Sriram, S., Singh, R.: Terahertz sensing of 7nm dielectric film with bound states in the continuum metasurfaces. Appl. Phys. Lett. 115, 151105 (2019)
Sun, C.: On the plasmonic properties of Ag@SiO2@graphene core-shell. Plasmonics 13, 1671–1680 (2018)
Sun, G., Khurgin, J.B., Bratkovsky, A.: Coupled-mode theory of field enhancement in complex metal nanostructures. Phys. Rev. B 84, 045415 (2011)
Tan, T.C.W., Plum, E., Singh, R.: Lattice-enhanced fano resonances from bound states in the continuum metasurfaces. Adv. Opt. Mater. 8, 1901572 (2020)
Theiss, J., Aykol, M., Pavaskar, P., Cronin, S.B.: Plasmonic mode mixing in nanoparticle dimers with nm-separations via substrate-mediated coupling. Nano Res. 7(9), 1344–1354 (2014)
Toroghi, S., Kik, P.G.: Cascaded plasmon resonant field enhancement in nanoparticle dimers in the point dipole limit. Appl. Phys. Lett. 100, 183105 (2012)
Wang, Q., Pan, S., Guo, Y., Li, R., Liu, K.: Plasmonic effect of a nanoshell dimer with different gain materials materials. Plasmonics 9, 1463–1469 (2014)

Publisher’s Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.