Boosting an anapole mode response through electromagnetic interactions beyond near-field limit in individual all-dielectric disk-ring nanostructures

Yan-Hui Deng, Zhong-Jian Yang*, Ma-Long Hu, Xiao-Jing Du and Jun He

Hunan Key Laboratory of Super Microstructure and Ultrafast Process, School of Physics and Electronics, Central South University, Changsha, Hunan 410083, People’s Republic of China

* Author to whom any correspondence should be addressed.
E-mail: zjyang@csu.edu.cn

Keywords: all-dielectric, nanophotonics, anapole, electromagnetic interaction, electric field enhancement

Abstract

Anapole modes of all-dielectric nanostructures hold great promise for many nanophotonic applications. However, anapole modes can hardly couple to other modes through far-field interactions, and their near-field enhancements are dispersed widely inside the nanostructures. These facts bring challenges to the further increasing of the response of an anapole mode. Here, we theoretically show that an anapole mode response in a dielectric nanostructure can be boosted through electromagnetic interactions with the coupling distance of a wavelength scale, which is beyond both the near-field and far-field limits. The all-dielectric nanostructure consists of a disk holding an anapole mode and a ring. Both analytical calculations and numerical simulations are carried out to investigate the electromagnetic interactions in the system. It is found that the electric dipoles associated with the fields of the anapole mode on the disk undergo retardation-related interactions with the electric dipoles associated with the ring, leading to the efficiently enhanced response of the anapole mode. The corresponding near field enhancement on the disk can reaches more than 90 times for a slotted silicon disk-ring nanostructure, where the width of the slot is 10 nm. This enhancement is about 5 times larger than that of an individual slotted disk. Our results reveal the greatly enhanced anapole mode through electromagnetic couplings in all-dielectric nanostructures, and the corresponding large field enhancement could find important applications for enhanced nonlinear photonics, near-field enhanced spectroscopies, and strong photon–exciton couplings.

1. Introduction

During the last several years, a new branch of nanophotonics has been growing that aims at manipulating the strong electric and magnetic Mie resonances in high-refractive-index dielectric nanostructures [1–3]. Compared to their plasmonic counterparts, dielectric nanostructures can also exhibit strong electromagnetic resonances while they have low material losses and are more compatible with the well-established semiconductor fabrication techniques. Thus, lots of applications enabled by dielectric nanostructures have been demonstrated such as metasurfaces [4, 5], color printing [6], lasing [7], biosensing [8, 9], and quantum optics [10, 11]. Strong electric and magnetic resonances of high-index dielectric nanostructures can be excited not only in spheres [12–17] but also in many other geometries including spheroids [18], disks and cylinders [19–21], and rings [22, 23]. The excited dipole or multipole electromagnetic modes can further interact with each other, which provides new routes for achieving strongly enhanced optical responses. Many optical phenomena induced by mode couplings have been reported, such as hybridization [24], Fano resonance [25–27], the magnetic field boosting [28], the formation of toroidal dipole (TD) modes from basic electric or magnetic dipole modes [29–31], and the
quasi bound states in the continuum based on the strong coupling between Mie-like and Fabry–Perot-like modes [32, 33].

Recently, nonradiating electromagnetic states in all-dielectric nanostructure have attracted lots of research interests [34, 35]. Among these modes, an electric optical anapole corresponds to destructive interference of the electric and electric TD moments results in a peculiar, low-radiating optical state [36, 37]. Owing to its nontrivial nonradiating feature, an anapole mode provides minimal far-field scattering and relatively high near-field enhancement among the common Mie resonance modes [37–40]. It has thus been widely investigated in many aspects of nanophotonics such as local field enhancement [41–44], nonlinear optical effects [45–48], nanolasers [49], ideal magnetic dipole generation [50], photon–exciton coupling [21, 51], hybrid dielectric-plasmonic antennas [52–54], metamaterial [55] and absorption enhancement [56, 57]. The further increasing of the response strength of an anapole mode plays a crucial role in making better use of it for many of the above applications. Currently, the relevant investigations are quite limited although there are a few reports in dielectric-plasmonic hybrid systems [45] and dielectric structures with complex geometries [42]. The challenges arise from the far-field and near-field characteristics of an anapole mode. Due to the canceled far-field response of an anapole mode, it is unlikely to utilize far-field couplings to enhance the anapole response. As for near-field couplings, the field of an anapole mode is widely distributed inside the whole volume, which brings challenge to the further enhancing of an anapole response through near-field interactions in an all-dielectric system.

In this work, we show theoretically that an anapole mode can be boosted through electromagnetic interactions with the middle coupling distances in an all-dielectric nanostructure, where such distances are beyond both the near-field and far-field limits. The all-dielectric nanostructure consists of a silicon (Si) nanodisk and a Si ring. The disk has an anapole mode response, where the corresponding electric dipole moments associated with the electric fields of the anapole mode have a certain distance. The distance between the separated dipoles of the disk can induce retardation-related interactions with the dipoles associated with the ring, leading to the efficiently enhanced response of the anapole mode on the disk. Analytical calculations are carried out to understand the electromagnetic couplings and the results agree well with the direct simulations. The corresponding electric near-field enhancement can reaches more than 90 times for a slotted Si disk-ring structure, where the width of the slot is 10 nm. This enhancement exceeds 5 times higher than that of an individual slotted disk. The geometric effects on the field enhancement will also be discussed.

2. Methods

Finite-difference time-domain (FDTD) Simulation method. A commercial FDTD software (Lumerical FDTD) is used for the numerical simulations. The excitation source is total-field scattered-field plane wave. To simulate an individual structure placed in an infinite space, perfectly matched layer boundary conditions were used. The dielectric constants of the Si are taken from Palik’s book [58]. The surrounding index is \( n = 1 \) for simulations. The mesh size is 5 × 5 × 5 nm\(^3\) for the region around the structures, while the mesh size is 1 × 1 × 1 nm\(^3\) around the slot region.

Multipole decomposition method. The different multipolar modes can be calculated by using the multipole decomposition method [59, 60] and their contributions to the scattering spectra can be obtained. Here we repeat the method for completeness. Cartesian multipole moments can be expressed by using the induced currents \( J_\omega (\hat{r}) \) as [60]

\[
\begin{align*}
\text{electric dipole moment: } p_\omega &= -\frac{1}{2\omega} \left\{ \int d^3\hat{r} J_\omega (\hat{r}) \cdot \hat{r} + \frac{k^2}{2} \int d^3\hat{r} \left[ 3 (\hat{r} \cdot \hat{J}_\omega) r_\omega - r^2 J_\omega \frac{\partial \hat{J}_\omega}{\partial r} \right] \right\}, \\
\text{magnetic dipole moment: } m_\omega &= \frac{3}{2} \left\{ \int d^3\hat{r} (\hat{r} \times \hat{J}_\omega) \right\}, \\
\text{electric quadrupole moment: } Q_{2\alpha\beta} &= -\frac{3}{2\omega} \left\{ \int d^3\hat{r} \left[ 3 (r_\alpha J_\alpha + r_\beta J_\beta) - 2 (\hat{r} \cdot \hat{J}_\omega) \delta_{\alpha\beta} \right] \right\}, \\
&\quad + 2k^2 \left\{ \int d^3\hat{r} \left[ 5r_\alpha r_\beta (\hat{r} \cdot \hat{J}_\omega) - (r_\alpha J_\beta + r_\beta J_\alpha) \hat{r} \cdot \hat{J}_\omega + r^2 (\hat{r} \cdot \hat{J}_\omega) \delta_{\alpha\beta} \right] \right\}, \\
\text{magnetic quadrupole moment: } Q''_{2\alpha\beta} &= 15 \int d^3\hat{r} \left\{ r_\alpha (\hat{r} \times \hat{J}_\omega)_\beta + r_\beta (\hat{r} \times \hat{J}_\omega)_\alpha \right\} \frac{\partial \hat{J}_\omega}{\partial r},
\end{align*}
\]

where \( \omega \) is the angular frequency, \( k \) is the wavenumber, \( c \) is the speed of light, \( \hat{r} \) is the location, and \( \alpha, \beta = x, y, z \). The induced electric current density is obtained by using \( J_\omega (\hat{r}) = \omega \varepsilon_0 (\varepsilon - 1) E_\omega (\hat{r}) \), where
$E_\omega(\hat{r})$ is the electric field distribution, $\varepsilon_0$ is the permittivity of free space, and $\varepsilon_r$ is the relative permittivity of the disk and the ring. The induced current has a harmonic time dependence $\exp(-i\omega t)$, which is omitted. We used the FDTD simulation to obtain the electric field distributions $E_\omega(\hat{r})/E_{inc}$. $E_{inc}$ is the electric field of the incident wave. The $j_1(\lambda r)$, $j_2(\lambda r)$ and $j_3(\lambda r)$ are the spherical Bessel functions of first, second and third kinds, respectively. The scattering cross section produced by these multipole moments can be written as:

$$C_{sca}^{\text{total}} = C_{sca}^p + C_{sca}^m + C_{sca}^Q + \cdots = \frac{k^4}{6\pi\varepsilon_0^2|E_{inc}|^2} \left[ \sum_\alpha \left( |p_{\alpha}|^2 + |m_{\alpha}|^2 \right) + \frac{1}{120} \sum_\alpha \left( |kQ_{\alpha}^p|^2 + \left| \frac{kQ_{\alpha}^m}{c} \right|^2 \right) + \cdots \right]$$

where, $p_\alpha$, $m_\alpha$, are the electric and magnetic dipole moments, respectively. $Q_{\alpha}^p$, $Q_{\alpha}^m$ are the electric and magnetic quadrupole (MQ) moments, respectively.

3. Results and discussion

Before considering the coupled disk-ring structure, let us first investigate the optical properties of individual dielectric nanostructures (figure 1). We choose the widely investigated Si as the material and its dielectric constants are taken from Palik’s book [58]. The index of surrounding medium is taken to be 1. The numerical simulations were carried out by using commercial FDTD software (Lumerical FDTD).

Figure 1(a) shows the scattering cross-section spectrum of an individual Si ring. The ring is excited by a normal incident plane wave and the polarization of the incoming beam in the $y$-direction. A peak appears at $\lambda = 1111$ nm on the scattering spectrum. The parameters of the ring is chosen to make the coupling with the disk strong enough, which will be discussed later. In order to understand this peak on the scattering spectrum, we calculate the contributions from different multipole modes to the spectrum and the near field distributions. The multipole mode contributions are calculated by using the multipole decomposition method. Note that in our decomposition method, each contribution mode consists of the multi-order responses [60]. Thus, an electric dipole term (ED) includes a common ED(- $\frac{1}{2} \int d^3 \hat{r} j_0^p$) and higher-order responses, for example, a toroidal dipole (TD, $\frac{1}{2} \int d^3 (\hat{r} \cdot \hat{J}_0) r_0 - 2r^2 j_0^p$) [60]. This is different from some literatures where an ED term means only the first order ($\frac{1}{2} \int \hat{J}_0 d^3 \hat{r}$) [31, 61].

Figure 1(b) shows the multipole decomposition results for the scattering spectrum of the ring. The sum of all the contributions from the different multipole modes [the black line in figure 1(b)] agrees well with the direct calculation of the scattering by FDTD. The peak on the scattering is mainly contributed from the MQ mode which shows a peak feature. A contribution from the ED mode is also seen, and it shows a dip feature. More calculations show that the ED mode here contains two contributions. One is a common electric dipole and the other one is a higher-order response which is a TD. These spectral lineshape features are similar to that of a common anapole mode in many dielectric nanostructures [37, 41, 62]. However, the scattering spectrum is a peak here while it is a dip for a common anapole mode. As an anapole mode corresponds to a minimal scattering, it is unusual to take this scattering response as an anapole mode. But if we consider only the ED spectrum, it is rational to take its spectral feature as an ED-related anapole response. Thus, we here take the scattering response of the ring as a ‘modified anapole’ mode. In fact, this scattering response is indeed caused by the modification of the geometries. It can be easily verified that the scattering spectral response gradually changes back to that of a normal anapole mode with decreasing the inner radius of the ring. We plot electric near field distributions on the $z = 0$ (left) and $y = 0$ (right) plane of the ring in figure 1(c). The wavelength is $\lambda = 1111$ nm corresponding to the scattering peak. The electric field distribution of this mode is also similar to the common anapole mode [37, 41, 59, 62]. At the same time, an enhanced field distribution also appears above the ring. It can be verified that the near field profile in the $750 \sim 1100$ nm range are similar to that of the peak. This field distribution is important for the strong couplings in the disk-ring structures, which will be discussed later.

The radius and height of the Si nanodisk are 230 and 100 nm, respectively. With the chosen geometric parameters, a resonance dip is found around $\lambda = 964$ nm [figure 1(d)]. The bottom inset shows the electric field distribution on the $z = 0$ plane, which indicates that the dip at $\lambda = 964$ nm corresponds to an anapole mode. Similar results have been reported in many other works [37, 41, 59, 62]. Here, the parameters of a disk are chosen to make the anapole mode appear at a given wavelength.
Figure 1. Optical responses of individual disk and ring. (a) The scattering spectrum of a Si ring. The inner and outer radius of the Si ring are $R_{\text{in}} = 390$ and $R_{\text{out}} = 490$ nm, respectively. The height is 100 nm. The inset shows the schematic of the structure with a plane wave excitation. The origin of the coordinate system is placed at the center of the ring. (b) The contributions from different expansion multipole modes to the scattering spectrum of the individual ring. They are ED, magnetic dipole (MD), electric quadrupole, and MQ. The MD contribution approaches 0, and it is covered by the pink line. (c) The near-field profiles on the $z = 0$ (top) and $y = 0$ (bottom) plane of the ring. The wavelength is $\lambda = 1111$ nm. The dashed lines show the outline of the structure. (d) The scattering spectrum of an individual Si nanodisk and the contributions from different expansion multipole modes. The radius and height of the Si disk are 230 and 100 nm, respectively. The top inset shows the schematic of the structure and the origin of the coordinate system is placed at the center of the disk. The bottom inset shows the electric field enhancement on the $z = 0$ plane at $\lambda = 964$ nm. The dashed line shows the edge of the disk.

Now let us turn to the coupled system as shown in figure 2(a). The coupled system consists of the Si nanodisk and ring discussed above. The disk is placed at $(0, 0, 100)$ nm, which is 100 nm above the center of the ring. The index of surrounding medium is also 1. The excitation configuration is shown in figure 2(a). Figure 2(b) shows the scattering spectrum of the coupled system. A sharp peak appears at $\lambda = 947$ nm on the spectrum, which is close to the anapole resonance of the individual disk. Multipole decomposition results of the coupled system are shown in figure 2(c). Their lineshapes around the resonance peak $\lambda = 947$ nm are similar to that of the individual disk, except that the contribution of the MQ mode to the scattering is increased a lot. The electric field distributions on the planes of $z = 100$ nm and $y = 0$ nm are shown in figure 2(d), respectively. Compared to the individual case, the field enhancement becomes $\sim 3$ times higher while the field profile of the disk still remains the same. It can be understood by the fact that such a field distribution on the disk corresponds to both the anapole and MQ mode responses, which has been confirmed in other similar systems [31]. An increasing of the field corresponds to the enhanced responses of both modes. But the anapole mode does not show far-field scattering. Thus only the enhanced MQ response appears on the scattering spectrum. The near field enhancement here ($\sim 9$) is larger than that achieved by a quasi-BIC mode ($\sim 6$) [32]. The giant modifications of the spectrum and field enhancement indicate that strong electromagnetic coupling occurs in the disk-ring system.

In order to understand the strong coupling of the disk-ring system, a series of analytical calculations and numerical simulations are carried out. It is found that this coupling is induced by the interactions of the electric dipole moments associated with the anapole mode of the disk and the ‘modified anapole’ mode of the ring, where the coupling distance is beyond the near-field limit and the retardation effect plays an important role. The electric field distribution of the individual ring on the $y = 0$ plane is shown in figure 3(a). Due to the symmetry reason, we consider only the right part of the ring. The field distribution of the ring can be divided into three different regions R1, R2, and R3, where each one corresponds to an electric dipole moment response. The field profiles in these regions still keep almost the same under couplings [figure 3(a)]. The fields of the disk can be divided into three different regions D1, D2 and D3,
where each also corresponds to an electric dipole moment response. Among them, R1 (R3) and D2 are in line with the ring and disk can be written as

\[ \omega \varepsilon_0 \frac{1}{r^2} \left( \frac{\omega^2}{c^2} \right) \cos \left( \frac{\omega t}{c} \right) - \frac{i \omega}{c} \sin \left( \frac{\omega t}{c} \right) \left| P \right| e^{i \omega t}, \]

(1)

where \( \omega \) is the angular frequency, \( c \) is the speed of light, \( \varepsilon_0 \) is the permittivity of free space, \( P \) is the dipole moment, which is expressed as \( P = P(\hat{r}) e^{-i \omega t} \). With equation (1) one can obtain the electric fields generated by R1, R2 and R3 at the location of disk. Here, the location \( r \) for the disk region is approximately taken to be perpendicular to the \( P \). Thus, equation (1) can be written in the form of a trigonometric function as

\[ E = \frac{1}{4 \pi \varepsilon_0 c^2} \left( \frac{\omega^2}{c^2} r^2 - 1 \right) \cos \left( \frac{\omega t}{c} \right) - \frac{i \omega}{c} \sin \left( \frac{\omega t}{c} \right) \left| P \right| \]

\[ \hat{r} \times \hat{r} \times \hat{r} + \left( \frac{1}{r^2} \right) \left[ 3 \hat{r} \cdot \mathbf{P} - \mathbf{P} \right] \] e^{i \omega t \varepsilon},

Figure 2. Optical responses of the coupled system of a nanodisk and a ring. (a) Schematic of the coupled system under normal incidence illumination. The polarization of the incident wave is along the \( y \)-axis. The origin of the coordinate system is placed at the center of the ring. The disk is placed above the ring with its center at (0, 0, 100 nm). (b) The scattering spectrum of the coupled system (red). The geometries of the ring and disk are the same as that in figure 1, respectively. The scattering spectrum of the individual Si nanodisk (black) and ring (blue) are also shown for comparison. (c) Multipole decomposition results of the coupled system. (d) The electric near-field profiles on the \( z = 100 \) nm plane (top) and \( y = 0 \) plane (bottom) of the coupled system, respectively. The wavelength is \( \lambda = 947 \) nm. The dashed lines show the outline of the structures. The color bar for the \( y = 0 \) plane is set to be a smaller value 3 to show the field around the ring for the coupling.
respectively. Figure 3(c) shows the normalized interaction energy $E_{int}/|P_{D1}|$ of the disk-ring structure, where the geometry of the ring is the same as that in figure 2. The distance between the coupling dipoles is around $kr \sim 1$, where $k$ is the wave vector. Such a distance means that neither near-field limit nor far-field limit can be used. Now let us consider the effect from the dipole moments of the ring. Electric near field distributions associated with the ring show that the field enhancement is almost unchanged in the wavelength ranged considered, while the size of the enhanced field increases with wavelength. Thus, the dipole moments also increase with wavelength as it approaches the resonance peak of the ‘modified anapole’ mode [figure 3(c)]. Taking this factor into account, one obtains the normalized interaction energy $E_{int}/|P_{D1}|$ of the coupled system as a function of working wavelength [figure 3(d)]. Such a disk-ring structure can be realized in the FDTD simulation by considering a structure where the size of the disk is the same while its anapole response wavelength is tuned by varying the refractive index of the disk. The geometries of the disk and ring are the same as that in figure 2, respectively. We define the relative field enhancement of the disk as its field enhancement in the coupled disk-ring structure divided by that of the individual disk. Then, the relative field enhancement of the disk is proportional to the interaction energy normalized by the dipole moment of the disk ($E_{int}/|P_{D1}|$). Figure 3(d) shows the direct FDTD calculation results of the relative field enhancement of the disk in the disk-ring system. The analytical and directly-simulated results agree well. Note that the relative field enhancement at resonance of the ring ($\sim 1100$ nm) is weaker. This can be understood by the results in figure 3(c), where the contribution from the normalized interaction energy $E_{int}/|P_{D1}|$ decreases faster than the increasing of the dipole moment of the ring with the working wavelength. The decreasing of $E_{int}/|P_{D1}|$ is due to the increasing of working wavelength which obeys equation (1).

We also consider more realistic cases in experiments where the disk and the ring have the same material Si while the radius of the disk is changed. It can be verified according to equation (1) that the interaction energy decreases when the distance between D1 (D3) and D2 becomes smaller, which corresponds to that the size of disk becomes smaller. This is rational because a smaller distance between D1 (D3) and D2 make the responses closer to an ideal anapole mode, where an ideal anapole mode will not be coupled to other modes. Taking the geometric factors of disk into account, one expects that there is a disk size for optimal the relative interaction energy, namely, the relative field enhancement of the disk. This is confirmed by the
Figure 4. Near-field enhancements of a coupled structure with a slotted Si nanodisk. (a) The schematic of the coupled structure of a slotted Si nanodisk and a Si ring under normal illumination. The slot has a length of \( L = 260 \) nm and a width of \( W = 10 \) nm. (b) The electric field enhancement on the \( z = 100 \) nm and \( y = 0 \) plane. The wavelength is \( \lambda = 889 \) nm. The dashed line shows the edge of the coupled structure. (c) Electric field enhancement at the center of the slotted Si nanodisk in the coupled structure (blue). The case for an individual slotted Si nanodisk (black) is also shown for comparison. (d) The magnetic field enhancement of the coupled structure on the \( z = 100 \) nm plane. The wavelength is \( \lambda = 889 \) nm. The dashed lines show the outline of the disk. (e) The resonant electric field enhancement as a function of slot length \( L \) while the slot width \( W \) is fixed at 10 nm. (f) The resonant electric field enhancement as a function of slot width \( W \) while the length \( L \) is fixed at 260 nm.

Direct FDTD simulation results as shown in figure 3(e). It is seen that the relative enhancement also becomes weaker when the working wavelength approaches the resonance of the ring. The explanation is also similar to that in figure 3(d), where both the distance and the working wavelength varies here while the decreasing of \( E_{\text{int}}/P_{\text{D1}} \) is still faster than the increasing of the dipole moment of the ring. Note that the working wavelength means the resonance enhancement on the spectrum, which is highly dependent on the anapole mode of the disk. The enhancement at a working wavelength does not necessarily mean the largest value at this wavelength. The strongly enhanced anapole response indicates that large electric field enhancement could be achieved in such a system by introducing a small slot in the disk \([41, 42]\). The small slot has a little effect on the scattering spectrum of the coupled system, while the electric near field inside it can be further enhanced a lot depending on the size of the slot. Furthermore, a slot can also make the enhanced electric field easily accessible to other objects. Figure 4(a) shows the coupled system with a slotted Si nanodisk, which is the same as that in figure 2, except that there is a slot in the center of the disk. The slot has a length of \( L = 260 \) nm and a width of \( W = 10 \) nm. Figure 4(b) shows the resonant electric field distributions on the \( z = 100 \) nm and \( y = 0 \) planes. They are similar to that of solid ones in figure 2(d), except that a huge electric field enhancement appears in the slot. Figure 4(c) provides the electric field enhancement calculated at the center of slotted disk in the coupled system. The resonant electric field enhancements \( |E|/|E_0| \) for the coupled system and individual case are around 96 and 19, respectively. The field enhancement of the coupled structure is about 5 times higher than that of the individual slotted disk. Here, it is noted that the resonance is blueshifted to 889 nm due to the appearance of slot in the disk. The relative field enhancement is increased more (\( \sim 5 \)) compared to the solid case (\( \sim 3 \)). This is inconsistent with the results in figure 3(d) as the working (resonant) wavelength is blueshifted and the corresponding relative enhancement is larger. Considerable value of the magnetic near field enhancement \( |H|/|H_0| \) of the coupled disk is also seen as expected [figure 4(d)]. There is almost no magnetic field enhancement at the center of the disk, which leaves a pure electric near-field hot spot at the center of the disk. The effect from the size of the slot is illustrated by figures 4(e) and (f). The field enhancement decreases with the slot width as expected. As for the slot length, the field enhancement first increases and then decreases with the length \( L \). This is associated with the fact that the anapole resonance of the disk varies with \( L \). Thus it shows a peak value around a given \( L \) as the ring is fixed. This is similar to the case of figure 3(e). Note that the electric-field enhancement under such an interaction still shows a relative large spectral width especially compared to the ones that achieve enhanced response by engineering the quality (\( Q \)) factors, for example, the quasi-BIC mode. This is spectral behavior is important for some applications.
such as the fluorescence enhancement where the fabrication accuracy needs to be high enough if the spectral width of the structure is too small.

Next, we investigate the effects from the geometry of coupled system. Figure 5(a) shows the resonant field enhancement as a function of the location $Z$ of disk. The other parameters are the same as that in figure 4. An optimal resonant field enhancement occurs at $Z = 100$ nm. This can be explained by the discussion in figure 3. The three dipoles of R1, R2 and R3 all contribute to the field at the location of the disk, and the variation of $Z$ induces the change of their corresponding $r$ in equation (1). There is an optimal $Z$ where the field contributed from the three dipoles is the largest. For the case of $Z = 0$ nm, the electric field enhancement of the coupled system reaches 81 times. The geometry of the ring is also an important factor that affects the value of field enhancement. The effect of outer radius $R_{out}$ of ring is investigated (from 430 nm to 590 nm) while the inner radius is kept at $R_{in} = 390$ nm. We set the relative location to $Z = 0$ nm as this is experimentally more feasible. The resonant electric field enhancement of the coupled system shows an optimal value around $R_{out} = 505$ nm [figure 5(b)]. This is due to the fact that with increasing $R_{out}$, the optical response of the ring increase while its resonant position moves further away from the working wavelength, and the relative distance between the dipoles of disk and the ring increases. The combination of these factors induces the optimal $R_{out}$. Similar behavior appears if $R_{in}$ varies with fixing the $R_{out}$, and the explanation is the same as that in figure 5(b). Figure 5(c) shows the results with varying the size of Si ring, where the $R_{out} - R_{in}$ is restricted to be $R_{out} - R_{in} = 100$ nm for each case. One can also find an optimal electric field enhancement at $R_{s} = 500$ nm. This can be explained by the factors that by increasing the size of the ring, the optical response of the ring increases while the resonance position also moves away from the working wavelength and the distance between the disk and ring also increases. The combination of these factors leads to the optimal phenomenon, which is similar to that in figure 5(b).

4. Conclusion

In conclusion, we have shown that the electric dipole moments associated with the optical anapole mode in dielectric nanostructures can induce significant electromagnetic interactions with other modes in the middle distance regime ($kr \sim 1$). We investigate a disk-ring coupled system, where the disk has an anapole mode. Strong electromagnetic interactions are found and the anapole response is significantly enhanced. This is also confirmed by analytical calculations. The near field enhancement of a coupled Si disk-ring structure can reach more than 90 times with a 10 nm-width slot in the disk, which is more than 5 times larger than the individual slotted disk. Our results reveal the rich strong mode couplings in individual all-dielectric nanostructures, and the near field enhancement could be further increased through more careful design based on the electromagnetic couplings in the middle distance regime. The strongly enhanced near-field response with considerable spectral width could find many applications such as near-field enhanced spectroscopies [64] and strong photon–exciton couplings [65–67].

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).
Acknowledgments

This work has been funded by the National Natural Science Foundation of China (NSFC) (11704416).

ORCID iDs

Zhong-Jian Yang 🔗 https://orcid.org/0000-0002-0492-6893

References

[1] Kuznetsov A I, Miroshnichenko A E, Brongersma M L, Kivshar Y S and Luk’yanchuk B 2016 Optically resonant dielectric nanostructures Science 354 aag2472
[2] Decker M and Staude I 2016 Resonant dielectric nanostructures: a low-loss platform for functional nanophotonics J. Opt. 18 103001
[3] Yang Z-J, Jiang R, Zhuo X, Xie Y-M, Wang J and Lin H-Q 2017 Dielectric nanoresonators for light manipulation Phys. Rep. 701 1–50
[4] Lin D, Fan P, Hasman E and Brongersma M I 2014 Dielectric gradient metasurface optical elements Science 345 298–302
[5] Khorasaninejad M and Capasso F 2017 Metalenses: versatile multifunctional photonic components Science 358 eaam8100
[6] Zhu X, Yan W, Levy U, Mortensen N A and Kristensen A 2017 Resonant laser printing of structural colors on high-index dielectric metasurfaces Sci. Adv. 3 e1602487
[7] Ha S T, Fu Y H, Emani N K, Pan Z, Bakker R M, Paniagua-Dominguez R and Kuznetsov A I 2018 Directional lasing in resonant semiconductor nanoantenna arrays Nat. Nanotech. 13 1042–7
[8] Yesilkoy F, Arvelos E R, Jahani Y, Liu M, Titil A, Cevher V, Kivshar Y and Altug H 2019 Ultrahigh-sensitivity hyperspectral imaging and biodetection enabled by dielectric metasurfaces Nat. Photon. 13 390–6
[9] Titil A, Leitis A, Liu M, Yesilkoy F, Choi D-Y, Neshov D N, Kivshar Y S and Altug H 2018 Imaging-based molecular barcoding with pixelated dielectric metasurfaces Science 360 1105–9
[10] Wang K et al 2018 Quantum metasurface for multiphoton interference and state reconstruction Science 361 1104–8
[11] Stav T, Faerman A, Maguid E, Oren D, Kleiner V, Hasman E and Segev M 2018 Quantum entanglement of the spin and orbital angular momentum of photons using metamaterials Science 361 1101–4
[12] Evlyukhin A B, Novikov S M, Zywietz U, Reinhardt C, Bozhevolnyi S I and Chichkov B N 2012 Demonstration of magnetic dipole resonances of dielectric nanospheres in the visible region Nano Lett. 12 3749–55
[13] Gomez-Medina R, Garciacamara B, Suarezlacalle I, Gonzalez F, Moreno E, Nieto-ovesperinas M and Saez J J 2011 Electric and magnetic dipole response of germanium nanospheres: interference effects, scattering anisotropy, and optical forces J. Nanophoton. 5 053512
[14] Gefrin I et al 2012 Magnetic and electric coherence in forward-and back-scattered electromagnetic waves by a single dielectric subwavelength sphere Nat. Commun. 3 1171
[15] Kuznetsov A I, Miroshnichenko A E, Fu Y H, Zhang J and Luk’yanchuk B 2012 Magnetic light Sci. Rep. 2 492
[16] Zhang S, Jiang R, Xie Y-M, Ruan Q, Yang B, Wang J and Lin H-Q 2015 Colloidal moderate-refractive-index CaO nanospheres as visible-region nanoantennas with electromagnetic resonance and directional light-scattering properties Adv. Mater. 27 7432–9
[17] Zhao Q, Yang Z-J and He J 2019 Coherent dipole transitions of quantum emitters and dielectric nanostructures Photon. Res. 7 1142–53
[18] Lukyanchuk B S, Voshchininnikov N V, Paniagua-Dominguez R and Kuznetsov A I 2015 Optimum forward light scattering by spherical and spheroidal dielectric nanoparticles with high refractive index ACS Photon. 2 993–9
[19] Evlyukhin A B, Reinhardt C and Chichkov B N 2011 Multipole light scattering by nonspherical nanoparticles in the discrete dipole approximation Phys. Rev. B 84 235429
[20] Habteyes T G, Staude I, Chong K E, Dominguez J, Decker M, Miroshnichenko A, Kivshar Y and Brener I 2014 Near-field mapping of optical modes on all-dielectric silicon nanodisks ACS Photon. 1 794–8
[21] Verre R, Baranov D G, Munkhbat B, Cuadra J, Kall M and Shegai T 2019 Transition metal dichalcogenide nanodisks as high-index dielectric Mie nanoresonators Nat. Nanotechnol. 14 679–83
[22] De Haar M A V, De Groep J V, Brenny B J M and Polman A 2016 Controlling magnetic and electric dipole modes in hollow silicon nanocylinders Opt. Express 24 2047–64
[23] Zenin V A et al 2020 Engineering nanoparticles with pure high-order multipole scattering ACS Photon. 7 1067–75
[24] Yesilkoy F, Schmidt M K, Evlyukhin A B, Reinhardt C, Aippuzura J and Chichkov B N 2015 Electromagnetic resonances of silicon nanoparticle dimers in the visible ACS Photon. 2 913–20
[25] Miroshnichenko A E and Kivshar Y S 2012 Fano resonances in all-dielectric oligomers Nano Lett. 12 6459–63
[26] Yan J, Liu P, Lin Z, Wang H, Chen H, Wang C and Yang G 2015 Directional Fano resonance in a silicon nanosphere dimer ACS Nano 9 2968–80
[27] Cai D-J, Huang Y-H, Wang W-J, Ji W-B, Chen J-D, Chen Z-H and Liu S-D 2015 Fano resonances generated in a single dielectric homogeneous nanoparticle with high structural symmetry J. Phys. Chem. C 119 4252–60
[28] Yang Z-J, Zhao Q and He J 2017 Boosting magnetic field enhancement with radiative couplings of magnetic modes in dielectric nanostructures Opt. Express 25 15927–37
[29] Huang T C, Wang B X and Zhao C Y 2019 Tuning toroidal dipole resonances in dielectric metamolecules by an additional electric dipole response J. Appl. Phys. 125 093102
[30] Yang Z-J, Deng Y-H, Yu Y and He J 2020 Magnetic toroidal dipole response in individual all-dielectric nanodisk clusters Nanoscale 12 10639–46
[31] Yang Z-J, Zhao Q and He J 2019 Fano interferences of electromagnetic modes in dielectric nanoblock dimers J. Appl. Phys. 125 063103
[32] Rybin M V, Koshelev K, Sadrivae Z F, Samusev K B, Bogdanov A, Limonov M F and Kivshar Y S 2017 High-Q supercavity modes in subwavelength dielectric resonators Phys. Rev. Lett. 119 243901
[33] Koshelev K, Kruk S, Melik-Gaykazyan E, Choi J-H, Bogdanov A, Park H-G and Kivshar Y 2020 Subwavelength dielectric resonators for nonlinear nanophotonics Science 367 288–92
[34] Koshelev K, Favraud G, Bogdanov A, Kivshar Y and Fratalocchi A 2019 Nonradiating photonics with resonant dielectric nanostructures Nanophotonics 8 723–45
[35] Yang Y and Bosheynolny S I 2019 Nonradiating anapole states in nanophotonics: from fundamentals to applications Nanotechnology 30 324001
[36] Baryshnikova K V, Smirnova D A, Luk’yanchuk B S and Kivshar Y S 2019 Optical anapoles: concepts and applications Adv. Opt. Mater. 7 1801350
[37] Miroshnichenko A E, Elyukhin A B, Yu Y F, Bakker R M, Chipouline A, Kuznetsov A I, Luk’yanchuk B S, Chichkov B N and Kivshar Y S 2015 Nonradiating anapole modes in dielectric nanoparticles Nat. Commun. 6 8069
[38] Colom R, Mpchedran R, Stout B and Bonod N 2019 Modal analysis of anapoles, internal fields, and Fano resonances in dielectric particles J. Opt. Soc. Am. B 36 2052–61
[39] Tian J, Liao H, Yang Y, Ding F, Qu Y, Zhao D, Qiu M and Bosheynolny S I 2019 Active control of anapole states by structuring the phase-change alloy Ge,Sn,Te Nat. Commun. 10 396
[40] Zenin V A, Elyukhin A B, Novikov S M, Yang Y, Malureau R, Lavrinenko A V, Chichkov B N and Bosheynolny S I 2017 Direct amplitude-phase near-field observation of higher-order anapole states Nano Lett. 17 7152–9
[41] Yang Y, Zenin V A and Bosheynolny S I 2018 Anapole-assisted strong field enhancement in individual all-dielectric nanostructures ACS Photon. 5 1960–6
[42] Wu J, Zhang F, Li Q, Feng Q, Wu Y and Wu L 2020 Strong field enhancement in individual Ψ-shaped dielectric nanostructures based on anapole mode resonances Opt. Express 28 570–9
[43] Baryshnikova K V, Filonov D, Simovski C R, Elyukhin A B, Kadochkin A S, Nenasheva E, Ginzburg P and Shalin A S 2018 Giant magnetoelectric field separation via anapole-type states in high-index dielectric structures Phys. Rev. B 98 165419
[44] Sabri L, Huang Q, Liu J-N and Cunningham B T 2019 Design of anapole mode electromagnetic field enhancement structures for biosensing applications Opt. Express 27 7196–212
[45] Shibanuma T, Grinblat G, Albella P and Maier S A 2017 Efficient third harmonic generation from metal-dielectric hybrid nanoanotants Nano Lett. 17 2647–51
[46] Grinblat G, Li Y, Nielsen M P, Oulton R F and Maier S A 2017 Degenerate four-wave mixing in a multiresonant germanium nanodisk ACS Photon. 4 2114–9
[47] Grinblat G, Li Y, Nielsen M P, Oulton R F and Maier S A 2016 Enhanced third harmonic generation in single germanium nanodisks excited at the anapole mode Nano Lett. 16 4633–40
[48] Xu L et al 2018 Boosting third-harmonic generation by a mirror-enhanced anapole resonator Light Sci. Appl. 7 1–8
[49] Gongora J S T, Miroshnichenko A E, Kivshar Y S and Fratalocchi A 2017 Anapole nanolasers for mode-locking and ultrafast pulse generation Nat. Commun. 8 13535
[50] Feng T, Xu Y, Zhang W and Miroshnichenko A E 2017 Ideal magnetic dipole scattering Phys. Rev. Lett. 118 173901
[51] Liu S-D, Fan J-L, Wang W-J, Chen J-D and Chen Z-H 2018 Resonance coupling between molecular excitons and nonradiating anapole modes in silicon nanodisk-J-aggregate heterostructures ACS Photon. 5 1628–39
[52] Du K, Li P, Gao K, Wang H, Yang Z, Zhang W, Xiao F, Chuang S J and Mei T 2019 Strong coupling between dark plasmon and anapole Modes J. Phys. Chem. Lett. 10 6899–7005
[53] Thakkar N, Rea M T, Smith K C, Heylman K D, Quillin S C, Knapper K A, Horak E H, Masiello D J and Goldsmith R H 2017 Sculpting Fano resonances to control photonic-plasmonic hybridization Nano Lett. 17 6927–34
[54] Liu J-N, Huang Q, Liu K-K, Singamaneni S and Cunningham B T 2017 Nanoantenna-microcavity hybrids with highly cooperative plasmonic-photonic coupling Nano Lett. 17 7569–77
[55] Wu P C et al 2018 Optical anapole metamaterial ACS Nano 12 1920–7
[56] Wang R and Dal Negro L 2016 Engineering non-radiative anapole modes for broadband absorption enhancement of light Opt. Express 24 19408–62
[57] Hüttenthaler F, Eckmann F, Lauri A, Cambiasso J, Pensa E, Li Y, Cortés E, Sharp J D and Maier S A 2020 Anapole excitations in oxygen-vacancy-rich TiO2-x nanoresonators: tuning the absorption for photocatalysis in the visible spectrum ACS Nano 14 2456–64
[58] Palik E D 1985 Handbook of Optical Constants of Solids (New York: Academic)
[59] Gurvitz E A, Ladutenko K S, Dergachev P A, Evlyukhin A B, Miroshnichenko A E and Shalin A S 2019 The high-order toroidal moments and anapole states in all-dielectric photonics Laser Photon. Rev. 13 1800266
[60] Alaee R, Rockstuhl C and Fernandez-Corbaton I 2018 An electromagnetic multipole expansion beyond the long-wavelength approximation Opt. Commun. 407 17–21
[61] Gurvitz E A, Ladutenko K S, Dergachev P A, Evlyukhin A B, Miroshnichenko A E and Shalin A S 2019 All-dielectric nanophotonics: the high-order toroidal moments and anapole states in all-dielectric photonics Laser Photon. Rev. 13 1970025
[62] Baranov D G, Verre R, Karpinski P and Käll M 2018 Anapole-enhanced intrinsic Raman scattering from silicon nanodisks ACS Photon. 5 2730–6
[63] Jackson J D 1975 Classical Electrodynamics (New York: Wiley)
[64] Calderola M, Albella P, Cortes E, Rahamani M, Roschuk T, Grinblat G, Oulton R F, Bragas A V and Maier S A 2015 Non-plasmonic nanoantennas for surface enhanced spectroscopies with ultra-low heat conversion Nat. Commun. 6 7915
[65] Wang H et al 2016 Resonance coupling in silicon nanosphere-mirror-shaped dielectric nanodisks Nat. Commun. 7 10316
[66] Yan J, Ma C, Liu P, Wang C and Yang G 2017 Generating scattering dark states through the Fano interference between excitons and an individual silicon nanogroove Light Sci. Appl. 6 e16197
[67] Ruan Q, Li N, Yin H, Cui X, Wang J and Lin H-Q 2018 Coupling between the Mie resonances of Cu2O nanospheres and the excitons of dye aggregates ACS Photon. 5 3838–48