Dual-Band Unidirectional Emission in a Multilayered Metal–Dielectric Nanoantenna

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ABSTRACT: Controlling the emission efficiency, direction, and polarization of optical sources with nanoantennas is of crucial importance in many nanophotonic applications. In this article, we design a subwavelength multilayer metal–dielectric nanoantenna consisting of three identical gold strips that are separated by two dielectric spacers. It is shown that a local dipole source can efficiently excite several hybridized plasmonic modes in the nanoantenna, including one electric dipole (ED) and two magnetic dipole (MD) resonances. The coherent interplay between the ED and MDs leads to unidirectional emissions in opposite directions at different wavelengths. The relative phase difference between these resonant modes determines the exact emission direction. Additionally, with a proper spacer thickness and filling medium, it is possible to control the spectral positions of the forward and backward unidirectional emissions and to exchange the wavelengths for two unidirectional emissions. An analytical dipole model is established, which yields comparable results to those from the full-wave simulation. Furthermore, we show that the wavelength of the peak forward-to-backward unidirectionality is essentially determined by the MD and is approximately predictable by the plasmonic wave dispersion in the corresponding two-dimensional multilayer structure. Our results may be useful to design dual-band unidirectional optical nanoantennas.

INTRODUCTION

Optical nanoantennas have been studied widely over the past decades, mostly for their ability to confine the optical fields into volumes of size far below the wavelength of the incoming light. Such nanoantennas are often characterized by different metrics, including scattering efficiency, directivity, emission pattern, and operating frequency bandwidth. Among these metrics, directional nanoantennas are particularly useful for modulating and steering the energy radiated by a single quantum emitter (e.g., a quantum dot or nitrogen-vacancy center) and enable the creation of an efficient single-photon source. Moreover, a highly unidirectional receiving nanoantenna is a suitable platform for creating a local field with an extreme spatial gradient, which is useful to control quantum source dynamics. Sufficiently high directionality has been demonstrated theoretically and experimentally for numerous nanophotonic applications, using Yagi–Uda antennas, core–shell nanoparticle arrays, dielectric nanoparticle arrays, ultracompact antennas, and even single metallic or dielectric nanoparticles.

Of special interest in this context are nanoantennas exhibiting both electric and magnetic resonances. In general, the interferences between the radiated optical fields from the induced electric dipole (ED) and magnetic dipole (MD) present an additional degree of freedom to tailor light emission characteristics, in terms of frequency, efficiency, phase, direction, and polarization. More specifically, these interactions allow for predictable highly unidirectional light emission if comparable strength of magnetic and electric responses is achieved. These interactions raise interesting possibilities for tailoring optical scattering and emission, such as controlling the coupling between a single-photon emitter and receiver, as well as unique processes arising from nonlinear optical interactions.

However, few natural materials exhibit an intrinsic MD transition, and even in those that do, the response is significantly weaker than that of their ED counterparts. Alternatively, optical magnetic responses can be achieved using nonmagnetic materials by properly structuring noble metals or high-index dielectrics, which behave as optical meta-atoms. The properties of such meta-atoms can be tuned via composition, geometry, and size. For active dipolar sources close to these structures with proper position and polarization, the magnetic resonance may become remarkably excitable. In
Figure 1. Illustration of unidirectional emissions by the ultracompact optical nanoantenna. (a) Schematic figure of the nanoantenna consisting of three identical gold nanostrips with length \( l = 100 \text{ nm} \), width \( w = 100 \text{ nm} \), and thickness \( t = 20 \text{ nm} \), and they are separated by two different dielectric spacers with thicknesses \( d_1 \) and \( d_2 \) and refractive indices \( n_1 \) and \( n_2 \). An ED source is positioned at the edge of the middle strip and is polarized along the \( y \) axis. The distance between the dipole source and the upper surface of the antenna is 10 nm. (b) Schematic representation of the color-switched directionality effect after setting \( d_1 = 15 \text{ nm}, d_2 = 25 \text{ nm}, n_1 = 1, \) and \( n_2 = 1 \). The high directionality is switched from the backward direction (+\( x \)) toward the forward direction (−\( x \)) as the operating wavelength is changed from \( \lambda = 664 \text{ nm} \) to 758 nm. (c) Schematic representation of the color-switched directionality when the parameters are as follows: \( d_1 = 47 \text{ nm}, d_2 = 25 \text{ nm}, n_1 = 1.26, \) and \( n_2 = 1.32 \). As the relative phase of ED and MD goes from \( \pi \) to 0 at the resonance of \( \lambda = 664 \text{ nm} \) and from 0 to \( \pi \) at the resonance of \( \lambda = 758 \text{ nm} \), the switching from forward (backward) to backward (forward) scattering occurs at these two wavelengths.

such a scenario, the structure generates ED- and MD-type responses at a comparable level.\(^{17}\) As such, unidirectional light emission resulting from ED–MD interference becomes possible.\(^{5}\) In this regard, plasmonic particles are attractive for such a purpose because plasmon resonance occurs with strongly confined and substantially controllable local fields. On this basis, one then expects large enhancement of the optical local density of states (LDOS) that can accelerate the spontaneous emission decay and substantial shaping of the emission patterns.

Recently, Pakizeh and Käll proposed a kind of nanoantenna made of a gold nanodisk dimer.\(^{17}\) In their system, an ED source can efficiently excite magnetic resonance in the dielectric gap and the induced ED and MD meet the Kerker condition.\(^{27}\) The local source–antenna coupled system radiates predominantly in one particular direction. Essentially, the directional emission is achieved by tuning the resonance wavelengths of the antenna elements, thereby adjusting the relative phase differences in their radiated fields. For an appropriate configuration, this may result in constructive interference of radiation in a particular direction and destructive interference in the opposite direction. Furthermore, in many applications, it is of great interest to provide similar functional operations at different and selective wavelengths simultaneously.

In this work, we show that in contrast to the dimer system a multilayer metal–dielectric–metal (MDM) nanoantenna can support more than one hybridized electric and magnetic dipolar modes. When excited by a properly positioned dipole source, the phase relationship between the different ED and MD resonant modes can be engineered and the overall light emission is controlled predominately toward opposite directions at different wavelengths. Furthermore, it is possible to switch the emission directions for the same wavelengths simultaneously. We demonstrate such a possibility by an optical nanoantenna consisting of three gold strips that are separated by two different dielectric layers, as schematically shown in Figure 1a. When such a nanoantenna is excited by a nearby dipole source (e.g., a quantum dot), it allows the localized surface plasmon resonances (LSPRs) sustained by the system to strongly interact, leading to excitation of the three hybridized plasmonic resonant modes. The detailed excitation strength and phase relations crucially depend on the retardation effect.\(^{30}\) More specifically, the parallel gold strips favor coupled electric resonance that is formed by in-phase currents, whereas the dielectric spacers can sustain magnetic resonances formed by out-of-phase (antigoing) currents on the neighboring metallic strips.\(^{31}\) This article shows that the interference of the scattered fields of these induced electric and magnetic resonances leads to controllable emission with high directionality. Moreover, we demonstrate that the emission direction can switch from one direction to the opposite direction at different wavelengths, along the normal multilayer structure. Furthermore, by judiciously varying the thickness and refractive index of the dielectric spacer, it is possible to switch optical emission from the backward (forward) direction to the forward (backward) direction at the fixed dual-band wavelengths (see the schematic in Figure 1b,c). The designed multilayered MDM antenna is quite flexible for steering the dipole emission. We expect that this bidirectional antenna can be integrated with dielectric waveguides and can provide an on-chip solution for two-color routing, which may lead to compact devices for wavelength-selective waveguide demultiplexing.\(^{32}\)

### RESULTS AND DISCUSSION

**Design and Characterization of the Nanoantenna.**

Figure 1a shows the antenna geometry, which consists of gold strips with length \( l = 100 \text{ nm} \) and thickness \( t = 20 \text{ nm} \), separated by two dielectric gap layers of thicknesses \( d_1 \) and \( d_2 \) and refractive indices \( n_1 \) and \( n_2 \). To examine the emission properties of a nearby dipole source coupled to this antenna (e.g., marked by the red arrow in Figure 1a), full-wave electromagnetic calculations based on the finite element
This indicates that the resonance at \( \lambda = 621 \text{ nm} \) corresponds to a superradiant (relatively bright) mode, whereas the other two resonances at \( \lambda = 672 \) and 746 nm result from the subradiant (relatively dark) modes. Furthermore, all of these modes partially overlap in the spectrum and may have different radiation interferences that can shape the emission pattern of a nearby active source. The differential directionality (measured in decibels) of an antenna reads as follows

\[
D(\theta, \varphi) = 10 \log_{10} \left[ 4\pi S(\theta, \varphi) \right] \int_{\varphi}^{\pi} S(\theta, \varphi) \sin(\theta) \, d\theta \, d\varphi,
\]

where \( \theta \) and \( \varphi \) are the spherical angles and \( S(\theta, \varphi) \) is the radiated power in the given directions \( \theta \) and \( \varphi \). Here, we are primarily interested in the forward–backward (FB) ratio, \( G_{FB} = D_{B} - D_{F} = 10 \log_{10} \left( S_{B}/S_{F} \right) \), where \( S_{F} \) and \( S_{B} \) are the far-field radiated powers in the forward (\( \theta = 90^\circ \), \( \varphi = 90^\circ \)) and backward directions (\( \theta = 90^\circ \), \( \varphi = 270^\circ \)), respectively. The FB ratio, \( G_{FB} \), allows a rough assessment of the directionality of the antennas. In our case, it reaches about \(-21 \text{ dB} \) at \( \lambda_1 = 664 \text{ nm} \) and nearly \( 20 \text{ dB} \) at \( \lambda_2 = 758 \text{ nm} \) (see the green solid line in Figure 2b). Notice that positive (negative) \( G_{FB} \) means that forward (backward) emission dominates. Figure 2a,b further shows that the spectral positions of extreme \( G_{FB} \) (at \( \lambda_1 = 664 \text{ nm} \) and \( \lambda_2 = 758 \text{ nm} \)) are very close to those of the two lower-energy subradiant modes (i.e., \( \lambda = 672 \) and 746 nm).

Because the multilayer MDM nanoantenna may sustain multipole resonances, it is essential to identify the multipolar moment contributions to the far-field at the resonant wavelength (i.e., \( \lambda_1 = 664 \text{ nm} \) and \( \lambda_2 = 758 \text{ nm} \)). The radiated power of the electric and magnetic multipoles can be calculated by the induced current volume density \( j(r) \) inside the nanostructure. As expected, the contributions from the induced ED and MD are significantly larger than those of the magnetic quadrupole (MQ) and electric quadrupole (EQ), see...
Therefore, it is reasonable to neglect the higher-order multipole moments that have negligible effects on the radiative decay rate and the radiation pattern.

Figure 2c shows the radiated powers, $P_{ED}$ (violet solid line) and $P_{MD}$ (pink solid line), of the induced dipole moments $p$ and $m$. It is seen that $P_{MD}$ maximizes at $\lambda = 672$ and $746$ nm, whereas a relatively large $P_{ED}$ covers nearly the entire visible spectrum. The broad $P_{ED}$ spectrum indicates that the ED resonance has a low quality factor. The ED resonance position is at about $\lambda = 621$ nm, identified from the scattering spectrum by plane-wave excitation (see Figure S1). To gain further insight into the resonant dipole modes, we plot the near fields ($E_x$ or $H_z$) for the three peak wavelengths in Figure 2d–f. Careful examination of the $E_x$ distribution shows that the first peak at $\lambda = 621$ nm corresponds to an electric resonance in which the LSPRs on the three plasmonic strips oscillate in-phase (see Figure 2d). Figure 2e,f shows the $H_z$ fields in the nanoantenna for the two magnetic resonances at $\lambda = 672$ and $746$ nm, respectively. It is evident that the magnetic fields are mainly localized and enhanced inside the left and right dielectric gaps, respectively. The electric fields over the left two (right two) strips oscillate out of phase at $\lambda = 672$ nm ($\lambda = 746$ nm), which forms strong circulating displacement currents in the left (right) dielectric gap, highlighting strong cavity magnetic resonance modes (for details, see Figure S3). As a result, it is reasonable to assume the induced ED to be oriented along the emitter polarization direction (i.e., $y$ axis) and the MD to be oriented along the $z$ direction. A corresponding three-layer metal–dielectric strip nanoantenna with similar parameters can support one ED and one MD, giving rise to highly directional emission at only one specific wavelength (see Figure S4).

**Dipole Interaction Model.** To qualitatively understand the roles of the two kinds of dipoles in achieving the dual-band unidirectional emission control, a schematic figure of the dipolar interference is sketched in Figure 2g. The hybridization occurs between a strip monomer and a strip dimer. When the monomer and the dimer are coupled strongly to each other, three hybridization cases can be characterized by one ED ($p$) and two MDs ($m_1^{(1)}$ and $m_1^{(2)}$). The solid arrows in the particles represent the EDs, and the green dashed arrows inside the gaps represent the MDs. For excitation by a dipole source at the proper position and polarization, the excitation spectra of $p$ and $m_1$ overlap partially, which enables the dual-wavelength unidirectional emission, as reflected by the $G_{FB}$ spectrum. The 3D radiation power pattern for the dip of $G_{FB}$ at $\lambda_1 = 664$ nm also is depicted in Figure 2g, showing an almost complete cancellation of the radiation toward the right-half space (+$x$ direction) and a predominated emission to the left-half space (−$x$ direction). In sharp contrast, for the low-energy peak of $G_{FB}$ at $\lambda_2 = 758$ nm, the nanoantenna–dipole source coupling system emits almost completely toward the +$x$ direction. For a three-layer MDM strip nanoantenna with similar geometry and materials (i.e., the parameters are the same as in Figure 2), the spectral position of $G_{FB}$ matches precisely with the spectral position of the MD resonance (see Figure S4b,c). For the five-layer MDM nanoantenna, the spectral positions of extreme $G_{FB}$ values slightly deviate from the resonance wavelengths of the corresponding two MDs. This deviation is partially due to the coupling effect (although weak) between the two magnetic cavity modes. Moreover, in this configuration, the nanoantenna ED and MD are significantly larger than the active dipole source because of the strong LSPR. As such, the total system’s far field can be expanded into a multipolar series that takes into account only the first two leading terms (i.e., ED and MD). With dipole moments $p$ and $m$, the antenna’s far field reads

$$E(r) = \frac{k^2 e^{ikr}}{4\pi\varepsilon_0 r} [n \times (p \times n) + \sqrt{\varepsilon_0\mu_0} (m \times n) + \ldots]$$

(2)
where \( k \) is the wave vector, \( n = k/|k| \) is the unit vector in the
emission direction, and \( r \) is the coordinate vector. According to
eq 2, zero forward or backward scattering requires the following:
(1) the two dipoles (ED and MD) to be orthogonal to each other;
(2) the radiated powers to be nearly identical, and
(3) the phase difference \( \Delta \phi = \phi_E - \phi_M = 0 \) (forward
scattering) or \( \Delta \phi = \pm \pi \) (backward scattering), where \( \phi_E \) and
\( \phi_M \) are the relative phases of the induced \( \mathbf{p} \) and \( \mathbf{m} \) in
the right-half space (+x direction). Likewise, when \( \Delta \phi = \phi_E - \phi_M \approx \pm \pi \)
(i.e., the second Kerker condition), the emission dominates in
the left-half space (−x direction).

In our system, with comparable amplitudes (see the solid
curves in Figure 2c) and relatively small phase difference,
\( \Delta \phi = 0.13 \pi \), of the induced \( p_x \) and \( m_z^{[2]} \) at \( \lambda = 758 \, \text{nm} \)
(see the green dashed curve in Figure 2c), the first Kerker condition
is approximately fulfilled. Similarly, the second Kerker condition
is nearly met at \( \lambda = 664 \, \text{nm} \) with \( \Delta \phi = 0.94 \pi \). We can have \( \Delta \phi \approx \pm \pi \)
and \( \Delta \phi \approx 0 \) in more than one position. However, highly
unidirectional emission does not happen, as seen in the spectra
of \( G_{FB} \) (black solid curve). This deviation is ascribed partially to
the dissipation in the nanoantenna structure. Figure 2b also
shows that the extreme \( k_{FB} \) wavelength matches the spectral
positions where \( \Delta \phi = 0.93 \pi \) and \( 0.96 \pi \). Similar results arise in
plasmonic systems with ED and EQ interference.\textsuperscript{19}

**Theoretical Analysis of Cavity Resonances.** On the
basis of the previous analysis, it becomes possible to control the
peak positions of \( G_{FB} \) by tuning the magnetic resonances. The
magnetic cavity modes in the MDM structure are considered to
result from the gap plasmonic waves.\textsuperscript{31} On the basis of the
Fabry–Pérot (FP) model, the resonant condition of the cavity
modes in our structure is approximately represented as
follows\textsuperscript{30,40}

\[
k_{GP} = \sqrt{k^2 + \frac{\pi^2}{L_{eff}^2}} = \frac{|p\pi|}{L_{eff}} + \frac{|q\pi|}{L_{eff}}^2 \quad (4)
\]

where \( k_{GP} \) denotes the gap surface plasmon polariton (SPP)
propagation constant, \( p \) and \( q \) are the quantum numbers in the
y and z directions (\( p = 1 \) and \( q = 0 \) in our case). Here, \( L_{eff} \)
is the effective side length of this resonator, which accounts for the
fringe field effect that may be considered as a phase shift in the
gap plasmonic wave upon reflection at the cavity edges.
Similarly, in the circular plasmonic patch nanoantennas,\textsuperscript{31,44}
we can replace \( L_{eff} \) with \( l + d \) in eq 4 as the first-order
approximation, where \( d \) is the gap thickness. The peak position
of \( G_{FB} \) for three-layer MDM strip nanoantennas can be
approximated by eq 4 directly (see Figure S6e). The five-layer
MDM structure can be viewed effectively as two intertwined
three-layer MDM nanoantennas. In our case, the fringe field
effect is expected to be different in the two dielectric layers (see
Figure S7) and the phase shift increases as the gap thickness
increases.\textsuperscript{41} Thus, \( L_{eff} = l + d_1 \) (or \( L_{eff} = l + d_2 \)) is considered to
be the effective side length of the FP resonator at dielectric
layer \( d_1 \) (or \( d_2 \)).\textsuperscript{42} Figure 4a shows the numerically calculated
resonance frequencies of the MD cavity modes versus \( L_{eff} = l + d_1 \)
(or \( L_{eff} = l + d_2 \)). Figure 4b shows the \( G_{FB} \) spectrum with the
extreme positions labeled by squares and circles. The data were
collected for different geometry lengths, \( l \). As the side length
increases from \( l = 100 \) to 250 nm, the MD resonances are
red-shifted and the peak positions of \( G_{FB} \) experience the same
varying trend. For a larger size (e.g., \( l = 200–250 \) nm), higher-
order multipole components contribute significantly to the
scattered field, leading to enhanced directionality at high
frequency (see the green and orange curves in Figure 4b).

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**Figure 4.** (a) Magnetic resonant frequencies (symbols) vs \( \pi/(l + d_1) \) or \( \pi/(l + d_2) \) for different side lengths \( l \) of the nanoantenna, superimposed with the
dispersion relation (solid curve) of the corresponding 2D multilayer structure. (b) \( G_{FB} \) spectra for different side lengths \( l \) of the nanoantenna.
The rest of the parameters are the same as in Figure 2.
According to eq 4, the resonant frequency and the size of the metal–dielectric resonator are correlated with $k_{pp}(\omega)$, which can be examined by the transfer matrix method for the corresponding 2D multilayer system. Figure 4a shows that the peak positions of extreme $G_{FB}$ approximately fall on the dispersion relation, $k_{pp}(\omega)$ (i.e., the black solid curves). The dispersion has several branches, and the lowest two are in accordance with the symmetric plasmonic gap modes in the two gap layers of thicknesses $d_1$ and $d_2$ respectively. More interestingly, it is confirmed that all of the magnetic modes excited in the same dielectric layer fall on the same dispersion branch, justifying the validity of the 2D analysis in eq 4. Figure 4 clearly shows that the peak positions of $G_{FB}$ can be approximated predicted by eq 4, by properly setting the effective side length $L_{eff}$.

**Switching of Unidirectional Emission.** Because the dispersion relation, $k_{pp}(\omega)$, depends on a bunch of parameters, including the material dielectric function ($n_1$ and $n_2$) and the geometry (e.g., $l$, $t$, $d_1$, and $d_2$), the hybridized MDs certainly not only depend on $l$ but also depend on the gap thickness and refractive index of the dielectric spacer. As a result, the directionality of $G_{FB}$ can be remarkably controlled by $d_1$, $d_2$, $n_1$, and $n_2$.

First, we examine the case of gradual variation of the refractive index, $n_2$, from 1 to 1.5, while keeping the rest of the parameters the same as in Figure 2. The directionality of $G_{FB}$, the radiated power of ED and MD, and their relative phase difference $\Delta \phi$ are shown in Figure 5a–r. As seen in the first column of Figure 5, the spectral position of extreme $G_{FB}$ experiences a slight redshift and the peak amplitude is gradually reduced when $n_2$ changes from 1 to 1.2. Simultaneously, the amplitude of MD is gradually reduced because of the weak interactions of the three metallic particles, whereas the amplitude of ED remains almost unchanged (see the second column of Figure 5). As a result, the mismatch between the ED and MD amplitudes increases, leading to decreased $G_{FB}$. Because the reduction is rather gradual, it allows for certain flexibility in the choice of parameters. More interestingly, when the refractive index approaches $n_2 = 1.3$, the signs of the two extreme $G_{FB}$ values become negative, indicating that $\Delta \phi$ values at both these two wavelengths are close to $\pi$ (see Figure 5i).

Furthermore, when $n_2$ increases to 1.4 (see Figure 5m–o), the high-energy peak of $G_{FB}$ disappears because the MD becomes off-resonance and its amplitude is almost extinguished. Further increasing $n_2$ to 1.5, it is seen that the signs of peak $G_{FB}$ at the short wavelength ($\lambda = 701$ nm) and the long wavelength ($\lambda = 804$ nm) flip, changing from negative (positive) to positive (negative), compared to those in the initial case of $n_2 = 1$ (the first row of Figure 5).

To demonstrate the unidirectional emission switching more clearly, the normalized 2D radiation patterns at the xy plane for different $n_2$ values at the two peaks of $G_{FB}$ (i.e., the shorter and longer wavelengths labeled $\lambda_1$ and $\lambda_2$) are plotted in Figure 5s,t, respectively. It is seen that the refractive index of the dielectric spacer plays a crucial role in determining the directionality of the nanoantenna. One can switch the emission between the forward (backward) and backward (forward) directions with a single element for two independent wavelengths. A similar behavior can be observed by properly changing the thickness of the dielectric spacer (see Figure S8).

The nature of this switching can be attributed to differences in the phase retardation effect on the left two (or right two) metal strips when excited by the dipole source, for systems characterized by different parameters (e.g., refractive index and thickness of the dielectric spacer). Such a phase retardation variation can be seen more clearly through careful examination of the near field. For example, $|H_z|$ is localized mainly inside the left and right dielectric gaps at the shorter and longer wavelengths, respectively, for the two MD resonances in the case of $n_2 = 1.5$, which is opposite to the situation of $n_2 = 1$, as shown in Figure 2e,f.

The switching between forward (backward) and backward (forward) directionality when $n_2 = 1$ is changed to $n_2 = 1.5$ is predicted by eq 4. Figure 6 shows that by properly setting the effective length, $L_{eff}$ which depends on the excitations of $m^{(1)}_z$ ($L_{eff} = l + d_1$) or $m^{(2)}_z$ ($L_{eff} = l + d_2$), the resonant frequencies of...
MDs for $n_s = 1$ (red symbols) and $n_s = 1.5$ (green symbols) approximately fall on the corresponding dispersion curves of the gap SPPs (see the red curve for $n_s = 1$ and the green curve for $n_s = 1.5$). Furthermore, the positive peak of $G_{FB}$ (circles) falls on the low-energy branch for $n_s = 1$ but on the high-energy branch for $n_s = 1.5$. Correspondingly, the negative peak (dip) of $G_{FB}$ (triangles) falls on the high-energy branch for $n_s = 1$ and on the low-energy branch for $n_s = 1.5$. Moreover, we also examined the gradual variation of the refractive index, $n_r$, from 1 to 1.5 (see Figure S9a), while keeping the rest of the parameters the same as those in Figure 2. The results show that the positive $G_{FB}$ peak position is gradually red-shifted and the negative positions remain almost unchanged because the high-energy dispersion branch is relatively more insensitive to $n_r$ (see Figure 9b). We also study the forward and backward scattering directionalities of $G_{FB}$ for different emitter polarizations (see Figure S10). The peaks of $G_{FB}$ have a spectral shift, whereas peak signs do not change at the short or long wavelength for different emitter orientations. This phenomenon can be explained by the Kerker condition, and color-switching can be achieved by different emitter polarizations. To this end, we have demonstrated the switching between forward (backward) and backward (forward) directionalities by properly tuning one parameter (thickness or refractive index of the dielectric layer), as shown in Figure 5 (also see Figure S8). However, the operating wavelengths cannot be fixed in these schemes. In view of the dispersion band dependence on both the geometry and material, we attempt to utilize gap thicknesses $d_1$ and $d_2$ simultaneously (or $n_1$ and $n_2$) to obtain the emission direction switching for two fixed wavelengths. Figure 7 shows the effects of gap thicknesses $d_1$ and $d_2$ on $G_{FB}$. Four cases of $d_1 = 10$ nm ($d_2 = 20$ nm), $d_1 = 15$ nm ($d_2 = 25$ nm), $d_1 = 25$ nm ($d_2 = 35$ nm), and $d_1 = 50$ nm ($d_2 = 60$ nm) are shown. It is evident that by varying the gap thickness, $d_1$ or $d_2$, the emission directionality can be altered remarkably. Because an increase in $d_1$ and $d_2$ leads to weaker near-field couplings ($\sim 1/d^3$) of the LSPRs, a blueshift for both the forward and backward directionalities is observed. This blue-shifting saturates for further increased gap thickness because the near-field interactions may diminish at a sufficiently large separation. In a similar strategy, a noticeable redshift can be seen in Figure 7b when we increase $n_1$ or $n_2$ from 1 to 1.5 (i.e., silicon dioxide). For all such cases, several combinations of $d_1$ ($d_2$) and $n_1$ ($n_2$) exist that make it possible to tune the direction emission between the forward (backward) and backward (forward) directionalities at fixed wavelengths. For example, we can first change $n_1$ to 1.5 while retaining $n_1 = 1$ to switch the sign of $G_{FB}$ at the peak positions and then we can properly increase $d_1$ and $d_2$ to compensate the wavelength shift.

To better illustrate this point, we carefully adjust and eventually set $d_1 = 47$ nm, $d_2 = 25$ nm, $n_1 = 1.26$, and $n_2 = 1.32$ and compare this nanoantenna to the one studied in Figure 2a. Figure 8 shows that the lowest two dispersion branches of these two cases coincide. In a similar strategy as shown in Figure 6, it is easy to demonstrate the exchange between forward (backward) and backward (forward) directionalities at a fixed wavelength. Figure 9a shows the spectrum of $G_{FB}$ for this case (see the green dotted line) compared to that for the case of $d_1 = 15$ nm, $d_2 = 25$ nm, $n_1 = 1$, and $n_2 = 1$, at $\lambda = 664$ nm, the dipole source emission is highly directed ($G_{FB} = -21$ dB) toward the $-x$ direction (the solid line in Figure 9b). However, in a dramatic contrast, at the wavelength of $\lambda = 758$ nm, the emission is highly directed ($G_{FF}$...)

![Figure 6](https://example.com/figure6.png)

Figure 6. Cavity resonant frequencies vs $\pi/(l + d_1)$ or $\pi/(l + d_2)$ for the nanoantenna with $n_1 = 1$ and $n_1 = 1.5$. The rest of the parameters remain the same as in Figure 2c.

![Figure 7](https://example.com/figure7.png)

Figure 7. Directionality of $G_{FB}$ tuned by the gap layer thickness and the refractive index. (a) Effects of thicknesses $d_1$ and $d_2$. (b) Effects of refractive indices $n_1$ and $n_2$.
= +20 dB) toward the +x direction (the solid line in Figure 9c). Conversely, for properly set parameters $d_1 = 47$ nm, $d_2 = 25$ nm, $n_1 = 1.26$, and $n_2 = 1.32$, an orange-color emission is directed toward the +x direction (the dashed line in Figure 9b) at $\lambda = 664$ nm and a red-color emission is directed toward the $-x$ direction at $\lambda = 758$ nm (the dashed line in Figure 9c). This unambiguously demonstrates the color-switching behavior as schematically shown in Figure 1b,c. In this way, the proposed nanoantenna acts like a two-channel optical demultiplexer. Therefore, it shows great potential for applications in integrated optical circuits, nano-optics, and nanophotonics.

It is important to study the directivity when the antenna is placed on a dielectric substrate because this is the typical experimental realization for optical antennas. The emitter–antenna system depicted in Figure 2 is placed on a glass substrate ($\varepsilon = 2.25$; see Figure 10a). The positive and negative directivity peaks also show up at 758 and 664 nm because the electromagnetic fields are localized mostly inside the antenna. Figure 10b,c shows the resulting angular far-field directivity for the two wavelengths. The emission is directed mainly toward the substrate$^{47}$ and is scattered into the +x ($-x$) direction at $\lambda = 758$ nm ($\lambda = 664$ nm). Thus, the present antenna can be fabricated to experimentally realize the bidirectional color routing.

**CONCLUSIONS**

We design and numerically demonstrate a dual-band ultra-compact plasmonic nanoantenna with controllable high unidirectionality for a nearby dipole emitter. The nanoantenna supports two spectrally tunable MD modes with a strength that is comparable to that of the overall ED resonance. Superior forward and backward radiation patterns are achieved, with forward-to-backward directionality reaching +20 and $-21$ dB, respectively. Analyses based on a simple dipole model are performed, and the reconstructed radiation patterns agree well with the full-wave simulation results. Furthermore, we show that the spectrum of the extreme directionality can be approximated by the SPP dispersion in the corresponding 2D
metal–dielectric multilayered structure and can demonstrate the possibility of color-switching. Our findings significantly broaden the versatility of plasmonic devices, and we envision the possible practical implementations in meta-materials, photon couplers, and chemo- or biosensors.

**METHODS**

**Transfer Matrix Method.** First, we extend the radius to infinity (i.e., \( r \to \infty \)) and treat the system as a seven-layer film system with air on the top and at the bottom, consisting of alternating three homogeneous metallic layers and two homogeneous dielectric layers. For TM polarization, the transfer matrix that relates electric fields across the interface from layer \( i \) to \( j \) reads

\[
D_j = \frac{1}{2} \begin{bmatrix} 1 + \eta_i & 1 - \eta_i \\ 1 - \eta_i & 1 + \eta_i \end{bmatrix}
\]

where \( \eta_i = k_{oi}^2 / k_{ei}^2 \) here, \( \varepsilon_i \) is the permittivity in material \( i \) and \( k_{oi} \) is the \( x \)-component of the wave vector in material \( i \) and can be written as \( k_{oi} = \sqrt{k_{oi}^2 - k_{ei}^2} \), where \( k_0 \) and \( k_\perp \) are the free space wave vector and the in-plane propagation constant, respectively. The field at \( x + \Delta x \) can relate to this at position \( x \) in material \( j \) by matrix \( \phi_j \)

\[
\phi_j \left[ \begin{array}{c} e^{ik_j x} \\
0 \\
0 \end{array} \right] \]

Then, the total transfer matrix to describe the nine-layer structure can be written as \( M = D_{11} D_{21} D_{31} D_{42} D_{53} D_{65} D_{76} \) and the reflection coefficient as \( r = M_{21} / M_{11} \). When the reflection coefficient, \( r_o \) is undefined (i.e., \( M_{11} = 0 \)), it corresponds to the eigenmodes of the structure, and then, the gap plasmon dispersion relation (\( k_{\text{gap}} \)) of this nanostructure can be obtained.

**FEM Modeling.** The radiative decay rate spectrum and the multipole analysis for the multilayered antenna were conducted using the radio frequency module of commercial FEM software COMSOL Multiphysics. The EM emitter was modeled as an electric current dipole moment with amplitude \( 1/(2\pi f) \), where \( f \) is the frequency. To absorb light scattered in all directions, the entire simulation space was then surrounded by a perfectly matched layer (PML), whose thickness equals \( \lambda_{\text{max}} / 2 \), where \( \lambda_{\text{max}} \) is the longest wavelength in the frequency domain study. Scattering boundary conditions were imposed on PML boundaries to preclude reflections. Far-field calculations were performed on a sufficiently large spherical surface (radius, \( R = 1 \) m) to ensure the accuracy of the near-field to far-field transformation. Test runs with different mesh sizes and domain sizes were conducted until convergence was reached.

**DDA Method.** DDSCAT 7.1 was chosen for calculating the radiative decay rate using the DDA method. The total system contains around \( 1.4 \times 10^7 \) dipoles, and test runs with different dipoles were also conducted until convergence was reached.

**ASSOCIATED CONTENT**

**Supporting Information**

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acsomega.7b00121.

Scattering cross-section spectrum and its multipole analysis for the five-layered antenna excited by normally incident plane wave; normalized radiated power of different multipole moments ED, MD, EQ, and MQ; charge distributions for the peaks of the ED and MDs in Figure 2c; simulation results of the MDM structure; \( G_{\text{FB}} \) dependence on the different dipole source positions; electric field along the \( y \) and \( z \) directions across the two dielectric layers; \( G_{\text{FB}} \) dependence on different \( d_i \) and \( n_i \); \( G_{\text{FB}} \) dependence on different emitter polarizations (PDF)

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**Notes**

The authors declare no competing financial interest.

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