Research article

Yilin Wang, Shilei Li, Jie-Yun Yan, Chao Li, Ping Jiang, Lulu Wang* and Li Yu*

Bidirectional to unidirectional emission of fluorescence controlled by optical traveling wave antennas

<https://doi.org/10.1515/nanoph-2019-0121>

Received April 22, 2019; revised May 27, 2019; accepted May 29, 2019

Abstract: Tailoring the fluorescence emission of quantum emitters to a desired direction is a crucial issue to achieve high efficient photodetection and realize unique optoelectronic devices. In this study, the directional emission of quantum dots controlled by optical traveling wave antennas based on 1D silver nanowires (NWs) was investigated. Both leaky waves and surface waves on a single NW are utilized for fluorescence emission control, and we show that the coupled fluorescence transforms from bidirectional to unidirectional emission when the surrounding medium changes from air to water. Moreover, in the unidirectional case, we obtain an ultra-narrow half-power bandwidth about 20° . Finite-difference time-domain simulations and Green's function method in a stratified medium are used to calculate the far-field emission patterns of the hybrid structures, which agree well with the experiments. Further analyses based on typical modes and the dipole-chain model also reveal the mechanism behind the bidirectional and unidirectional fluorescence emission. These results show that the structures have great potential in integrated on-chip, sensing and photon-collection devices.

Keywords: fluorescence emission; nanoantennas; bidirectional emission; unidirectional fluorescence.

1 Introduction

The isotropic nature of fluorescence emission from quantum emitters (QEs) severely limits its application in various fields, such as effective photon detection [1, 2], fluorescence imaging [3, 4], biochemical sensing [5, 6], and quantum information [7, 8]. Optical antennas, possessing the capability to interface near fields and far fields, offer unprecedented possibilities for directional fluorescence emission control [9–12]. Various kinds of optical antennas have been designed for this purpose. For example, nanorod antennas and U-shaped resonators based on resonant electric dipoles or magnetic quadrupoles [13, 14], parabolic reflectors and bull's-eye structures relying on the geometrical effect to redirect far-field emission by reflection or refraction on appropriately shaped surfaces [15, 16], and antenna arrays using the interference of antenna elements with different relative phases [17, 18]. To realize the desired emission control of fluorescence, all these antennas need a robust parameter design and costly nanofabrication technology, and the emitter should be precisely placed at a certain location with respect to the antennas [19, 20], which limits the wide application of such antennas. Recently, optical traveling wave antennas (OTWAs), a new branch of optical antennas, have been investigated [21, 22]. OTWAs can transform free-space light into nanoscale leaky or guided waves travelling on the optical wave guide, which can be classified as leaky wave antennas (LWAs) and surface wave antennas (SWAs) [23]. The LWAs have been successfully achieved both by dielectric nanofibers and metallic nanowires (NWs), while the SWAs can be achieved by metallic NWs due to the confinement of surface plasmons (SPs).

Chemically synthesized crystalline Au or Ag NWs possessing relatively low ohmic losses are usually the preferred structures to serve as OTWAs [24–27]. Former studies on light-matter interactions of Au or Ag NWs are focused on their transmission or enhancement to the QEs' emission [28–31]. The unique potential of these structures to achieve far-field fluorescence directional control of QEs

***Corresponding authors: Lulu Wang and Li Yu,** School of Science, Beijing University of Posts and Telecommunications, Beijing 100876, China; and State Key Laboratory of Information Photonics and Optical Communications, Beijing University of Posts and Telecommunications, Beijing 100876, China, e-mail: llwang@bupt.edu.cn (L. Wang); yuliyuli@bupt.edu.cn (L. Yu)

Yilin Wang, Jie-Yun Yan, Chao Li and Ping Jiang: School of Science, Beijing University of Posts and Telecommunications, Beijing 100876, China; and State Key Laboratory of Information Photonics and Optical Communications, Beijing University of Posts and Telecommunications, Beijing 100876, China

Shilei Li: School of Physics and Optoelectronics Engineering, Shandong University of Technology, Zibo 255049, China

is rare. Moreover, former studies on metallic NW-based OTWAs do not give detailed analyses about the emission patterns in the far field [32]. Therefore, the unique radiation properties and mechanism behind NW-based OTWAs to direct emission by QEs are still unclear.

In this paper, hybrid structures with quantum dots (QDs) uniformly wrapped on the Ag NWs by an SiO_2 spacer are designed and fabricated to achieve far-field emission control of QDs. We experimentally observed bidirectional emission lobes of fluorescence in the Fourier images when the hybrid NWs (HNWs) were immobilized on the substrate and exposed in the air. While the surrounding medium changed from air to water, the bidirectional emission disappeared and a unidirectional emission emerged with an ultra-narrow divergence. The divergence of the emission assessed by the half-power bandwidth (HPBW) can be reduced to 20° at certain diameters of the HNWs. To confirm the validity of our experiments, finite-difference time-domain (FDTD) simulations and Green's function method on stratified medium were used to construct the full-field emission patterns. The calculations agreed well with the experiment measurements. Further calculations based on mode analysis and the dipole-chain model revealed that the bidirectional and unidirectional emissions originated from the leaky radiation and the scattering of the confined mode at the NW end. Therefore, single NWs can serve both as LWAs and SWAs, and the fluorescence emission patterns of QDs can be tuned diversely by controlling the contribution of these two parts. These findings enable us to better understand the emission process of QDs modulated by NWs and show great potential in nanophotonics devices.

2 Results and discussion

The experimental schematic diagram is present in Figure 1A. The HNW with axis points to the positive direction of the x-axis was placed on the glass substrate. CdSe/ZnS core/shell QDs which are more stable and slow to photo-bleach were chosen as the fluorescence source. The QDs absorbed on the HNW were excited by a focused continuous laser beam ($\lambda_0=532$ nm) from the glass side ($n_2=1.52$) and the power of the incident laser beam was kept at about $200\text{ }\mu\text{W}$. Then, the fluorescence emission of the QDs (with a central peak at $\lambda=645$ nm) will partially couple to the SPs traveling along the HNWs. While the SPs propagate along the HNW, most of the energy will leak into the substrate or scatter at the HNW end, while only a tiny fraction reflects back. According to the scattering process of light, two coordinate systems

(rectangular and spherical coordinate systems) are defined in this configuration. Due to the specific dispersion in relation to SP waves, the leaky light will mainly distribute above the critical angle θ_c , which can be calculated by the relation $n_1=n_2\times\sin(\theta_c)$ [22, 33, 34]. In the experiment, Fourier optical imaging microscopy was used to investigate the direction of the scattered light. The scattered light was recorded at the glass side by a charge-coupled device camera with an integration time of 1000 ms. The angular distribution described by θ and ϕ can both be inferred from the measured Fourier image according to the internal relation between the spherical coordinate system and the Fourier image [34, 35]. A cross-sectional view of the HNW on a glass substrate is present in Figure 1B, where the HNW was immobilized on glass substrates ($n_2=1.52$), and immersed in the medium with a refractive index (RI) of n_1 . The QDs with a radius of about 4 nm were uniformly adsorbed onto the SiO_2 spacer.

Figure 1: The designed structure and optical images.

(A) Schematic of the hybrid nanowire (HNW) on the glass substrate and the fluorescence emission process of quantum dots (QDs). In the defined rectangular and spherical coordinate systems, the x-axis is along the nanowire and the z-axis is perpendicular to the glass substrate, while θ and ϕ are the polar and azimuthal angles, respectively. θ_c is the critical angle due to the symmetry breaking of the refractive index in the z-axis. (B) The cross-sectional view of the HNW on the glass substrate. (C) Transmission electron microscopy (TEM) image of a representative HNW. Scale bar: 200 nm. (D), (E) The optical bright field images of the HNWs excited by a focused laser beam when the upper surrounding mediums are air ($n_1=1.00$) and water ($n_1=1.33$), respectively. Scale bar: $5\text{ }\mu\text{m}$.

The SiO_2 layer with a thickness $d = 11.96 \pm 1.71$ nm is a carefully designed layer to prevent QDs from quenching and to achieve high fluorescence enhancement. The D , which denotes the diameter of the Ag NW, is a crucial parameter to adjust the divergence of the scattered fluorescence. A transmission electron microscopy (TEM) image of a representative HNw with a hemispherical end is shown in Figure 1C. Figure 1D and E are the optical images of the excited HNws when they were immersed in air ($n_1 = 1.00$) and water ($n_1 = 1.33$), respectively. We can observe that the light on the HNw surface in air is much brighter than that in water, which is because of the stronger leaky radiation of SP energy into the glass substrate. In all experiments, we kept the excitation of the focused laser spots about $10 \mu\text{m}$ away from the right end of the HNws. In addition, we obtained the optical images by adding a long-pass filter to the light path to remove the laser spot. In Figure 1D, A_1 represents the fluorescence of excited QDs radiating into free space, while A_2 is the coupled fluorescence scattering at the HNw end. To filter out A_2 for the directional study, the spatial filtering system must be employed and the spatial filtering region is denoted with a black dashed square in Figure 1E.

To reveal the changes of the emission patterns from QDs induced by NW antennas, we first measured the Fourier images of QDs deposited on the glass substrate, without the Ag NW antenna (Figure 2A). Due to the limiting numerical aperture (NA) of the objective lens, only fluorescence emission of $0^\circ \leq \theta \leq \theta_{\text{NA}}$ could be captured. The outer circle in the Fourier image is determined by $\text{NA} = 1.40$ of the objective, and the inner circle is determined by the critical angle θ_c . The captured image shows a uniform ring distribution between the critical angle $\theta_c = 41^\circ$ and $\theta_{\text{NA}} = 67^\circ$, which implies the isotropic characters of the QDs' fluorescence emission in the ϕ direction.

In the next step, the Fourier images of the QDs' emission modulated by HNws ($D = 230.37 \pm 28.09$ nm) were recorded and are shown in Figure 2B. The isotropic emission of QDs transformed into a line-shaped main lobe concentrated near θ_c . Also, $(\theta_m, \phi_m) = (43^\circ, 0^\circ)$ representing the maximum intensity point in the Fourier image is used to describe the direction of the main lobe. Moreover, a secondary lobe in an arc shape with a much smaller intensity can also be observed near θ_{NA} . Therefore, there are bidirectional emission lobes when the HNws are immersed in air. However, when the upper surrounding medium of the

Figure 2: Measured and calculated Fourier images.

(A) Measured Fourier image of fluorescence from excited quantum dots (QDs) immobilized on the glass substrate, without a nanowire (NW) antenna ($n_1 = 1.00$, $n_2 = 1.52$). The inner dashed circle at $\theta_c = 41^\circ$ represents the critical angle between the air and glass substrate. The outer dashed circle at $\theta_{\text{NA}} = 67^\circ$ marks the experimentally accessible angular range. (B), (C) Measured Fourier images of excited hybrid nanowires (HNws) immersed in air ($n_1 = 1.00$) and water ($n_1 = 1.33$), respectively. The inner dashed circle at $\theta_c = 61^\circ$ in (C) denotes the critical angle in the case of water. (θ_m, ϕ_m) is the maximum intensity point. (D–F) Calculated Fourier images show a similar behavior as the experimental Fourier images.

Figure 3: The radiation properties for unidirectional emission.

(A–D) Normalized intensity distributions versus ϕ at θ_m extracted from the Fourier images. Hybrid nanowires (HNWs) with four different diameters were measured and calculated ($n_i = 1.33$). The green circles and red solid lines represent the experimental and calculated data, respectively. (E) Experimental and calculated results with respect to half-power bandwidth (HPBW, $\Delta\phi$) for diameter (D).

HNWs changed from air into water, the line-shaped main lobe disappeared and the fluorescence emission exhibited a unidirectional arc-shaped lobe concentrated near θ_{NA} , as shown in Figure 2C. The θ_c changed to 61° , which is also marked as an inner dashed circle and the emission direction was measured to be $(\theta_m, \phi_m) = (62^\circ, 0^\circ)$. Obviously, the emission lobes for both cases are at $\phi = 0^\circ$, corresponding to the ϕ direction of the HNW axis, which is due to the symmetry of the RI in the ϕ direction. The Fourier images in Figure 2D–F constructed by FDTD simulations and Green's function method are consistent with the experimental results, and are described in the next section.

To further investigate the unidirectional emission, a series of HNWs with varying diameters (D) were fabricated. The statistical values of D according to the TEM images were 102.65 ± 11.40 nm, 173.89 ± 37.72 nm, 230.37 ± 28.09 nm and 444.84 ± 89.75 nm (see section S1 in the Supporting information). Figure 3A–D are the polar diagrams of normalized intensity distributions versus ϕ for θ_m extracted from the Fourier images. We can clearly observe that the unidirectional lobes point toward $\phi = 0^\circ$ both in the experimental and the calculated results. As D increased, $\Delta\phi$ increased as well, but the increment speed became slower, as shown in Figure 3E. The data for each

D were obtained by measuring five HNWs. The minimum HPBW was reduced to $\Delta\phi = 21.5 \pm 1.52^\circ$ for $D = 102.65$ nm, and the calculated value $\Delta\phi = 22.9^\circ$ was well within the error bar of the experiment results. The measured and calculated HPBW at about 20° for unidirectional emission was much narrower than the previous report [16, 36], which is crucial for efficient collection of fluorescence from QDs.

3 Calculation methods and mechanisms

For full-space radiation patterns of the HNWs, the 3D FDTD simulations and Green's function method for stratified medium were utilized. In the FDTD simulations, the smallest mesh size was 4 nm. HNWs were modeled as cylindrical Ag NWs with a layer of silica nanotubes tightly wrapped on them, and the lengths of the whole structures were reduced to 6 μm due to computational constraints. The HNW ends were enclosed with a hemisphere to mimic the end shape according to the TEM image in Figure 1C. The parameters of the simulated models of HNWs and the

Figure 4: Far-field radiation patterns calculated by Green's function method.

(A–D) The calculated far-field radiation patterns projected onto the yz -plane by varying n_1 ($D = 230.37$ nm). L_1 and L_2 (A) denote the bidirectional emission lobes. The grid lines indicate the spherical coordinate system. (E–G) The calculated far-field radiation patterns corresponding to three lowest-order modes (TM_0 , TM_1 and TM_2) in the hybrid nanowire (HNW), for $\lambda_0 = 645$ nm. The insets show the transverse electric near field intensity distributions ($|E|$) and vector plots of the three typical modes. The white arrows indicate field directions in the transverse plane.

properties of the surrounding medium strictly followed the experimental scheme. The optical index for the Ag NWs was taken from the experimental values provided by Palik [37]. A dipole (z -polarizations) with a modified spectrum according to the emission spectrum of the QDs was used as the optical source. This is because when Ag NWs are excited by z -polarized dipoles, the far-field intensity of the scattered light will be much higher than that excited by x - or y -polarized dipoles (see section S2 in the Supporting Information). Firstly, we obtained the near-field complex electric distributions of HNWs excited by the dipole by including emission from the final $0.5\text{--}3\text{ }\mu\text{m}$ of wire length. Then, the far-field radiation patterns of the structures were calculated through Green's function method in a stratified medium [38, 39]:

$$S = \frac{1}{2} c \epsilon_0 \sqrt{\epsilon_b} \left| E^0(\vec{r}) + \int d\vec{r}' \tilde{G}(\vec{r}, \vec{r}') k_0^2 \Delta \epsilon(\vec{r}') E(\vec{r}') \right|^2 \quad (1)$$

where S denotes the radial component of the Poynting vector at a large distance r from the scatterer, k_0 and c are the wave number and speed of light in vacuum, respectively, ϵ_0 is the permittivity of vacuum, and ϵ_b is the dielectric permittivity of the material the radiation is scattered into. In $\Delta \epsilon(\vec{r}') = \epsilon(\vec{r}') - \epsilon_b$, $\epsilon(\vec{r}')$ corresponds to the

dielectric function of the material where the scatterer is present. $E^0(\vec{r})$ and $E(\vec{r}')$ represent the electric source field and total near field, respectively. $\tilde{G}(\vec{r}, \vec{r}')$ is the Green's function, which describes field propagation in a certain direction (see section S3 in the Supporting Information).

Figure 4A illustrates the calculated 3D radiation pattern projected onto the yz plane when the HNW was on the substrate and exposed in air. Bidirectional emission can clearly be observed with the directions of the main lobe (L_1) centered at $(\theta, \phi) = (41^\circ, 0^\circ)$ and the secondary lobe (L_2) at $(\theta, \phi) = (70^\circ, 0^\circ)$, respectively. To better demonstrate the experiments, we also calculated the cases when the upper mediums were water ($n_1 = 1.33$), ethylene glycol (EG) ($n_1 = 1.42$) and index matched oil ($n_1 = 1.52$) and the results are shown in Figure 4B–D. The bidirectional emission became unidirectional emission with the directions centered at $(\theta, \phi) = (66^\circ, 0^\circ)$, $(70^\circ, 0^\circ)$ for the cases of water and EG, respectively, which meant that the maximum value of θ for each emission was approximately located at their θ_c . For $n_1 = n_2 = 1.52$, corresponding to the case that the HNW was placed in a homogenous medium, the emission direction $(\theta, \phi) = (90^\circ, 0^\circ)$ well along the HNW axis was due to the complete symmetry of the structure.

To investigate the mechanism behind the evolution of bidirectional to unidirectional fluorescence emission, we calculated the three basic modes (TM_0 , TM_1 and TM_2) supported by HNWs ($D=230.37$ nm, $n_1=1.00$). Figure 4E shows the emission pattern of the HNW individually fed by the confined plasmon mode TM_0 . There was a unidirectional lobe at $(\theta, \phi)=(70^\circ, 0^\circ)$, corresponding to L_2 in bidirectional cases (Figure 4A). The transverse mode pattern of the TM_0 mode with the electric field mainly confined around the HNW surface at the glass side is also shown in the inset. For the bound plasmon modes, their effective RIs were larger than that of the substrate, and for the leaky modes, their effective RIs were smaller than that of the substrate. The effective index of the TM_0 mode was calculated to be 1.49 when the upper medium was air. However, it was 1.66 when the upper medium changed into water, which was larger than the RI of the substrate (1.52). Thus, TM_0 is a bound plasmon mode in water and a leaky mode in air. For the TM_1 and TM_2 modes, the far-field radiation patterns (Figure 4F and G) both exhibited a unidirectional lobe centered around $(\theta, \phi)=(41^\circ, 0^\circ)$, corresponding to L_1 . For the transverse mode pattern of TM_1 and TM_2 modes in the insets, the electric field mainly concentrated at the air side while it leaked at the glass side. The effective indexes for the TM_1 and TM_2 modes were 1.10 and 1.04, approaching that (1.05) of the infinite silver/air interface plasmon mode. Given that their effective RIs were considerably smaller than that of the substrate, a large portion of energy will have leaked into the substrate during propagation. Moreover, when the surrounding medium changed

from air into water, the effective index of the leaky modes increased (1.50 for TM_1 and 1.48 for TM_2), being much closer to that of the substrate $n_2=1.52$ (see section S4 in the Supporting Information). This will have reduced the energy that leaks into the substrate. Therefore, the bidirectional emission will have evolved into unidirectional emission when the upper medium changed from air into water or medium with higher RIs.

For further exploration of the fluorescence emission from HNWs, the charge densities of these structures were calculated by solving the Poisson's equation [19, 40]. Figure 5A shows the case where HNW is exposed in air ($n_1=1.00$) and illuminated by a nearby dipole source with $\lambda_0=645$ nm. The excited charges periodically propagated along the HNW with the effective wavelength $\lambda_{\text{air}} > \lambda_{\text{air-glass}}$ and reverse charges were induced at the glass side. As we changed the upper medium from air into water or EG, the reverse charges decreased substantially (Figure 5B and C). Until the RI of the upper medium (oil) matched with that of glass perfectly, the induced inverse charges disappeared completely (Figure 5D). Based on the above discussion, we used a chain of oscillating electric dipoles with polarizations perpendicular to the substrate to model SPs propagation on the HNW (see section S5 in the Supporting Information). The far-field radiation pattern of this configuration was calculated and is shown in Figure 5E. The direction at $(\theta, \phi)=(41^\circ, 0^\circ)$ and the shape of this lobe corresponded well to the radiation of the leakage plasmon mode TM_1 (L_1 in Figure 4A and F). Thus, the leaky radiation on the HNW surface originates from the induced reverse charges

Figure 5: The dipole-chain model.

(A–D) The charge density distributions at the xz-plane that cut cross the axis of the hybrid nanowires (HNWs) ($D=230$ nm, $d=12$ nm) when they are deposited on the glass substrate ($n_2=1.52$) and immersed in air ($n_1=1.00$), water ($n_1=1.33$), ethylene glycol (EG) ($n_1=1.42$) and index matched oil ($n_1=1.52$) under dipole ($\lambda_0=645$ nm) excitation. Scale bar: 200 nm. (E) The far-field radiation patterns for the surface waves of HNWs at the glass side are modeled as a chain of electric dipoles with polarization perpendicular to the glass substrate.

caused by the mismatch of RI. Moreover, the reduced reverse charges for those in higher RI will lead to the weakening of leaky radiation. Therefore, the model further proved that by controlling the RI of the surrounding medium, which will change the contribution of the leaky radiation to the total radiation, the fluorescence radiation patterns of QDs can be tuned diversely to the desired directions.

4 Conclusion

In conclusion, we realized the bidirectional and unidirectional fluorescence emission by employing HNWs immersed in different surrounding mediums. The divergence of the unidirectional lobe can be reduced to 20° by decreasing the diameter of the NW. The calculated results from FDTD and Green's function method are consistent with the Fourier images obtained experimentally. From the analysis of the far-field emission patterns for three typical travelling modes and the constructed dipole-chain model, we found that the evolution of the fluorescence emission from bidirectional to unidirectional comes from both the leaky and bound waves supported by the HNW. Therefore, we realized the fluorescence directional control both by leaky waves and surface waves in a single structure. By controlling the contribution of these two parts, the fluorescence emission patterns of QDs can be tuned diversely. These findings enable us to better understand the emission process of QEs modulated by the travelling wave antennas and show great potential in achieving multifarious nanophotonics devices.

Acknowledgments: This work was supported by the National Key R&D Program of China (2016YFA0301300), the BUPT Excellent Ph.D. Students Foundation (CX2019320), the National Natural Science Foundation of China (NSFC) (11574035, 11374041, 11604020), and the State Key Laboratory of Information Photonics and Optical Communications.

References

- [1] Choudhury SD, Badugu R, Nowaczyk K, Ray K, Lakowicz JR. Tuning fluorescence direction with plasmonic metal-dielectric-metal substrates. *J Phys Chem Lett* 2013;4:227–32.
- [2] Lee KG, Chen XW, Eghlidi H, et al. A planar dielectric antenna for directional single-photon emission and near-unity collection efficiency. *Nat Photonics* 2011;5:166.
- [3] Andersen SKH, Bogdanov S, Makarova O, et al. Hybrid plasmonic bullseye antennas for efficient photon collection. *ACS Photonics* 2018;5:692–8.
- [4] Zanten TSV, Lopez-Bosque MJ, Garcia-Parajo MF. Imaging individual proteins and nanodomains on intact cell membranes with a probe-based optical antenna. *Small* 2010;6:270–5.
- [5] Stokes JL, Yu Y, Yuan ZH, et al. Analysis and design of a cross dipole nanoantenna for fluorescence-sensing applications. *J Opt Soc Am B* 2014;31:302–10.
- [6] Liu X-Q, Liu Q, Cao S-H, et al. Directional surface plasmon-coupled emission of CdTe quantum dots and its application in Hg(II) sensing. *Anal Methods* 2012;4:3956–60.
- [7] Yifat Y, Eitan M, Iluz Z, Hanein Y, Boag A, Scheuer J. Highly efficient and broadband wide-angle holography using patch-dipole nanoantenna reflectarrays. *Nano Lett* 2014;14:2485–90.
- [8] Exarhos AL, Hopper DA, Patel RN, Doherty MW, Bassett LC. Magnetic-field-dependent quantum emission in hexagonal boron nitride at room temperature. *Nat Commun* 2019;10:222.
- [9] Kuznetsov AI, Miroshnichenko AE, Brongersma ML, Kivshar YS, Luk'yanchuk B. Optically resonant dielectric nanostructures. *Science* 2016;354:aag2472.
- [10] Vaskin A, Bohn J, Chong KE, et al. Directional and spectral shaping of light emission with mie-resonant silicon nanoantenna arrays. *ACS Photonics* 2018;5:1359–64.
- [11] Chu XL, Brenner TJK, Chen XW, et al. Experimental realization of an optical antenna designed for collecting 99% of photons from a quantum emitter. *Optica* 2014;1:203–8.
- [12] Livneh N, Harats MG, Yochelis S, Paltiel Y, Rapaport R. Efficient collection of light from colloidal quantum dots with a hybrid metal-dielectric nanoantenna. *ACS Photonics* 2015;2:1669–74.
- [13] Cihan AF, Curto AG, Raza S, Kik PG, Brongersma ML. Silicon Mie resonators for highly directional light emission from monolayer MoS_2 . *Nat Photonics* 2018;12:284–90.
- [14] Hancu IM, Curto AG, Castro-López M, Kuttge M, Hulst NFV. Multipolar interference for directed light emission. *Nano Lett* 2014;14:166–71.
- [15] See K-M, Lin F-C, Chen T-Y, et al. Photoluminescence-driven broadband transmitting directional optical nanoantennas. *Nano Lett* 2018;18:6002–8.
- [16] Ho J, Fu YH, Dong Z, et al. Highly directive hybrid metal-dielectric Yagi-Uda nanoantennas. *ACS Nano* 2018;12:8616–24.
- [17] Morozov S, Gaio M, Maier SA, Sapienza R. Metal-dielectric parabolic antenna for directing single photons. *Nano Lett* 2018;18:3060–5.
- [18] Curto AG, Volpe G, Taminiau TH, Kreuzer MP, Quidant R, Hulst NFV. Unidirectional emission of a quantum dot coupled to a nanoantenna. *Science* 2010;329:930.
- [19] Shen H, Chou RY, Hui YY, et al. Directional fluorescence emission from a compact plasmonic-diamond hybrid nanostructure. *Laser Photonics Rev* 2016;10:647–55.
- [20] Vercruysse D, Zheng X, Sonnefraud Y, et al. Directional fluorescence emission by individual V-antennas explained by mode expansion. *ACS Nano* 2014;8:8232–41.
- [21] Gaio M, Moffa M, Castro-Lopez M, Pisignano D, Camposeo A, Sapienza R. Modal coupling of single photon emitters within nanofiber waveguides. *ACS Nano* 2016;10:6125–30.
- [22] Peter M, Hildebrandt A, Schlickriede C, et al. Directional emission from dielectric leaky-wave nanoantennas. *Nano Lett* 2017;17:4178–83.
- [23] Balanis CA. *Antenna theory: analysis and design*. New York, Harper & Row, 1982.

- [24] Zhang D, Xiang Y, Chen J, et al. Extending the propagation distance of a silver nanowire plasmonic waveguide with a dielectric multilayer substrate. *Nano Lett* 2018;18:1152–8.
- [25] Ma Y, Li X, Yu H, Tong L, Gu Y, Gong Q. Direct measurement of propagation losses in silver nanowires. *Opt Lett* 2010;35:1160–2.
- [26] Wei H, Zhang S, Tian X, Xu H. Highly tunable propagating surface plasmons on supported silver nanowires. *Proc Natl Acad Sci USA* 2013;110:4494–9.
- [27] Zou C-L, Sun F-W, Xiao Y-F, et al. Plasmon modes of silver nanowire on a silica substrate. *Appl Phys Lett* 2010;97:183102.
- [28] Wang L-L, Zou C-L, Ren X-F, et al. Exciton-plasmon-photon conversion in silver nanowire: polarization dependence. *Appl Phys Lett* 2011;99:061103.
- [29] Li Q, Wei H, Xu H. Quantum yield of single surface plasmons generated by a quantum dot coupled with a silver nanowire. *Nano Lett* 2015;15:8181–7.
- [30] Fedutik Y, Temnov VV, Schöps O, Woggon U, Artemyev MV. Exciton-plasmon-photon conversion in plasmonic nanostructures. *Phys Rev Lett* 2007;99:136802.
- [31] Akimov AV, Mukherjee A, Yu CL, et al. Generation of single optical plasmons in metallic nanowires coupled to quantum dots. *Nature* 2007;450:402.
- [32] Shegai T, Miljkovic VD, Bao K, et al. Unidirectional broadband light emission from supported plasmonic nanowires. *Nano Lett* 2011;11:706–11.
- [33] Drezet A, Hohenau A, Stepanov AL, et al. How to erase surface plasmon fringes. *Appl Phys Lett* 2006;89:091117.
- [34] Massenot S, Grandidier J, Bouhelier A, et al. Polymer-metal waveguides characterization by Fourier plane leakage radiation microscopy. *Appl Phys Lett* 2007;91:243102.
- [35] Wang Y, Li C, Duan G, Wang L, Yu L. Directional modulation of fluorescence by nanowire-based optical traveling wave antennas. *Adv Opt Mater* 2019;7:1801362.
- [36] Dasgupta A, Singh D, Tripathi RPN, Kumar GVP. Directional fluorescence emission mediated by chemically-prepared plasmonic nanowire junctions. *J Phys Chem C* 2016;120:17692–8.
- [37] Palik ED. Handbook of optical constants of solids. New York, Academic Press, 1985.
- [38] Martin OJF, Dereux A, Girard C. Iterative scheme for computing exactly the total field propagating in dielectric structures of arbitrary shape. *J Opt Soc Am A* 1994;11:1073–80.
- [39] Johansson P. Electromagnetic Green's function for layered systems: Applications to nanohole interactions in thin metal films. *Phys Rev B* 2011;83:195408.
- [40] Li Q, Pan D, Wei H, Xu H. Plasmon-assisted selective and super-resolving excitation of individual quantum emitters on a metal nanowire. *Nano Lett* 2018;18:2009–15.

Supplementary Material: The online version of this article offers supplementary material (<https://doi.org/10.1515/nanoph-2019-0121>).