Two-Color Light Routing using Bi-Directional Nanoantennas on Waveguides

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Abstract

We introduce the novel concept of Fano nanoantennas that allows for directional scattering of light in two opposite directions depending on the wavelength. We furthermore show that this antenna can be used as a two-color bi-directional waveguide coupler.

1. Introduction

In the last decade, plasmonic nanoparticles and nanoantennas have proven to provide unprecedented opportunities to control and guide of light at the nanoscale [1-3]. Due to their unique ability to confine and enhance light to sub-wavelength volumes they provide the basis for the development of novel types of advanced plasmonic sensors, solar cells, photo detectors, imaging devices and nanolasers, just to name a few.

Plasmonic nanoantennas have also opened up an effective way of manipulating and directing light, particularly, the emission from quantum emitters [3]. Furthermore, nanoantennas can provide a convenient way of directional scattering of light into and out of waveguides and, therefore, can also be used as a new type of optical couplers [4,5]. As such, the development of single nanoantennas for wavelength-selective directional scattering into dielectric nano-waveguides is of major importance.

Typically, directional scattering/radiation of antennas is achieved by detuning the resonance wavelengths of two or more antenna elements and, thereby, creating constructive interference in one direction and destructive interference in the other direction, hence, resulting in uni-directional scattering/radiation for the operating wavelength of the antenna.

2. Results and Discussion

Here, we present a new type of a single-particle Fano-nanoantenna that shows the capability of simultaneously directing light with two different wavelengths in two opposite directions (see Fig. 1). In contrast to previous nanoantenna designs, we make use of the Babinet-principle [6] to effectively merge two antenna elements into one particle. Thereby, we are able to create a Fano resonance [7] that gives rise to bi-directional radiation patterns at $\lambda_R = 700$ nm and $\lambda_L = 800$ nm with a front-to-back ratio of about 25 for radiation in opposite directions.

In order to identify the conditions that have to be fulfilled to achieve uni-directional radiation for one wavelength on the one hand and a change of direction of the radiation pattern for a different wavelength on the other hand, we develop a simple picture based on the superposition of the radiation of two (identical) dipoles in vacuum separated by a fixed distance d (see Fig. 2). From Fig. 2 it becomes clear that for all distances $d = m*\lambda/2$ (m is an integer) no directional radiation pattern is possible [Fig. 2(a)] since the relative phases of the dipole fields are identical in both directions. In contrast to that the radiation in one direction can be completely suppressed for

$$d = (2m-1)*\lambda/4 \quad (1)$$

depending on the relative phase angles α_1, α_2 of the two dipoles [Fig. 2(b)]. Ideal uni-directional scattering, however, can only be achieved when $(\alpha_1 - \alpha_2) = \pm 90°$.

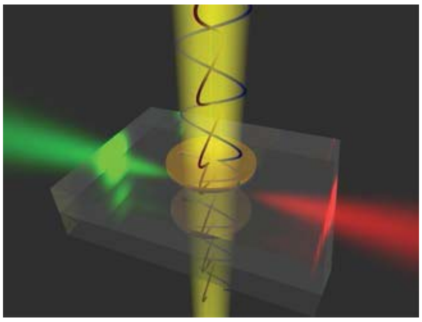


Figure 1: Artist view of our bi-directional Fano-antenna. The incident light (yellow) is scattered in opposite directions for different wavelengths (red and green).

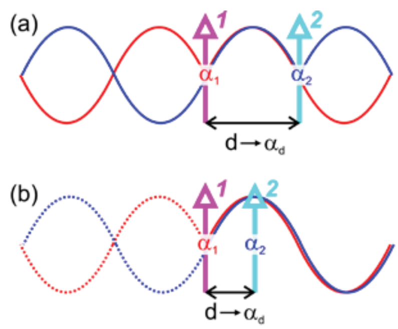


Figure 2: Electric field amplitude of the radiation of two (identical) electric dipoles *1* and *2* with the phase angles α_1 and α_2 separated by the distance d for (a) $d = \lambda/2$ and (b) (a) $d = \lambda/4$.

Furthermore, we find that for $(\alpha_1 - \alpha_2) = +90°$ we get uni-directional scattering in one direction, while for $(\alpha_1 - \alpha_2) = -90°$ we obtain uni-directional scattering in the other direction. One of these two conditions can be easily satisfied by choosing metal nanoparticles with specific dimensions as electric dipoles and by appropriately adjusting the separation between the two particles [4,5] and is also the basic design principle for Yagi-Uda (nano)antennas. However, for this antenna design, one can only obtain either positive or negative relative phase differences between the responses of the two nanoparticles [(α_1 - α_2) > 0 or (α_1 - α_2) < 0] and no bi-directional scattering is possible.

In our approach, we overlap and couple two plasmonic resonances with very different resonance widths. Our design consists of a gold nanodisk with a diameter of 400 nm and thickness of 30 nm. Inside the disk, we inscribe a 15 nm wide and 120 nm long slit in *x*-direction (see Fig. 1). We calculated the optimum position of the slit in order to maximize the bi-directional scattering properties and obtain an optimum displacement of the nanoslit by $d = 100$ nm from the center of the disk. This corresponds to a relative phase difference due to the separation of two dipoles of approximately 48° at 750 nm wavelength in vacuum.

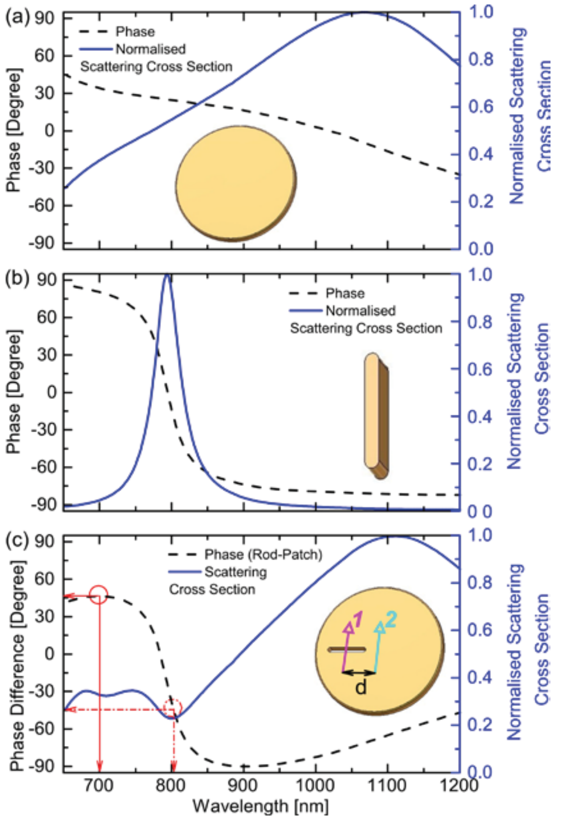


Figure 3: The normalised scattering cross section (blue curve) and the phase spectrum (black dashed curve) of (a) a circular patch with a diameter 400 nm and (b) a nanorod with a length of 120 nm and a width of 15 nm. (c) shows the normalised scattering cross section of the nanodisk/nanoslit antenna (blue curve), and the phase difference between the rod and the circular patch (black dashed curve). The red circles mark a phase difference of +47° at 700 nm and -45° at 800 nm, respectively. All structures are excited with vertical-linear polarization.

In order to investigate and tailor the optical response of the nanoantenna we perform numerical calculations using the finite-integral frequency-domain simulation software package CST Microwave Studio. First we calculate the scattering cross section of a single gold nanodisk of the same size as in the final antenna design [see Fig. 3(a)] suspended in vacuum and illuminated with a plane wave at normal incidence. We then compare our results with the scattering cross section of the nanodisk/nanoslit antenna shown in Fig. 3(c). Figure 3 clearly shows that the peak in the scattering cross section of the nanodisk/nanoslit antenna at around 1.1 μm wavelength can be identified as the fundamental (electric dipole) resonance of the nanodisk. Secondly, we calculate the response of a gold nanorod with the same dimensions as the slit in the final nanoantenna design but with perpendicular orientation [Fig. 3(b)]. By applying the Babinet principle [6], we can use these results to determine the response of the nanoslit. We find that the nanorod shows a resonance (scattering peak) at 800 nm wavelength that can be linked to the resonance of the nanoslit. Importantly, this resonance coincides with the minimum of the scattering cross section of the nanodisk/nanoslit-antenna. This behavior is, indeed, a clear sign of destructive interference between the nanodisk and the nanoslit and results in the characteristic Fano line shape [7], as shown in Fig. 3(c).

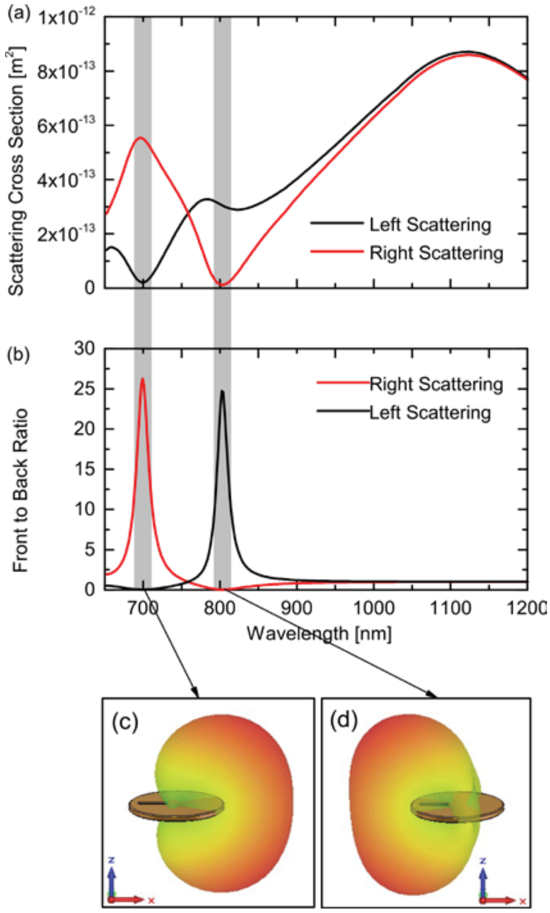
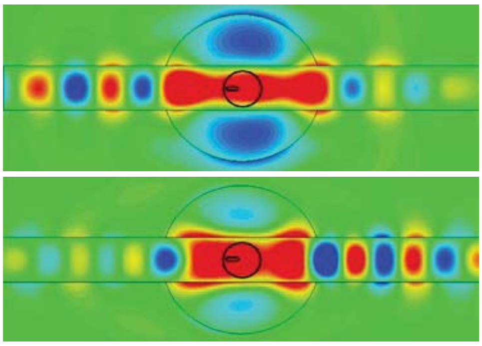


Figure 4: (a) Left-scattering cross section (black) and and right-scattering cross section (red) of the Fano-antenna. (b) Front-to-back ratio for scattering to the right (red curve, +*x*-direction) and to the left (black curve,-*x*-direction). (c,d) Calculated far-field radiation patterns at 700 nm and 800 nm, respectively.

In a third step, we calculate the relative phase of the electric near-fields of the the nanodisk and the nanorod by evaluating the complex electric fields [see dashed lines in Fig. 3(a),(b)] and determine the relative phase difference between the nanodisk and the nanoslit response [see dashed line in Fig. 3(c)]. Importantly, we find that we obtain positive as well as negative phase differences for different wavelengths of light which, again, is a unique feature of a Fano resonance [7]. In this way we fulfill the second fundamental requirement for the observation of frequency-selective bi-directional scattering.

Finally we calculate the scattering cross section of our Fano-antenna and analyze the obtained scattering cross sections to obtain the amount of light scattered to the right (+*x*-direction) and to the left (-*x*-direction). The results are shown in Fig. 4(a). The evaluation of the directional scattering cross section around the Fano resonance at 800 nm results in a significant difference in the scattering cross section for the light scattered to the left, $C_{sca,L}$ and to the right, $C_{sca,R}$. Figure 4(b) presents the ratio of the corresponding scattering cross sections shown in Fig. 4(a) that defines the front-to-back ratio $FBR_L = C_{sca,L}/C_{sca,R}$ and $FBR_R = C_{sca,R}/C_{sca,L}$ of the nanoantenna. Our results show, that our Fano-antenna design supports bi-directional radiation properties with a directivity of 2.4 at 800 nm, and 2.8 at 700 nm. Particularly, we find enhanced scattering in +*x*-direction at $\lambda_R = 700$ nm with a $FBR_R = 27$ and enhanced scattering in -*x*-direction at $\lambda_L = 800$ nm with a $FBR_L = 24$. The corresponding radiation patterns of the nanoantenna at 700 nm and 800 nm are shown in Fig. 4(c),(d), respectively.

(a)



(b)

Figure 5: Calculated electric-field distribution of a hybridized Fano-antenna/waveguide system at (a) 1380 nm and (b) 1530 nm wavelength (top view) showing directional coupling to the left and to the right side of the waveguide, respectively.

Our bidirectional Fano-antenna design can also be integrated onto dielectric waveguides and, consequently, enables us to couple light with different wavelengths into opposite waveguide directions as well. Figure 5 shows our Fano antenna on top of a chalcogenide waveguide excited by an optical fibre with a core diameter of 1 μm. The electric field distribution at 1380 nm wavelength clearly indicates directional coupling of the incident light to the left side of the waveguide while coupling to the right is suppressed. For 1530 nm wavelength coupling into the opposite direction is observed.

3. Conclusions

In summary, we have introduced a new type of single-element plasmonic nanoantenna consisting of a gold nanodisk and a Babinet-inverted nanorod (nanoslit). We have shown that this nanoantenna design provides a pronounced Fano response that ultimately leads to bi-directional nanoantenna radiation patterns for different wavelength of light. The maximum front-to-back ratio for the two (opposite) directions of radiation is about 25 with a directivity of 2.4 at 800 nm and 2.8 at 700 nm. Our bi-directional Fano-antenna design can be readily integrated into dielectric waveguide architectures to provide an on-chip solution for two-colour routing of light. Furthermore, due to the presence of the Fano resonance, the antenna properties are inherently sensitive towards changes in the dielectric environment and makes this optical Fano-antenna a promising candidate for future integrated sensing applications.

Acknowledgements

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