Broadband light beaming from a helical traveling-wave nanoantenna

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Abstract

Nanoantennas are appealing for their ability to directionally radiate light, with important implications in the optical detection of nanoscale objects. Based on the control of the resonant or dispersive properties of nanostructures, nanoantennas usually radiate light at a given direction over a narrow spectral bandwidth. Here, we show that a broadband light beaming can be obtained from an individual helical traveling-wave nanoantenna. We experimentally find an emerging light pointing towards the helix axis with a divergence half-angle smaller than 25° over a spectral range of 1.47 µm - 1.65 µm (limited by our laser bandwidth). Numerical simulations show that such a beaming property holds over a wavelength range spanning from 1.2 µm to 1.8 µm. Our nanoantenna thus offers a broadband subwavelength and efficient optical interface between the nanoscale and remote bulky light sources and detectors.

1. Introduction

Resonant nanoparticles and nano-apertures are currently used to concentrate light in nanoscale volumes. Such a strong confinement usually imposes highly diverging scattered light in free space, laying difficulties for the far-field detection of nanoscale objects. Light beaming from an individual nano-aperture is possible when the nanostructure is surrounded by a periodic grating [1], at the expense of an overall structure larger than the wavelength of light and a strongly wavelength-dependent radiation directionality. Alternative solutions of smaller footprint are based on the interference of the multipolar modes of an individual dielectric nanoparticle [2], or on near-field interactions in a plasmonic chain (Yagi-Uda nanoantennas [3]). Relying on optical resonances, such nanoantennas ensure directional radiation over a narrow spectral bandwidth.

Nonresonant optical antennas offer the prospect of a high directivity over a broad spectral range [4]. However, relying on dispersive propagating modes, these antennas lead to collimated radiations whose propagation direction is intrinsically wavelength-dependent. Moreover, they suffer from modest compactness with spatial footprints far exceeding the wavelength of light. An individual subwavelength nanoantenna capable of preserving a specific radiation direction over a broad spectral range is thus still lacking. In this paper, we present the beaming properties of an individual aperture nanoantenna coupled to a subwavelength plasmonic helix. The resulting hybrid nanoantenna, called helical traveling-wave nanoantenna, is the extension to optics of the low-frequency helical antenna operating in the "axial mode" [5].

2. Results

Our helical nanoantenna is realized from a three-step fabrication process [6]. Figures 1(a) and (b) show the scanning electron microscope images of a resulting structure. The nanoantenna consists of a gold-coated carbon helix standing on a gold-coated glass substrate. A rectangle nano-aperture is milled in contact to the helix pedestal to locally feed the helix. The resulting hybrid nanoantenna is illuminated from the backside (the substrate). An optical image of the far-field radiation is shown in Fig. 1(c), featuring a single light spot. To investigate the directional property of the nanoantenna, the back focal plane (Fourier plane) of a 0.9 numerical aperture objective is imaged with a lens coupled to a camera. A coordinate transformation from the cartesian (x,y) to spherical (θ,ϕ) coordinates is then applied (see Fig. 1(a)).

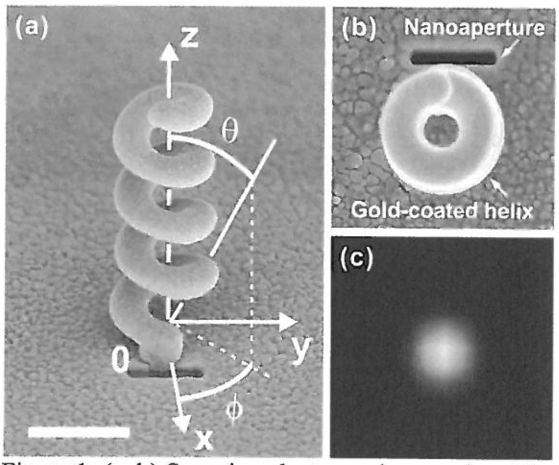

Figure 1: (a, b) Scanning electron micrographs of the helical traveling-wave antenna. (a) side view, (b) top view. (c) Optical image of the hybrid nanoantenna illuminated from the backside of the substrate at

λ=1.5 μm. Scale bar: 500 nm.

Figures 2 shows the angular radiation patterns at λ=1.5 μm of a single rectangular nano-aperture in a gold film and of our hybrid helical nanoantenna, respectively. Identical nano-apertures are used in Fig. 2(a) and for building the helical nanoantenna (Fig. 2(b)). The radiation pattern of the nano-aperture alone shows a poor directionality with the presence of two off-axis lobes (showing maxima in the cross-sectional plane ϕ =0°). Such a diagram refers to the dipolar properties of the nano-aperture. As a contrast, due to the existence of the plasmonic helical structure, the hybrid helical nanoantenna develops a highly directional and near axis-symmetrical beam pointing toward the direction θ=0° (i.e., along the helix axis). The angular divergence of this main radiation lobe is less than 25° (half-width at half-maximum).

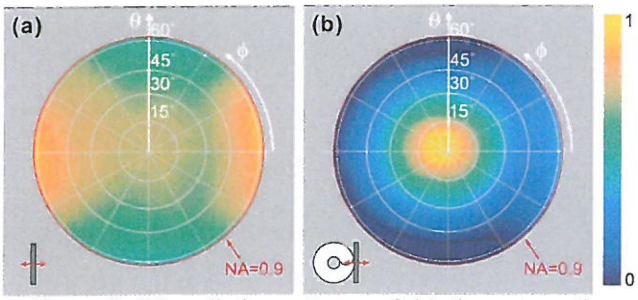

Figure 2: 2D radiation patterns of (a) the rectangular nano-aperture alone and (b) the same nano-aperture coupled to a plasmonic helix to form the helical traveling-wave nanoantenna. "NA" denotes the numerical aperture of the objective used to perform imaging.

Remarkably, we experimentally observe an axial beaming narrower than 25° (half width at half maximum) over a spectral range of 1.47-1.65 μm limited by our laser bandwidth. Numerical simulations using FDTD (Finite Difference Time Domain) further show that axial beaming occurs over a broader spectral bandwidth spanning from 1.2 μm to 1.8 μm.

3. Discussion

The directional radiation occurs with an individual structure of subwavelength lateral size (~λ/3). Such a property is consistent with the "axial" mode of the radio-frequency helical antenna which inspired our plasmonic structure [5]. The resulting broadband beaming may thus reveal a non-resonant operation of our nanoantenna. The numerically predicted current distribution along the helical nanowire is in favor of such a non-resonant operation as no current nodes are observed along the helix. This also indicates a good impedance matching of the traveling mode of the helix to vacuum. Such an interpretation may differ from previous theoretical approaches of plasmonic nano-helices [7,8].

4. Conclusions

By extending the concept of helical antenna to the optical regime, we demonstrate broadband light beaming from an individual subwavelength plasmonic structure. Used in a non-resonant traveling-wave regime, the plasmonic helix can be seen as a compact, versatile and efficient interface between free-space propagating waves and confined light fields. This nanostructure provides new opportunities in the achievement of directional radiation from nanoscale objects and emitters, thus impacting many research domain including quantum optics, optical information processing, sensing, communications, and miniaturized displays.

Acknowledgements

This work is supported by the Labex ACTION program (contract ANR-11-LABX-01-01), the EIPHI Graduate School (contract ANR-17-EURE-0002), the Region "Bourgogne Franche-Comte", the French Agency of Research (contract ANR-18-CE42-0016), and the French RENATECH network and its FEMTO-ST technological facility.

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