Spiral Surface Plasmon Modes on Uniform and Tapered Metallic Nanorods

Chih-Min Chen¹, Chih-Kai Young¹, Kuan-Ren Chen²,³ and Yung-Chiang Lan¹,³*
¹Department of Photonics, National Cheng Kung University
²Department of Physics, National Cheng Kung University
³Advanced Optoelectronic Technology Center, National Cheng Kung University
*No. 1 University Road, Tainan City 701, Taiwan; E-mail: lanyc@mail.ncku.edu.tw

The interaction of circularly polarized light with chiral molecules or chiral metamaterials has drawn a lot of research interests [1]. To address it, highly localized and circularly polarized electromagnetic fields as a source are required. The metallic nanorods play a key role in the probing tip of a near-field optical microscopy. Various surface plasmon (SP) eigenmodes on a metallic nanorod have been derived and identified [2]. However, the time-averaged field energies of these modes are azimuth-independent and not related to the chirality.

This study explores the spiral SP (SSP) modes that are formed on uniform and tapered silver (Ag) nanorods by performing both FDTD simulations and theoretical analyses. Figure 1(a) plots the simulated uniform Ag nanorod. The radius of the nanorod (a) is set to 60 nm and 240 nm. Figure 1(b) presents the simulated tapered Ag nanorod. The radii of the lower and upper bases are 120 nm and 60 nm, respectively. The length of the tapered section is 9000 nm. The Ag nanorod is embedded in matching oil with the relative permittivity of 2.25. The incident wavelength (λ0) is 633 nm. The FDTD program MEEP is utilized to perform the simulation [3]. A three-dimensional Cartesian x-y-z coordinate system is used (the axis of nanorod is along the z-direction). The x and y dimensions of the grid cells are both 1 nm (4 nm) for the uniform nanorod with a = 60 nm and the tapered nanorod (for the uniform nanorod with a = 240 nm).

The z dimension of the grid cells is 10 nm. The surrounding boundaries are perfectly matched layers. The Drude model of Ag is used with the plasma frequency and collision frequency set to \(1.6 \times 10^{16} \text{s}^{-1}\) and \(0.68 \times 10^{14} \text{s}^{-1}\), respectively.

On a uniform nanorod with a = 240 nm, the SSP modes can be generated by linearly superposed higher-order HE1 and HE2 eigenmodes. The spiral pattern originates from the beating of the two component modes. Both the single- and triple-stranded SSP modes are produced by controlling the relative rotation direction of the two component modes (Fig. 2). On a tapered nanorod, the spiral pitch of the SSP mode decreases with the reduction of nanorod radius (Fig. 3). However, the field energy density along the nanorod axis increases to a maximum value and then falls.

Fig. 1 Simulated structures: (a) uniform and (b) tapered Ag nanorods.

Fig. 2 Simulated time-averaged contours of E-field energy density in three-dimensional space and in x-y plane at z = 5400 nm for incident (a) counterclockwise HE\(_1\) and counterclockwise HE\(_2\) and (b) clockwise HE\(_1\) and counterclockwise HE\(_2\). (a = 240 nm and \(\lambda_0 = 633\ nm\))

Fig. 3 (a) Calculated spiral pitch vs. incident frequency for a uniform Ag nanorod with different radii. (b) Simulated time-averaged contour of E-field energy density and predicted spiral pattern (blue line) in three-dimensional space for a tapered Ag nanorod. (c) \(\theta\)-integrated E-field energy density in (b) as a function of z. In (b) and (c), \(\lambda_0 = 633\ nm\).