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Experimental demonstration of high-order magnetic localized spoof surface plasmons

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We experimentally demonstrate that an ultrathin metallic spiral structure is able to support multiple high-order magnetic localized spoof surface plasmons (LSSPs), which were absent in previously reported magnetic LSSPs. Near-field response spectra and near-field mapping are performed in the microwave regime to confirm this phenomenon. We also show that the high-order magnetic LSSPs are more sensitive to the surrounding refractive index change than the previously reported magnetic dipole mode. Our study may be useful in electromagnetic near-field sensing from microwave to infrared frequencies. © 2015 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4927658>]

Geometrically induced, or spoof, surface plasmons have been developed to control the surface electromagnetic modes at a subwavelength scale from microwave to far-infrared frequencies with great flexibility.^{1–20} Recently, a subwavelength textured metallic spiral structure²¹ that supported spoof surface plasmons was proposed with properties resembling those of subwavelength nanoparticles studied at optical frequencies, particularly including a magnetic localized surface mode. This previously reported magnetic localized surface mode²¹ was the fundamental magnetic dipole mode, while high-order magnetic modes, which should exhibit better sensitivity to the environmental refractive index change,¹⁹ have not been observed. While electric high-order plasmon-like modes have been widely observed in various photonic systems, high-order modes of magnetic localized spoof surface plasmons (LSSPs) still lack a clear picture and thus deserve a detailed study.

In this letter, we experimentally demonstrate high-order magnetic LSSPs by directly mapping their field patterns on an ultrathin metallic spiral structure.²¹ Compared with the fundamental magnetic dipole mode,²¹ we show that these high-order magnetic LSSPs possess better sensitivity to environmental refractive index changes.

The photograph of the fabricated ultrathin metallic spiral structure is shown in Fig. 1(a), which consists of four metallic spiral arms wrapped 1.5 turns with inner radius $r = 0.5$ mm and outer radius $R = 12.5$ mm. Each spiral arm has a width $w = 0.5$ mm and the spacing of neighboring arms at the outer radius is $d = 1.5$ mm. The thickness of each spiral arm is 0.018 mm. The whole spiral structure was manufactured through a standard printed circuit board fabrication process on a 0.2 mm-thick dielectric substrate (FR4), whose relative permittivity is $\epsilon = 3.5$ and loss tangent $\delta = 0.01$.

To evaluate the electric and magnetic LSSPs of this plasmonic “meta-atom,” we first simulate its near-field

response by locating a monopole antenna as the source and another monopole antenna as the probe at proper positions, as indicated by a pair of red dots in Fig. 1(a). The metal is modeled as perfect electric conductor (PEC) in the simulation. The simulated near-field response spectrum is shown in Fig. 1(b). Apart from previously reported two LSSPs²¹ (E_1 , M_1), high-order electric (E_2 , E_3) and magnetic (M_2 , M_3) LSSPs are also observed. The indices 1, 2, and 3 indicate the fundamental mode, second-order mode, and third-order mode, respectively (the labelling of modes will be explained later). We plot the simulated E_z , H_z fields in the transverse xy plane 1 mm above the metallic spiral structure as well as surface current distributions on the metallic structure at the six resonance frequencies in Figs. 2(a)–2(c), corresponding to the electric dipole mode (E_1), magnetic dipole mode (M_1), second-order electric mode (E_2), second-order magnetic mode (M_2), third-order electric mode (E_3), and third-order magnetic mode (M_3) at frequencies 1.089, 1.796, 3.296, 4.112, 5.572, and 6.245 GHz, respectively. The electric fields of the electric dipole mode and the magnetic dipole mode match well with the previously reported electric and magnetic LSSPs.²¹

Huidobro *et al.*²¹ identified the magnetic (electric) mode through observing field patterns directly. Here, we adopt an alternative way to label the modes based on the surface current distribution. We plot the surface current distributions of the six resonant modes in Fig. 2(c), where the color and arrow heads of the cones indicate the modulus and the direction of surface currents, respectively. The current points in different directions at different locations of the spiral-shaped metallic structure. Supplementary videos E1 to M3 illustrate the dynamic current changes for these six modes. It is evident that the surface current distributions of the electric dipole mode (E_1) and the magnetic dipole mode (M_1) are different. For the electric dipole mode [E_1 in Fig. 2(c)], we observe that two major electric currents propagate along two curved routes on the metallic spiral structure with opposite directions (clockwise and anti-clockwise), resembling an

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FIG. 1. (a) The photograph of the fabricated ultrathin metallic spiral structure (thickness of 0.018 mm) printed on a dielectric substrate (FR4) with thickness of 0.2 mm. The inner radius $r = 0.5$ mm and outer radius $R = 12.5$ mm. The width of the spiral arms is $w = 0.5$ mm. The spacing between neighboring arms at the outer radius is $d = 1.5$ mm. (b) The simulated near-field response spectrum of the ultrathin metallic spiral structure. The distinct six resonance peaks are indicated as E_1 - M_3 , respectively.

electric dipole along a curved line whose center reaches maximum current modulus. On the other hand, for the magnetic dipole mode [M_1 in Fig. 2(c)], we can see that major surface currents propagate along the arms of the metallic spiral structure with the same direction (clockwise) to form a major closed current loop, which is analogous to the molecular current that generates the molecular magnetic momentum of Ampere's hypothesis. A general criteria can be made as follows: given an arbitrary circle centered at the center of the spiral structure, if all currents on this circle flow in the same direction (clockwise or anti-clockwise) and form a current loop, we label this mode as "M" for magnetic mode. If

currents on this circle cancel each other and cannot form a current loop, we label this mode as "E" for electric mode.

Before discussing the high-order modes, one should note that there are two different kinds of localized resonant modes which can be termed as "high order" (we emphasize here that all previously observed high order modes are electric, not magnetic). The first kind is those corresponding to the azimuthal dependence of the resonant electromagnetic fields, which are named as dipole mode, quadrupole mode, octopole mode, etc. This kind of high-order electric modes have already been predicted theoretically¹⁶ and verified experimentally¹⁹ in the context of spoof plasmon modes.

FIG. 2. (a) The simulated near-field patterns of vertical electric field (E_z) on a transverse (xy) plane 1 mm above the upper metallic spiral surface for the fundamental electric dipole mode (E_1) at 1.089 GHz, the fundamental magnetic dipole mode (M_1) at 1.796 GHz, the second-order electric mode (E_2) at 3.296 GHz, the second-order magnetic mode (M_2) at 4.112 GHz, the third-order electric mode (E_3) at 5.572 GHz, and the third-order magnetic mode (M_3) at 6.245 GHz, respectively. (b) The simulated near-field patterns of vertical magnetic field (H_z) on a transverse (xy) plane 1 mm above the upper metallic spiral surface for all modes as in (a). (c) The simulated surface current distribution on the metallic spiral surface for all modes as in (a). Supplementary movies E_1 , E_2 , E_3 , M_1 , M_2 , and M_3 show dynamical videos of surface currents changes for these six different resonant modes, respectively. (Multimedia view) [URL: <http://dx.doi.org/10.1063/1.4927658.1>][URL: <http://dx.doi.org/10.1063/1.4927658.2>][URL: <http://dx.doi.org/10.1063/1.4927658.3>][URL: <http://dx.doi.org/10.1063/1.4927658.4>][URL: <http://dx.doi.org/10.1063/1.4927658.5>][URL: <http://dx.doi.org/10.1063/1.4927658.6>]

FIG. 3. (a) The measured near-field response spectrum of the ultrathin metallic spiral structure. The distinct six resonance peaks are indicated as E_1 - M_3 , respectively. (b) The measured near-field patterns of vertical electric field (E_z) on a transverse (xy) plane 1 mm above the upper metallic spiral surface for the fundamental electric dipole mode (E_1) at 1.128 GHz, fundamental magnetic dipole mode (M_1) at 1.864 GHz, the second-order electric mode (E_2) at 3.304 GHz, the second-order magnetic mode (M_2) at 4.176 GHz, the third-order electric mode (E_3) at 5.568 GHz, the third-order magnetic mode (M_3) at 6.296 GHz, respectively.

The other kind of high-order electric modes correspond to the radial dependence of the resonant electromagnetic fields. This radial high-order electric modes have also been reported experimentally recently.²² In Figs. 2(a) and 2(b), we observe that for the high-order modes of electric LSSPs (E_2 , E_3), the E_z and H_z fields vary along azimuthal direction, which seem to be “azimuthal high order” resonances, while for the high-order modes of magnetic LSSPs (M_2 , M_3), the E_z and H_z fields are largely uniform in the azimuthal direction but vary along radial direction, which look like “radial high order” resonances. However, from the surface current distributions shown in Fig. 2(c), the high-order modes of electric LSSPs (E_2 , E_3) and magnetic LSSPs (M_2 , M_3) show both “radial” and “azimuthal” resonant properties. It is thus difficult to identify these LSSPs as purely radial or azimuthal. In fact, they are both radial and azimuthal because of the nature of spiral structure.

We thus label the order number of these high-order modes based on the current distribution. Following one arm of the spiral structure, if the variation of the surface current experiences two (three) maxima, then we label the corresponding mode as the second (third) order mode. This labeling scheme also applies to the dipole modes (E_1 and M_1) where the surface current variation experiences only one maximum. We thus use this scheme to label all electric modes (E_1 , E_2 , and E_3) and all magnetic modes (M_1 , M_2 , and M_3).

To experimentally verify the multiple high-order magnetic LSSPs modes, we first measure the near-field response spectra. A transmitting monopole antenna at the position of one of the red dots in Fig. 1 is used to excite the resonant modes; another receiving monopole antenna placed at the other red dot is used to measure the near-field response spectra. Both monopole antennas are connected to a vector network analyzer (Rohde & Schwarz ZVL-13) and placed perpendicular to the experimental sample. The probe monopole antenna detects the local E_z field on the metallic spiral structure. The measured near-field response spectrum for the metallic spiral structure is plotted in Fig. 3(a). Six distinct resonance peaks (E_1 - M_3) are clearly observed at frequencies 1.128, 1.864, 3.304, 4.176, 5.568, and 6.296 GHz, respectively, matching well with the simulation results in Fig. 1(b). We then scan the probe to map the E_z -field distributions corresponding to the six different resonant peaks

on the metallic spiral structure, as shown in Fig. 3(b). The agreement between the numerical results (Fig. 2(a)) and the experimental results (Fig. 3(b)) is evident.

The tight confinement and sharp resonances of localized spoof surface plasmons make them sensitive to the small change in their dielectric environment. This feature can be used as a plasmonic sensor at low frequencies from microwave to infrared.¹⁹ We then demonstrate refractive index sensing of various dielectric materials using these magnetic LSSPs. In experiment, we place different dielectric materials on top of the metallic spiral structure and measure the near-field response spectra. Spectra with the spiral structure covered by air (red line), paper (cyan line), and Teflon (blue line) are shown in Fig. 4.

Three conclusions can be drawn as follows. First, a dielectric environment change can significantly affect the near-field response spectra: all resonance peaks are red shifted with increasing refractive index of the dielectric environment.

Second, for the same order modes, the resonance shift of the magnetic mode is larger than that of the electric mode with the same environmental refractive index change due to the difference of their field distributions. Specially, when the

FIG. 4. The measured near-field response spectra of the metallic spiral structure covered by air (red line), paper (cyan), and Teflon (blue line), respectively. Much larger redshifts are observed for the high-order LSSPs than the fundamental dipole modes.

environment material changes from air to a Teflon plate ($\epsilon = 2.2 + i0.001$, thickness 3 mm), the resonance frequency of the second-order magnetic LSSPs (M_2) red shifts from 4.155 GHz to 3.862 GHz, while for the second-order electric LSSPs (E_2) the resonance frequency shifts from 3.273 GHz to 3.126 GHz. The former obtains a 0.293 GHz shift, while the later only obtains a 0.147 GHz shift.

Third, the high-order electric and magnetic LSSPs modes have larger red shift than the fundamental electric and magnetic dipole modes (E_1 and M_1), even though the fundamental electric and magnetic dipole modes possess sharper resonant peaks and higher quality factors. An important comparative parameter of sensing devices is the figure of merit, $FOM = (\Delta f / \Delta n) / (\Delta \omega)$ (where $\Delta \omega$ is the full-width of the resonant peak at half-maximum and Δf is the resonance shift for Δn refractive-index change), which takes into account the sharpness of the resonance and thus examines the ability to sensitively measure tiny frequency changes. The FOM researches 3.0572 for the fundamental electric dipole mode (E_1) and 6.6568 for the fundamental magnetic dipole mode (M_1), while for the second-order electric mode (E_2) and second-order magnetic mode (M_2), this value researches 2.716 and 9.186, respectively. Since the third-order electric mode (E_3) and third-order magnetic mode (M_3) overlap significantly, it is difficult to extract their full-width at half-maximum.

In conclusion, we have numerically and experimentally demonstrated the multiple high-order magnetic LSSPs modes supported by a metallic spiral structure at microwave frequencies. Both near-field response spectra and scanning near-field distributions show excellent agreement between simulation results and experimental measurements. We also show that the high-order magnetic LSSPs exhibit higher sensitivity to the environmental refractive index change than the fundamental magnetic dipole modes. Our work may be useful for future near-field sensing of the refractive index of the surrounding materials.

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