Plasmonic Super-oscillations and Sub-Diffraction Focusing

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Abstract: We demonstrate experimental focusing of surface plasmon polaritons beyond the plasmon diffraction limit using a super-oscillatory plasmonic antenna at the wavelength of 785nm, achieving a hot-spot as small as 300nm.

OCIS codes: (100.6640) Superresolution; (240.6680) Surface plasmons

We report the first experimental demonstration of focusing surface plasmon polaritons beyond the conventional diffraction limit using a super-oscillatory plasmonic antenna stimulated with free-space coherent light wave at the wavelength of 785nm, achieving a hot-spot as small as 300nm. The new technology simultaneously exploits the high value of plasmon wave-vectors and the effect of super-oscillations that, in principle, allows focusing of waves to an arbitrarily small hot-spot. The reported results experimentally prove universality of the super-oscillatory approach and its applicability to plasmons, in addition to previously reported super-oscillatory effects in free space light and quantum wave functions.

Surface plasmon polaritons (SPP) are collective oscillations of light and electrons that propagate along the interface between a metal (e.g., gold, silver) and a dielectric, featuring tight localization and remarkable electric field enhancement properties and thus having widespread applications in tight focusing, super-resolution imaging, fluorescence enhancement and surface enhanced Raman scattering. As with optical lenses that focus free-space light, effective focusing of SPP is of high importance to concentrate incoming energy on a metal surface. Various methods for focusing SPP have been extensively reported. As plasmon wavelengths are somewhat shorter than those of light at the same frequency, plasmonic focusing devices promise smaller spots and better resolution than optical devices. However, the conventional diffraction limit sets constraints on the achievable plasmonic focal spot size, typically larger than $\lambda_{spp}/(2NA)$ where λ_{spp} is the effective SPP wavelength determined by the cutoff spatial frequency $Re(k_{spp}) = 2\pi/\lambda_{spp}$ and NA is the numerical aperture.

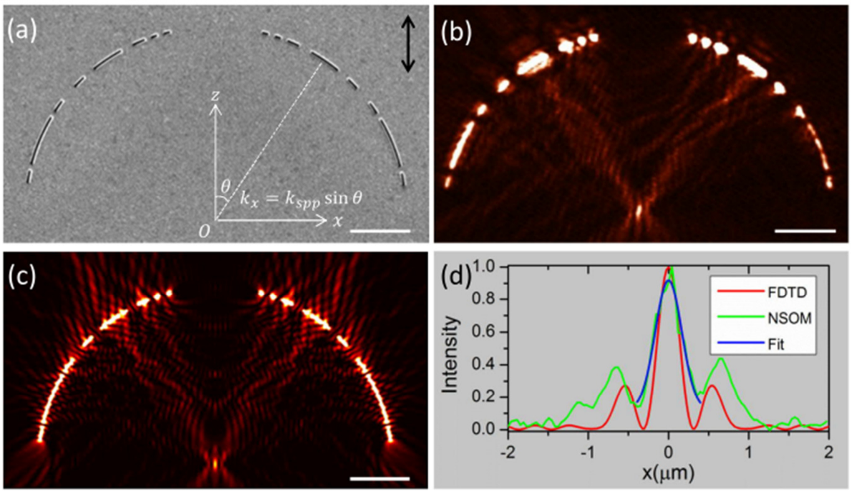

Fig. 1: (a) SEM micrograph of curved PSOL fabricated by FIB on 200nm-thickness Au film. The radius of the arc-slits is 15μm and slit width is 200 nm. (b) Electric intensity distributions registered by near-field scanning optical microscopy (NSOM). (c) Simulation results by FDTD. (d) Comparison of spot between FDTD and NSOM in focal plane. The wavelength is 785nm and the white scale bar is 5μm.

Super-oscillations have shown the capability to break the diffraction limit. The idea of super-oscillation is that a super-resolution hotspot with high-spatial-frequency components (local wavevector $|k_{local}| > |k_{max}| = 2\pi/\lambda_{eff}$) can be locally formed by the interference of electromagnetic waves with band-limited wavevectors ($|k| \leq |k_{max}|$), where λ_{eff} is the effective wavelength in the surrounding medium. This phenomenon has been investigated in the quantum wave region [1] and for free-space super-resolution focusing and imaging [2,3]. Plasmonic super-oscillatory fields could also be achieved by an appropriately designed diffraction mask, as theoretically pointed out previously [4]. In this work, we provide the first experimental demonstration of plasmonic super-oscillatory lens (PSOL) capable of focusing SPPs into sub-diffraction-limited hotspots. Plasmonic super-oscillatory focusing is intrinsically different from the hotspots generated by metallic nanoparticles and defects where the former relies on the direct interference of band-limited wavevectors of propagating SPP while the latter is caused by the excitation of localized surface plasmons which involve infinite wavevectors.

The SEM image of fabricated curved PSOL is shown in Fig. 1(a), consisting of predefined arc-slits perforated into gold film (thickness~200nm, $\varepsilon_m = -24.6 + 1.755i$@λ=785nm). The diffracted SPPs emanating from the slits will interfere with each other at the geometrical center. By carefully choosing the angular position of these discrete slits and corresponding wavevectors, sub-diffraction-limited plasmonic hotspots can be generated. The electric intensity distribution recorded by NSOM is given in Fig. 1(b), displaying a bright mainlobe with two weaker sidelobes. The simulation results obtained from FDTD is given in Fig. 1(c) for comparison. From detailed analysis, the FWHMs of the mainlobe in the NSOM measurement and calculation are evaluated to be 300nm ($0.39\lambda_{spp}$) and 350nm ($0.45\lambda_{spp}$) respectively, both breaking the diffraction limit ~$0.5\lambda_{spp}$. In contrast, the continuous slits with the same overall angle range of 92 degree give hotspots much larger than the diffraction limit ($0.73\lambda_{spp}$).

In a similar manner, a straight PSOL has been designed and tested, with the advantage of increased mainlobe-to-sidelobe separation (field of view). The fabricated single-period structure, NSOM and FDTD calculation results are shown in Fig. 2(a)(c)(e) respectively, where the spot sizes are 340nm and 390nm for NSOM and FDTD respectively, inferred from Fig. 2(g). Both the spot sizes are smaller than the diffraction limit ~430nm. In order to increase the focusing efficiency, multiple-period PSOLs can be utilized. However, it is noted that super-oscillatory spots cannot be achieved by simply duplicating the single-period PSOL as was previously done for common plasmonic lenses because PSOLs in different positions will provide different *k*-components. Therefore, we optimize the PSOL by taking the whole structure into consideration and acquire the design in Fig. 2(b). Its focusing performance is tested by NSOM (Fig. 2(d)) and FDTD (Fig. 2(f)), and the spot size calculated from Fig. 2(h) is identical to that of the single-period, but the efficiency is greatly improved by 3 times.

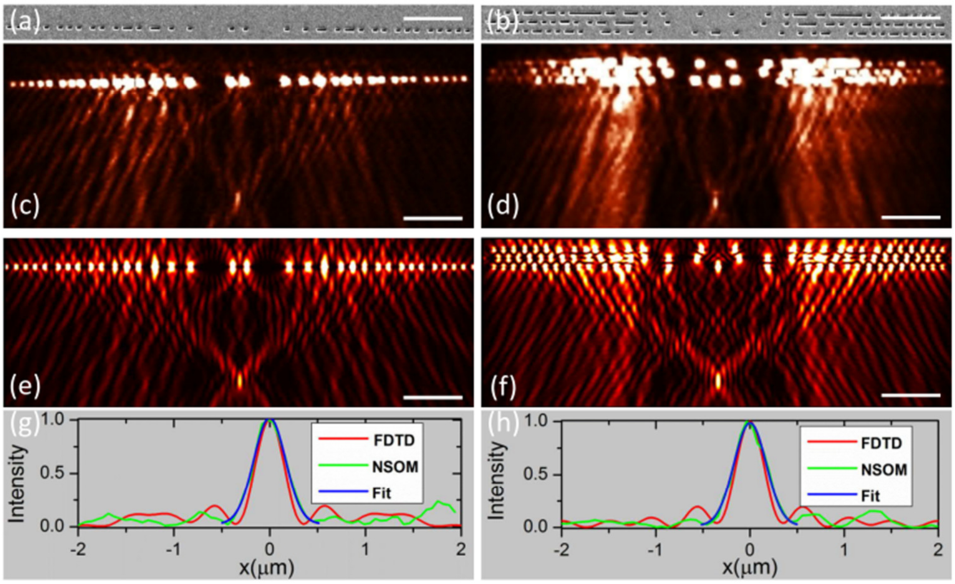

Fig. 2 SEM micrographs of single-period (a) and triple-period (b) PSOL. (c)(d) NSOM captured electric field intensity distributions. (e)(f) FDTD calculation results. (g)(h)The line-scans of electric field intensity in the focal plane, where the spot size is estimated from Gaussian fit.

References

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