Nanofocusing via Efficient Excitation Surface Plasmon Polaritons in a Hollow Aluminum Wedge

Yongzhu Chen, Xiangsheng Xie, Li Li, and Jianying Zhou

***Abstract*— Efficient nanofocusing down to a few nanometers in a hollow aluminum wedge is numerically investigated. The waveguide propagation modes are efficiently converted to internal surface plasmon polaritons via a pair of grooves fabricated at the inner surface of the wedge and a remarkable field enhancement is realized at the aperture. The excitation efficiency can be further improved by optimizing spatial wavefront modulation of the incident light field via a binary optical element, and the output intensity through a 5-nm aperture is enhanced by 786 times compared with a conventional 100-nm aperture hollow metallic wedge.**

***Index Terms*— Aluminum waveguide, nanofocusing, nanostructrues, surface plasmon polaritons (SPPs).**

I. Introduction

NANOFOCUSING of optical radiation [1], [2], characterized as nano-scale confinement beyond the diffraction limit, offers unique opportunities for nano-scale miniaturization and integration of photonic devices and circuits [3], [4], high resolution near-field scanning optical microscopy (NSOM) [5], surface enhanced Raman scattering spectroscopy [6], non-linear plasmonics [7], etc. Nanofocusing can be realized by forming surface plasmon polaritons (SPPs) via coupling light to a metallic-dielectric surface. Different metallic guiding nanostructures such as tapered metal rods, metal wedges, tapered gaps, metal pyramids, dielectric conical tip, etc., were widely used to realize plasmon nanofocusing [8]–[13].

Most plasmon nanofocusing methods are based on the SPPs propagating on the outer surface of the tapered waveguides, which are generally exited by photon tunneling in the total internal reflection geometry (the Kretschmann configuration) or light diffraction effect on a grating created on the outer surface of the waveguides [14]. In the Kretschmann configuration, a considerable portion of the input energy absorbed by the metallic wall and the incident angle of optical field for SPPs excitation is difficult to be met accurately. In the diffraction grating configuration, the grating must be created on the outer surface far away from the tip to remove the disturbance from the background light, so the energy loss is quite large during the propagation of SPPs. Moreover, using the external excitation methods, the nanofocusing field is not only confined by the size of the apex, but also influenced by the contaminant on the surface and the adjacent sample.

A more common method to realize nanofocusing is confining the light with an aperture tapered aluminum waveguide. This kind of waveguide has certain advantages, such as reduction of far-field background, the potential to characterize a plasmonic device and extensive use in aperture NSOM. But the mechanism of this nanofocusing is based on light evanescent decay through the tiny aperture and it suffers from comparatively low resolution and throughput governed by the size of the aperture. The transmission of aperture NSOM is generally in the order of 10^{-7}–10^{-5} with typical optical fiber probes ($\sim$100 nm aperture) produced by heating and pulling method or chemical etching method. The transmission of a 5 nm aperture will be reduced to about 10^{-14}, which is useless in practice [15]. SPP modes propagating on the internal surface of the tapered metal-coated waveguide were regarded as a solution to the low throughput of aperture NSOM. Nonetheless, noble metals are known as the best plasmonic materials while aluminum is seldom adopted because of its small energy propagation length for the SPPs, i.e., only 2 um at a wavelength of 500 nm [15].

Choi et al. [12] demonstrated a nanofocusing via excitation gap SPPs in gold V-grooves. Antosiewiez and Szoplik [13] reported throughput enhancement via excitation SPPs in corrugated silver–coated tapered tips. In their schemes, the taper angles were designed to be small for exciting SPPs. However, SPPs excited were too close to the apex of the waveguide where most waveguide modes have been cut off for small taper angles and only small amounts of energy can transform from optical field to SPPs, so the field enhancement is restrained. In this letter, we propose a scheme for plasmon nanofocusing via excitation SPPs on the internal wall of a two-dimensional (2D) hollow tapered aluminum waveguide, i.e., hollow aluminum wedge (HAW) by fluting a pair of grooves inside. The efficient conversion of the internal radiations to SPPs and their nanofocusing are obtained numerically. A spatial phase modulation method is introduced to further improve the excitation efficiency and a 786 times enhancement of the peak optical intensity at the apex of a fluted 5 nm-aperture HAW

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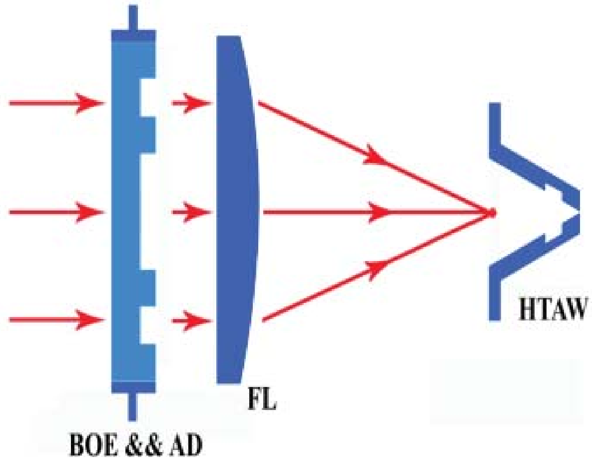

Fig. 1. Schematic diagram of the wavefront modulation in a fluted HAW.

is obtained, compared with that in the smooth 100 nm-aperture HAW.

II. Theoretical Basis and Modeling Structure

SPPs at a dielectric-metal interface should fulfill the SPPs dispersion relation, that is, the frequency-dependent SPPs wave-vector k_{sp}. The prerequisite to excite SPPs is that the component of the light wavevector must be equal to k_{sp}. An elegant plasmon probe was demonstrated by Fischer and Pohl [16] utilizing the large wavevector component of the evanescent field to generate SPPs. Hence, SPPs at aluminum-air interface can also be excited by the evanescent field components generated at the grooves fluted inside a HAW and propagate to the apex without experiencing mode cut off.

The schematic diagram is shown in Fig. 1. The HAW is tapered down from 4 μm at the entrance to 5 nm at the apex with a 60 degree full taper angle, coating with 200 nm aluminum. A linearly polarized Gaussian beam at 530 nm passes through a binary optical element (BOE) and is coupled into the HAW via a focusing lens (FL) with a numerical aperture NA = 0.76, which is described by the Fourier transformation method. The size of the BOE is limited to 9 mm by an aperture diaphragm (AD) and divided into 9 uniform units. Each unit provides a phase shift from 0 to a non-zero value between 0 and 2π, which is denoted as V. The binary pattern of the BOE is assumed to be symmetrical with respect to the central (5th) unit. The focal spot is assumed to be exactly located at the entrance of the HAW.

III. Simulations and Discussion

The optical evolutions in the HAWs are simulated by the FDTD method based on MATLAB language and p polarization input is adopted for excitation SPPs. In the FDTD calculations, the grid scales are given as $\Delta x = \Delta z = 1$ nm and an anisotropic perfectly matched layer absorbing boundary condition is adopted for the truncation of FDTD lattices. In addition, the dielectric constant of aluminum is chosen as $\varepsilon = -38.2 + 11.0i$ for 530 nm wavelength according to the

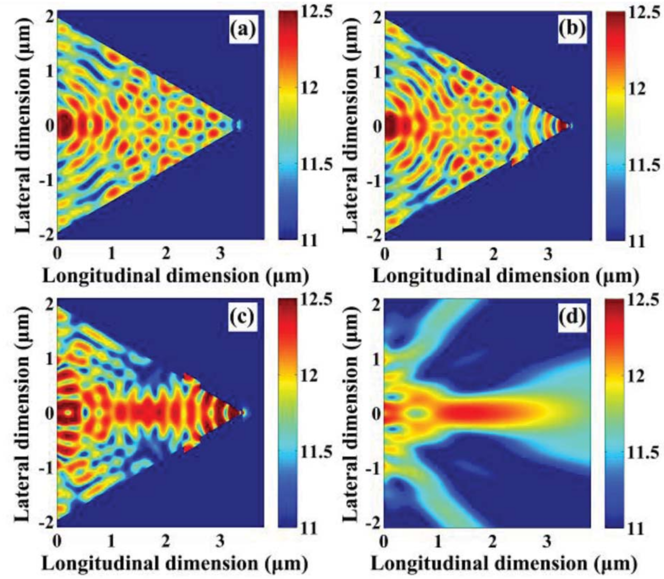

Fig. 2. Optical intensity distributions. (a) In the smooth 100-nm aperture HAW without wavefront modulation. (b) In the fluted 5-nm aperture HAW without wavefront modulation. (c) In the fluted 5-nm aperture HAW with the wavefront modulation. (d) In the absence of HAW with the wavefront modulation.

Lorentz-Drude model presented by Racik et al. [17]. The time-averaged intensity distributions in the HAWs are shown in Fig. 2.

Firstly, a common smooth 100 nm-aperture HAW is considered. In the smooth 100 nm-aperture HAW (Fig. 2(a)), different waveguide modes are excited and only small amounts of energy is delivered as the fundamental propagation mode (TM_0) to the tip region. For the non-adiabatic condition, deficient energy transferring from TM_1 to the lowest mode (TM_0) results in a tiny throughput at the apex [18]. When the aperture diameter reduces to 5 nm, the throughput will decrease sharply.

In a fluted 5 nm-aperture HAW, the situation is completely different. Strong standing wave modes on both sides of the metal wall between the grooves and the apex show that SPP waves are efficiently excited. Actually, the excitation efficiency of SPP waves depends on the proportion of the component of the wavevector matching the SPPs dispersion relation, which is sensitive to the groove width, depth and position. After running a series of FDTD simulations, the optimal enhancement without wavefront modulation in the fluted 5 nm-aperture HAW is obtained by setting the groove width, depth and position from the apex as 350 nm, 100 nm and 900 nm respectively, as shown in Fig. 2(b). Comparing with the normalized peak optical intensity at the apex of the smooth 100 nm-aperture HAW (Fig. 2(a)), the peak optical intensity at the apex is enhanced to 263 (shown as green curve in Fig. 3).

It is not practical to fabricate a highly accurate groove inside a HAW and any deviation will reduce the transmission substantially. An optical wavefront modulation method via BOEs is introduced to control the waveguide modes and optimize the proportion of the desirable wavevector for SPPs in the fluted HAW. There are 32 ($2^5 = 32$) coding combinations for a 9-bit BOE with centro-symmetrical (i.e., symmetrical with

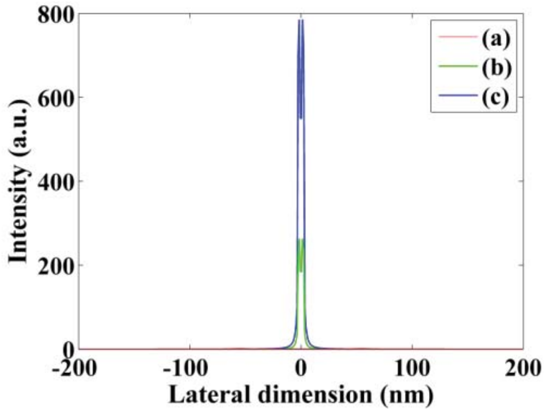

Fig. 3. Intensity distributions at the apex of the HAWs. (a) In the smooth 100-nm aperture HAW without wavefront modulation. (b) In the fluted 5-nm aperture HAW without wavefront modulation. (c) In the fluted 5-nm aperture HAW with the wavefront modulation.

respect to the 5th unit) binary pattern, but only 30 combination forms can be adopted because the forms {000000000} and {VVVVVVVVV} describe no wavefront modulation. After comparing the excitation effects for these 30 phase combinations with the discrete spacing of 0.1π, the optimal throughput is obtained in the form {0V0VVV0V0} with "V" set as 0.8π or in the form {V0V000V0V} with "V" set as 1.2π, as shown in Fig. 2(c). The optical intensity distribution in the absence of HAW with optimal wavefront modulation is also given as Fig. 2(d). In this case, the focused field mainly converts into a sub-wavelength size collimating beam, which means that most of the light energy transfers to the tip region of the fluted HAW as low propagating modes. Then the collimating beam begins to spatially disperse at the place near the grooves and the optimal collocation between the field wave vector and the groove structure results in the resonant excitation of SPPs.

It is shown in Fig. 3 that the peak optical intensity at the apex of the fluted 5 nm-aperture HAW can be enhanced to 786 after optimal wavefront modulation. Accordingly, its throughput is enhanced to 33 times as that of a smooth 100 nm-aperture HAW, which signifies a practical application for this fluted 5 nm-aperture HAW in aperture SNOM.

For a three-dimensional (3D) SNOM probe illuminated by a linearly polarized beam, the polarization state of the light field nearly remains unchanged in an ideal pyramid probe. The electric energy density in the aperture plane in the polarization direction is much larger than that with orthogonal direction [19], [20]. And SPPs can only be excited on the two metal walls orthogonal to the polarization direction. The propagation of electromagnetic field is more complicated [21] and it is difficult to search the optimal result since the calculations are very time-consuming. Even so, our preliminary calculations demonstrate that efficient excitation of SPPs and field enhancement can also be realized in a 3D model.

IV. Conclusion

We propose and demonstrate that the throughput at the apex of a HAW can be substantially enhanced by fluting a pair of grooves inside the aluminum walls. The results show that the remarkable enhancement is mainly from the efficient internal excitation of SPPs via the evanescent field components at the fluted grooves. The excitation efficiency of the SPPs can be greatly improved by modulating the wavefront of the incident light and a field enhancement of near 786 is obtained in a fluted 5 nm-aperture HAW. The optimized throughput which is 33 times of that in a commonly used smooth 100 nm-aperture HAW indicates a great application prospect for this fluted 5 nm-aperture HAW.

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