Theoretical study on the generation of a low-noise plasmonic hotspot by means of a trench-assisted circular nano-slit

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Abstract: We propose a novel trench-assisted circular metal nano-slit (CMNS) structure implementable on a fiber platform for the generation of a low-noise cylindrical surface plasmon (CSP) hotspot. We design trench structures based on a multi-pole cancellation method in order that a converging surface plasmon signal is well separated from co-propagating non-confined diffracted light (NCDL) at the hotspot location. In fact, the secondary radiation by the quasi-pole oscillation at the edge of the trench cancels the primary NCDL, thereby enhancing the signal-to-noise ratio (SNR) of the CSP hotspot. In particular, we investigate two types of trench structures: a rectangular-trench (RT) structure and an asymmetric-parabolic-trench (APT) structure, which are considered for the sake of the simplicity of fabrication and of the maximal enhancement of the SNR, respectively. In comparison with a conventional CMNS having no trenches, we highlight that the mean SNR of the CSP hotspot is enhanced by 6.97 and 11.89 dB in case of the optimized RT and APT CMNSs, respectively. The proposed schemes are expected to be useful for increasing the SNR of plasmonic devices that are interfered by NCDL, such as various types of nano-slits for generating high-resolution plasmonic signals, for example.

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References and links
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1. Introduction

Surface plasmons, which are collective oscillations of free electrons propagating along the interface of metal and dielectric, have extensively been studied because of their fascinating properties that cannot be obtained with conventional optical approaches [1–9]. In particular, surface plasmons can be focused onto a sub-wavelength hotspot, which can overcome the diffraction limit of light [10–22]. Plasmonic focusing is useful for a variety of novel applications, such as lithography [10], imaging [11], high harmonic generation [12], sensing [13], etc. To date, a number of structural configurations have been suggested for plasmonic focusing, exploiting the extraordinary characteristics of the focused surface plasmons, which include nanoparticles [14], circular nano-slits [15–19], bowtie structures [20], metal tips [21,22], etc. Among them circular metal nano-slit (CMNS) structures patterned on a thin metal film are of great interest because of their high capability of generating focused cylindrical surface plasmons (CSPs), i.e., plasmonic hotspots, via relatively simple fabrication methods [15–19]. In recent years, a variety of studies on CMNSs have been investigated in the direction of intensifying the hotspot, utilizing various structures [15–18] as well as differentiating the polarization state of incident light [18,19]. For example, Kim et al. proposed a novel scheme utilizing a modified circular slit with linearly polarized light, which could significantly improve the plasmonic hotspot intensity and control the focal position [16]. Steele et al. experimentally demonstrated an efficient way to focus surface plasmons via using a multi-ring structure [17]. Lerman et al. utilized radially polarized light as incident light to a CMNS, scaling up the energy density of the hotspot, which could eventually lead to much higher efficiency than when linearly polarized light was used [19]. In addition, Chen et al. combined the previous two techniques, thereby applying radially polarized light to a multi-ring structure for further enhancements [18].

While such a variety of structures and schemes were extensively investigated for intensifying the plasmonic hotspots, the impact of the disturbance of non-confined diffracted light (NCDL) that normally accompanies surface plasmons has little been discussed to an extensive level [23,24]. In fact, in most cases of CMNSs the disturbance of NCDL is hardly avoidable [25,26], which inevitably results in a severe increment of background noise against the surface plasmon signal [27–30], thereby degrading the signal-to-noise ratio (SNR) of the surface plasmons and enlarging its “effective” spot size. To the best of our knowledge, suppressing the background noise of a plasmonic hotspot has little been studied although merely in a limited one-dimensional slit regime, the reduction of unwanted NCDL has been investigated by some of the authors [31]. For this, trench-assisted slit structures were proposed by means of a multi-pole cancelation method [31,32]. In fact, a trench structure adjacent to the slit aperture forms a collective quasi-pole at the edge of the trench via surface plasmons. The detoured plasmonic path due to the existence of the trench gives rise to a phase deviation to the quasi-pole oscillation against the primary NCDL that is directly generated from the slit aperture. Thus, a large fraction of the primary NCDL can be cancelled out by the
secondary radiation from the quasi-pole oscillation if the phase of the secondary radiation is out of phase regarding that of the primary NCDL [31–34].

Here, we extend the multi-pole cancelation method to a full-vectorial model applicable to the design of CMNSs with enhanced noise-cancelling characteristics. Based on the method, we propose novel trench-assisted CMNS structures implementable on a fiber platform. In particular, the fiber platform format allows for much simplifed procedures to excite CSPs because a radially polarized optical mode can readily be excited or generated through an optical fiber [35]. Thus, this integrated scheme can offer a great merit of localizing and intensifying the resultant plasmonic hotspot in a compact and efficient form.

Hence, in the following we firstly present brief theoretical descriptions on the proposed multi-pole cancelation method applicable to CMNSs and discuss how the quasi-pole oscillations via trench structures suppress NCDL noises. Secondly, we design two types of trench structures utilizing the proposed method, a rectangular-trench (RT) structure and an asymmetric-parabolic-trench (APT) structure. While the former is considered for the sake of the simplicity of fabrication, the latter presents the further optimized cancelling performance of the quasi-pole oscillations. Then, we numerically analyze the optical and plasmonic characteristics of the proposed structures, and compare them with that of a conventional CMNS having no trench structure, with which we show that the proposed structures are capable of generating CSP hotspots with much enhanced SNRs. We also discuss the tolerance of the device fabrication, considering the currently available nano-scale processing technology. Finally, we conclude our discussion.

2. Numerical modelling of a circular metal nano-slit structure

In general, a CMNS can produce a single plasmonic hotspot at its center via the inward-propagating CSP excited from a concentric annular slit structure formed on the metal surface. Different from straight, one-dimensional nano-slits, the surface plasmon signal formed at the center of the CMNS can be much intensified because of the focusing effect. Furthermore, its efficiency can be maximized if radially polarized light is used as an excitation beam [18,19]. Here, one can think of using an optical fiber as a device platform for a CMNS because radially polarized optical mode (e.g., TM_{01} mode) can readily be excited or generated through its core [35]. This is of great interest from a viewpoint of practicality because the plasmonic function can be realized in an all-fiber format, which will allow for great flexibility and simplicity compared to other conventional bulk-type CMNSs.

Thus, we first consider a full-vectorial model on a CMNS patterned on an optical fiber end. The schematic of the proposed CMNS structure is shown in Fig. 1, including its cross-sectional view and the fiber-optical field intensity pattern across the diameter of the fiber. We assume that the fiber is a standard step-index fiber, which has a core diameter of 8 μm, and a numerical aperture of 0.1. We also assume that the metal is gold, the material parameters of which, i.e., the refractive index and extinction coefficient, are given by \( n = 0.16918 \) and \( k = 3.8816 \), respectively [36]. The input wavelength of light is set to \( \lambda = 700 \) nm. The width of the slit opening and the thickness of the metal coating are set to 87.5 nm and 500 nm, respectively, which are typical values for metal nano-slits [5–7,16]. The annular slit is assumed to be concentric with the fiber core. In particular, to maximize the light incidence on the CMNS, the inner and outer radii of the annular slit are scaled for their center line to match with the peak intensity location of the TM_{01} mode of the fiber, as depicted in Fig. 1. In addition, it is worth noting that this metallic structure can readily be fabricated via the conventional e-beam [37,38] or focused ion beam (FIB) technology [39].
First of all, a simple conventional CMNS structure having no trench structure is analyzed by utilizing the numerical model based on a full-vectorial finite element method (FEM: COMSOL Multiphysics®). It is worth noting that the separation of the CSP and NCDL fields from the total field is obtained by utilizing the overlap integral method based on the orthogonality principle of the mode field [40]. The CSP (depicted in graded red/yellow) and NCDL (depicted in graded blue) field intensity patterns are shown in Fig. 1. One can see that while a plasmonic hotspot is formed at the center of the metal surface, the NCDL propagating through free space is also focused at the same location because all the inward-going NCDL components are inherently in phase because of the circular symmetry of the CMNS. In particular, the horizontally propagating NCDL components are hardly distinguishable with the CSP hotspot signal, so that the SNR (defined as the ratio of the CSP intensity to the NCDL intensity) of the device is inevitably degraded [23,32]. In particular, as shown graphically in Fig. 1, the CSP components are significantly overlapped with the NCDL components at the center of the metal surface. Here, we define the peak and mean SNRs within the main lobe of the CSP hotspot because those parameters can primarily represent the performance of the device. The main lobe of the plasmonic hotspot is defined as the region where $\Delta z \leq 540$ nm and $\Delta r \leq 260$ nm, based on the attenuation length of the surface plasmon in the $z$ direction and the distance between two first zeroes in the $r$ direction, respectively. In the given condition, the calculated peak and mean SNRs are given by 22.74 and 14.70 dB, respectively, which are by no means ideal for many applications that invariably demand high SNRs [27–30], implying that there is room for significant enhancements.

3. Design principle of trench-assisted circular metal nano-slit structure

With the conventional CMNS as discussed in the previous section, a CSP hotspot is inherently overlapped with NCDL components to a significant level. In particular, NCDL components propagating horizontally just above the metal surface severely result in degrading the SNR of the plasmonic hotspot. Therefore, to improve the SNR, the impact of the primary NCDL, which is generated virtually from the slit center, should be suppressed. To achieve that, trenches are introduced nearby the slit as follows. The proposed trench-assisted structure and its operation principle are illustrated in Fig. 2. The main strategy of introducing the trenches is to eliminate the significant portion of the primary NCDL (blue line) originated from the slit center using the secondary NCDL (red line) excited from the edge of the trench lying alongside the slit, which eventually leads to destructive interference with the primary NCDL [21,24], as depicted in Fig. 2(b). It should be noted that the trench can be devised to have a sharp edge where charges are strongly induced due to its geometrical merit [14], so that it can be a “quasi-pole source” for generating the secondary NCDL [41,42].
Fig. 2. (a) The schematic of proposed CMNS structure. (b) Cross-section of the trench-assisted CMNS in the radial direction and its operation principle.

In order to induce destructive interference between the primary and secondary NCDL components, it is not too difficult to understand that the phase retardation between the primary NCDL along path $l_1$ and the CSP along path $l_2$ for the travel from $P_0$ to $P_2$ should be an odd integral multiple of $\pi$ because the phase of the secondary NCDL is mainly determined by that of the CSP traveling from $P_0$ to $P_2$ along path $l_2$. The principle can be formulated by the following equation:

$$k_{\text{csp}} l_2 - k l_1 = (2n-1)\pi,$$

where $k$ and $k_{\text{csp}}$ denote the wavenumbers of the NCDL and the CSP, respectively, and $n$ is an integer number. In fact, the geometry, including the positions of $P_1$, $P_2$, and $P_3$ of the trench, determines the phase retardation between the CSP and the primary NCDL, which has yet to be determined through appropriate optimization (which will be discussed in the next section). It is worth noting that the NCDL radiation from $P_1$ via the CSP is nearly in phase with the primary NCDL radiation from $P_0$ because, in general, the distance between $P_0$ and $P_1$ is substantially short, even with considering the material dispersion of the metal. Thus, it is too hard to expect a destructive interference effect from it. Subsequently, we instead need to minimize the accumulation of charges at $P_1$, simply letting the most CSP pass to $P_2$, thereby maximizing the NCDL cancellation by means of the charges accumulated at $P_2$. Thus, the cavity structure formed between the two inner edges of the trenches ($P_1$ and $P_1'$) should satisfy the resonance condition in order that the CSP transmission through the cavity is maximized. The resonance condition is fulfilled when the cavity satisfies the following relation [43]:

$$\text{Re}(k_{\text{csp}})d + \varphi_{\text{trench}} = 2n\pi,$$

where $\text{Re}$ denotes the real part of the argument, $d$ the distance between $P_1$ and $P_1'$, $\varphi_{\text{trench}}$ the phase shift caused by the reflection at the trench wall, and $n$ an integer number.

4. Numerical analysis of the trench-assisted circular metal nano-slit structure

In particular, we propose to use two different types of trench structures: One is an RT structure and the other is an APT structure as mentioned in Sect. 1. While the former is the simplest form to realize the NCDL cancellation via the multi-pole cancelation method, we have found that the asymmetric apodization of an RT structure into an APT structure can eventually improve the overall SNR performance because too abrupt a transition of the geometry at $P_1$ can induce an unnecessarily large amount of charge accumulation there [8].
We now discuss the general procedure to determine the key parameters for the trench structure, i.e., \( P_1, P_2, \) and \( P_3 \) shown in Fig. 2(b), following the multi-pole cancelation method discussed in the previous section. First, the width of the trench is set to 1050 nm, considering the material loss as well as the fabrication resolution. Then, the geometry of the trench is determined such that the CSP and the primary NCDL at \( P_2 \) are fully out of phase, i.e., they satisfy the condition given in Eq. (1). In order to minimize the device dimension, the phase retardation between the CSP and the primary NCDL at \( P_2 \) is given by \( \pi \). For an RT-CMNS, once the width of the trench \( (P_2 - P_1) \) is fixed, the depth of \( P_3 \) is the only parameter to be determined because of its symmetry. In contrast, for an APT-CMNS both the horizontal and vertical positions of \( P_3 \) (where the two asymmetric parabolas are joined) should be determined at the same time while the other general procedures are similar to those for an RT-CMNS. Finally, the detailed geometry of the trench, including the absolute position of \( P_1 \), is fine-tuned in order that it eventually offers the highest SNR via Eq. (2).

The evolution of the mean SNR at the center of the CMNS is shown in Figs. 3(a) and 3(b) for the RT-CMNS and APT-CMNS regimes, respectively. It is worth noting that for the APT-CMNS, both the positions \( P_1 \) and \( P_3 \) are considered for optimization while for the RT-CMNS the position \( P_1 \) is only considered for optimization because of the symmetry. One can see that all the parameters can be fine-tuned through iterations to maximize the SNR at the hotspot location. The parameters of the optimized trenches are summarized in Table 1. Hereinafter, we will use the optimized trenches in analyzing their detailed characteristics.

![Graphs showing mean SNR for RT-CMNS and APT-CMNS](image)

**Table 1. Design Parameters of Optimized Trench Structures**

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<tr>
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<th>RT-CMNS</th>
<th>APT-CMNS</th>
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<tbody>
<tr>
<td>Trench width ( (</td>
<td>r_1-r_2</td>
<td>) )</td>
</tr>
<tr>
<td>Trench depth ( (</td>
<td>z_1-z_2</td>
<td>) )</td>
</tr>
<tr>
<td>Distance between trenches ( (</td>
<td>r_1-r_3</td>
<td>) )</td>
</tr>
<tr>
<td>Apex point ( (</td>
<td>r_1-r_3</td>
<td>) )</td>
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</tbody>
</table>

Figure 4 shows the field intensity distributions of the total field, the CSP component, and the NCDL component for both the optimized RT and APT structures. One can see a general trend that the CSP field forms a hotspot at the center of the device as shown in Fig. 4(b). However, in terms of the NCDL suppression characteristics, there are clear differences among the CMNSs with and without trenches. With trenches, the NCDL noises are substantially reduced in the central region of the device. In particular, it is worth noting that the NCDL noise is nearly completely cancelled out at the center of the device for the APT-CMNS. It is also worth noting that although the maximum CSP intensity at the center is slightly reduced by ~5.5 dB for trench-assisted CMNSs in comparison with the conventional CMNS (as specified in Sect. 2) because of the additional loss incurred by the inclusion of the trenches, the gain in terms of SNR is substantially higher than the intensity reduction level, which is to be quantified in the following through Fig. 5 and Table 1. We stress that such a linear loss can readily be compensated by means of increasing the input power.
Fig. 4. Top and cross-sectional side views of (a) $|E_{\text{total}}|^2$, (b) $|E_{\text{CSP}}|^2$, and (c) $|E_{\text{NCDL}}|^2$ for each structure as denoted.
Figure 5 shows the spatial variations of the SNR for the three different types of CMNSs discussed in Fig. 4: Figs. 5(a) and 5(b) for the SNR variations in the horizontal direction on the device surface and in the vertical direction at the center of the device, respectively, and Fig. 5(c) for the SNR distribution of each CMNS in the horizontal and vertical directions. It is worth noting that the SNR near the device surface in the central region is most important because the region is where the CSP is most intensive, thereby interacting with ambient material most effectively. In particular, if the APT-CMNS is employed instead of the conventional CMNS, one can expect 11.89 or 16.44 dB improvement in terms of the mean or peak SNR in the central part of the device, respectively, which is really substantial. Considering the dimension of the hotspot formed at the center of the device, which is as small as 520 nm, the peak SNR of 50.71 dB highlights a dramatic performance of the APT-CMNS.

Table 2 summarizes the SNR characteristics for the three CMNSs, respectively.

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<th>CMNS</th>
<th>RT-CMNS</th>
<th>APT-CMNS</th>
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<tbody>
<tr>
<td>Peak SNR</td>
<td>34.27 dB</td>
<td>38.58 dB</td>
<td>50.71 dB</td>
</tr>
<tr>
<td>Mean SNR</td>
<td>24.14 dB</td>
<td>31.11 dB</td>
<td>36.03 dB</td>
</tr>
</tbody>
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As numerically demonstrated above, one can substantially improve the overall SNR by fabricating a sophisticatedly designed trench structure nearby the slit opening. However, one may doubt whether the improvement can be maintained when the trench is not fabricated exactly to the design parameters. In fact, this can be an issue if the design parameters allow for too small tolerance. Thus, we pay our attention further to this matter. In general, the current e-beam or FIB lithography technology can routinely allow for a depth resolution of ~5 nm or even better [38,44], so that one can consider that the tolerance of the depth control over the proposed trench-assisted CMNSs is in line with that resolution. In addition, because the lateral dimension of the trench structure is much larger than its vertical dimension (depth), and also the lateral resolution of FIB milling process is substantially higher than its longitudinal resolution, one may reserve the discussion of the tolerance of the width control of the trench structure until the longitudinal tolerance issue is clarified.

Here, we estimate the change of the SNR caused by the inaccurate control of the depth of the trench. Considering the typical depth resolution of the FIB process, we modify the depth
of the trench by ± 5 nm, which is, in fact, the maximum value for the depth uncertainty [44]. Even with considering the tolerance range, we obtain that the trench-assisted structures still show improved SNR performance in comparison with the conventional CMNS: The RT structure allows for at least 28.46 dB in terms of the mean SNR and 34.52 dB in terms of the peak SNR. The APT structure allows for at least 34.83 dB in terms of the mean SNR and 44.70 dB in terms of the peak SNR. These results further confirm that that the improved performance of the trench-assisted CMNS is completely feasible even with the current FIB technology.

5. Conclusion

We have proposed trench-assisted CMNS schemes that can efficiently generate a low-noise CSP hotspot on a fiber end. The nearby trenches are designed based on the multi-pole cancelation method in order that a converging CSP signal is well separated from co-propagating NCDL at the hotspot location. In fact, the secondary radiation by the quasi-pole oscillation from the edge of the trench cancels the primary NCDL, thereby drastically enhancing the SNR of the CSP hotspot.

Two types of trench-assisted CMNSs were proposed and investigated: an RT-CMNS for the sake of its simplicity in fabrication and an APT-CMNS for the sake of further promoting the multi-pole cancelation effect. We verified the plasmonic and optical characteristics of them through full-vectorial numerical analyses. As summarized in Fig. 4 and Table 2, the optimized RT-CMNS and APT-CMNS could generate low-noise plasmonic hotspots with substantially high performance characteristics. We stress that in the case of the APT-CMNS, the multi-pole cancellation effect was maximized to yield an order of magnitude enhancement both in peak and mean SNRs of the generated plasmonic hotspot in comparison with the conventional CMNS having no trenches. Furthermore, the enhancement levels would still be maintained even for the depth tolerance range up to 5 nm, which is the typical depth resolution of the FIB process.

We expect that the proposed scheme will also be useful for designing other subwavelength plasmonic devices which normally require high SNR as well as high generation efficiency, such as bio-sensing and surface-enhanced Raman spectroscopy imaging. It is also noteworthy that our study highlights the surface-plasmon-based technique can be implemented on a fiber platform, which must have great potential for many useful and exotic applications across various fiber-optic and surface-plasmonic research fields.

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