Plasmonic meta-slit: shaping and controlling near-field focus: supplementary material

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This document provides supplementary information to “Plasmonic meta-slit: shaping and controlling near-field focus,” <http://dx.doi.org/10.1364/optica.2.000006>. In this supplement, we detail the calculation method used in the main manuscript. We also identify the detail geometry of meta-slits for readers who try to reproduce the results. © 2015 Optical Society of America

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Part A. Method for numerical calculations

For the calculation of surface electric fields generated by dipole sources which represent the slit segments, we applied the fast Fourier transform (FFT) method directly to Eq. (1). The functions $\mathbf{G}_0(\mathbf{r}, \mathbf{r}_m)$ and $\mathbf{G}_\sigma(\mathbf{r}, \mathbf{r}_m)$ represent a free space and surface Green dyadic tensors for three-dimensional Helmholtz equation, respectively, which can be expressed as [1],

$$\mathbf{G}_0(\mathbf{r}, \mathbf{r}_m) = j \frac{1}{k_0^2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} dk_x dk_y \begin{bmatrix} k_0^2 - k_x^2 & -k_x k_y & -k_x k_z \\ -k_x k_y & k_0^2 - k_y^2 & -k_y k_z \\ -k_x k_z & -k_y k_z & k_0^2 - k_z^2 \end{bmatrix} \Psi, \quad (\text{S1})$$

$$\mathbf{G}_\sigma(\mathbf{r}, \mathbf{r}_m) = j \frac{1}{k_0^2} \int_{-\infty}^{\infty} dk_x dk_y (\mathbf{M}_p R_p + \mathbf{M}_s R_s) \frac{\Psi}{k_z}, \quad (\text{S2})$$

where,

$$\Psi = \exp(j\mathbf{k} \cdot (\mathbf{r} - \mathbf{r}_m)), \quad (\text{S3})$$

$$\mathbf{M}_p = \frac{1}{(k_x^2 + k_y^2)} \begin{bmatrix} k_x^2 k_z^2 & k_x k_y k_z^2 & -k_x k_z (k_x^2 + k_y^2) \\ k_x k_y k_z^2 & k_y^2 k_z^2 & -k_y k_z (k_x^2 + k_y^2) \\ -k_x k_z (k_x^2 + k_y^2) & -k_y k_z (k_x^2 + k_y^2) & (k_x^2 + k_y^2)^2 \end{bmatrix}, \quad (\text{S4})$$

$$\mathbf{M}_s = \frac{k_0^2}{(k_x^2 + k_y^2)} \begin{bmatrix} k_y^2 & -k_x k_y & 0 \\ -k_x k_y & k_x^2 & 0 \\ 0 & 0 & 0 \end{bmatrix}. \quad (\text{S5})$$

$\mathbf{k} = (k_x, k_y, k_z)$ is an arbitrary wavevector, and R_p and R_s represent the reflection coefficients for p and s polarized

lights, respectively, at the metal-air interface, which are given as

$$R_p = \frac{\sqrt{\varepsilon_m k_0^2 - k_x^2 - k_y^2} - \varepsilon_m \sqrt{k_0^2 - k_x^2 - k_y^2}}{\sqrt{\varepsilon_m k_0^2 - k_x^2 - k_y^2} + \varepsilon_m \sqrt{k_0^2 - k_x^2 - k_y^2}}, \quad (\text{S6})$$

$$R_s = \frac{\sqrt{k_0^2 - k_x^2 - k_y^2} - \sqrt{\varepsilon_m k_0^2 - k_x^2 - k_y^2}}{\sqrt{k_0^2 - k_x^2 - k_y^2} + \sqrt{\varepsilon_m k_0^2 - k_x^2 - k_y^2}}, \quad (\text{S7})$$

where ε_m is permittivity of metal. By substituting Eqs. (S1) and (S2) into Eq. (1), it can be seen that the electric field vector is finally expressed into a form of double integral along k_x and k_y . In actual numerical calculations, we divided k_x and k_y into 6000 by 6000 discrete values in the range of $-4k_0$ to $4k_0$, and applied a two-dimensional FFT algorithm to the integrand in order to collect information regarding the electric field.

On the other hand, FEM simulations for the bare slit and single nanoslit were performed by the commercial calculation tool (COMSOL Multiphysics 4.3).

Part B. Extinction ratio of double-lined tilted slit array

According to the phase diagram shown in Fig. 4(b), the perfect destructive interference for one side of SPP excitation from a double-lined tilted slit arrays occurs when the condition of Eq. (4) is satisfied. For those cases with different tilted angle conditions, the extinction ratio defined

by the ratio of the intensity between left- and right-side excited SPPs are plotted in Fig. S1(a) (black line). As mentioned in the main text, the extinction ratio can be maximized for the conditions of $\theta = \pi/4$, which gives a perfect constructive interference for the opposite side. The other colored lines of Fig. S1(a) show the extinction ratio for a fixed value of d . For each value of d , the extinction ratio sharply increases near the specific tilted angle value which satisfies Eq. (4). In an ideal case, the black line must connect the maximum values of the colored lines, but some mismatches can exist due to the finite length ($l = 24 \mu\text{m}$) of the double-lined slit. Field distributions for $\theta = 0, \pi/4, \pi/2$ satisfying Eq. (4) are shown in Figs. S1(b)–S1(d), respectively. A difference between the cases of $\theta = 0$ and $\theta = \pi/2$ is clearly shown between the two meta-slits. For the case of $\theta = 0$, nanoslit segments are laid parallel to the meta-slit; so a strong excitation of SPPs occurs between the two arrays. On the other hand, SPPs are very weakly generated normal to the meta-slit for the case of $\theta = \pi/2$, which means that the nanoslit segments are positioned perpendicular to the meta-slit. For the cases of obliquely laid nanoslit segments with $\theta = \pi/4$, strong SPP propagations are observed on the right-side of the meta-slit due to the constructive interference of SPPs generated from each line of the meta-slit.

Fig. S1. (a) Plot of extinction ratio with varying tilted angle and the distance between two arrays. (b)–(d) E_z field distributions of double lined nanoslit arrays with tilted angle of 0, $\pi/4$, and $\pi/2$ are shown, respectively. d is set to the condition of perfect destructive interference condition for left-side excitation, which is shown in Eq. (4) of main text. Other parameters are set to $\lambda_0 = 980 \text{ nm}$, $P_y = 400 \text{ nm}$, and $l = 24 \mu\text{m}$.

Part C. Plot of focus characteristics for the numerical and experimental results

1. Single-lined meta-slit

Figure S2 compares the numerical and experimental plots of electric field generated from the single-lined meta-slit along the axis of focus. Solid lines indicate the on-focus state (RCP incidence for our configuration), whereas dotted lines show the off-focus state (LCP incidence).

Fig. S2. Plot of plasmonic focus generated by single-lined meta-slit structure.

2. DFZ meta-slit

Figure S3 shows a plot of focus generated by the proposed DFZ meta-slit structure. We compared the focus of numerical and experimental results along the focal plane in Fig. S3(a). Due to the nature of the Fresnel lens, some side-lobes are shown beside the center focus even for the case of numerical results that were calculated by dipole modeling. Nevertheless, the FWHMs of the two cases are reasonably well matched. As written in the main text, the degradation of FWHM in the experimental result originates from the imperfect fabrication and difference between the ideal dipole moment and field generated from a slit segment. In Fig. S3(b), we also compare the focal lengths of numerical and experimental results by plotting the field intensity along the axis of the proposed lens.

Fig. S3. Plot of surface plasmon focus generated by the DFZ meta-slit structure (a) along the right-side focal plane ($20 \mu\text{m}$ right away from the center of meta-slit) and (b) the axis of the lens ($y = 0 \mu\text{m}$). The red dotted line shown in (a) is numerically calculated intensity distribution along left-side focal plane. The incident polarization state is set to RCP.

3. Hybrid DFZ meta-slit for asymmetric focusing

Similar to previous results, we also plot the focus of numerical and experimental results along the focal plane and the axis of the lens in Fig. S4. In the simulation results of Fig. S4(b), two foci are simultaneously shown at $20 \mu\text{m}$ and $30 \mu\text{m}$, although one is much stronger than the other. This can be explained by the finite extinction ratio of unidirectional launching phenomenon in DFZ structure. Interestingly, such multiple foci are not shown for the case of NSOM result. We assume that weaker spots are not measured due to the threshold of signal detection of NSOM.

Fig. S4. Plot of surface plasmon focus generated by the hybrid DFZ meta-slit structure (a) along the right-side focal plane ($20 \mu\text{m}$ for RCP, $30 \mu\text{m}$ for LCP) and (b) the axis of the lens ($y = 0 \mu\text{m}$). The solid lines indicate the cases of RCP incidence ($f = 20 \mu\text{m}$), whereas dotted lines are the cases of LCP incidence ($f = 30 \mu\text{m}$).

Part D. Wavelength dependency and field coupling efficiency of DFZ meta-slit structure

In Fig. S5(a), plots of focal length and extinction ratio varying with the incident wavelength are shown. For the case of focal length, the characteristic is quite similar to the case of single-lined meta-slit due to the same reason. On the other hand, extinction ratio of the DFZ meta-slit shows sharp peak near the designed wavelength.

Table 1. Tilted angle distribution of single-lined meta-slit for focal length tuning ($l = 10.4 \mu\text{m}$, $f_0 = 15 \mu\text{m}$).

$y_m (\mu\text{m})$	-5.2	-4.8	-4.4	-4.0	-3.6	-3.2	-2.8	-2.4	-2.0	-1.6	-1.2	-0.8	-0.4	0
$\theta_m (^\circ)$	168	143	120	100	80.3	63.5	48.6	35.7	24.8	15.9	9	4	1	0
$y_m (\mu\text{m})$	0.4	0.8	1.2	1.6	2.0	2.4	2.8	3.2	3.6	4.0	4.4	4.8	5.2	
$\theta_m (^\circ)$	1	4	9	15.9	24.8	35.7	48.6	63.5	80.3	100	120	143	168	

Table 2. Tilted angle distribution of double-lined Fresnel zone meta-slit for directional switching. θ_m denotes the tilted angle for left-side slit array ($l = 23.2 \mu\text{m}$, $f_0 = 20 \mu\text{m}$, $d = 1210 \text{ nm}$, $N = \text{No slit}$).

$y_m (\mu\text{m})$	-11.6	-11.2	-10.8	-10.4	-10.0	-9.6	-9.2	-8.8	-8.4	-8.0	-7.6	-7.2	-6.8
$\theta_m (^\circ)$	45	45	N	N	45	45	45	N	N	N	45	45	45
$y_m (\mu\text{m})$	-6.4	-6.0	-5.6	-5.2	-4.8	-4.4	-4.0	-3.6	-3.2	-2.8	-2.4	-2.0	-1.6
$\theta_m (^\circ)$	45	N	N	N	N	45	45	45	45	45	45	45	45
$y_m (\mu\text{m})$	-1.2	-0.8	-0.4	0.0	0.4	0.8	1.2	1.6	2.0	2.4	2.8	3.2	3.6
$\theta_m (^\circ)$	45	45	45	45	45	45	45	45	45	45	45	45	45
$y_m (\mu\text{m})$	4.0	4.4	4.8	5.2	5.6	6.0	6.4	6.8	7.2	7.6	8.0	8.4	8.8
$\theta_m (^\circ)$	45	45	N	N	N	N	45	45	45	45	N	N	N
$y_m (\mu\text{m})$	9.2	9.6	10.0	10.4	10.8	11.2	11.6						
$\theta_m (^\circ)$	45	45	45	N	N	45	45						

Table 3. Tilted angle distribution of hybrid DFZ meta-slit for asymmetric focusing. θ_m denotes the tilted angle for left-side slit array ($l = 32 \mu\text{m}$, $f_1 = 20 \mu\text{m}$, $f_2 = 30 \mu\text{m}$, $d = 1210 \text{ nm}$, $N = \text{No slit}$).

$y_m (\mu\text{m})$	-16.0	-15.6	-15.2	-14.8	-14.4	-14.0	-13.6	-13.2	-12.8	-12.4	-12.0	-11.6	-11.2
$\theta_m (^\circ)$	0	45	45	45	-45	-45	0	45	N	N	0	0	0
$y_m (\mu\text{m})$	-10.8	-10.4	-10.0	-9.6	-9.2	-8.8	-8.4	-8.0	-7.6	-7.2	-6.8	-6.4	-6.0
$\theta_m (^\circ)$	N	N	45	45	0	-45	-45	-45	45	45	45	45	N
$y_m (\mu\text{m})$	-5.6	-5.2	-4.8	-4.4	-4.0	-3.6	-3.2	-2.8	-2.4	-2.0	-1.6	-1.2	-0.8
$\theta_m (^\circ)$	N	-45	-45	0	0	0	0	0	0	0	0	0	0
$y_m (\mu\text{m})$	-0.4	0.0	0.4	0.8	1.2	1.6	2.0	2.4	2.8	3.2	3.6	4.0	4.4
$\theta_m (^\circ)$	0	0	0	0	0	0	0	0	0	0	0	0	0
$y_m (\mu\text{m})$	4.8	5.2	5.6	6.0	6.4	6.8	7.2	7.6	8.0	8.4	8.8	9.2	9.6
$\theta_m (^\circ)$	-45	-45	N	N	45	45	45	45	-45	-45	-45	0	45
$y_m (\mu\text{m})$	10.2	10.6	11.2	11.6	12	12.4	12.8	13.2	13.6	14.0	14.4	14.8	15.2
$\theta_m (^\circ)$	45	N	N	0	0	0	N	N	45	0	-45	-45	45
$y_m (\mu\text{m})$	15.6	16.0											
$\theta_m (^\circ)$	45	0											

The spectral full-width at half-maximum of the extinction ratio is obtained as 70 nm.

Fig. S5. (a) The focal length (blue dash-dotted line) and extinction ratio (red solid line) of the DFZ meta-slit varying with the incident wavelength. (b) Numerically calculated FDTD result for proposed DFZ meta-slit. The field intensity is normalized by that of the incident field.

To show the coupling efficiency from input signal to near-field focus generated by the DFZ meta-slit, we conduct a full-electromagnetic simulation done by FDTD method, which is

shown in the Fig. S5(b). Here, we define the field coupling efficiency of the device as a maximum intensity value of the focus divided by that of the input signal, which is 6.5 %.

Part E. Detail distribution of fabricated samples

For readers who try to reproduce the results presented in this paper, detail distributions of the single-lined, DFZ, and hybrid DFZ meta-slits are shown in Tables 1, 2, and 3, respectively.

References

1. L. Novotny and B. Hecht, *Principle of Nano-Optics* (Cambridge University Press, New York, 2006).