Plasmonic Light Beaming Manipulation and its Detection Using Holographic Microscopy

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***Abstract*—Plasmonic off axis beaming and focusing of light by the use of asymmetric or non-periodic dielectric gratings around a metallic slit are experimentally demonstrated. The far-field probing was done by holographic microscopy. While the conventional near-field microscopes can probe only near-fields, our four-step phase-shift interferometer provides an efficient way of probing and reconstructing light paths coming out from the plasmonic devices. We hope our experimental work contributes to the practical applications of plasmonics such as optical interconnection and optical data storage.**

***Index Terms*—Holographic interferometry, plasmonics, surface plasmons.**

I. Introduction

Since extraordinary transmission phenomenon on the periodically perforated metallic film was shown to defy the explanation of the conventional diffraction theory [1], there has been intensive study on the surface plasmon polariton (SPP) that exists at the metal-dielectric interface [2]–[4]. Moreover, thanks to this highly confined optical mode [5], [6], lots of technically advanced optical devices as well as novel concepts in nano-scale regime have been proposed [7]–[11]. Previously, the emission on the exit region of the subwavelength metal slit or hole could be significantly enhanced, where the phase-matching to SPPs was permitted by periodically patterning the exit region [12]–[27]. Hence, forming the highly intense Gaussian-like beam utilizing the radiation property of SPPs has been proposed, and a metal slit with corrugated structures as well as patterned dielectric surface gratings circumventing the subwavelength metal slit maneuvers the travelling SPPs around the metal slit [12]–[26]. With the advanced fabrication methods such as focused ion beam machining, practical application adopting the plasmonic light beaming phenomena has been provided [27]. In addition, light waves generated by surface plasmon resonance have been commonly detected by scanning near-field optical microscope (SNOM) [28], [29]. However, detecting the plasmonic light beaming phenomena necessitates another method because beaming light is formed in an optical far-field region. Thus, it was shown that the generated beaming light can be detected by a simple microscopy configuration adopting a charge coupled device (CCD) with high resolution [12], [26]. However, when those generated optical fields are detected at the optical far-field region, it is hard to distinguish conventional on axis light beaming from manipulated plasmonic light beaming such as off axis light beaming and focusing of light which were numerically shown in our previous papers [30]–[32] and partially probed recently [33], [34]. In exciting those beaming fields, coherent light sources, i.e., laser, can be used, which makes it possible to adopt holographic microscopy in detecting the beaming light at the optical far-field region. Generally, holographic microscopy is widely used in detecting and identifying micromechanical structures and micro-organism by measuring the micro-optical field [35]–[39]. In addition, by accurately measuring the wavefront of a certain optical field, the diffracted wave emanating from a target object can be reconstructed, so the extended focused image of the target object can be obtained [40]–[43]. In this paper, we are not only to experimentally demonstrate the off axis light beaming and the beam focusing for plasmonic structures but also to show that holographic microscopy can be effectively used for a clear demonstration of light beaming from plasmonic devices. After giving a brief explanation about the concept of the manipulation of plasmonic light beaming, which mainly refers to our previous theoretical works [30]–[32], light fields generated from the fabricated structures are to be probed and the light paths are to be reconstructed by adopting holographic microscopy.

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II. Principles

Generally, when there is a narrow metal slit with the width less than half of the wavelength, transmission of light is considerably low. Hence, light passing through it is hard to form a well-collimated beam at the exit region because of the severe diffraction engendered by the narrow metal slit. However, when there is a periodically corrugated structure surrounding the narrow metal slit, transmission can be increased by properly controlling the phase-matching condition imposed by the periodic structure and adjusting the radiation field of SPPs can produce the well-collimated beam [12]–[27]. Since this concept has been known, it has been shown that the beaming light can be controlled by putting dielectric surface gratings on the exit region of the metal slit structure. In addition, by utilizing the radiation property of SPPs, the properly selected surface gratings can change the radiation direction accompanied with them [14], [30]–[32]. In other words, periodicity of the dielectric surface gratings circumventing a sub-wavelength metal slit

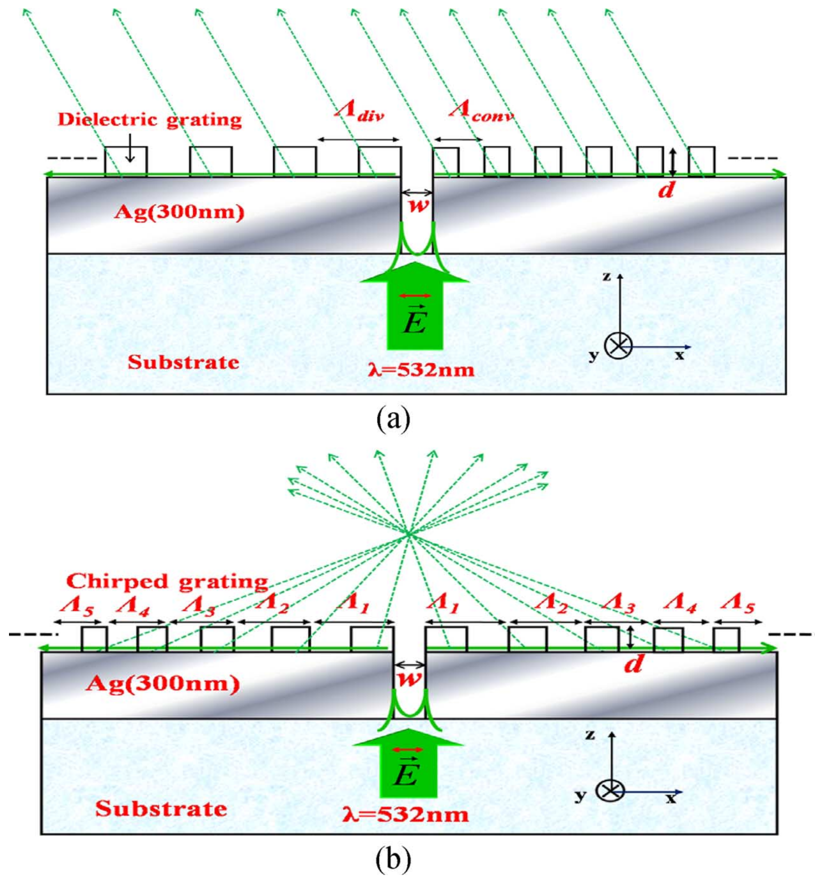
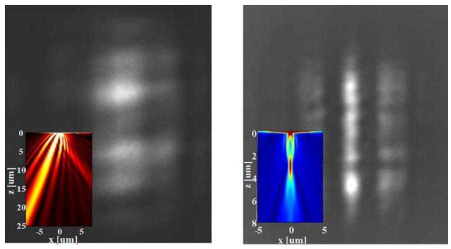


Fig. 1. Schematic of the manipulation of plasmonic light beaming using dielectric surface gratings circumventing the sub-wavelength metal slit: (a) off axis beaming structure; (b) beam focusing structure.

can affect the radiation direction of light emitted from SPPs propagating along the metal-dielectric interface. In Fig. 1, the schematic of the basic concept to manipulate the plasmonic beaming light using dielectric surface gratings is shown, where Fig. 1(a) and (b) are off axis beaming structure and beam focusing structure, respectively.

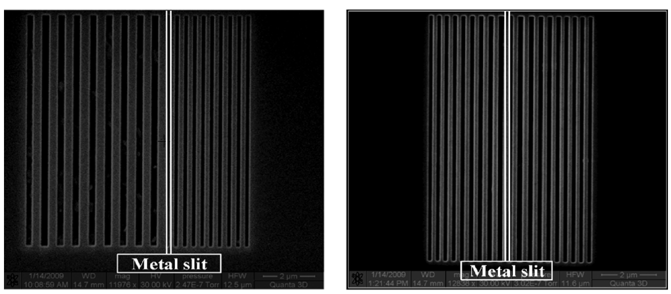
As is shown in Fig. 1(a), if surface gratings are arranged non-symmetrically, that is to say, if the period of surface gratings placed on one side of the exit region is shorter than that of on axis light beaming and the period of the other side is longer than that of the on axis light beaming, it is possible to change the direction of the propagation of the beaming light with a specific deviation angle. Thus, if the converging and the diverging radiation fields having the same absolute radiation angle can be generated in each side of the sub-wavelength metal slit, the off axis optical beam can be formed, and its deviation angle with respect to the perpendicular axis to the metal substrate corresponds to the absolute radiation angle of radiation fields from the SPPs. Here, the concepts of converging and diverging directly refer to the corresponding explanation given in the [14], [30] and [31]. As is shown in Fig. 1(b), focusing the beaming light with a Gaussian beam-like profile can also be generated by appropriately chirped gratings. In this case, based on the concept that each surface grating surrounding the sub-wavelength metal slit can play a role as an independent radiating element, we can construct the beam focusing configuration with a single sub-wavelength metal slit. Hence, it is possible to control the radiation of the beaming light by varying physical properties of the dielectric surface gratings such as shape, period and refractive index. When the period of dielectric surface gratings is chirped away from the central point of the metal slit exit, the radiation direction of each surface grating can be met at a specific point just as light waves passing through a Fresnel lens can be focused at a specific point. Those concepts related to the manipulation of beaming lights by the use of dielectric surface gratings have been numerically shown. The resultant optical fields for the off axis beaming light and focusing based on the surface gratings can be found, and the corresponding calculated light field distribution of them are respectively shown in the inset of the Fig. 2(a) and (b).

When the wavelength of the incident light is 532 nm, the refractive indexes of Ag and dielectric surface gratings are respectively $0.13+i3.2$ and 1.49. Referring to our previous theoretical works [30], [31], design values are given by the rigorous coupled analysis technique. The calculated values of the periods of surface gratings designed for the off axis beaming structure are 324 nm (for converging) and 556 nm (for diverging), so the deviation angle of the off axis beaming light with respect to the surface normal direction is 20°. The width of the metal slit, w, and the height of the dielectric surface grating, d, are respectively 100 nm and 120 nm. In addition, concerning the design of the beam focusing structure, the period of each surface grating is 382.8 nm, 353.6 nm, 331 nm, 313.8 nm, 300.6 nm, 290.2 nm, 282 nm, 275.5 nm and 270.1 nm, sequentially ar-



(a) (b)

Fig. 2. Far-field views (in a plane parallel to metal surface) of the modified plasmonic light beaming fields captured by CCD: (a) off axis light beaming. (b) beam focusing. (Insets are numerically calculated x-z plane results obtained by our rigorous coupled wave analysis technique.).



(a) (b)

Fig. 3. SEM images of the fabricated beaming structures for: (a) off axis light beaming; (b) beam focusing. (The metal slit is located at the center of the grooves.).

ranged away from the exit of the metal slit, and the fill factor is 0.5. The designed focal length is 3.08 μm and the full width at half maximum (FWHM) is 487 nm. In Fig. 2(a) and (b), the optical far-fields of the off axis beaming and beam focusing away from the metal-slit surface are captured by the charge-coupled device (CCD) camera (Sony Corp, XCDSX-90). We can see that using the CCD in detecting these light beaming fields does not provide the information of the field-distribution patterns along beam paths. Thus, in our experiments, to detect and identify far-field distribution generated by the off axis light beaming and by the beam focusing in free space, we are to adopt the holographic microscopy.

III. Experiments

To experimentally verify the off axis light beaming and the focusing of the light beaming, we prepare a polymethylmethacrylate (PMMA)-coated metal structure, where the dielectric surface grating is to be inscribed in the PMMA layer. After the silver layer with the thickness of 300 nm is deposited on the SF10 glass substrate, the PMMA layer is spin-coated on the Ag layer. In fabricating the metal slit and surface gratings, focused ion beam (FEI Corp. Quanta200 3D) machining is used, and the off axis beaming structure and the beam focusing structure fabricated by it are respectively shown in Fig. 3(a) and (b).

The physical parameters such as the metal-slit width, the period of each surface grating and the depth of the grating along the horizontal direction directly refer to the aforementioned design values, and the vertical length of both structures is 9 μm. As is seen in the off axis structure, nine grooves on each side circumvent the metal slit, where the period of the left grooves is longer than that of the right grooves so that the off axis light beaming can emanate from the metal slit. Also, referring to the beam focusing structure, nine grooves are located around the metal slit, and the period of each surface grating gets shorter and shorter as the grating location gets away from the exit region of the metal slit so that the period of surface gratings is to be chirped. The scanning electron microscope (SEM) images for fabricated structures are shown in Fig. 3(a) and (b), and the corresponding CCD images captured at the far-field region are shown in Fig. 2(a) and (b), respectively. Distinguishing the optical fields generated by these modified light beaming configurations requires the use of a delicate field-detecting method in the optical far-field region.

We use off axis holographic microscopy because holographic microscopy can provide three-dimensional reconstruction of the complex wavefront distribution, and the schematic of our off axis holographic microscopy setup is shown in Fig. 4. In our experimental setup, the second harmonic Nd:YAG laser (Coherent Corp. Verdi-V5) with the wavelength of 532 nm is used as the light source, and the fabricated beaming structure is placed in front of the objective lens with the magnitude of 100, the numerical aperture of which is 0.8 (OLYMPUS Corp. LMPlanFLN). In compensating for the aberration caused by the objective lens in holographic microscopy, we refer to the method proposed in [44], [45]. In our holographic microscopy setup, a negative lens in the reference arm is used to compensate for the wavefront curvature induced by the objective lens in the signal arm, so the beam profile of the signal wave passing through the objective lens is equivalent to that of the reference wave, as shown in Fig. 4. Therefore, the spherical negative lens compensates the spherical phase at the 1st order level enough for the uniform phase profile to be formed over the whole area on the CCD. And then, the interference pattern can be formed after both the signal beam and the reference beam pass through the beam-splitter placed in front of the CCD. Here, the signal beam passing through the beaming structure reaches the CCD by way of the objective lens, and the reference beam undergoes phase-shift controlled by the piezoelectric-driven mirror. After recording the interference pattern, we reconstruct the recorded optical fields generated by the plasmonic light beaming configurations through the convolution form of Fresnel transform given as follows [46]:

$$U(x,y) = \iint U(\xi,\eta)h(x-\xi,y-\eta)d\xi d\eta. \tag{1}$$

Here, $h(x,y)$, is given as follows:

$$h(x,y) = \frac{\exp(jkz)}{j\lambda z}\exp\left[\frac{jk}{2z}(x^2+y^2)\right] \tag{2}$$

where k and λ are wave number and wavelength, respectively. In frequency domain, it is relatively easy to rewrite (1) as follows:

$$F.T[U(x,y)] = F.T[U(\xi,\eta)]H(f_x,f_y). \tag{3}$$

Here, $F \cdot T$ means Fourier transform. And, $H(f_X,f_Y)$ represents the transfer function, which is

$$H(f_x,f_y) = \exp(jkz)\exp\left[-j\pi\lambda z(f_x^2+f_y^2)\right] \tag{4}$$

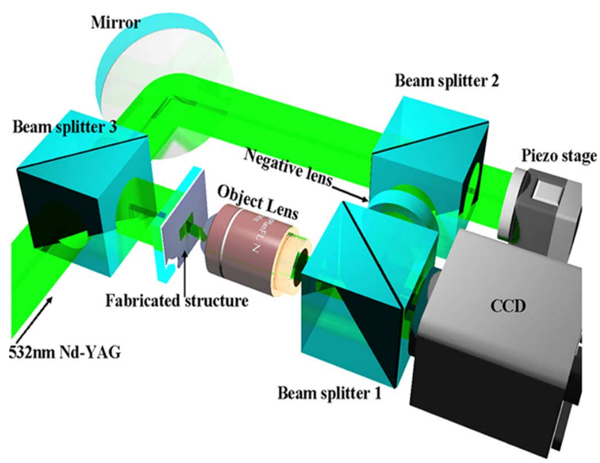


Fig. 4. Schematic of our off axis holographic microscopy setup.

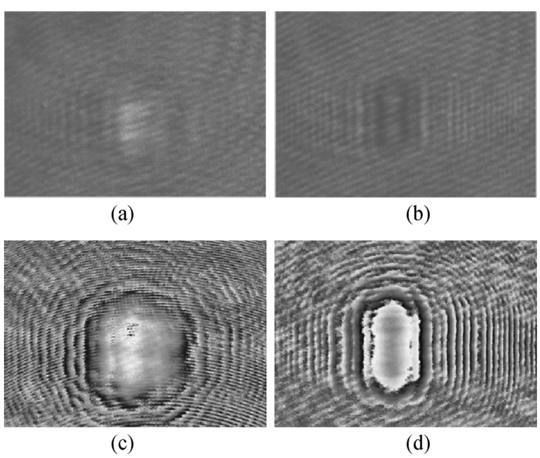


Fig. 5. Experimental results for holographic detection of off axis light beaming and focusing of light: (a) and (b) are captured images of the interference patterns of the off axis and focusing, respectively. And (c) and (d) correspond to extracted phase profiles.

where f_x and f_y are spatial frequencies along the corresponding subscript axes. The recorded interference images of off axis beaming and focusing of the beaming on the CCD are respectively shown in Fig. 5(a) and (b), of which field of view is 24 μm (horizontal) by 18 μm (vertical). The corresponding phase profiles extracted from the recorded interference images are shown in Fig. 5(c) and (d).

From these recorded interference patterns and extracted phase profiles, we can reconstruct the optical fields formed at the optical far-field region. In reconstructing the beam path of the beaming light fields, we use the convolution algorithm adequate for the relatively short distance range [47]. Also, by adopting the piezoelectric device placing in the reference arm, we constitute a phase-shifting interferometer configuration. Hence, through our 4-step phase-shifting interferometer, interferograms, composed of four distinctive reference waves with a relative phase difference of $\pi/2$, contribute to the reconstruction of the optical fields generated by the plasmonic light beaming fields. In addition, the possible phase shift errors are corrected by analyzing the twin-image in frequency domain, as presented in [48]. The

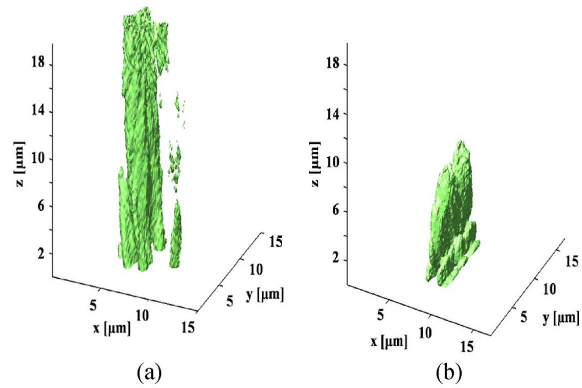


Fig. 6. Reconstructed optical fields with the three-dimensional view: (a) off axis light beaming; (b) beam focusing.

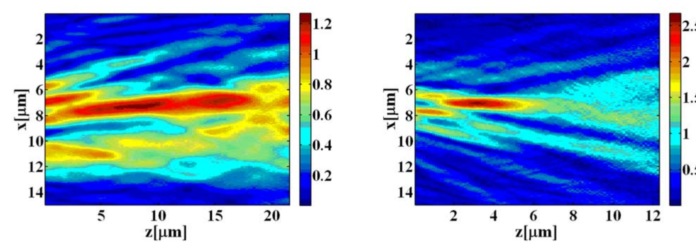


Fig. 7. X-Z cross section images of the intensity distribution: (a) off axis light beaming (b) beam focusing.

reconstructed images with three-dimensional view are shown in Fig. 6(a) and (b).

To investigate those generated optical beaming fields, the x-z cross section images of the intensity distribution are inspected and shown in Fig. 7(a) and (b).

As is seen in Fig. 7(a) and (b), the numerically evaluated results from the experimental data for the off axis angle and focal length are approximately 14.9° and 3.75 μm, respectively, where the corresponding expected numerical results were 20° and 3.05 μm. The difference between the numerical results and experimentally obtained data are mainly caused by the slight aperiodicity of the fabricated dielectric surface gratings. Also, the unwanted damage of the metal surface resulting from the FIB milling affects the radiation angle of each surface grating, which deteriorates the expected radiation direction. However, as is seen in Figs. 6 and 7, our off axis holographic microscopy can not only detect the optical fields forming at the far-field region, but it can also provide reconstructed images of detected light fields.

IV. Conclusion

In conclusion, we have experimentally demonstrated the manipulation of plasmonic beaming fields based on the variation of dielectric surface gratings. These plasmonic devices may find applications in optical interconnection and optical data storage. In addition, we showed that holographic microscopy can be effectively used to probe the modified plasmonic beaming fields as well as to provide the full reconstruction of the generated plasmonic light beaming wavefront, which makes it possible to distinguish the conventional on axis beaming from off axis beaming field and the focusing field in the far-field region. Unlike the near-field scanning microscope, the holographic microscope can provide three-dimensional beam path information coming out from plasmonic devices.

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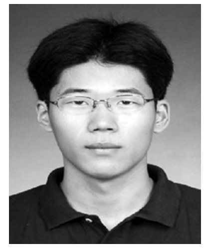

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