Optical transmission enhancement by a sub-wavelength film lens

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A new sub-wavelength metallic film lens configuration is proposed, which is embedded in a thin ideal metal film, and its near field optical properties are investigated by finite-difference time-domain (FDTD) method. It is found that the optical transmission is greatly enhanced, and the spot size can be reduced by the sub-wavelength metallic film lens in comparison with the bare aperture. This kind of lens is expected to have practical applications in the very small aperture laser (VSAL), a promising nanosource for near-field optical storage and lithography.

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The spatial resolution limit of an optical system imposed by diffraction has already been overcome by using a sub-wavelength aperture in the near field region[1,2], which is mostly made by a tapered fiber probe with a glass core and a metallic coating. Although a lot of endeavor has been made to improve the performance of the fiber probe in the past twenty years[3,4], the extremely low transmission is still an obstacle in some applications. For instance, in the near-field optical storage, sufficient power for acceptable signal-to-noise ratio (SNR) is highly required. In order to improve the transmission of the probe, a very small aperture laser (VSAL), a promising light source for near-field optical recording, was proposed by Partovi *et al.*[5]. Extraordinary optical transmission through sub-wavelength aperture arrays was reported by Ebbesen *et al.*[6]. Thio *et al.*[7] also reported that a set of concentric circular grooves surrounding a single through aperture could enhance the power throughput by 34 times. Lezec *et al.*[8,9] showed that when the exit surface was flanked by such circular grooves, the transmitted light was focused around the direction of the incident beam. Recently, a C-shape aperture was proposed by Shi *et al.*[10], which could achieve transmission enhancement of about 1000 times than that of a square aperture.

In this letter, we propose a novel configuration — sub-wavelength metallic film lens[11], and its near-field optical properties are investigated by employing the finite-difference time-domain (FDTD) method[12]. The results show that the transmission is greatly enhanced and the optical spot size is reduced within near-field region of the sub-wavelength metallic film lens in comparison with the bare aperture.

The FDTD method is employed to investigate the near-field optical properties of the thin metallic film sub-wavelength lens. The FDTD technique is a numerical solution to Maxwell's equations and is formulated by replacing temporal and spatial derivatives in Maxwell's equations with their finite-difference correspondences. This method can be accurately applied to general electromagnetic structures. For calculation convenience, the physical model is simplified as follows: a thin film sub-wavelength lens is embedded in the center of a circular aperture in an ideal metallic thin film. A polarized homogeneous plane wave is perpendicularly incident on this film. The refractive index is Gaussian distribution within the sub-wavelength lens, as shown in Fig. 1.

Our homemade FDTD program have some advantages over the commercial counterparts, such as in flexibility of modelling and outputs, especially in the computer memory consuming. This program could solve $200 \times 200 \times 200$ cells computation domain, running in typical PC with about 700M RAM. To ensure the correct implementation of our algorithm, we have compared the results with the analytical ones for the filed of dipoles. We also compared the results with those produced by commercial software of RSoft[13]. Excellent agreement was found for both comparisons. The center of the thin film lens is defined as the origin of the Cartesian coordinates. The parameters of the numerical model used in this paper are adopted as follows. The wavelength of incident plane wave is 632.8 nm, propagating along z axis, polarized along x direction. The diameter of the thin film sub-wavelength lens is 120 nm, and the thickness of the metallic film is 30 nm. The Gaussian distribution refractive indices are $n_1 = 3.22$ and $n_2 = 4.51$, at the edge and center of the sub-wavelength lens, respectively. The refractive index values are assigned to the corresponding grids. The whole simulation space is divided into $200 \times 200 \times 100$ uniform cells. The cell size is $\Delta x = \Delta y = \Delta z = 3$ nm. The time step is set to be $\Delta t = 0.95\Delta x/(\sqrt{3}c) = 5.49 \times 10^{-18}$ s, where c is the speed of light in vacuum.

Figure 2 illustrates the cross-sectional view of intensity

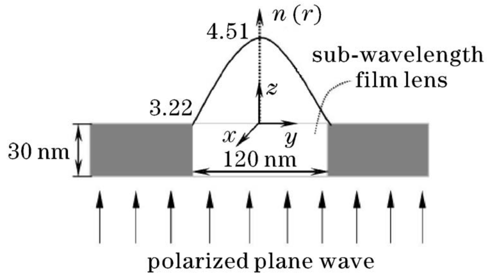

Fig. 1. Sub-wavelength film lens configuration.

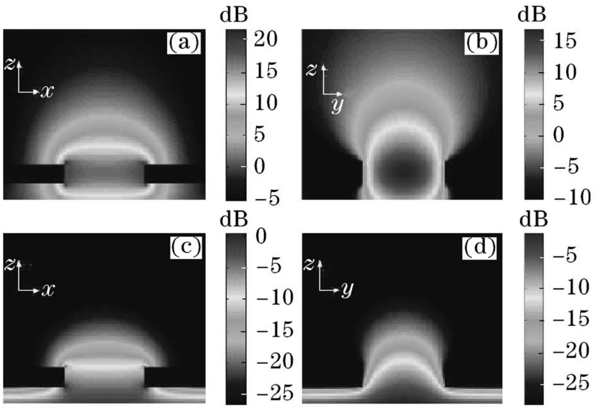

Fig. 2. Cross-sectional view of intensity distributions. (a) $y = 0$, sub-wavelength film lens; (b) $x = 0$, sub-wavelength film lens; (c) $y = 0$, bare aperture; (d) $x = 0$, bare aperture.

distributions. Comparing Fig. 2(a) with Fig. 2(b), and Fig. 2(c) with Fig. 2(d), the intensity distributions in parallel and perpendicular polarization directions are very different, because surface plasma enhancement only occurs in polarization direction. The near field of transmitted light was re-distribution for the presence of sub-wavelength film lens. The local maximum of intensity in the aperture for sub-wavelength film lens area is located at the center as shown in Figs. 2(a) and (b), and the maximum intensity for bare aperture is located at the incident side of the aperture as shown in Figs. 2(c) and (d). Comparing Figs. 2(a) and (b) with Figs. 2(c) and (d), intensity is greatly enhanced, furthermore, focused in the perpendicular polarization direction by the sub-wavelength film lens. In higher refractive index material the wavelength is shorter, the aperture size is relatively larger. That is why the high index material facilitates transmission.

Intensity distributions in parallel and perpendicular polarization planes for different z are shown in Fig. 3. It is clearly shown that the intensity decays exponentially. For z = 36 nm, in the parallel polarization direction, see Figs. 3(a) and (c), the surface plasma enhancement effect almost disappears, the field distribution approximately takes Gaussian profile, the light spot is larger than the perpendicular polarization direction, and we can also see that the intensity is greatly enhanced by

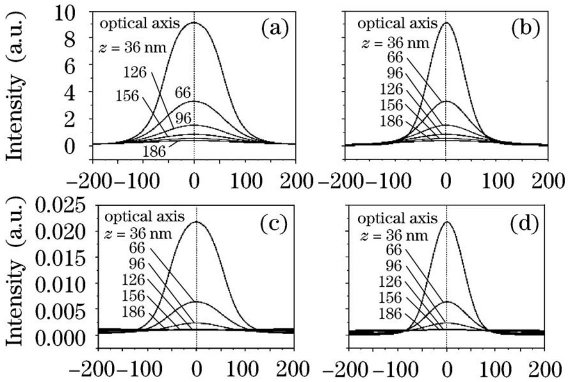

Fig. 3. Intensity distributions for different z. (a) $y = 0$, sub-wavelength film lens; (b) $x = 0$, sub-wavelength film lens; (c) $y = 0$, bare aperture; (d) $x = 0$, bare aperture.

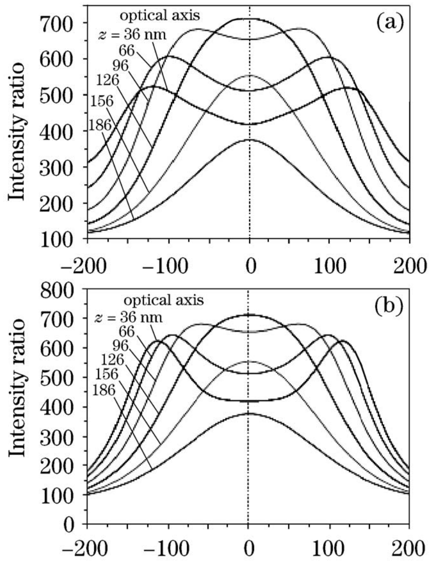

Fig. 4. Normalized intensity distributions for different z. (a) $y = 0$, (b) $x = 0$.

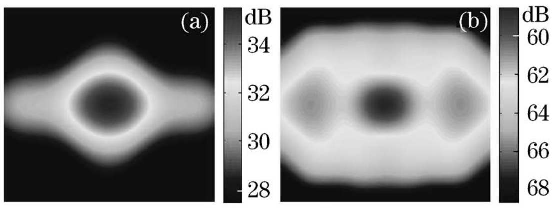

Fig. 5. Transmitted light spot in z = 126 nm plane. (a) Sub-wavelength film lens; (b) bare aperture.

sub-wavelength film lens.

The normalized intensities in parallel and perpendicular polarization directions for different z are shown in Fig. 4, which are given by the ratio of the intensity distribution of the sub-wavelength film lens to that of bare aperture. It is shown that with the sub-wavelength film lens, the intensity is enhanced by about 400 to 700 times for different z. The enhancements in parallel and perpendicular polarization directions share the same pattern, and the enhancement increases with z when $z < 126$ nm and comes to the maximum of about 650 when $z = 126$ nm and then decreases with z when $z \geq 126$ nm. For $z < 126$ nm the enhancement curves reveal concave around the center of aperture in both directions, such pattern implies that the transmitted light is broadened, because the enhancement in the center is not the maximum; for $z \geq 126$ nm the curves reveal convex around the center, such pattern indicates that the transmitted light is focused (3 dB reduction from the maximum value), this focusing effect is clearly shown in Fig. 5, which gives the intensity distributions in z = 126 nm plane.

In summary, a novel configuration of sub-wavelength film lens for optical transmission enhancement is proposed. Its near-field distribution is investigated with FDTD method. It is shown that giant enhancement (about 700 times) of transmission occurs combined with a considerable focusing effect of transmitted light, in comparison with the bare aperture. These giant transmission enhancement phenomena are, for example, very useful for the VSAL, a promising nanosource for near-field optical storage and lithography.

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13. RSoft is a commercial package for photonic design and simulation. Website: http://www.rsoftdesign.com.