学术期刊可以用微信做什么，快来看看！

微信自动应答服务平台

微服务
移动互联网时代的营销革命

简单快捷 • 高效互动 • 随时随地 • 广泛传播

微信扫一扫
开启智慧“微服务”
A hyperlens-based device for nanoscale focusing of light

Jiangnan Zhao (赵江南), Guoxing Zheng (郑国兴)*, Song Li (李 松), Hui Zhou (周 轼),
Yue Ma (马 鹏), Rulying Zhang (张瑞玲), Yan Shi (shit), and Ping’an He (何平安)

School of Electronics Information, Wuhan University, Wuhan 430072, China

*Corresponding author: gxzheng@whu.edu.cn

Received August 18, 2011; accepted October 8, 2011; posted online November 25, 2011

To resolve the problem of missed evanescent waves in a beam focusing system, a hyperlens–based beam focusing device is proposed in this letter. This device can convert the evanescent waves into propagating waves, and then a super–resolution spot is formed at the center of the hyperlens. The working principle of the device is presented, and the way in which the material and structural parameters of the hyperlens affect the resolution and transmission is analyzed in detail. A multibeam focusing device is optimally designed, and the simulated results verify that a nanoscale spot with a diameter of 15.6 nm (corresponding to $\lambda_0/24$, where $\lambda_0$ is the working wavelength in vacuum) is achieved, which is far less than the diffraction limited resolution with a value of 625 nm (1.7$\lambda_0$). The device is expected to find numerous applications in optical data storage and nano–photolithography, among others.

doi: 10.3788/COL201210.042302.

In an optical data storage and nano–lithography area, an ultra–small beam spot is required for information recording. With the phase transformation of an ideal positive lens, an input plane wave can be converted into a converging spherical wave and then eventually focused into a point at the focal plane. However, limited by diffraction, the ideal focusing point is through an Airy pattern. This can be explained by the fact that when the beam is focused toward the focal plane, the conservation of the angular momentum forces the tangential wave vector $k_\theta$ to increase toward the center, however, light with $k_\theta > k_0$ corresponds to the evanescent wave that cannot reach the focal plane, where $k_0$ is the wavenumber in vacuum. According to the equation $\Delta x \Delta k \approx 2\pi[1]$, where $\Delta x$ is the beam size and $\Delta k$ is the bandwidth of the angular spectrum, the maximum $\Delta k$ that could be delivered is determined by the maximum transverse wavenumber $k_0 \times \text{NA}(\Delta k = k_0 \times \text{NA} \text{ and NA is the numerical aperture of the focusing lens})$ and the minimum beam size $\Delta x = \lambda_0/\text{NA}$, which corresponds to the diffraction limit. To further reduce the beam size, we should find materials that allow waves with transverse wavenumber exceeding $k_0 \times \text{NA}$ to propagate in it with a propagating wave mode, instead of an evanescent wave mode. Conventional isotropic materials such as optical glasses do not show such characteristics, whereas artificial materials such as metamaterials[2] hold such potential. By optimization design[3–5], metamaterials can achieve the desired effective dielectric permittivity $\varepsilon$ and magnetic permeability $\mu$ and have been theoretically shown to support propagating waves with very large wavenumbers. Lenses fabricated by metamaterials, such as near–field planar superlens[6,7], far–field superlens[8], and hyperlens[9–12], can support the propagation of evanescent waves and thus are capable of imaging an ultra–small object far below the diffraction limit. In this letter, we concentrate on another application and report on how a hyperlens–based device can work for super–resolution beam focusing.

The hyperlens consists of alternating metallic and dielectric layers in a cylinder– or sphere–shape. According to the effective medium theory[4], a cylinder–shape hyperlens is equivalent to a structured metamaterial with effective positive tangential dielectric permittivity $\varepsilon_\theta$ and negative radial dielectric permittivity $\varepsilon_\phi$. Meeting the hyperbolic dispersion relation $\varepsilon_\theta^2/\varepsilon_\phi - k_0^2/|\varepsilon_\phi| = k_0^2[9]$ in cylindrical coordinates, hyperlens with its ring structure allows far–field propagation for the propagating waves (not evanescent waves) with the tangential wave vector $k_\theta$ larger than $k_0$. The working principle of a hyperlens–based beam focusing device is illustrated in Fig. 1. In Fig. 1(a), the dimension of the converging wave will no longer be reduced starting at the focal plane of the focusing lens marked with $B$ for the diffraction limit. However, if a half–spherical hyperlens is inserted between plane $A$ and plane $B$ with its bottom planar surface coinciding with plane $A$ (the ideal focal plane), the converging wave will be re–focused, and waves with tangential wave vectors $k_\theta$ larger than $k_0$ will undergo propagating modes in the hyperlens and continue focusing until they eventually reach the ideal focal plane $A$, leading to a super–resolution focusing spot.

The material and structural parameters of the hyperlens should be optimized to obtain a high resolution (or beam spot size) and system transmission. The resolution is related to the wavenumber. According to the above analysis, when the beam focuses into the core, the largest transverse wavenumber that could be delivered is $(R_2/R_1)k_0 \times \text{NA}$, where $R_1$ and $R_2$ are the radii of the outmost and innermost layers of the hyperlens, respectively, and the corresponding resolution $Res$ can be expressed as follows:

$$Res = \frac{\lambda_0}{2\text{NA}(R_2/R_1)}. \quad (1)$$

From Eq. (1), we can see that the resolution improves along with the increasing of $R_2/R_1$ and that the ideal spot can be obtained when $R_1$ is approximate to zero (corresponding to a half–spherical hyperlens, as seen in Fig. 1(b)).
transfer–matrix method[15,16] can be used to evaluate system transmission. The system transmission coefficient versus metal layer thickness is shown in Fig. 3, where the optimized thickness for the maximum transmission is about 56.5 nm for some concrete parameters of hyperlens. The thickness of the silver is chosen as 56.5 nm in the following numerical simulations.

To verify the ability of super-resolution focusing, we propose a hyperlens-based beam focusing system, as shown in Fig. 4. In a beam focusing application, the resolution and the transmission are both important. To compensate the metal loss and then improve the intensity of focusing spots, multibeam focusing lens are employed, as shown in Fig. 4(a). For example, a three-beam focusing device is designed, and Multiphysics 3.5 (COMSOL) is used to simulate the performances of the proposed hyperlens-based beam focusing device. The simulation results of the power flow traveling through three focusing lens and the hyperlens in the transverse-magnetic (TM) mode are shown in Fig. 4(b). In the simulations, the working wavelength is 375 nm and the main parameters of the focusing lens are as follows: focal length of 2 μm, numerical aperture of 0.3, and lens material of silica. For the hyperlens in Fig. 4(b), the outmost radius \( R_2 \) is 1.017 μm, and the layer thickness is 56.5 nm with alternating Al2O3 (\( \varepsilon_d=3.21 \)) and Ag (\( \varepsilon_m=-3.12+0.21i \)). As
shown in Fig. 4(b), the focused spot is localized within the circle with the minimum curvature radius, indicating the presence of large transverse wavenumbers. As seen in Fig. 4(c), the spot size near the bottom planar surface of the hyperlens is about 15.6 nm (full-width at half-maximum (FWHM) corresponding to \( \lambda_0/24 \)), which is far less than the theoretically diffraction limited resolution of the single focusing lens (\( \approx 1.7\lambda_0 \)), and thus super-resolution focusing is realized. Figure 4 also shows that the beams are spreading when they leave away from the hyperlens. Therefore, the working plane should be as close to the bottom surface as possible in applications.

In optical data storage and other applications, the dimension of the incident beam is generally much larger than the value used in our simulation. However, as long as the numerical aperture of the focusing lens remains unchanged, the aperture and the focal length can be scaled in proportion to the actual size in order to meet the size of the beam in reality without disturbing the wavefront. Along with the unchanged mode of transmission, the device proposed is still applicable.

In conclusion, we report a new beam focusing device based on hyperlens to realize super-resolution focusing. The device’s working principle and characteristics such as resolution and transmission are discussed in detail. A multibeam focusing device is proposed, and numerical simulations have verified the effectiveness of the device. The simulated minimum beam spot size could be reduced to \( \lambda_0/24 \), which is far below the diffraction limit (1.7\( \lambda_0 \)). The newly proposed device, with its simple design structure, is expected to find numerous applications in the fields of optical data storage and nanophotolithography, among others.

This work was supported by the National Natural Science Foundation of China (No. 10904118), the Natural Science Foundation of Hubei Province (No. 2009CDB211), and the Fundamental Research Funds for the Central Universities.

References