REVIEW NANO BULLETIN Vol. 2, No. 1, 130105, January 2013

Toward conventional-optical-lens-like superlenses

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Received 15 Nov 2012; revised 20 Dec 2012; accepted 18 Jan 2013; published 26 Jan 2013.

ABSTRACT: Superlenses that achieve resolutions beyond the diffraction limit received much attention after Pendry proposed the negative index material (NIM) based perfect lens concept in 2000. The essence of this idea is to make the evanescent waves that contain high spatial frequency information contribute to the image. Other than this scheme, there are different routes towards viable superlenses. Here we review the advances in superlenses that utilize evanescent waves and their development towards conventional-optical-lens-like superlenses, from the NIM superlens to the silver film superlens, the far-field superlens (FSL), the hyperlens and finally to the phase compensated metalenses. These five schemes are compared and the exotic imaging properties of the hyperbolic metalens are revealed by directly analyzing the newly derived general imaging equation. © Global Scientific Publishers 2013

KEYWORDS: superlenses, conventional-optical-lens-like metalenses, evanescent waves, phase compensation, exotic imaging properties.

1. Introduction and the perfect lens concept

In 1873, Ernst Abbe concluded that the resolving ability of an optical imaging system is limited to half the working wavelength due to the diffraction of light; this fundamental phenomenon is referred to as diffraction limit [1]. In Fourier space, it is understood that this limit is due to the fine features or high spatial frequency information of an object, which are evanescent waves decaying exponentially from the object, cannot propagate to the image, and thus imposing a cutoff in the resolution of the image. Having an optical lens that can achieve resolution beyond the diffraction limit would be beneficial for many applications.

The superlens concept emerged in 2000 for this purpose; Pendry theoretically proved that a negative index material (NIM) [2] slab could make both the propagating and evanescent waves contribute to the resolution of the image. The evanescent waves are coupled, enhanced and transferred to the image by the NIM slab. Using this scheme, the images could have superior resolution compared to those obtained using conventional lenses [3]. The theory of the concept is shown in Fig. 1. The idea is not limited to negative index materials; any materials that are able to couple and enhance evanescent waves in the optical band will do to improve the resolution, for example, metals with negative permittivities. Using a 40-nm thick silver film, Pendry numerically showed the resolution of two 80-nm separated 15-nm wide objects at the wavelength of 356 nm. Although there has been a debate between this and other ideas [4], such as the “fish eye” [5, 6] and the super oscillation [7] concepts that do not use evanescent waves to achieve super resolution, this idea has sparked intense efforts in searching for a viable superlens [8].

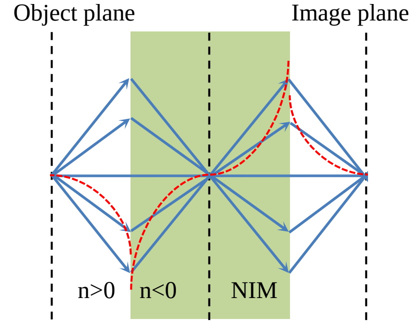

Figure 1. Superlens concept based on negative index materials. The solid blue lines are propagating rays which are negatively refracted twice by the NIM. The dashed red lines are the amplitude profiles of evanescent waves, which are coupled, enhanced and transferred to the image plane by the NIM.

2. The silver film superlens

The superlens concept was independently demonstrated by Fang [9] and Melville [10] using silver films of 30 nm and 50 nm thick respectively, as shown schematically in Fig. 2. A grating mask serves as the object, which is planarized using PMMA. When the grating is illuminated using light at the plasmonic resonant frequency of silver in the structure, evanescent waves can be picked up, significantly enhanced and transferred to the image on the other side of the silver film. By operating at the plas-

ISSN 2159-0427/130105/06/$60.00

monic resonance, a negative refraction can be achieved in the material. A photoresist is used to record the image. After development, the image is obtained using an atomic force microscopy (AFM) or focused ion beam (FIB). The image can also be obtained directly using near-field scanning optical microscopy (NSOM) without the photoresist recording [11]. The PMMA spacing between the object and the silver film plays an important role in proving the concept in that it prevents the direct transfer of the grating tomography to the other side of the silver film, which may also create subwavelength scale patterns in the photoresist [10]. The two groups achieved subwavelength scale resolution of 89 nm and 145 nm respectively at the wavelength of 365 nm. The grating objects in both experiments are in the near field regime, and so are their images, due to the exponential decaying of evanescent waves from the object to the silver film in the object space and from the other side of the silver film to the image in the image space.

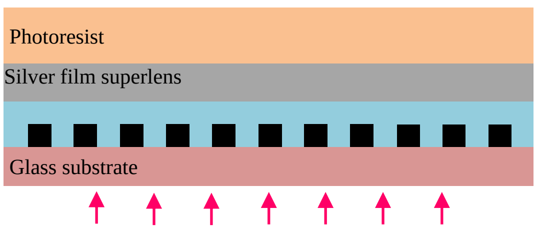

Figure 2. Schematic experimental setup of the silver film superlens.

3. The far-field superlens

The high spatial frequency information transmitted to the near-field image of a silver film superlens can be sent to the far field by momentum conversion from evanescent waves to propagating waves. A grating built on the top of the silver film superlens is one of the simplest structures that can accomplish this, as shown in Fig. 3. In 2007, Liu proposed such a superlens, which is referred to as a far-field superlens (FSL) [12]. This approach requires subtle transfer function design and intense numerical image reconstruction computing, as the image cannot be directly formed by a grating in this application. The proof of concept was demonstrated using a silver film and a built-on grating at the wavelength of 377 nm with the aid of a conventional microscope, resolving two 70-nm gapped 50-nm wide line objects [12].

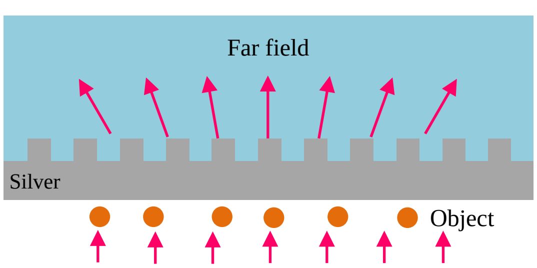

Figure 3. Schematic of a far-field superlens.

The aforementioned superlenses cannot provide magnification to the image, which is one of the fundamental properties of conventional optical lenses. This drawback limits their applications in conventional optical systems, as the image would have the same dimensions as the object; the image could not be directly resolved by a conventional optical system if the object itself is already irresolvable by the same system. These superlenses have to rely on non-optical imaging systems like AFM, FIB, scanning electron microscopy (SEM), NSOM, or nontrivial numerical image reconstructions to generate images beyond the diffraction limit.

4. The hyperlens

In 2006, Jacob proposed and theoretically studied a hyperlens concept that could provide magnification to the image containing high resolution information in the far field [13]. The hyperlens concept is schematically shown in Fig. 4(a). It is composed of a metamaterial of cylindrical multilayers of dielectric/metallic materials possessing a (nearly) straight hyperbolic dispersion, as shown in Fig. 4(b); the hyperbolic dispersion in cylindrical coordinate system is $k_r^2/\varepsilon_\theta + k_\theta^2/\varepsilon_r = k_0^2$ with $\varepsilon_r < 0$. Here k_r and k_θ are the wavevector components in the radial and tangential directions, respectively, and ε_r and ε_θ are the corresponding components of the permittivity. A metamaterial is artificially structured for exceptional material properties that are not available in natural materials, for example, negative permittivity [14]. The nearly straight dispersion curve in the hyperlens material requires that $|\varepsilon_r| \gg 1$, which is usually realized near the resonant frequency of the metamaterial; thus the metamaterial is highly lossy.

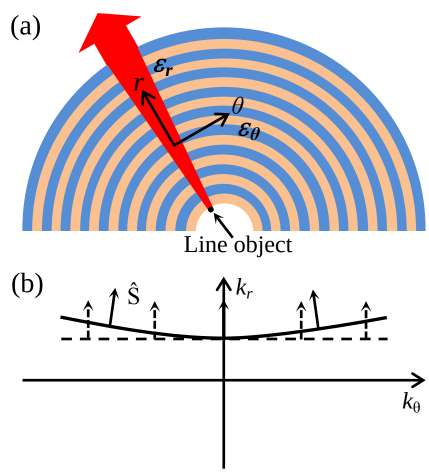

Figure 4. Principle of hyperlens. (a) schematic of a cylindrical dielectric/metallic multilayer hyperlens; (b) dispersion of hyperlens in cylindrical coordinate system: the solid and nearly straight hyperbolic curve of a real metamaterial for hyperlens, in which the wavevectors propagate in slightly different directions (the solid nearly vertical arrows on the curve); the dashed horizontal straight line is the ideal dispersion for a hyperlens, in which all wavevectors propagate in the same direction (the dashed vertical arrows on the line). Ŝ denotes the group velocity.

ISSN 2159-0427/130105/06/$60.00

The high spatial frequency information of an object in proximity can be coupled by the inner surface of the metamaterial. The dispersion of a hyperlens would ideally be straight. Because of this, the waves do not spread out and overlap in the tangential direction when propagating in the radial direction, which also results in point-to-point mapping from the center surface to the outer one. While this yields sub-diffraction resolution, it implies that the hyperlens is incapable of focusing plane waves [15]. The image gets magnified at the larger outer surface of the metamaterial. In cylindrical coordinate system space, the wavevectors are gradually compressed while propagating from the center surface to the outer one, or vice versa. The impedance of the outer surface matches that of the surrounding medium, e.g., air, which enables the image to be detectable in the far field by conventional optical systems. In 2007, Liu and Smolyaninov experimentally and independently demonstrated two hyperlenses: the former resolved two 80nm-gapped 50nm-wide line objects at the wavelength of 365 nm, with a magnification of 2.3; the latter claimed the achievement of 70 nm resolution at the wavelength of 495 nm, with a magnification of 10 [16, 17]. While these demonstrations are at light frequencies, in 2009 Li experimentally demonstrated an acoustic hyperlens, resolving two 1.2cm-separated 1cm-diameter sound sources at 6.6 kHz, with a magnification of 8 [18].

Because the hyperbolic dispersion is unbound, such a metamaterial may support the propagation of infinitely large wavevectors, and thus the resolving power of a hyperlens would not be limited. However, the following four points may limit the resolving power and applications in practice: (i) the losses of metamaterials due to the involvement of metallic materials and the nearly resonant working condition impose a cutoff in the actual coverage of the wavevectors; (ii) the hyperbolic dispersion can only be nearly straight, making the waves actually spread out in the tangential direction when propagating from inner to outer surface, and thus blurring the image; (iii) the curved geometry of a hyperlens makes it hard to use; (iv) the point-to-point mapping makes a hyperlens work differently from a conventional optical lens, making its incorporation into conventional optical systems difficult.

5. The metalens

5.1 The metalens concepts

While all the above superlens concepts could achieve super resolution and the hyperlens can even provide magnification, they work differently from a conventional lens. The most notable difference is that these superlenses cannot focus plane waves, which is due to the lack of a phase compensation mechanism. Focusing plane waves is one of the fundamental properties of a conventional optical converging lens, and it gives the lens its ability to perform a Fourier transform. It is thus advantageous that a

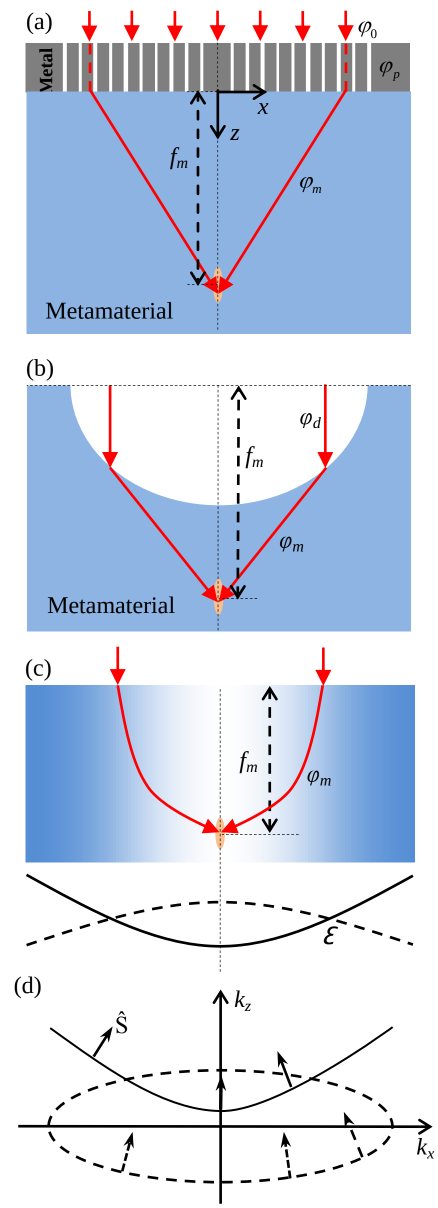

Figure 5. Phase compensation mechanisms for focusing a normal plane wave to a spot through constructive interference in metalenses. This constructive interference requires that the phase of all light paths from the wavefront of the plane wave to the focus be constant, e.g., in (a), $\varphi_0 + \varphi_p + \varphi_m + 2l\pi$ = constant, with $l = 0, \pm1, \pm2$ …, φ_0 being the initial phase of the plane wave, φ_p being the phase change by the plasmonic waveguide, and φ_m being the phase change in the metamaterial. Modulating the phase using (a) a plasmonic waveguide coupler (PWC); (b) the curvature of the metamaterial; (c) gradient-index (GRIN) metamaterial. (d) non-straight dispersion of metalens, which can be either hyperbolic (the solid one) or elliptic (the dashed one), in which the wavevectors propagate in different directions (the solid arrows on the hyperbolic curve and the dashed arrows on the dashed ellipse). $\hat{S}$ denotes the group velocity. The MIL in (b) is a hyperbolic metalens. The curves in (c) are the gradient permittivity profiles, which can be high for elliptic dispersion or low for hyperbolic dispersion in the center. f_m is the focal length in the metamaterial space.

ISSN 2159-0427/130105/06/$60.00

superlens be able to focus a plane wave and work like a conventional lens. Ma recently proposed a series of phase compensated metamaterial superlenses that have the capability of focusing plane waves, including the metalens [19, 20], the metamaterial immersion lens (MIL) [21] and the gradient index (GRIN) metalens [22]. These three, which are also generally referred to as metalenses, use a plasmonic waveguide coupler (PWC), a shaped interface or a material gradient to provide phase compensation, respectively, as shown in Fig. 5.

The phase compensation is designed for focusing the plane wave to a spot through constructive interference in a metamaterial that can support the propagation of waves with high transverse wavevectors. This is similar to the manner in which a conventional lens focuses plane waves to a spot in a medium. Because waves in different directions need to contribute to the focal spot, the dispersion of the metamaterial of a metalens, whether elliptic (referred to as an elliptic metalens) or hyperbolic (referred to as a hyperbolic metalens), must be curved such that the wavevectors can spread out to different directions in the material, as shown in Fig. 5(d). It is furthermore advantageous that the non-straight dispersion curve requirement enables the metalens to work off resonance, which is less lossy as compared to the hyperlens. These two properties of the metamaterial in a metalens result in the contribution of high wavevectors to the focus in the metamaterial. As a result, the lateral dimension of the focal spot can be much smaller than the wavelength in free space. When such a metalens is truncated in the focal plane, it can work like a solid immersion lens (SIL) [23]. While a conventional SIL is made of natural optical material with limited wavevector supporting ability ($\le nk_0$, with n being the refractive index of the SIL material), a metamaterial can be designed to have a much broader wavevector coverage that is not achievable by natural materials. So the metalenses can well surpass conventional SILs in resolution. When the light comes from the medium above the metalens, it can be focused to a spot on the focal plane, so the metalens can be used for nanolithography. On the other hand, when an object is brought to the focal plane, the high spatial frequency information can be coupled into the metamaterial and then propagate to the top interface of the metamaterial. The PWC, the curved interface and the GRIN material profile enable the light to be coupled into the medium above the metamaterial. As a result, a magnified image of the object with super-resolution information can be directly formed [19] and detected in the far field by conventional optical systems. Super focusing resolution has been numerically demonstrated for the three types of metalens recently, for example, a 60-70 nm linewidth (FWHM) at 633 nm wavelength by a MIL, a 50-60 nm linewidth at 365 nm wavelength by a PWC based metalens, and a 156 nm linewidth at 830 nm by a GRIN metalens [19-22]. A demagnification of 4.65 was also obtained using a metalens [19].

5.2 The exotic imaging properties of hyperbolic metalenses

Because of the phase compensation, a metalens works similar to a conventional SIL, except for the capability of focusing a plane wave to a deep subwavelength light spot. A focal length can be defined in the metalens, which is not the case with other superlenses. Exotic imaging properties have been discovered in metalenses with a hyperbolic dispersion, i.e., in hyperbolic metalenses [24]; the imaging behavior of an elliptic metalens is similar to that of a conventional optical lens. A general imaging equation was formulated as the following,

$$\frac{1}{v_d}+\frac{\varepsilon_z^{'}/\sqrt{\varepsilon_x^{'}}}{v_m}=\frac{\varepsilon_z^{'}/\sqrt{\varepsilon_x^{'}}}{f_m} \tag{1}$$

where v_d is the image/object distance in the dielectric material space above a metalens, v_m is the image/object distance in the metamaterial, f_m is the focal length in the metamaterial, $\varepsilon_x^{'}$ and $\varepsilon_z^{'}$ are the permittivities of the metamaterial in the x and z directions respectively. Because $\varepsilon_z^{'}$ can be either positive or negative, the well-known imaging equation of conventional optical lenses in air is only a special case of this general one with $\varepsilon_z^{'} = \varepsilon_x^{'} = 1$.

The imaging properties of a hyperbolic metalens with $\varepsilon_z^{'} < 0$ can be readily found in eq. (1). When a plane wave is incident upon the metalens from the dielectric space above, $v_d = \infty$, the light is focused to a spot in the metamaterial. When a plane wave is coming from the metamaterial space, $v_m = \infty$, it diverges, instead of converging to a spot, in the dielectric space, resulting in a virtual focal spot in the metamaterial space. So a hyperbolic metalens is a converging lens from one side but a diverging lens from the other side; it is a 'Janus lens' with two different 'focusing' behaviors in opposite directions. This newly found focusing behavior has broken the imaging symmetry; a conventional converging lens focuses plane waves from both sides. Eq. (1) also implies the following exotic imaging properties by a hyperbolic metalens: (1) when an object is in the dielectric space, its image is minified, erect, real, and outside the focus in the metamaterial space; (2) when an object is outside $2f_m$ in the metamaterial, its image is minified, inverted and virtual in the dielectric space; (3) when an object is between f_m and $2f_m$, its image is magnified, inverted and virtual in the dielectric space; (4) when an objects is outside the focus in the metamaterial, its image is magnified, erect and real in the dielectric space; (5) when an object is at $2f_m$, its image is inverted, virtual and has the same size as the object; (6) when an object is at f_m, its image is at infinity. These new behaviors, which do not exist in conventional optical lenses, extend the range of possibilities for imaging systems.

Table 1. Comparisons of NIM perfect lens, silver film superlens, far-field superlens, hyperlens and metalens.

Property \ Superlens	NIM perfect lens	Silver film Superlens	Far-field superlens	Hyperlens	Metalens
Super resolution	Yes	Yes	Yes	Yes	Yes
Shape and material	Slab NIM	Thin film silver	Thin film silver with built-in grating atop	Cylindrical metamaterial	Slab, shaped slab or GRIN metamaterial
Plane wave	Transmitted as plane wave, not focused	Transmitted, reflected as plane wave, not focused	Reflected, transmitted in different directions, not focused	Transmitted as somewhat converging waves, not truly focused	Transmitted and Focused
Phase compensation	No	No	No	No	Yes
Focal length	No	No	No	No	Yes, can be defined
Object	In the near field	In the near field	In the near field	In the near field	In the near field
Image	In the near field, directly formed	In the near field, directly formed	High resolution can be sent to the far field, image not directly formed	In the far field, directly formed	In the far field, directly formed
Image detection	Rely on non-optical imaging systems (AFM, SEM, NSOM, FIB, etc.)	Rely on non-optical imaging systems (AFM, SEM, NSOM, FIB, etc.)	Numerically reconstructed	Image directly detected by conventional optical imaging systems	Image directly detected by conventional optical imaging systems
Magnification	No	No	No	Yes	Yes
Fourier transform	No	No	No	No	Yes
Image reconstruction	No	No	Yes	No	No
Light frequency	At resonance	At resonance	At resonance	Close to resonance	Not at resonance
3D	Yes	Yes	Yes	Yes	Yes

6. Comparisons of the superlenses, discussions and perspectives

Since the advent of the perfect lens concept, we see that superlenses have been developed through five generations: the NIM perfect lens, the silver film superlens, the FSL, the hyperlens and finally the metalens, with properties closest to conventional optical lenses. Table 1 summarizes and compares the characteristics of the five generations of superlenses.

It can be seen that aside from the fact that all these superlenses can achieve super resolution, they all require the object to be in the near field, i.e., nearby or on the lens surface. This is because the high spatial frequency information is in the form of evanescent waves that can only be collected in the proximity of the object. It can be concluded that a dual far-field superlens with both object and image in the far field is not possible. Nevertheless, the metalens stands out with several advantages: its image can be directly formed in the field with magnification and thus can be directly detected by conventional optical systems with no need of numerical image reconstruction, and it can focus plane waves and thus can perform Fourier transforms. Therefore, a metalens truly works similar to a conventional optical lens, more precisely an SIL, enabling better compatibility with conventional optics. Along with the super resolution capability and the newly found imaging properties of hyperbolic metalenses, metalenses could have a profound effect on developing optical systems with novel functionalities and exceptional performance. The proof of concept of metalenses has been theoretically studied so far. Better resolution could be achieved by further optimization of material properties, geometric properties and wavelengths. Experimental demonstration of such devices would be needed to pave the way toward realistic applications, which requires subtle nanofabrication. As metalenses require metal involving metamaterials, losses, although not at resonance, would adversely affect their resolving performance and limit the size of the device. Furthermore, because of the focusing nature of metalenses, they are more efficient in energy concentration than hyperlenses, as the energy in a broader range of directions can converge to the focus at non-resonant frequencies. The field of view (FOV) of a metalens is theoretically limited to $2\mathrm{Re}\left(f_m\sqrt{\varepsilon_x}/\varepsilon_z\right)$ [21], which is usually small; on the order of or less than a few microns. In practice, the FOV is even much smaller due to the increased aberration at larger angles. Therefore, to increase the FOV of a metalens, f_m needs to be increased, which requires a larger device. The size of a metalens is restricted by the losses of metamaterial. It would be beneficial to develop low-loss metamaterials and to apply active mechanisms to reduce the losses [25], and thus enhancing the resolving power and FOV. It's worth noting that metalens concepts have been researched in 2D and the visible light band. They can be readily extended to 3D, to other light bands such as UV or IR, and to acoustic waves. These developments could find applications in numerous fields, such as nanolithography, nanoimaging, high density data storage, metrology, and medical imaging.

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