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Removal of absorption and increase in resolution in a near-field lens via optical gain

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A recent paper [J. B. Pendry, Phys. Rev. Lett. **85**, 3966 (2000)] showed how to construct a superlens that focuses the near-field radiation and, hence, produce an image resolution unlimited by wavelength. The prescription requires lossless materials with a negative refractive index: finite loss cuts off the finer details of the image. In this paper we suggest a compensation for the losses by introducing optical gain media into the lens design. Calculations demonstrate a dramatic improvement in performance for a silver/gain composite medium at optical frequencies.

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There are two sorts of electromagnetic radiation: near field and far field. The latter propagates as plane waves with a real wave vector, the former has an imaginary wave vector resulting in an exponential decay and therefore is confined to the vicinity of the source. Conventional lenses act only on the far field: focusing the near field requires amplification. Unfortunately for imaging purposes the finer details of an object are contained in the near field. Recently, it was shown[1] that how a "perfect lens" could be designed in which both the near and far fields could be persuaded to contribute to an image. The *perfect lens*[1] is just a slab of negative refractive material (NRM), where both the dielectric permittivity (ε) and the magnetic permeability μ are negative simultaneously ($n=-\sqrt{\varepsilon\mu}$ in this case):[2,3] a lens proposed earlier by Veselago[4] using a ray analysis for the propagating modes. The perfect lens amplifies the near field through a series of surface-plasmon resonances. In a lossless system, this process of amplification requires no energy input, other than that from the source, but in the presence of losses the performance of the lens rapidly degrades as the quality factor of the resonances deteriorates. For such a lens one requires negative ε and μ that are as free of loss as possible.[5]

Losses are the ultimate limiting factors for resolution and even a highly conducting metal such as silver, which was suggested in Ref. 1 as a near-field lens material at optical frequencies has a restricted performance. Redesigning the lens to minimize absorption will help to attain improved subwavelength resolution. We have earlier suggested how to use a large magnitude of the real part of ε[6] and to use a layered stack of alternating negative-positive dielectric layers.[7,8] This gives a greatly improved performance, but even in these systems losses eventually limit the resolution. Absorption in the lens materials will always limit the attainable subwavelength resolution in any implementation. One possibility that arises in optics is to use optical amplification to overcome absorption and this represents an interesting option to increase the subwavelength resolution of these superlenses. However, it is not obvious how to incorporate the optical amplification into the design of the perfect lens. Further, the influence of the optical amplification on the surface plasmons that are crucial to the operation of the perfect lens is not clear either. We note here that stimulated emission of surface plasmons in nanostructures has been proposed very recently.[9] In this Rapid Communication, we explore the possibility of compensating for the losses in silver by constructing a composite material consisting of alternate slices of silver and an optical gain material. Our conclusions are that considerable improvement in performance is possible by this means. This enables us to design a "fiber-optic bundle" that consists of a multilayer stack of alternating thin layers of lossy metal (silver) and an amplifying positive dielectric medium (an optically pumped semiconductor, for example) to transfer images with good subwavelength resolution across large stack thicknesses (of the order of a few wavelengths). Such a fiber-optic probe has the property of acting on the near-field evanescent components as well as the radiative components of a source.

First, let us carefully examine the operation of the perfect lens. The electromagnetic field in the two-dimensional object (x-y) plane can be conveniently decomposed into the Fourier components k_x, k_y, and k_z and polarization defined by σ:

$$E(x,y,z;t)=\sum_{k_x,k_y,\sigma} E_\sigma(k_x,k_y,k_z)\times\exp[i(k_x x+k_y y+k_z z-\omega t)], \quad (1)$$

where the source is assumed to be monochromatic at frequency ω, $k_x^2+k_y^2+k_z^2=\omega^2/c^2$, and c is the speed of light in free space. Obviously, when we move out of the object plane, the phase of the propagating radiative components (real k_z for $k_x^2+k_y^2<\omega^2/c^2$) and the amplitude of the nonpropagating evanescent components (imaginary k_z for $k_x^2+k_y^2>\omega^2/c^2$) change, and the image gets blurred. The perfect lens performs the dual function of correcting the phase of the radiative components as well as amplifying the near-field components, bringing both of them together to make a perfect image and thereby eliminating the diffraction limit on the image resolution. In general, the conditions under which this perfect imaging occurs are

$$\varepsilon_-=-\varepsilon_+, \quad \mu_-=-\mu_+, \quad (2)$$

where ε_- and μ_- are the dielectric permittivity and magnetic permeability of the NRM slab, respectively, and ε_+ and μ_+ are the dielectric permittivity and magnetic permeability of the surrounding medium, respectively. Under these conditions, the transmission coefficient of the slab is exactly $\exp(-ik_z d)$, where d is the thickness of the slab. We have earlier pointed out that these are precisely the conditions for the existence of surface-plasmon modes at the surface[1,6] and that it is sufficient to meet these conditions at any one of the interfaces to enable the amplification of evanescence in the slab.[6]

As it is difficult to obtain negative permeable media at optical frequencies, it was suggested in the original paper[1] that metals (such as silver) with negative permittivity alone could be good lens materials for *p*-polarized light. Particularly in the near-field limit, where $k_x^2+k_y^2 \gg \omega^2/c^2$, the electric and magnetic fields are independent of one another, if we confine our attention to electric fields, we have a simplified requirement for the function of the lens,

$$\varepsilon_- = -\varepsilon_+ , \tag{3}$$

with the magnetic permeability now becoming irrelevant. The performance of a silver lens is, however, limited by losses and the positive magnetic permeability. Their effects can be reduced by redesigning the lens as a multilayer stack of very thin alternating layers of metal (or NRM) and positive dielectric medium.[7,8] In Eq. (3) above we see the possibility that if ε_- is lossy, i.e.,

$$\mathrm{Im}(\varepsilon_-) > 0, \tag{4}$$

then the condition may still be satisfied, provided that

$$\mathrm{Im}(\varepsilon_+) < 0. \tag{5}$$

In other words, we need a medium that exhibits gain. Thus, the use of optical amplification is implied in the *perfect-lens condition* itself. Note here that keeping with the standard practice, we have subsumed all the processes relating to the amplification (or absorption) of the electromagnetic wave into the negative (or positive) imaginary part of the dielectric constant.

We approach this by considering the perfect-lens condition on the dielectric permittivity in Eq. (3). The dissipation which shows up as an imaginary part of the dielectric constant represents a deviation from the perfect lens condition, and limits the image resolution. To satisfy the perfect-lens conditions in both the real and the imaginary parts, we would require

$$\varepsilon_+ = \varepsilon_+' - i\varepsilon_+'' , \quad \varepsilon_- = -\varepsilon_+' + i\varepsilon_+'' . \tag{6}$$

In other words, the positive medium should be optically amplifying (as in a laser gain medium) in order to counter the effects of absorption in the negative medium. Then the perfect-lens conditions would be ‘‘perfectly’’ met and the perfect image would result, at least in the quasistatic limit. Now the surface states at the interface between the dissipative metal and an amplifying positive dielectric displays a very interesting behavior. There is a net flux of energy across the interface—from the positive amplifying medium into the absorbing negative medium. This is in contrast to the lossless (and gainless) system, where there is no net flux of energy normal to the interface, and the fields are purely evanescent. We should also note that such a cancellation of absorption in one location by generation in another is possible only because both absorption and amplification do not cause dephasing of the wave—a consequence due to the bosonic nature of light, which permits stimulated absorption and stimulated emission.

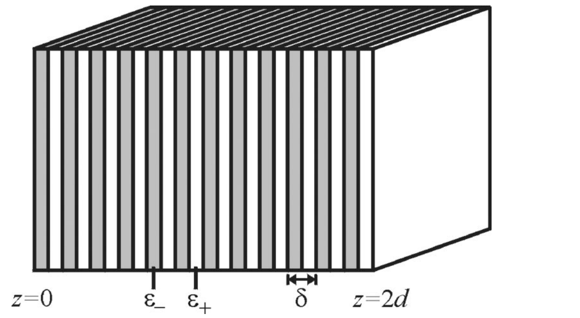

FIG. 1. Schematic of the layered structure considered here. The positive amplifying and negative dissipative dielectric layers are assumed to be of equal thickness $\delta/2$. The object and image planes are on either side of the stack at a distance of $\delta/4$ from the edges. The total length of the systen is $2d = N\delta$, where N is the number of layers with negative dielectric constant.

Now let us consider the layered system shown in Fig. 1, but with the gain included in the positive medium, so as to exactly counter the effects of absorption in the negative medium. This can, for example, be accomplished by using a semiconductor laser material such as GaN or AlGaAs for the positive medium and silver for the negative medium. Using blue/ultra-violet light to pump the AlGaAs, one can make the AlGaAs now optically amplifying in the red region of the spectrum, where one can satisfy the perfect-lens condition for the real parts of the dielectric constant. By adjusting the pump laser intensity, the imaginary part of the positive gain medium can be tuned. The imaging can now be carried out in red. Of course, it would be possible to use other materials and, correspondingly, different wavelengths of light. Alternatively, one could also use other high gain processes such as Raman gain for this purpose.

We show the transmission coefficient, calculated using the transfer matrix method,[10] for this layered medium with gain in Fig. 2. Our numerical calculations are exact and are not carried out in the near-field approximation. The transmission is large and comparatively flat (compared to the lossy passive case), almost up to the point k_x, where the transmission resonances for the corresponding lossless system occurs[6,7] and the transmission begins to decay exponentially. It is almost as if the effects of absorption have been canceled out. Further, it is almost independent of the total length of the stack. However, it does not result in an exact cancellation and this can be seen from the fact that the transmission resonances of a completely lossless (and gainless) system are not restored. One can see some remnants of these resonances for the case when $\varepsilon_- = -1 + i0.1$, and even lesser for the more absorptive (realistic for silver) case of $\varepsilon_- = -1 + i0.4$. But it is clear that the image resolution will be improved vastly and to an almost similar extent in both cases, regardless of the levels of absorption/gain, provided that the gain is large enough to compensate for the absorption. Thus, with amplification included, the deleterious aspect of absorption that it

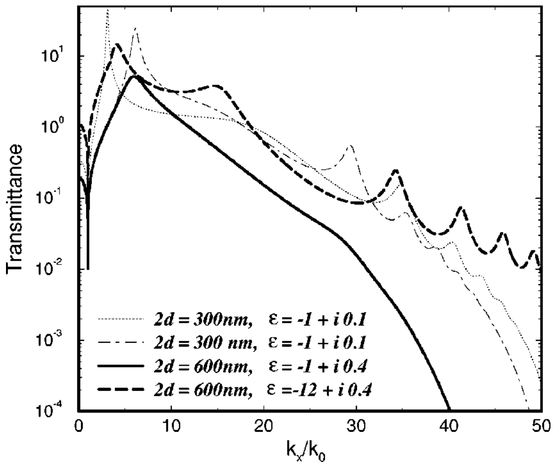

FIG. 2. The transmission coefficient for a layered stack of positive and negative dielectric layers when the positive media are optically amplifying. The thicknesses of the positive and the negative dielectric layers are $\delta/2 = 10$ nm.

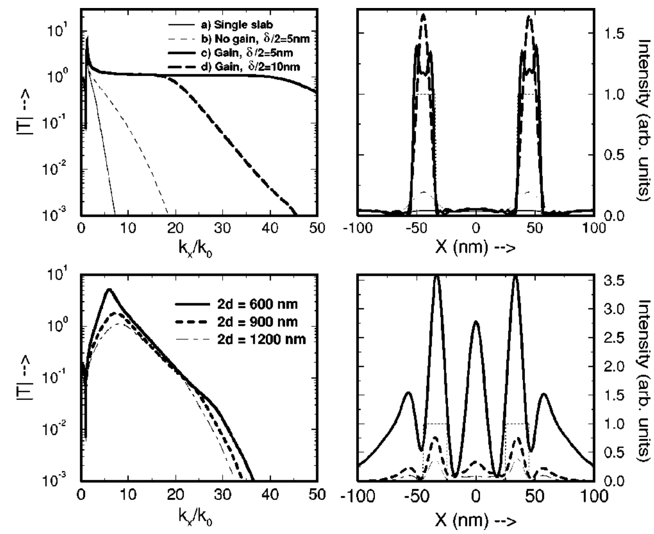

FIG. 3. Top panels: The transmission function (left) and the electromagnetic field intensity at the image plane (right) obtained (a) with a single slab of silver of 40 nm thickness, (b) when the slab is split into eight thin layers of $\delta/2 = 5$ nm thicknesses, (c) layered silver-dielectric stack with optical gain and $\delta/2 = 5$ nm and (d) layered silver-dielectric stack with optical gain and $\delta/2 = 10$ nm. $\varepsilon_{\pm} = \pm 1 \mp i0.4$ in (c) and (d). Bottom panels: For a layered stack of large total thickness with optical gain ($\varepsilon_{\pm} = \pm 1 \mp 0.4$) and $\delta/2 = 10$ nm for $2d = 600$ nm, 900 nm, and 1200 nm. The dotted lines show the position of the slit in the object plane

limits resolution, is canceled out while the desirable aspect that it softens the transmission resonances by preventing divergences is retained. Only the transmission resonance close to k_0 is relatively undamped. In Fig. 2, the transmission across a multilayer stack of 600 nm thickness is shown (the individual layers are of 10 nm thickness). We see that the transmission reduces only to 0.1 at $k_x/k_0 \sim 20$ for $\varepsilon_- = -1 + i0.4$ and an image with a resolution of about $\lambda/20$ can, in principle, be transferred across the distance of the order of λ (the wavelength of light). Note that the resolution can be marginally larger when the small transmission tail beyond is considered. The case when a high index dielectric such as AlGaAs is used and the wavelength is tuned to match the perfect-lens conditions $\varepsilon_{\pm} = \pm 12 \mp i0.4$, ($\lambda \simeq 578$ nm for silver), is also shown in Fig. 2. We should also note that making the layers thinner would improve the resolution even further, and we have been quite conservative in our choice of layer thickness. We show in Fig. 3 the transmission as a function of the parallel wave vector and the images obtained by such layered media with optical gain. The object consists of two slits of 20 nm width which are separated by 80 nm peak-to-peak distance. In the top panel we show the images for the case when the distance between the object plane to the image plane is $2d = 80$ nm. For comparision, we also show the case of the original single slab of silver as the lens (solid line and $\delta/2 = 40$ nm) and a layered but gainless system. The two peaks in the image for the single slab can hardly be resolved, while they are clearly resolved in the case of the layered system with no gain. The improvement in the image resolution for the layered system with gain over the corresponding gainless systems is obvious with the sharp edges of the slits becoming visible. In the bottom panel, we show the images formed by layered media with gain, but with very large total thicknesses of the order of few wavelengths ($2d = 600$ nm, 900 nm, and 1200 nm). For a lossy passive system, in comparision, almost nothing would be visible at such large distances from the source. In the case of the layered system with gain, although the slits in the image are well resolved, there are extra background structures that show up in the image corresponding to the larger transmission at smaller k_x. There is an overcompensation in the lens for (subwavelength) wave vectors in the range $k_0 < k_x < 10k_0$ due to the band of transmission resonances that are relatively undamped near k_0 and, hence, the transmission function is not constant with the wave vector. This overcompensated amplification also results in the large image intensity. We note that the effect of these resonances reduces for much larger thicknesses and the transmission function is actually more constant for thicker stacks. Although waves with very large wave vectors also get effectively amplified even for large stack thicknesses, the transmission resonances do not allow a clean image to be produced. We note, however, that since the high spatial frequency components are transferred across, knowledge of the transmission function of the lens would enable one to recover a clean image from the observed image. Alternatively, structuring the silver slabs in the transverse direction will create plasmonic band structures and one can engineer these band structures to inhibit the transmission resonances close to k_0. The transmission functions suggest that an image resolution of almost $\lambda/25$ could easily be achieved with these systems.

As a note of caution, we note that in the presence of intense field enhancements that are expected in this system, the gain is likely to get saturated. The largest field enhancements will be for the largest transverse wave vectors. If we make the layers very thin, the local field enhancements will not be as intense and the gain might not get completely bleached. In general, however, we do expect that the effective gain will be somewhat reduced and the corresponding enhancements of the image resolution will be smaller. Another point of concern is that the system with gain could become unstable[9] and undergo self-sustaining oscillations in the transverse direction due to spontaneous symmetry breaking. It is clear that such effects will be minimized for a system with very thin layers. We are analyzing the effects that are beyond the scope of this paper and those results will be presented elsewhere.

In conclusion, we have shown that a multilayer stack of thin alternating layers of silver and a positive amplifying dielectric medium with optical gain/amplification can transport evanescent waves with very little attenuation even over large stack thicknesses. This *optical-fiber bundle* can thus act on the evanescent near field of a radiating source and images with high subwavelength resolution can be transferred across. The potential applications are immense and range from nanoscale lithography to near-field optical imaging and data storage.

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