Restoration of s-polarized evanescent waves and subwavelength imaging by a single dielectric slab

Omar El Gawhary\textsuperscript{1,2}, Nick J Schilder, Alberto da Costa Assafrao, Silvania F Pereira and H Paul Urbach

Optics Research Group, Department of Imaging Science and Technology, Delft University of Technology, Lorentzweg 1, 2628 CJ Delft, The Netherlands
E-mail: o.elgawhary@tudelft.nl

\textit{New Journal of Physics} 14 (2012) 053025 (10pp)
Received 24 December 2011
Published 18 May 2012
Online at http://www.njp.org/
doi:10.1088/1367-2630/14/5/053025

\textbf{Abstract.} It was predicted a few years ago that a medium with negative index of refraction would allow for perfect imaging. Although no material has been found so far that behaves as a perfect lens, some experiments confirmed the theoretical predictions in the near-field, or quasi-static, regime where the behaviour of a negative index medium can be mimicked by a thin layer of noble metal, such as silver. These results are normally attributed to the excitation of surface plasmons in the metal, which only leads to the restoration of p-polarized evanescent waves. In this work, we show that the restoration of s-polarized evanescent waves and, correspondingly, sub-wavelength imaging by a single dielectric slab are possible. Specifically, we show that at $\lambda = 632$ nm a thin layer of GaAs behaves as a superlens for s-polarized waves. Replacing the single-metal slab by a dielectric is not only convenient from a technical point of view, it being much easier to deposit and control the thickness and flatness of dielectric films than metal ones, but also invites us to re-think the connection between surface plasmon excitation and the theory of negative refraction.

\textsuperscript{1} Also at: VSL Dutch Metrology Institute, Thijsseweg 11, 2629 JA Delft, The Netherlands.
\textsuperscript{2} Author to whom any correspondence should be addressed.
1. Introduction

The spatial information carried by an optical field is limited by the wavelength $\lambda$. Spatial details in an object that are subwavelength give rise to evanescent waves and are lost during propagation. Beating this limit represents the most challenging problem in imaging science and great effort is made to overcome it in both academia and industry. Different techniques have been proposed to obtain subwavelength imaging, among which the most successful is certainly near-field optical microscopy. Although the spatial resolution of near-field techniques can easily reach the nanometer scale, being limited not by diffraction but by the size of the probe used for detecting the near field, these techniques have the main drawback of being point by point scanning techniques, which makes them impractical for many applications.

Since the resolution limit stems from losing the contribution of the evanescent waves carried by an optical field, a method is needed that restores the amplitude and phase of these waves. Some years ago, it was proposed to restore their amplitude by using a single slab made of a material with negative relative electric permittivity $\varepsilon$ and negative relative magnetic permeability $\mu$ [1]. A medium like that, possessing a negative index of refraction $n$ and some of whose physical properties were already theoretically explored more than 30 years ago by the Russian physicist V Veselago [2], could restore the evanescent waves and would allow them to contribute to the formation of the image. Accordingly, the obtained image would have a subwavelength spatial resolution. While no natural material is known to have such properties, at optical frequencies noble metals could mimic such behaviour in the near-field regime. The argument is that, in the near field, electric and magnetic fields are essentially decoupled and one can replace the condition $n < 0$ by the less demanding $\varepsilon < 0$. This is exactly the case for noble metals at frequencies below their plasma frequency. Thus, a thin slab of silver will enhance the contribution of the evanescent waves, leading to super-resolved images. It was also noted that this can only happen when the metal interacts with p-polarized light, where the condition of having a negative $\varepsilon$ coincides with the physical excitation of surface plasmons in the metal. Actually, the argument can be mirrored to magnetic media as well, where one should have a medium with $\mu < 0$ and use s-polarized light as the source. A thorough review of the subject can be found in [3].

The theory of perfect lensing has given rise to a lively debate within the scientific community. In particular, strong criticisms were raised on the ill-posedness of the field propagation in such devices, suggesting that in reality the enhancement of evanescent waves, in an ideal negative index medium, would be hampered by the unavoidable presence of experimental noise [4]. On the other hand, recent experimental works on contact lithography seem to confirm the theoretical predictions on superlensing in the near-field regime [5–9] so that this controversial issue has been considered to be resolved [10, 11]. However, it is important
to point out that the criticism of the intrinsic ill-posedness of the field propagation in negative refraction media only applies to structures longer than the wavelength $\lambda$, which excludes all the cases that have been experimentally investigated so far. The aim of the present work is to show that similar superlensing effects can be obtained by a planar lens made of only a single homogeneous dielectric medium. It is shown that a thin layer of GaAs efficiently enhances the s-polarized evanescent waves contained in the angular spectrum of a subwavelength object to be imaged. While periodic nanostructures, made up of many layers of dielectric or metal–dielectric media, are known to be capable of reproducing some of the features of a metallic superlens [12–15], the possibility of getting subwavelength imaging by a much simpler structure (no periodic structures, no metals) is surely of practical interest. In fact, it is known that the problem of realizing a metal-based superlens resides in the difficulty of controlling the flatness of a thin slab of metal. Any roughness would be a source of additional surface plasmon excitation that would have detrimental effects on the quality of the image. On the other hand, roughness at levels attainable with currently available standard deposition techniques has negligible effects on the dielectric superlens treated in the present work. In the next section, we describe the main properties of such a dielectric superlens.

2. A single-medium dielectric superlens

For simplicity, and without loss of generality, from now on we will refer to the typical near-field superlens as that schematically shown in figure 1. In that figure, a homogeneous medium (medium 1) contains a subwavelength object (an infinite metallic grating) whose image has to be transferred, by the superlens (medium 2), to the image space (represented by medium 3 in the figure). In order to do that, a dielectric lens, made of GaAs, of thickness $d_2$ is interposed between the fused-silica and the photoresist layers. The distance between the grating and the interface fused-silica/GaAs is $d_1$. Note that $d_3$ represents the plane where the image of the grating is checked on the photoresist side. In the specific case we are going to discuss here, we have chosen $d_1 = 20$ nm, $d_2 = 35$ nm and $d_3 = 20$ nm, respectively. The photoresist (medium 3) is supposed to extend to distances much longer than $d_3$, which is the observation plane. The choice of this specific structure is intentionally made to facilitate comparison with the mentioned silver-based near-field experiments [5, 9].

As already mentioned, the image of the grating is intended to be transferred into the photoresist by illuminating the whole structure, from the bottom, with monochromatic light at $\lambda = 632.8$ nm. The incident field is s-polarized and at normal incidence on the grating. The chosen polarization for the incident field guarantees that no plasmons are excited in the chromium grating. In fact, for an infinitely periodic grating, and normal incidence, no p-polarized wave can be excited by an s-polarized wave incident upon the grating. Additionally, we will assume that the grating has period $L$, linewidth $w = L/2$ and height $h = 50$ nm. Before rigorously computing how such an incident optical field interacts with the structure, it is always useful to have a simple model that helps us to explain what are the physical mechanisms that lead to a given observation. For this reason, in figure 2 we plot the amplitude and phase of

3 At $\lambda = 632.8$ nm, the index of refraction of fused silica is $n_{SiO_2} = 1.457$ (the small absorption is neglected), that of gallium arsenide (GaAs) is $n_{GaAs} = 3.855 + i 0.1979$ and for the photoresist $n_{res} = 1.489$. The grating is made of chromium, with $n_{Cr} = 3.135 + i 3.310$. In the rigorous calculations, the resist layer has been supposed to be infinitely thick by using a simple matching layer (PML) as the boundary of the computational box.
Figure 1. General structure of a near-field superlens. The object to be imaged is a diffraction grating buried in medium 1 with period \( L \), linewidth \( w \) and height \( h \). The structure is illuminated from the bottom, at normal incidence. Medium 2, with index of refraction \( n_2 \), is the actual lens (in all previous works almost always silver) and the last medium 3, of index \( n_3 \), is the photoresist where the object will be imaged. The grating is usually a metal far from plasmon resonances. For the dielectric lens we consider here, the excitation of plasmons in the grating is prevented by using an s-polarized light as the incident field. \( d_1 \) denotes the distance between the object and the second medium of index \( n_2 \), \( d_2 \) is the thickness of the middle layer, while \( d_3 \) is the distance between the second medium and the image plane. Throughout the paper, medium 3 is considered to fill the whole upper half-space.

The total transmission coefficient \( t_s \) of the s-polarized incident electric field, as a function of the dimensionless wavenumber \( k_x / k_0 \), where \( k_0 = 2\pi / \lambda \) is the wavenumber in vacuum and \( k_x \) is the \( x \)-component of the wavevector perpendicular to the grating. For normal incidence, a grating of period \( L \) generates a discrete set of diffracted orders for which \( k_x = 2\pi m / L \), with \( m = 0, \pm 1, \pm 2, \ldots \). The different curves in figure 2, each one corresponding to a particular structure as shown on the left of the figure, were obtained by using the expressions for Fresnel transmission and reflection coefficients at each planar interface and then applying the classical multiple beam interference formula, as in a Fabry–Perot resonator [16]. The model clearly predicts (blue curve) the existence of a spectral region, with maximum transmission around \( k_x / k_0 = 2.5 \) and spatial spectral width \( 0.5k_0 \), where evanescent waves incident on the GaAs lens are enhanced. In order to confirm that this effect originates from the presence of the thin layer of GaAs, the same transmission function has been computed for different structures, but with GaAs either removed (figure 2, green curve) or replaced by a layer of the same thickness.
Transmission of the s-polarized electric field through different structures, as shown in figure 1, as a function of the transverse dimensionless wave component $k_x/k_0$. The solid blue curve refers to the structure with a middle layer of GaAs present. It is evident that the restoration of evanescent waves takes place in a band centred around the point $k_x = 2.5k_0$. The corresponding phase of the transmission function (dashed blue line) shows that at maximum transmission the phase of the transmitted field lies $\pi/2$ behind that of the incident one. To show that this effect is due to the presence of the thin layer of GaAs, the transmission function is plotted for other structures as well. The red curve corresponds to the case when GaAs is replaced by a layer of the same thickness, but made of fused silica. In the grey one, GaAs is replaced by silver. Finally, in the green curve the middle layer is removed. In all these cases, no enhancement occurs.

Figure 2. Transmission of the s-polarized electric field through different structures, as shown in figure 1, as a function of the transverse dimensionless wave component $k_x/k_0$. The solid blue curve refers to the structure with a middle layer of GaAs present. It is evident that the restoration of evanescent waves takes place in a band centred around the point $k_x = 2.5k_0$. The corresponding phase of the transmission function (dashed blue line) shows that at maximum transmission the phase of the transmitted field lies $\pi/2$ behind that of the incident one. To show that this effect is due to the presence of the thin layer of GaAs, the transmission function is plotted for other structures as well. The red curve corresponds to the case when GaAs is replaced by a layer of the same thickness, but made of fused silica. In the grey one, GaAs is replaced by silver. Finally, in the green curve the middle layer is removed. In all these cases, no enhancement occurs.
Figure 3. Transmission $|t_p|$ of a p-polarized wave through a silver slab (panel (a)) or a dielectric absorber (panel (b)) as a function of the slab thickness and the normalized wavenumber $k_x/k_0$, where $k_0 = 2\pi/\lambda$, $\lambda = 341$ nm being the wavelength of the incident field. The incident wave has amplitude one. Silver (or the dielectric absorber) is surrounded by two layers of PMMA (having roughly $n = 1.5$) of thickness $60$ nm each. The dielectric absorber is chosen to have index of refraction with an imaginary part identical to that of silver, while the real part is set equal to 2. The figure clearly shows a strong field enhancement for incident evanescent waves (surface plasmon excitation) in the case of silver with $k_x \in (1.5k_0, 1.7k_0)$ and a thickness for the silver slab below $25$ nm, which agrees well with what one would expect from a simple calculation of the penetration depth of surface plasmons in silver immersed in PMMA at $\lambda = 341$ nm ($\sim 28$ nm). This field enhancement is almost absent in panel (b) (except in a very narrow region around $k_x = 1.5k_0$), where silver is replaced by the hypothetical dielectric. On the other hand, one should note that for the thickness used in [18], namely $120$ nm, the amplitude of the transmitted evanescent waves in panel (a) never goes above $0.007$ and is even lower than the amplitude of the field transmitted by the dielectric absorber with the same thickness.

like to direct the reader’s attention. In [18], it has been experimentally shown that there is an improvement of the quality of the image of a submicron (please note: not subwavelength) object induced by a $120$ nm thick silver lens. In that case, the thin slab of silver was surrounded, on both sides, by PMMA layers of thickness $60$ nm each. The wavelength used was $\lambda = 341$ nm and the polarization was p-type. It is easy to check that, under those conditions, surface plasmons excited in silver have a penetration depth of about $28$ nm, which is less than one-fourth the total thickness of the silver slab. Thus, any field enhancement due to plasmons excitation should be barely visible in the transmitted field in this case and there should not be so much difference between using silver and using any other dielectric medium with a comparable level of absorption. In order to check this, we have computed the transmission for p-polarized waves of different wavenumbers $k_x$ and for different values of thickness of the silver slab (figure 3(a)). In figure 3 we also show (panel (b)) the field transmitted, under the same conditions, by a layer
made of a hypothetical dielectric absorber. This dielectric is chosen such that the imaginary part of its index of refraction coincides with the imaginary part of the index of refraction of silver. The real part of the index of refraction is set in such a way that that medium is a dielectric (in this case we set it equal to 2). The figure shows that the transmission for any evanescent wave, when \( d_{Ag} = 120 \text{ nm} \), is always below 0.007. This agrees well with what we predicted simply by looking at the plasmon penetration depth. More interestingly, figure 3(b) shows that a layer of the same thickness, but made of the aforesaid dielectric, leads to a comparable (actually even slightly higher) transmitted field. In this case no plasmons are excited, as clearly shown by the figure. This suggests that in the results reported in [18], surface plasmon excitation is not the origin of the observed image improvement. In contrast, such an image improvement seems to be more related to the excitation of guided modes into the lens, as discussed in recent works on the subject [13, 19].

As remarked above, when the object to be imaged by the superlens is a grating of period \( L \), the possible values for \( k_x \) (known as diffracted orders) are actually determined by the periodicity of the grating, that is, \( k_x = 2m\pi / L \), where \( m \) is an integer. In order to produce a proper image of the grating, the first diffracted order (for which \( m = 1 \)) surely has a fundamental role, compared to the higher orders. In fact, it is the first order that contains the main periodicity of the structure. Any lens that is not able to accurately image the first order will yield a degraded image of the grating. This means that one can predict how efficiently a grating can be transferred into the resist by looking at how the first diffracted order is transmitted through the whole structure. If the period of the grating is gradually changed, from values much larger than \( \lambda \) to subwavelength sizes, the quality of the image written in the resist should change as well. In particular, from the model described before, we expect that for some particular choice of the period the first order should be almost completely suppressed (namely, when \( L = \lambda / 1.95 \) for the lens we are studying here), while for smaller periods, one should see a recovery in the image quality. This rather counter-intuitive phenomenon, that subwavelength gratings can be imaged better than gratings with period larger than \( \lambda \), fully agrees with the experiments reported in [7, 8].

As a check of the correctness of the predictions obtained by the simplified model, we have rigorously simulated the interaction of the incident field with the GaAs superlens by using two different, and independent, rigorous solvers: one based on the finite element method (FEM) and the other based on the finite domain time domain (FDTD) approach. A benchmark of these two solvers is available in [20]. The computer simulations led to results that are in excellent agreement with each other. From the simulations, we have extracted the electric field profile inside the resist, 20 nm away from the interface with the GaAs layer. Gratings with different periods were considered, and for each case the visibility of the first diffracted order in the resist has been computed. One expects the visibility to be high (namely, close to 1) for gratings that are not subwavelength, since, in addition to the zeroth order, in this case there is always a first diffracted order reaching the image side. However, according to the transmission curve plotted in figure 2, the visibility should drop when the period of the grating approaches the critical value of \( \lambda / 1.95 \cong 324 \text{ nm} \). It should then become very high, for gratings having a period around \( L = 253 \text{ nm} \ (k_x/k_0 = 2.5) \), for which the first order is propagating in GaAs but is evanescent in fused silica and in the resist. Finally, it should monotonically decrease for periods smaller than that. All our theoretical predictions were confirmed by rigorous calculations, since the visibility curve behaves just as expected (black dashed line in figure 4(a)). For the reader’s convenience, we have included, in the same plot, the transmission coefficient \( |t| = |E_i / E| \) of the electric field between the input and output planes (blue curve in figure 4(a)). In the same image, we also

\[ \text{New Journal of Physics} \ 14 \ (2012) \ 053025 \ (\text{http://www.njp.org/}) \]
Figure 4. Visibility of the first diffracted order as a function of the period of the grating (panel (a), black dashed curve). The visibility is a positive quantity, always between 0 and 1, defined as \((I_{\text{max}} - I_{\text{min}})/(I_{\text{max}} + I_{\text{min}})\) where \(I = |E|^2\) is the field intensity. In the same figure, we show also the transmission of the electric field through the whole lens (panel (a), blue curve) computed using the approximated model described in the text. It is evident that the visibility, computed via rigorous electromagnetic solvers, follows the behaviour of the transmission curve. Two field profiles (within one period of the grating) into the whole structure (panels (b) and (d)), and the corresponding intensity profiles, extracted 20 nm away from the interface with GaAs (i.e. \(d_3 = 20\) nm), are also shown (panels (c) and (e)). In particular, when the first order is almost completely suppressed \((k_x/k_0 \approx 1.95, \text{panels (d) and (e)})\), the field profile is fully dominated by the second diffracted order (located at \(k_x/k_0 \approx 3.9\)), leading to a distorted image of the grating. In contrast, when the first order is efficiently amplified, the visibility gets very high \((k_x/k_0 \approx 2.5, \text{panels (b) and (c)})\) and the subwavelength grating is correctly imaged. For the reader’s convenience, we have also indicated, in panels (b) and (d), the grating and the interfaces between fused silica, GaAs and the resist by white dashed lines.

show the field intensity profiles, in the resist, for two choices of the pitch \(L\), corresponding to a maximum and a minimum of the visibility, respectively (panels (b)–(e)). As one can easily see, when the first order is almost suppressed the image in the resist is degraded, being dominated by the second diffraction order. In contrast, around the maximum of the transmission curve, the intensity profile is dominated by the first order, leading to a good image of the grating. It is worth emphasizing that the image of the grating, around this maximum, shows a visibility up to 0.9993, although it deals with a strongly subwavelength object. Considering that a visibility of
about 0.1 still leads to a good contrast in an image, figure 4 also shows that the superlens can be profitably used in a bandwidth larger than $k_0$, centred around $k_x = 2.5k_0$.

Also note that our prediction that the image and the object should have a $\pi/2$ phase shift in this case (as anticipated in the discussion on figure 2) was confirmed by rigorous calculations. In fact, in figures 4(b)–(e) we see that the positions where the image of the grating shows maxima for the intensity are located exactly in correspondence with the lines (instead of the grooves) of the grating, which contradicts what one would expect by applying simple geometrical optics arguments or the classical Kirchhoff boundary conditions, clearly not applicable in this situation.

3. Conclusions

To conclude, we have described a superlens based on a single GaAs slab that is able to enhance s-polarized evanescent waves, which is formally impossible by using the standard metal-based superlenses. The superlens we have proposed has the advantage of being less demanding in terms of surface flatness, since no surface plasmons are excited in a dielectric by some unwanted residual surface roughness. More importantly, the presented analysis has also indicated that the excitation of surface plasmons is not always the physical mechanism behind a superlensing effect. In fact, we have shown that these effects are obtained, theoretically or experimentally, either when no plasmons are excited (s-polarization, only dielectrics) or when the thickness of the lens is much larger than the plasmon penetration depth. Several materials can be found that lead to the same effect, working at different wavelengths, and the geometry can then also be engineered such that the evanescent part of the spectrum of strongly subwavelength objects is enhanced. We have described a model that predicts exceptionally well the rigorous behaviour of the superlenses. High-density optical data storage, optical lithography and subwavelength imaging in life science are just some of the possible fields where the outcomes of the present research can be profitably applied.

Acknowledgments

We thank Joseph Braat and Lieven Vandersypen (Delft University of Technology) for useful discussions and for revising the manuscript. We also thank Olaf Janssen and Arthur Wachters for providing us with the FDTD and FEM rigorous solvers and for help with the simulations. OEG and ACA acknowledge partial support from the European FP7 project SURPASS (SUper-Resolution Photonics for Advanced Storage Systems).

References

[1] Pendry J B 2000 Phys. Rev. Lett. 85 3966
[2] Veselago V G 1968 Sov. Phys.—Usp. 10 509–14
[3] Veselago V G, Braginsky L, Shklover V and Hafner C 2006 J. Comput. Theor. Nanosci. 3 1–30
[4] Garcia N and Nieto-Vesperinas M 2002 Phys. Rev. Lett. 88 207403
[5] Fang T N and Zhang X 2003 Appl. Phys. Lett. 82 161
[6] Fuji M, Freude W and Leuthold J 2008 Opt. Express 16 21039
[7] Fang N, Lee H and Sun C X 2005 Science 308 534
[8] Melville D O S and Blaikie R J 2005 Opt. Express 13 2127

New Journal of Physics 14 (2012) 053025 (http://www.njp.org/)
[9] Taubner T et al 2006 Science 313 1595
[10] Smith D R 2005 Science 308 502
[11] Kawata S, Inouye Y and Verma P 2009 Nature Photonics 3 388–94
[12] Li X, He S and Jin Y 2007 Phys. Rev. B 75 045103
[13] Mandatori A and Bertolotti M 2011 J. Eur. Opt. Soc. Rap. Public. 6 11004
[14] Pendry J B and Ramakrishna S A 2003 Physica B 338 329–32
[15] Luo C, Johnson S G, Joannopoulos J. D and Pendry J B 2003 Phys. Rev. B 68 045115
[16] Born M and Wolf E 2003 Principles of Optics 7th expanded edn (Cambridge: Cambridge University Press)
[17] Novotny L and Hecht B 2006 Principles of Nano-Optics (Cambridge: Cambridge University Press)
[18] Melville D O S, Blaikie R J and Wolf C R 2004 Appl. Phys. Lett. 84 4403–5
[19] Christensen J and Javier Garcia de Abajo F 2010 Phys. Rev. B 82 161103
[20] Lalanne P et al 2007 J. Eur. Opt. Soc. Rap. Public. 2 07022