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Bringing the ‘perfect lens’ into focus by near-perfect compensation of losses without gain media

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Abstract

In this paper, the optical properties and imaging performance of a non-ideal Pendry’s negative index flat lens with a practical value for loss are studied. Analytical calculations of the optical properties of the lens are performed, and those results are used to further study the lens and corresponding imaging system numerically. An inverse filter emulating the plasmon injection scheme for loss compensation in negative index metamaterials is applied to the results from the imaging system, resulting in a perfect reconstruction of a previously unresolved image that demonstrates sub-diffraction-limited resolution.

Introduction

Metamaterials provide unprecedented control of light for diverse applications such as wireless communications [1, 2], novel optical materials [3–8], optical analog simulators [9, 10], photovoltaics [11–13], quantum manipulation of light [14–16], and imaging [17–26], among many others. The extent to which an imaging system is capable of capturing high spatial frequency components of an incoming wave determines its resolution. Those components with spatial frequency greater than ω/c, where ω is the angular frequency of the wave and c is the speed of light in a medium, constitute evanescent modes that decay rather than propagate. In a conventional imaging system, the image detector is located far enough away from the source so that the evanescent modes are decayed beyond the sensitivity and noise level of the detector, i.e. in the far-field. Consequently, conventional imaging systems can only detect spatial frequencies up to ω/c. This is the so-called diffraction limit first discovered by Abbe [27]. In order to increase the resolution of imaging systems and retain spatial frequency components greater than ω/c, imaging with a slab of negative refractive index material was proposed [17]. This approach relies on the negative index material for focusing of propagating modes and amplification of evanescent modes incident on the slab. Unfortunately, current negative index metamaterial designs are not suitable for optical imaging due to the extreme sensitivity to absorptive losses in the constitutive components [28, 29]. A number of metamaterial loss compensation schemes using gain media have been proposed [30–35]. However, the use of gain media for loss compensation can result in instability and spasing [36].

Previously, a loss compensation scheme that provides full compensation in negative index metamaterials without the need for a gain medium was proposed, called the plasmon injection or Π scheme [25]. In the Π scheme, loss compensation is achieved by coherent excitation of the eigenmodes of a plasmonic negative index metamaterial by superimposing externally injected surface plasmon polaritons (SPPs) with the lossy domestic SPPs in the metamaterial [25, 37, 38]. Here, in analogy with optical amplifiers, the externally injected and domestic SPPs resemble the ‘pump’ and ‘signal,’ respectively. The plasmonic resonator structure presented in [25] is solely a proof-of-concept device that functions only for normal incidence. However, the underlying loss compensation mechanism can be generalized to any negative index metamaterial structure or even homogeneous material and arbitrary angle of incidence, as long as the physical configuration is such that the
Injected fields can be superimposed coherently with the eigenmodes of the metamaterial or the homogeneous material. In the supplemental material of [25], a brief analytical calculation is carried out to demonstrate how the II scheme could be applied to a flat silver superlens operating for a single polarization (i.e., so called ‘poor man’s superlens’ under the electrostatic limit as considered in [17]) to compensate the absorption losses in the superlens. Interestingly, this purely physical phenomenon for loss compensation in the superlens has been shown to be equivalent to a simple spatial filtering post-processing algorithm. However, no imaging procedure is carried out explicitly, nor is any demonstration of imaging with the II scheme intended in [25]. The question which naturally arises is ‘can we use the II scheme to enhance the performance of a metamaterial superlens, particularly Pendry’s negative index flat lens’ that is known to be extremely sensitive to losses [28–30, 39]. In the current work, we exactly answer this important question, which is not considered in [25]. Therefore in the present work we demonstrate, for the first time, application of the II scheme to sub-diffraction-limited imaging with a ‘non-ideal Pendry’s negative index flat lens’ (referred to as NIFL for short in the rest of the paper). By applying this loss compensation scheme, we achieve resolution of a previously unresolved sub-diffraction-limited object.

Unlike previous near-field negative index flat lens imaging systems, this technique does not benefit from a lossless negative index material and has no gain requirements. The technique developed here is based on a NIFL with a practical value for loss. Recently, a similar spatial filtering approach to counteracting losses was proposed which also considered tuning the material parameters of the NIFL and surrounding media [40]. However, the optimum values for loss in the NIFL that were assumed are around one to two orders of magnitude lower than what is used to obtain the imaging results presented here. Also, there is little deviation between the optimized material parameters for different spatial frequencies, which suggests the results may be sensitive to any small changes in those values.

Methods

Figure 1 shows the block diagram of the II scheme applied to imaging with a NIFL.

The procedure begins by producing an image with a NIFL. Then, a filter is applied to the image that compensates the attenuation of the high spatial frequency components. This compensation filter is the inverse of the NIFL transfer function, which can be calculated analytically or numerically. We should note that the method of inverse filtering is well known in the field of image processing, however there are two distinctions to be made between the work presented here and traditional inverse filtering. First, the method in this paper provides compensation for evanescent waves. Secondly, the compensation of these decayed evanescent waves is intimately related to a physical phenomenon for loss compensation in metamaterials as described in [25]. The remainder of this paper explains the methods used to perform the II scheme loss compensation procedure and form the resulting resolved image.

As previously mentioned, the transfer function of the NIFL can be found through either analytical or numerical calculation. Here, a numerical approach for determining the NIFL transfer function is presented. For any spatial frequency component, the transfer function can be described by the relationship between the electric field at the object plane and image plane. Therefore, in order to find the transfer function it is sufficient to send known plane waves with different spatial frequency \( k_y \), and measure the electric field at the image plane. Figure 2 shows the geometry for the NIFL transfer function calculation using the finite element commercial software package COMSOL Multiphysics. Periodic boundary conditions (PBC) are imposed on the top and bottom boundaries, however the simulation domain itself has limited extent in the \( y \)-direction. As a result of the applied PBC in the \( y \)-direction, \( k_y \) becomes a discretized quantity which can have values of \( k_y = \pm m \frac{2\pi}{W_y} \), where \( W_y \) is length of the simulation domain in the \( y \)-direction and integer \( m = 0, 1, 2, \ldots \). Therefore, an increase in \( W_y \) results in more accurate transfer function in terms of number of data points, but also increases the computational domain and in turn the simulation time.

![Figure 1. Block diagram of the II loss compensation scheme for imaging with a non-ideal Pendry's negative index flat lens.](image)
After defining the geometric parameters of the NIFL transfer function simulation, the next step is to define the optical properties of the NIFL itself. Consider $\varepsilon_r = -\varepsilon' + j\varepsilon''$ to be the relative complex permittivity and $\mu_r = -\mu' + j\mu''$ to be the relative complex permeability of the NIFL, where $\mu'$, $\mu''$, $\varepsilon'$, $\varepsilon'' \geq 0$ and $j = \sqrt{-1}$.

Then, the refractive index $n$ of the NIFL is

$$n = -\sqrt{\varepsilon_r \mu_r} = -(\varepsilon' \mu' - j(\mu' \varepsilon'' + \varepsilon' \mu'')) + \varepsilon'' \mu'')^{1/2}.$$ (1)

Since $\varepsilon'', \mu'' \ll \varepsilon', \mu'$, the $\varepsilon'' \mu''$ term can be neglected, and the expression for the refractive index is simplified to

$$n \approx -(\varepsilon' \mu' - j(\mu' \varepsilon'' + \varepsilon' \mu''))^{1/2} = -\sqrt{\varepsilon' \mu'} \left(1 - j \left(\frac{\varepsilon''}{\varepsilon'} + \frac{\mu''}{\mu'}\right)\right)^{1/2}. \quad (2)$$

Using the binomial approximation, equation (2) can be further reduced to

$$n \approx \sqrt{\varepsilon' \mu'} \left(1 + j \frac{1}{2} \left(\frac{\varepsilon''}{\varepsilon'} + \frac{\mu''}{\mu'}\right)\right). \quad (3)$$

If the real part of the relative permittivity and relative permeability are considered to be $-1$, the relations for the refractive index and impedance $z$ of the NIFL can be written as

$$n = n' + jn'' = -1 + jn'' \approx -1 + j \left(\frac{\varepsilon'' + \mu''}{2}\right) \quad (4)$$

and

$$z = \sqrt{\mu_r \varepsilon_r} = \sqrt{\left(-1 + j\mu''\right)^{1/2} \left(-1 + j\varepsilon''\right)^{1/2}} \approx 1 + j \frac{\varepsilon'' - \mu''}{2}. \quad (5)$$

Considering the result of equation (5), it can be seen that setting $\varepsilon'' = \mu''$ results in an impedance match with free space. However, the effect on the imaging performance of an impedance mismatch introduced when $\varepsilon'' \neq \mu''$ is small compared to the effect of the imaginary part of the refractive index $n''$ in equation (4), which characterizes the absorptive loss in the NIFL. As an example to illustrate this, consider the case of $\varepsilon'' = 0.2$ and $\mu'' = 0.1$. From equations (4) and (5), the resulting $n''$ would be 0.15, however the imaginary part of $z$ would be only 0.05. Therefore, for simplicity of analysis the case of $\varepsilon'' = \mu''$ can be chosen without much consideration of the effect of impedance mismatch. By inspection of figure 3, it can be determined that ideally the loss in the NIFL would be small in order to preserve the higher spatial frequency components of an image. Unfortunately, fabrication of negative index metamaterials with low loss operating at optical frequencies is difficult. Therefore,
an $n^n$ of $10^{-1}$ is selected for the rest of the analysis, which is reasonable given current fabricated structures [24]. This corresponds to a figure-of-merit of $[n'/n^n] = 10$. Although having such realistic loss levels in the base materials that form the NIFL is sufficient to benefit from the II scheme, any further improvement in the loss characteristics of the base materials using different techniques [12, 30, 41–44] can have a profound effect on the II scheme results.

To conclude the methods used here for characterization of the NIFL, a discussion of the effect of the NIFL thickness on the performance of the imaging system is required. Figure 4 shows the transfer function as the NIFL thickness $2d$ is changed from $\lambda_0/2 = 0.5 \mu m$ to $2\lambda_0 = 2 \mu m$. The results suggest the employment of a thinner NIFL will result in better imaging performance.

After characterizing the NIFL itself, the next step is to numerically evaluate the imaging performance. Figures 5(a) and (b) show the simulation geometry and material settings used to produce an image of some arbitrary object with the NIFL using COMSOL Multiphysics. The object is formed by defining the $z$-component of the electric field $E_z$ over the object plane, and image is produced by recording $E_z$ on the image plane.
figure 5(c), an object with three Gaussian features separated by 1 μm is defined on the object plane, and the corresponding electric field on the image plane is recorded. Figure 5(d) shows a surface plot of the resulting field distribution over the simulation domain.

This imaging simulation can be repeated to produce the image from any object with arbitrary feature size. Once the image is formed, the resolution can be improved by applying an inverse filter to emulate the Π scheme for compensation of losses in the NIFL.

**Results**

In order to improve the resolution of the image obtained by the NIFL, it is important to amplify the suppressed spatial frequency components. A compensation filter is required to undo this attenuation made by the imaging system. Obviously, a proper choice for the compensation filter would be the inverse of the imaging system transfer function. This corresponds to the Π scheme loss compensation technique for imaging, where a portion (i.e., pump or auxiliary object) of the total incident field in the object plane can be thought of as coherently exciting the underlying modes of the system in order to compensate the losses in the other portion (i.e., signal or actual object to be imaged) [25]. The equivalent is applying a filter in the spatial frequency domain that amplifies
the components with $k_y > k_0$. Figure 6(a) shows the compensation filter for the NIFL imaging system described in figure 5. As an example, an object with features separated by a distance $\lambda_0/4$, twice beyond the diffraction limit, was imaged by the NIFL. The results of this procedure are shown in figure 6(b). It can be seen that the sub-diffraction-limit features of the object are not resolved in the raw image produced by the NIFL. However, after applying the compensation filter a perfect reconstruction of the original object is achieved.

This procedure can be replicated for any arbitrary object field, provided that enough of the spatial frequency components required to reproduce the field are available to be compensated by the post-processing. Therefore, the limitation to the smallest feature size one could resolve with this technique would solely be the noise floor of the detection mechanism at the image plane, in this case the numerical simulation. Since inverse filtering is prone to noise amplification, it is required to roll off or truncate the filter at some spatial frequency where the noise floor is reached on the image plane. In figure 6(a), it can be seen that the raw image spectrum begins to flatten around $k_y = 2.5k_0 - 3k_0$. Therefore, simply truncating the filter at $3k_0$ gives a good compensated image that avoids noise amplification at high-$k_y$. It is important to note that truncating the filter in this way requires no a priori knowledge of the object; only the detected raw image is needed. While this noise limitation is present in practice, there is no theoretical limit imposed on the compensation scheme presented here.

The compensated image shown in figure 6(b) results solely from post-processing the raw image with the inverse filter in figure 6(a) without using any auxiliary source. To explain the link between the $\Pi$ scheme and such inverse filtering step, it can be shown that providing the appropriate auxiliary source with the original object field is equivalent to the inverse filter compensation scheme with no auxiliary source. By adding the auxiliary source, the imaging system is essentially being ‘pre-processed’ to physically inject high spatial
frequency components of the incident field at the necessary magnitudes to reconstruct the original object at the image plane. This is analogous to providing power to the auxiliary ports in the plasmonic structure presented in [25]. For the present imaging system, the total field incorporating the appropriate auxiliary field can be calculated from the compensated image spectra in figure 6(a) using the transfer function of the NIFL. The resultant auxiliary input field, which is simply the difference between the total field and the object field, is plotted in figure 7.

The images resulting from the inverse filter alone and total input are compared in figure 8. There is some small deviation in the two images, which can likely be attributed to the numerical methods used. In the case of the inverse filtered image with no auxiliary source, Maxwell’s equations are solved with the finite element method, and then that result is processed with discrete Fourier transforms. These two steps are also used to calculate the superposition of the original object and auxiliary input (i.e. total input), however the finite element method is again applied to obtain the resulting image. The accumulation of numerical error as the imaging system is solved multiple times could likely be the source of the small discrepancy between the sole inverse filter and total input images. Another source of error which is important to point out is the width of the auxiliary input field in the spatial domain. In figure 7, it can be seen that the auxiliary input has a width of 80 μm. This large aperture auxiliary input is used to calculate the image in figure 8(b) in order to minimize the error resulting from truncating the aperture size, however this error was observed to not have a strong effect on the image resolution after the width was increased to approximately 15 μm.

It can be hypothesized that the II scheme could be applied to compensation of decayed evanescent components in the absence of absorptive loss or negative index. To test this, calculations were performed to determine if the same compensation scheme can be applied to the loss of high spatial frequencies due to diffraction in free space. This was done by performing the same calculations as in figure 6, but with the NIFL replaced by free space. The results are shown in figure 9. In contrast to the NIFL imaging system where absorptive loss dominates the transfer function characteristics [28–30, 39], in this case diffraction dominates and the transfer function drops more steeply. Upon initial inspection of figure 9(a), the spatial frequencies $k_f/k_0 > 1$ which are lost due to diffraction in the raw image can be somewhat recovered, though only up to $k_f/k_0 \approx 1.9$ where the noise floor is reached. This is as expected, since the evanescent components of the image decay faster and the noise floor is reached at a smaller spatial frequency for free space compared to the NIFL imaging system, where despite some material absorption, the NIFL still provides amplification for the evanescent components with respect to the free space. Also, free space does not perfectly preserve the phase of the propagating field components as is the case for the NIFL imaging system. Consequently, the compensation scheme is less successful and works for a narrower band than with the NIFL as in figure 6, limiting the resulting resolution. This is evident in figure 9(b), where an attempt to recover the object with $\lambda_0/4$ feature size is unsuccessful. Therefore, the advantages of applying the compensation scheme with the NIFL instead of free space is that the NIFL preserves a larger band of spatial frequencies that can be recovered by the compensation scheme, and it also provides perfect phase compensation for the propagating field components with $k_f/k_0 < 1$. In other words, it is
still important to include the negative index slab in the imaging system in order to successfully reconstruct images with sub-diffraction-limited feature size. However, it would be possible to preserve more spatial frequency components of the free space image if the image plane is moved closer to the object plane.

Conclusion

In this paper, a study of the optical characteristics and near-field imaging performance of a NIFL with a practical value for loss was performed. The optical properties of the NIFL were investigated analytically, and a numerical calculation of the transfer function was performed and studied. The simulation results yielded an unresolved image from the NIFL, which subsequently underwent loss compensation using an inverse filter that emulates the II scheme from [25]. This involves the simple post-processing step of multiplying the raw image produced by the NIFL with the inverse of the transfer function in the Fourier domain. There are no requirements for electric or magnetic gain in the NIFL and surrounding media. The demonstrated result is a perfect reconstructed image with sub-diffraction-limited feature size. Our findings decouple the more-than-a-decade-long loss problem from the general problem of how to realize a practical ‘perfect lens’ operating in the optical frequencies, and reduce the problem mainly to amenable design and fabrication issues [45–52]. Further developments in

Figure 8. (a) Fourier spectra for the total input field incorporating the auxiliary field in figure 7 calculated for an object plane length of 15 μm (same simulation setup as figure 5) and image resulting from the total input. Fourier spectra for the original object, raw image produced by the NIFL with no auxiliary source, and the corresponding compensated image resulting from the inverse filter are reproduced from figure 6(a) for comparison. (b) Electric field intensities of the original object, image resulting from the total input field and the inverse filter with no auxiliary source are compared. Electric field intensity of the raw image (same as figure 6(b)) is also shown. It can be seen that the images from inverse filtering with no auxiliary source and the total input are equivalent with some small discrepancy in the total input image likely resulting from accumulated numerical error.
metamaterials and the II scheme approach can lead to advances in other applications besides ultra-high resolution imaging such as photolithography and optical storage technologies.

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References

[1] Bulu I, Caglayan H, Aydin K and Ozbay E 2005 New J. Phys. 7 223
[2] Odabasi H, Teixeira F L and Guney D O 2013 J. Appl. Phys. 113 084905
[3] Valentine J, Zhang S, Zentgraf T, Ulin-Avila E, Genov D A, Bartal G and Zhang X 2008 Nature 455 376
[4] Landy N I, Sajuyigbe S, Mock J J, Smith D R and Padilla W J 2008 Phys. Rev. Lett. 100 207402
[5] Temnov V V 2012 Nat. Photon. 6 728
[6] Aslam M I and Guney D O 2013 Prog. Electromagn. Res. B 47 203
[7] Zhang X, Ust E, Khan S K, Sadatgol M and Guney D O 2015 Prog. Electromagn. Res. 152 95
[8] Sadatgol M, Rahman M, Forati E, Levy M and Guney D O 2016 J. Appl. Phys. 119 103105
[9] Guney D O and Meyer D A 2009 Phys. Rev. A 79 063834
[10] Genov D A, Zhang S and Zhang X 2009 Nat. Phys. 5 687
[11] Rockstuhl C, Fahr S and Lederer F 2008 J. Appl. Phys. 104 123102
[12] Vora A, Gwamuri J, Pala N, Kulkarni A, Pearce J and Guney D O 2014 Sci. Rep. 4 4901
[13] Vora A, Gwamuri J, Pearce J M, Bergstrom P L and Guney D O 2014 J. Appl. Phys. 116 093103
[14] Al Farooqui M A, Bredland J, Aslam M I, Sadatoglu M, Oezdemir S K, Tame M, Yang I and Guney D O 2015 Opt. Express 23 17941
[15] Asano M, Bechu M, Tame M, Oezdemir S K, Ikuta R, Guney D O, Yamamoto T, Yang I, Wegener M and Imoto N 2015 Sci. Rep. 5 18313
[16] Jha P K, Ni X, Wu C, Wang Y and Zhang X 2015 Phys. Rev. Lett. 115 025501
[17] Pendry J B 2000 Phys. Rev. Lett. 85 3966
[18] Fang N, Lee H, Sun C and Zhang X 2005 Science 308 534
[19] Taubner T, Korobkin D, Urzhumov Y, Shvets G and Hillenbrand R 2006 Science 313 1595
[20] Liu Z, Lee H, Xiong Y, Sun C and Zhang X 2007 Science 315 1686
[21] Zhang X and Liu Z 2008 Nat. Mater. 7 435
[22] Rho J, Ye Z, Xiong Y, Yin X, Liu Z, Choi H, Bartal G and Zhang X 2010 Nat. Commun. 1 143
[23] Kehr S C et al 2011 Nat. Commun. 2 249
[24] Xu T, Agrawal A, Abashin M, Chau K J and Lezec H J 2013 Nature 497 470
[25] Sadatoglu M, Oezdemir S K, Yang I and Guney D O 2015 Phys. Rev. Lett. 115 35502
[26] Sun J, Shalaev M I and Litchinitser N M 2015 Nat. Commun. 6 7201
[27] Abbé E 1873 Arch. Mikr. Anat. 9 413
[28] Smith D R, Schurig D, Rosenbluth M, Schultz S, Ramakrishna S A and Pendry J B 2003 Appl. Phys. Lett. 82 1506
[29] Podolskiy V A and Narimanov E E 2005 Opt. Lett. 30 75
[30] Ramakrishna S A and Pendry J B 2003 Phys. Rev. B 67 201101
[31] Noginov M A, Podolskiy V A, Zhu G, Masy M, Bahoura J, Adegoke J A, Ritzo B A and Reynolds K 2008 Opt. Express 16 1385
[32] Xiao S, Drachev V P, Kildishev A V, Ni X, Chettiar U K, Yuan H K and Shalaev V M 2010 Nature 466 735–8
[33] Wuestner S, Pusch A, Tsakmakidis K L, Hamm J M and Hess O 2010 Phys. Rev. Lett. 105 127401
[34] Ni X, Ishii S, Thoreson M D, Shalaev V M, Han S, Lee S and Kildishev A V 2011 Opt. Express 19 25242
[35] Savelev R S, Shadrivov I V, Belov P A, Rosanov N N, Fedorov S V, Sukhorukov A A and Kivshar Y S 2013 Phys. Rev. B 87 115139
[36] Stockman M I 2011 Phys. Rev. Lett. 106 156802
[37] Guney D O, Koschny T and Soukoulis C M 2011 Phys. Rev. B 83 045107
[38] Aslam M I and Guney D O 2011 Phys. Rev. B 84 195465
[39] Koschny T, Moussa R and Soukoulis C M 2006 J. Opt. Soc. Am. B 23 485
[40] Chen Y, Hsieh Y C, Man M and Webb K J 2016 J. Opt. Soc. Am. B 33 445
[41] Guney D O, Koschny T and Soukoulis C M 2009 Phys. Rev. B 80 125129
[42] Tassin P, Zhang L, Koschny T, Economou E N and Soukoulis C M 2009 Phys. Rev. Lett. 102 053901
[43] Tassin P, Koschny T, Kafesaki M and Soukoulis C M 2012 Nat. Photon. 6 259
[44] Wang Y T, Cheng B H, Ho Y Z, Lan Y C, Luan P G and Tsai D P 2012 Opt. Express 20 22953
[45] Guney D O, Koschny T, Kafesaki M and Soukoulis C M 2009 Opt. Lett. 34 506
[46] Guney D O, Koschny T and Soukoulis C M 2010 Opt. Express 18 12348
[47] Soukoulis C M and Wegener M 2010 Science 330 1633
[48] Verhagen E, de Waale R, Kuipers L and Polman A 2010 Phys. Rev. Lett. 105 223901
[49] Soukoulis C M and Wegener M 2011 Nat. Photon. 5 523
[50] Vora K, Kang S Y, Shukla S and Mazur E 2012 Appl. Phys. Lett. 100 061120
[51] Vora K L 2014 Three-dimensional nanofabrication of silver structures in polymer with direct laser writing PhD Dissertation Harvard University
[52] Zhang X, Debnath S and Guney D O 2015 J. Opt. Soc. Am. B 32 1013