Impact of Non-Zero Effective Surface Sources on Negative Index Perfect Lenses

Weiguo Yang[1], Michael A. Fiddy[2]

[1]Department of Engineering & Technology, Western Carolina University, Cullowhee, NC 28723, USA

[2]Center for Optoelectronics and Optical Communications, University of North Carolina at Charlotte, Charlotte, NC 28223, USA

[1]wyang@email.wcu.edu; [2]fiddy@uncc.edu

***Abstract*-The widely accepted theoretical treatment of the electromagnetic boundary problem of evanescent wave refraction at an interface between a normal medium of $n=1$ and an ideal negative index medium of $n=-1$ seems to predict that the negative index of refraction would result in perfect lenses. The treatment, however, disregards the effects of non-zero surface potentials due to the nonlocal nature of surface optics at the microscopic level, and is self-inconsistent. This paper proposed to capture the microscopic non-zero surface potentials by introducing the macroscopic electromagnetic description non-zero effective surface current and charge densities at the interface. This treatment provides a self-consistent solution to the aforementioned electromagnetic boundary problem by finding the effective surface current and charge distributions, and after which solving the refracted and reflected fields analytically using Green's function method. The self-consistent solution yielded a transmission coefficient of 1 and reflection coefficient of 0 for all evanescent waves at this special interface, making it impossible for resonant amplification of those waves to occur.**

Keywords- Applied Classical Electromagnetism; Reflection and Refraction; Metamaterials; Surface Plasmon Polariton

I. INTRODUCTION

It is widely accepted that a slab of negative index medium (NIM) with $\epsilon=-1$ and $\mu=-1$ makes a perfect lens that transports all spatial frequency components of an object to the image plane without loss [1]. The concept of the negative index perfect lens has inspired an exciting new research field in negative index materials and, more generally, metamaterials as well as hyperbolic natural materials. These extraordinary materials have shown great promise in many breakthrough applications such as super-resolution imaging and invisibility cloaking [2-25]. Metamaterials have also shown potential in other practical applications such as electronically small antennas, enhancement of solar cell absorption, laser diode (LD) and light-emitting diode (LED) light extraction, photonic density of state engineering, and radiation control [26-30]. With advancements in nano-fabrication technology, metamaterials research has seen and will continue to see many more successful applications in the future. However, the widely accepted theory of the NIM perfect lens disregards the effect of non-zero surface potentials due to the nonlocal nature of surface optics at the microscopic level [31] and is therefore self-inconsistent. Initially, the surprising predication that a passive slab of negative index medium with $\epsilon=-1$ and $\mu=-1$ can amplify all evanescent waves was hotly debated. Hooft alleged that Pendry used incorrect arguments to arrive at his otherwise accurate conclusions [32]. Hooft also pointed out that, due to the amplification of the evanescent waves, the amplitude of the electric and magnetic fields grow extremely large and “can easily reach values beyond the breakdown of any material.” In reply, Pendry argued that the approach he took in his original paper was in accordance with multiple scattering theory as documented in textbooks and that because evanescent waves do not transport energy, energy conservation is not violated by amplification of evanescent waves [33]. This reply to the diverging energy density issue is unsatisfactory because, although evanescent waves do not transport energy, they do possess electro-magnetic field energy. With exponentially growing amplitude, the electromagnetic field energy density, due to the presence of these evanescent waves, grow exponentially, and this amplified electromagnetic field energy cannot be supported by a passive medium. The fact that evanescent waves possess electromagnetic energy was also pointed out by Williams [34, 35]. As early as 2002, Garcia and Nieto-Vesperinas [36-38] argued that although there is amplification of evanescent waves in ideal lossless, dispersive-less NIM, they still do not make a perfect lens since the effect is limited to the finite thickness of a slab, which prevents image forming. Furthermore, Garcia and Nieto-Vesperinas pointed out that any loss could dramatically diminish the evanescent wave amplification effect, and instead cause it to decay [38]. Smith and colleagues [39] also addressed the NIM issue and concluded that the loss may indeed pose a severe limitation to image resolution as well as the thickness of NIM slab lenses, limiting it to only a small fraction of a wavelength with any practical material loss. Much of these early debates were downcast, especially after experimental results by Liu, et al. [40], which indicated support for the amplification of evanescent waves in a silver slab, as originally suggested. Since 2008, the authors raised another issue regarding the perfect lens theory [41-43]. The issue centered on the realization that the usual textbook treatment of electromagnetic waves refraction and reflection at an interface used in Pendry's original paper [1] was self-contradictory when evanescent waves impinged upon the interface between air and ideal NIM of $\epsilon=-1$ and $\mu=-1$. However, this realization has not been well accepted so far. Only recently the realization has come that such inconsistencies are actually inherent in any system supporting surface electromagnetic fields including the air/NIM

DOI: 10.5963/JBAP0403003

interface at question here. For example, Feibelman has long believed that the usual theory of refraction and reflection is inadequate at the microscopic level due to its discontinuity, locality, and incompleteness [31]. At the microscopic level, a non-local theory has to be invoked, which leads to non-zero surface potentials [31]. This paper proposed to capture the microscopic non-zero surface potentials by introducing the macroscopic electromagnetic description non-zero effective surface current and charge densities at the interface. In the special case of evanescent wave reflection and refraction at the interface of air and an ideal NIM, exact effective surface current and charge distributions can be derived [43]. Accordingly, the transferred electromagnetic field can be solved analytically using Green's function method of knowing the effective macroscopic field sources at the boundary. This self-consistent solution yields a transmission coefficient of 1 and reflection coefficient of 0 for all evanescent waves. The same transmission and reflection can be obtained at both interfaces of a NIM slab for evanescent waves. In particular, due to the zero reflection at the interfaces, no multipath interference will build up inside the slab, as originally predicated [1]. As a result, it is believed that the evanescent waves will not be amplified by the NIM slab, but rather decay through it. Therefore, it was concluded that, contrary to popular belief, negative index of refraction does not make perfect lenses, as Pendry previously proposed.

In the following sections, the self-inconsistency in the original perfect lens theory that results from the underlying assumptions of the continuous tangential components of BOTH electrical and magnetic fields is presented. In Section III, the exact distributions of the effective surface current and charge densities are derived, and from these macroscopic effective source terms, the solutions to the refracted waves are given, followed by the transmission and reflection coefficients. It then can be shown that for all evanescent waves the transmission coefficient is 1 and the reflection coefficient is 0, which leads to the conclusion that the NIM slab does not make a perfect lens. Section IV focuses on the discussion of a popular alternative derivation of the original perfect lens theory that does not require the explicit reflection and transmission coefficients or the explicit summation of the multi-path interference of evanescent waves in the NIM slab, which, therefore, hides the explicit inconsistency of the original theory of the perfect lens as was pointed out in Section II. It is shown that the transport of evanescent waves in the NIM slab according to this implicit approach will still depend on the underlying assumptions of surface sources. Finally, the discussions are summarized in Section V, and comments on experimental studies that claim to verify the NIM perfect lens theory are presented.

II. SELF-CONTRADICTION IN THE PERFECT LENS THEORY

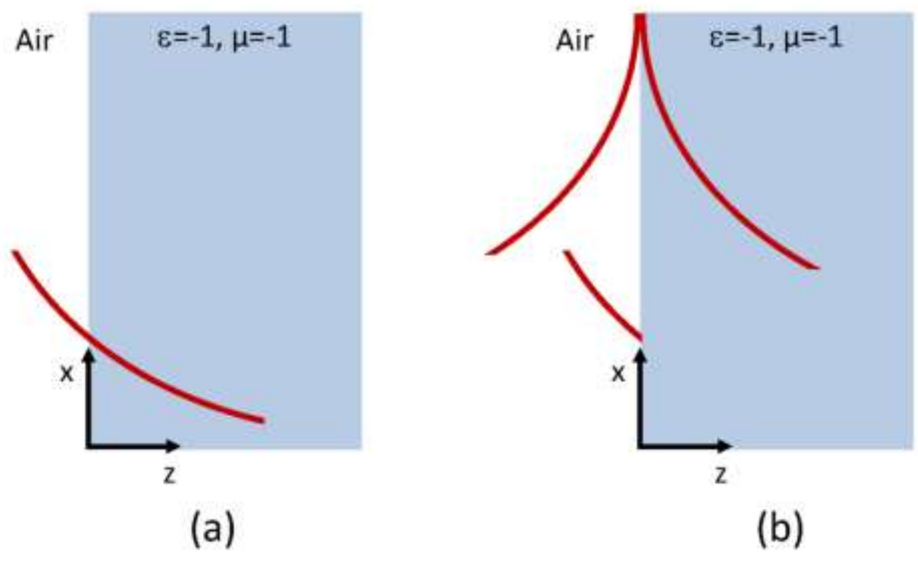

Fig. 1 Illustration of evanescent wave refraction at an interface between air and ideal NIM of $n=-1$: (a) Taking into account the non-zero effective surface sources, all evanescent waves have unit transmission and zero reflection; (b) Assuming continuous tangential components of both electrical and magnetic fields, the transmission and reflection coefficients diverge for all evanescent waves to infinitely large

Consider the case of an interface between air and an ideal NIM with the relative permittivity $\epsilon=-1$ and relative permeability $\mu=-1$, as shown in Fig. 1. Light propagates from left to right along the z-axis. Following the notation in Ref. [1], the S-polarized evanescent wave is first considered for which the electric field is given, by:

$$\mathbf{E}_{0S+}=[0,1,0]E_0\exp(ik_z z+ik_x x-i\omega t), \tag{1}$$

where the wave vector $k_z=+i\sqrt{k_x^2-k^2}$ and $k=\omega/c<|k_x|$. The electric field of the reflected evanescent waves is obtained in the following:

DOI: 10.5963/JBAP0403003

$$\mathbf{E}_{0S-} = r[0,1,0]E_0 \exp(-ik_z z + ik_x x - i\omega t), \tag{2}$$

and the electric field of the transmitted evanescent waves is as follows:

$$\mathbf{E}_{1S+} = t[0,1,0]E_0 \exp(ik_z z + ik_x x - i\omega t). \tag{3}$$

The choice of the sign of k_z in NIM, according to Ref. [1] takes into account the causality requirements that both the reflected and transmitted evanescent waves must decay away from the interface. Snell's law of refraction has also been applied to impose that k_x remains the same across the interface. Maxwell's equations relate the electric field to the magnetic field in the media. In air, $i\omega\mu_0\mathbf{H} = \nabla\times\mathbf{E}$, and in NIM ($\mu = -1$), $-i\omega\mu_0\mathbf{H} = \nabla\times\mathbf{E}$, as shown in the following:

$$\mathbf{H}_{0S+} = \frac{E_0}{\omega\mu_0}[-k_z, 0, k_x]\exp(ik_z z + ik_x x - i\omega t), \tag{4}$$

$$\mathbf{H}_{0S-} = \frac{rE_0}{\omega\mu_0}[k_z, 0, k_x]\exp(-ik_z z + ik_x x - i\omega t), \tag{5}$$

$$\mathbf{H}_{1S+} = \frac{tE_0}{\omega\mu_0}[k_z, 0, -k_x]\exp(ik_z z + ik_x x - i\omega t), \tag{6}$$

Ref. [1] assumed the ordinary boundary conditions, namely, both the tangential components of **E** and **H** are continuous. From Eqs. (1 - 6), this obviously yields $r+1=t$ and $r-1=t$, which are self-inconsistent.

For P-polarized evanescent waves, explicitly, for the input magnetic field, there is the following:

$$\mathbf{H}_{0P+} = [0,1,0]H_0 \exp(ik_z z + ik_x x - i\omega t), \tag{7}$$

The magnetic field of the reflected evanescent waves is as follows:

$$\mathbf{H}_{0P-} = r_H[0,1,0]H_0 \exp(-ik_z z + ik_x x - i\omega t), \tag{8}$$

and the magnetic field of the transmitted evanescent waves is as follows:

$$\mathbf{H}_{1P+} = t_H[0,1,0]H_0 \exp(ik_z z + ik_x x - i\omega t). \tag{9}$$

Assuming bulk electric current density is zero, Maxwell's equations give $-i\omega\epsilon_0\epsilon\mathbf{E} = \nabla\times\mathbf{H}$, as in the following:

$$\mathbf{E}_{0P+} = -\frac{H_0}{\omega\epsilon_0}[-k_z, 0, k_x]\exp(ik_z z + ik_x x - i\omega t), \tag{10}$$

$$\mathbf{E}_{0P-} = -\frac{r_H H_0}{\omega\epsilon_0}[k_z, 0, k_x]\exp(-ik_z z + ik_x x - i\omega t), \tag{11}$$

$$\mathbf{E}_{1P+} = \frac{t_H H_0}{\omega\epsilon_0}[-k_z, 0, k_x]\exp(ik_z z + ik_x x - i\omega t), \tag{12}$$

Similar to the S-polarization cases, self-inconsistent equations will again result from the ordinary continuous boundary conditions for both electrical and magnetic fields. Explicitly, for continuous tangential magnetic field boundary condition, one has $1 + r_H = t_H$, which is inconsistent with the continuous tangential electric field boundary condition that requires that $1 - r_H = -t_H$.

These self-contradictory equations resulted in both reflection and transmission coefficients diverging and, according to Ref. [1]'s approach, resulted in the amplification of evanescent waves going through the NIM slab via the multipath interference build-up of the evanescent waves.

DOI: 10.5963/JBAP0403003

III. NON-ZERO EFFECTIVE SURFACE CURRENTS AND SURFACE CHARGES

The usual theory of refraction and reflection based on the assumptions of continuous tangential components of both electrical and magnetic fields is inadequate and breaks down at a microscopic level due to its discontinuity, locality, and incompleteness [31]. Taking into account the non-local nature of the optical surface at the microscopic level, non-zero surface potentials may arise and result in various optical surface phenomena, including surface electromagnetic fields, which the air/NIM interface is capable of supporting [31]. At the macroscopic level, one can capture the effect of the non-zero surface potentials by introducing non-zero effective surface current and charge densities. When these effective field source terms are introduced, while the tangential component of the electric field is always continuous, the tangential component of the magnetic field may not be continuous if there is a non-zero effective surface current density. Similarly, the non-zero effective surface charge density will make the normal component of the electric field discontinuous at the macroscopic level. The effective source terms at the surface capture the effects of non-zero surface potentials at the microscopic level. In the following, the exact distributions of the effective surface current and charge densities are derived at the interface of air and ideal NIM of $n=-1$. Then, from these effective source terms, the refracted and transmitted waves can be calculated.

For S-polarized light input, since the normal components of the electric fields are zero in both media, it can be concluded that the effective surface charge density Σ remains zero. However, the effective surface current density may not be zero in evanescent wave refraction cases. In fact, assuming the effective surface current density is **K**, there is the following for the tangential components of the magnetic fields:

$$\mathbf{n}\times(\mathbf{H}_1-\mathbf{H}_0)=\mathbf{K} \tag{13}$$

where $\mathbf{n}$ is the unit surface normal vector pointing from air (medium 0) to the NIM (medium 1). Using Eq. (4) to Eq. (6) for the magnetic fields, one can derive that $K_x=0$, and the following:

$$K_y=\frac{k_z E_0}{\omega\mu_0}(t-r+1)\exp(ik_x x-i\omega t) \tag{14}$$

Since the boundary condition for the tangential component of the electric field is continuous, one still has $r+1=t$. Accordingly, one can conclude that for this special case,

$$K_y=\frac{2k_z E_0}{\omega\mu_0}\exp(ik_x x-i\omega t) \tag{15}$$

This expression gives the exact distribution of the effective surface current and is zero only when the input field is zero.

Following Green's function method [44-46], the vector potential in the NIM is as follows:

$$\mathbf{A}(\mathbf{r})=-\mu_0\int\int\mathbf{K}(\mathbf{r}')\frac{\exp\left(-ik\,|\mathbf{r}-\mathbf{r}'|\right)}{4\pi\,|\mathbf{r}-\mathbf{r}'|}dS' \tag{16}$$

and the electric field will be as:

$$\mathbf{E}=i\omega\mathbf{A} \tag{17}$$

Eq. (16) can be integrated analytically, which yields $A_x=A_z=0$ and the following:

$$A_y(x,y,z)=-\frac{k_z E_0}{\omega}\exp(ik_x x-i\omega t)\int_0^\infty J_0(k_x\rho)\frac{\exp\left(-jk\sqrt{\rho^2+z^2}\right)}{\sqrt{\rho^2+z^2}}\rho d\rho \tag{18}$$

where $J_0(x)$ is the Bessel function of the 0-th order. For $|k_x|>k$ and $z>0$, there is the following [47]:

$$A_y(x,y,z)=-\frac{k_z E_0}{\omega\sqrt{k_x^2-k^2}}\exp(ik_x x-i\omega t)\exp(-\sqrt{k_x^2-k^2}\,z) \tag{19}$$

Recall $k_z=+i\sqrt{k_x^2-k^2}$ for evanescent waves, as in:

DOI: 10.5963/JBAP0403003

$$A_y(x,y,z) = -\frac{iE_0}{\omega}\exp(ik_x x + ik_z z - i\omega t) \tag{20}$$

Therefore, using Eq. (17), for $z > 0$ in the NIM, $E_x = E_z = 0$ and the following:

$$E_y(x,y,z) = E_0 \exp(ik_x x + ik_z z - i\omega t) \tag{21}$$

Comparing this to Eq. (3), $t = 1$. Accordingly, $r = 0$. This analytical solution to the refraction and reflection of evanescent waves from air to the ideal NIM of $n = -1$ is completely self-consistent and satisfactory. The conclusion that $t = 1$ and $r = 0$ also agrees with the intuitive analysis where one can argue that since the wave impedance of air and the ideal NIM matches, no reflection of waves should be expected.

A similar analysis can be conducted for P-polarized evanescent waves. From Eqs. (7-12), the continuous tangential component of electric field boundary condition yields $-1 + r_H = t_H$. The effective surface current densities in this case can also be determined by $K_y = 0$ and the following:

$$K_x = 2H_0 \exp(ik_x x - i\omega t) \tag{22}$$

For the effective surface charge density Σ, there is the following:

$$\mathbf{n}\cdot(\mathbf{D}_1 - \mathbf{D}_0) = \Sigma. \tag{23}$$

Accordingly, from Eqs. (10-12) and $\epsilon = 1$ for air and $\epsilon = -1$ for the NIM, there is the following:

$$\Sigma = \frac{2H_0 k_x}{\omega}\exp(ik_x x - i\omega t) \tag{24}$$

It should be noted that these results are also self-consistent and satisfy the continuity equation $\nabla\cdot\mathbf{K} - i\omega\Sigma = 0$.

The vector potential field is still given by Eq. (16) and relates to the magnetic flux and the magnetic field in NIM as in the following:

$$\mathbf{B} = -\mu_0\mathbf{H} = \nabla\times\mathbf{A} \tag{25}$$

Following similar steps to those above, there is $z > 0$ in the NIM, $A_y = A_z = 0$, and the following:

$$A_x(x,y,z) = -\frac{i\mu_0 H_0}{k_z}\exp(ik_x x + ik_z z - i\omega t) \tag{26}$$

and there is also the following:

$$H_y(x,y,z) = -H_0 \exp(ik_x x + ik_z z - i\omega t) \tag{27}$$

Compared to Eq. (12), there is $t_H = -1$ and accordingly, $r_H = 0$.

A similar analysis can be conducted at the interface between the NIM and the air when evanescent waves impinge from the NIM side. The conclusion is the same in that all evanescent waves are transmitted and there is no reflection. Accordingly, a slab of NIM with $n = -1$ on the macroscopic scale, i.e., with a thickness that is many times that of the wavelength, behaves like the same thickness of air for any evanescent wave input, and there is no amplification effect for the evanescent waves. On the other hand, one can design a poor man's lens made of alternating negative-positive permittivity layers having an effective medium with zero permittivity, and hence, zero index. The resulting waves, including both propagating and evanescent waves, will simply tunnel through as if that volume of material is not present and assuming very low losses, which can lead to the perception that there is an improvement in resolution at a distance when in fact the phenomenon is better explained in terms of an effective shift of the object being imaged closer to the detector plane.

IV. IMPACT OF NON-ZERO EFFECTIVE SURFACE CURRENTS AND CHARGES

As mentioned in previous sections, it is obvious that the original derivation of a NIM slab perfect lens [1] is based on a set of self-inconsistent equations of reflection and transmission coefficients. When the actual required non-zero effective surface current and charge densities are considered, the ideal NIM of $n = -1$ does not provide the opportunity to amplify the evanescent waves or to make a perfect lens. An alternative derivation of the NIM slab perfect lens, however, does not explicitly

DOI: 10.5963/JBAP0403003

involve the self-inconsistent reflection and transmission coefficients, and sometimes is presented in favor of the NIM perfect lens. This approach is demonstrated here; it should be pointed out that it is still implicitly based on the underlying assumptions of zero effective surface current and surface charge densities. When the actual required non-zero effective surface current and charge densities were considered, the results were the same as those in previous sections in which no evanescent wave amplification was obtained through a NIM slab.

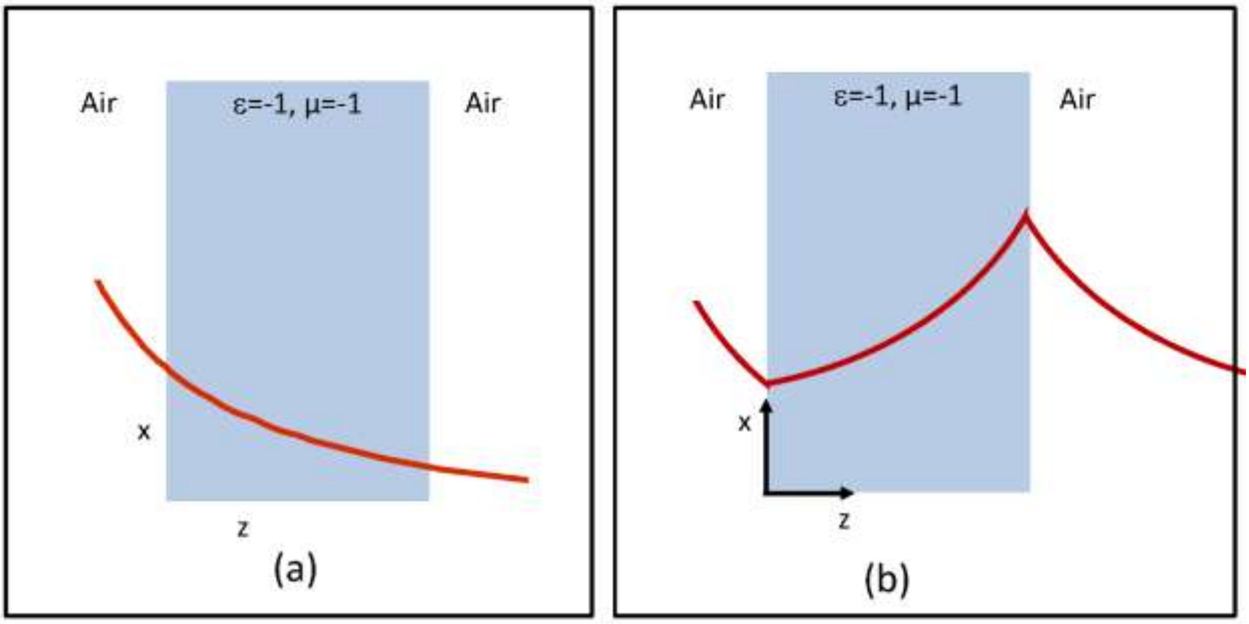

Fig. 2 Illustration of evanescent wave transport through an infinitely large slab in x direction of ideal NIM of $n=-1$. The NIM slab has a thickness of L and is sandwiched in air: (a) Taking into account the non-zero effective surface sources, all evanescent waves decay through the NIM slab; (b) Assuming continuous tangential components of both the electrical and magnetic fields, all evanescent waves are predicted to be amplified in the NIM slab

Referring to Fig. 2, the infinitely large NIM slab has a finite thickness of L. For S-polarization waves, the electric field can be expressed as in the following in Region 1, where $z<0$:

$$\mathbf{E}_{0S}=[0,1,0](e^{ik_z z}+Re^{-ik_z z})E_0\exp(ik_x x-i\omega t) \tag{28}$$

in Region 2, where $0<z<L$:

$$\mathbf{E}_{1S}=[0,1,0](Ae^{ik_z z}+Be^{-ik_z z})E_0\exp(ik_x x-i\omega t) \tag{29}$$

; and in Region 3, where $z>L$:

$$\mathbf{E}_{2S}=T[0,1,0]E_0\exp[ik_z(z-L)+ik_x x-i\omega t] \tag{30}$$

Accordingly, the magnetic fields can be found using the following in Region 1:

$$\mathbf{H}_{0S}=[-k_z(e^{ik_z z}-Re^{-ik_z z}),0,k_x(e^{ik_z z}+Re^{-ik_z z})]\frac{E_0}{\omega\mu_0}\exp(ik_x x-i\omega t) \tag{31}$$

as the following in Region 2:

$$\mathbf{H}_{1S}=[k_z(Ae^{ik_z z}-Be^{-ik_z z}),0,-k_x(Ae^{ik_z z}+Be^{-ik_z z})]\frac{E_0}{\omega\mu_0}\exp(ik_x x-i\omega t) \tag{32}$$

and as the following in Region 3:

$$\mathbf{H}_{2S}=T[-k_z,0,k_x]\frac{E_0}{\omega\mu_0}\exp[ik_z(z-L)+ik_x x-i\omega t] \tag{33}$$

DOI: 10.5963/JBAP0403003

The continuous tangential electrical field boundary condition at both $z=0$ and $z=L$ yields the following:

$$1+R=A+B, \tag{34}$$

and also the following:

$$Ae^{ik_zL}+Be^{-ik_zL}=T. \tag{35}$$

The continuous tangential magnetic field boundary condition at both $z=0$ and $z=L$ yields the following:

$$-1+R=A-B, \tag{36}$$

and also the following:

$$Ae^{ik_zL}-Be^{-ik_zL}=-T. \tag{37}$$

Solving Eqs. (34-37), one obtains $A=0$, $B=1$, $R=0$, and $T=\exp(-ik_zL)$. Given $k_z=+i\sqrt{k_x^2-k^2}$ for evanescent waves, one derives Pendry's original result that $T=\exp(|k_z|L)$, which implies that the NIM slab amplifies evanescent waves of all spatial frequency components.

Although the approach demonstrated above does not explicitly involve the diverging reflection and transmission coefficients of evanescent waves at individual interface of air and the NIM, it still relies on the underlying assumptions that the tangential magnetic fields are continuous across the interface between air and the NIM. In turn, this assumes that there are no effective surface charges or current densities. Obviously, the solutions to R, T, A, and B will change if there are non-zero effective surface currents and/or charge densities. For example, if one assumes the effective surface current density is given as $K_x=0$, $K_y=\frac{2k_zE_0}{\omega\mu_0}\exp(ik_xx-i\omega t)$, and accordingly, $\Sigma=0$ for the interface between air and the NIM ($z=0$), and $K_x'=0$, $K_y'=-\frac{2k_zE_0}{\omega\mu_0}e^{ik_zL}\exp(ik_xx-i\omega t)$, and $\Sigma=0$ at the interface $z=L$, then Eqs. (36-37) become the following:

$$A-B+1-R=2, \tag{38}$$

and

$$Ae^{ik_zL}-Be^{-ik_zL}+T=2e^{ik_zL}, \tag{39}$$

while Eqs. (34-35) and Eq. (37) stay the same. The solution, however, is now $R=0$, $T=e^{ik_zL}$, $A=1$, and $B=0$. Incidentally, these results are in agreement with the results presented in Section III, which indicate that the NIM slab will not amplify evanescent waves. Rather, all evanescent waves will simply decay through the NIM slab and will have no reflection.

This example demonstrates that the approach taken in this section cannot actually define R, T, A, or B by itself. The exact surface conditions at the microscopic level or the alternative effective surface current and surface charge density distributions must be known to yield an unequivocal solution using this approach when surface electromagnetic fields are involved, such as in the case discussed here.

Together with previous sections, the problem of evanescent wave refraction and reflection at an interface of air and an ideal NIM of $\epsilon=-1$ and $\mu=-1$ were resolved in detail. It was discovered that the previous treatments neglect the effect of non-zero surface potentials due to the nonlocal nature of the surface optics. This paper proposed to capture the microscopic non-zero surface potentials by introducing the macroscopic electromagnetic description non-zero effective surface current and charge densities at the interface. The self-consistent treatment provided here takes into account the potentially non-zero effective surface current and charge densities and yields the result that all evanescent waves are transmitted, and there is no reflection. The same conclusion holds at both interfaces of a NIM slab for evanescent waves. In particular, the zero reflection at both interfaces of an NIM slab also diminishes the multipath interference inside the slab. Consequently, there is no evanescent wave amplification in the NIM slab.

V. CONCLUSIONS

In summary, it was concluded that a fundamental inconsistency and mistake in the popular negative index perfect lens theory were identified. The widely accepted NIM perfect lens theory neglected possible non-zero surface potentials and non-local

DOI: 10.5963/JBAP0403003

effects at the surface between a normal medium of $n = 1$ and an ideal negative index medium of $n = -1$. Capturing these microscopic level effects by non-zero effective surface current and surface charge densities at the macroscopic level, the boundary problem of the evanescent wave refraction and reflection self-consistently were resolved and the exact distributions of the non-zero effective surface current and surface charge densities were derived when the evanescent wave was considered in special cases of air/NIM interfaces. The self-consistent solution is able to predict a unit transmission and zero reflection for all evanescent waves at such interfaces.

The conclusion here, however, is not in contradiction to other numerically simulated and experimentally demonstrated super-lens effects since the slab thickness in those studies was usually only a fraction of a wavelength, in which case surface electromagnetic fields in forms of surface plasma polaritons (SPP) can couple efficiently between the front and back interfaces. As such, the demonstrated super-lens effects, or the transport of evanescent wave components, may be purely due to the SPP coupling [48], rather than the evanescent wave amplification of the NIM slab.

REFERENCES

[1] J. B. Pendry, "Negative refraction makes a perfect lens," *Phys. Rev. Lett.*, vol. 85, no. 18, pp. 3966-3969, October 2000.

[2] David R. Smith, "APPLIED PHYSICS: how to build a superlens," *Science*, vol. 308, no. 5721, pp. 502-503, 2005.

[3] Nicholas Fang, Hyesog Lee, Cheng Sun, and Xiang Zhang, "Sub-diffraction-limited optical imaging with a silver superlens," *Science*, vol. 308, no. 5721, pp. 534-537, 2005.

[4] Thomas Taubner, Dmitriy Korobkin, Yaroslav Urzhumov, Gennady Shvets, and Rainer Hillenbrand, "Near-field microscopy through a SiC superlens," *Science*, vol. 313, no. 5793, p.1595, 2006.

[5] Igor I. Smolyaninov, Yu-Ju Hung, and Christopher C. Davis, "Magnifying superlens in the visible frequency range," Science, 315(5819):1699–1701, 2007.

[6] E. Cubukcu, K. Aydin, E. Ozbay, S. Foteinopolou, and C. M. Soukoulis, "Subwavelength resolution in a two-dimensional photonic-crystal-based superlens," *Phys. Rev. Lett.*, vol. 91, no. 20, p. 207401, November 2003.

[7] Hyesog Lee, Yi Xiong, Nicholas Fang, Werayut Srituravanich, Stephane Durant, Muralidhar Ambati, Cheng Sun, and Xiang Zhang. "Realization of optical superlens imaging below the diffraction limit," *New Journal of Physics*, vol. 7, p. 255, 2005.

[8] David Melville and Richard Blaikie, "Super-resolution imaging through a planar silver layer," Opt. Express, vol. 13, no. 6, pp. 2127-2134, 2005.

[9] D. Schurig, J. J. Mock, B. J. Justice, S. A. Cummer, J. B. Pendry, A. F. Starr, and D. R. Smith, "Metamaterial electromagnetic cloak at microwave frequencies," *Science*, vol. 314, no. 5801, pp. 977-980, 2006.

[10] Wenshan Cai, Uday K. Chettiar, Alexander V. Kildishev, and Vladimir M. Shalaev, "Optical Cloaking with Non-Magnetic Metamaterials," [Online]. Available: arxiv.org/pdf/physics/0611242, 2006.

[11] Wenshan Cai, Uday K. Chettiar, Alexander V. Kildishev, Vladimir M. Shalaev, and GraemeW. Milton, "Nonmagnetic cloak with minimized scattering," *Applied Physics Letters*, vol. 91, no. 11, p. 111105, 2007.

[12] Wenshan Cai, Uday K. Chettiar, Alexander V. Kildishev, and Vladimir M. Shalaev, "Designs for optical cloaking with high-order transformations," *Opt. Express*, vol. 16, no. 8, pp. 5444-5452, 2008.

[13] Steven A. Cummer, Bogdan-Ioan Popa, David Schurig, David R. Smith, and John Pendry, "Full-wave simulations of electromagnetic cloaking structures," *Physical Review E* (Statistical, Nonlinear, and Soft Matter Physics), vol. 74, no. 3, p. 036621, 2006.

[14] Zhichao Ruan, Min Yan, Curtis W. Neff, and Min Qiu, "Ideal cylindrical cloak: Perfect but sensitive to tiny perturbations," *Physical Review Letters*, vol. 99, no. 11, p. 113903, 2007.

[15] Zhaowei Liu, Hyesog Lee, Yi Xiong, Cheng Sun, and Xiang Zhang, "Far-field optical hyperlens magnifying sub-diffraction limited objects," *Science*, vol. 315, no. 5819, p. 1686, 2007.

[16] Anthony Grbic, Lei Jiang, and Roberto Merlin, "Near-field plates: Subdiffraction focusing with patterned surfaces," *Science*, vol. 320, no. 5875, pp. 511-513, 2008.

[17] Alessandro Salandrino and Nader Engheta, "Far-field subdiffraction optical microscopy using metamaterial crystals: Theory and simulations," *Physical Review B* (Condensed Matter and Materials Physics), vol. 74, no. 7, p. 075103, 2006.

[18] Michael Scalora, Giuseppe D'Aguanno, Nadia Mattiucci, Mark J. Bloemer, Domenico de Ceglia, Marco Centini, Antonio Mandatori, Concita Sibilia, Neset Akozbek, Mirko G. Cappeddu, Mark Fowler, and Joseph W. Haus, "Negative refraction and sub-wavelength focusing in the visible range using transparent metallo-dielectric stacks," *Opt. Express*, vol. 15, no. 2, pp. 508-523, 2007.

[19] B. Wood, J. B. Pendry, and D. P. Tsai, "Directed subwavelength imaging using a layered metal-dielectric system," *Physical Review B* (Condensed Matter and Materials Physics), vol. 74, no. 11, pp. 115116, 2006.

[20] Alexander Poddubny, Ivan Iorsh, Pavel Belov, and Yuri Kivshar, "REVIEW: Hyperbolic metamaterials," *Nature Photonics*, vol. 7, pp. 948-957, 2013.

[21] Jingbo Sun, Natalia M. Litchinitser, and Ji Zhou, "REVIEW: Indefinite by Nature: From Ultraviolet to Terahertz," ACS Photonics, vol. 1, no. 4, pp. 293-303, 2014.

[22] R. Macedo, R. Rodrigues da Silva, T. Dumelow, and J. A. P. da Costa, "MgF2 as a material exhibiting all-angle negative refraction and subwavelength imaging due to the phonon response in the far infrared," Optics Communications, vol. 30, pp. 94-99, 2014.

[23] Moritz Esslinger, Ralf Vogelgesang, Nahid Talebi,Warawut Khunsin, Pascal Gehring, Stefano de Zuani, Bruno Gompf, and Klaus Kern, "Tetrasymites as Natural Hyperbolic Materials for the Near-Infrared to Visible," ACS Photonics, vol. 1, no. 12, pp. 1285-1289, 2014.

[24] Jingbo Sun, Ji Zhou, Bo Li, and Feiyu Kang, "Indefinite permittivity and negative refraction in natural material: Graphite," Applied

DOI: 10.5963/JBAP0403003

Physics Letters, vol. 98, p. 101901, 2011.

[25] R. Macedo, and T. Dumelow, “Tunable all-angle negative refraction using antiferromagnets,” *Physical Review B*, vol. 89, p. 035135, 2014.

[26] Andrea Alu and Nader Engheta, “Achieving transparency with plasmonic and metamaterial coatings,” *Physical Review E* (Statistical, Nonlinear, and Soft Matter Physics), vol. 72, no. 1, p. 016623, 2005.

[27] Alexander A. Govyadinov and Viktor A. Podolskiy, “Metamaterial photonic funnels for subdiffraction light compression and propagation,” *Physical Review B* (Condensed Matter and Materials Physics), vol. 73, no. 15, p. 155108, 2006.

[28] Z. Jacob, I. Smolyaninov, and E.E. Narimanov, “Single photon gun: Radiative decay engineering with metamaterials,” Frontiers in Optics 2009/Laser Science XXV/Fall 2009 OSA Optics & Photonics Technical Digest, paper PDPB6, 2009.

[29] M. A. Noginov, H. Li, Yu A. Barnakov, D. Dryden, G. Nataraj, G. Zhu, C. E. Bonner, M. Mayy, Z. Jacob, and E. E. Narimanov, “Controlling spontaneous emission with metamaterials,” *Opt. Lett.*, vol. 35, no. 11, pp. 1863-1865, 2010.

[30] Kirill Sinchuk, Richard Dudley, John D. Graham, Michael Clare, Mesfin Woldeyohannes, John O. Schenk, Robert P. Ingel, Weiguo Yang, and Michael A. Fiddy, “Tunable negative group index in metamaterial structures with large formbirefringence,” *Opt. Express*, vol. 18, no. 2, pp. 463-472, 2010.

[31] Peter J. Feibelman, “Surface electromagnetic fields,” *Progress in Surface Science*, vol. 12, pp. 287-408, 1982.

[32] J. B. Pendry and D. R. Smith, Comment on “wave refraction in negative-index media: Always positive and very inhomogeneous,” *Phys. Rev. Lett.*, vol. 90, no. 2, p. 029703, January 2003.

[33] John Pendry, Pendry replies: Phys. Rev. Lett., vol. 87, no. 24, p. 249702, November 2001.

[34] John Michael Williams, “Some problems with negative refraction,” Phys. Rev. Lett., vol. 87, no. 24, p. 249703, November 2001.

[35] John Pendry. Pendry replies: Phys. Rev. Lett., vol. 87, no. 24, p. 249704, November 2001.

[36] N. Garcia and M. Nieto-Vesperinas, “Left-handed materials do not make a perfect lens,” Phys. Rev. Lett., vol. 88, no. 20, p. 207403, May 2002.

[37] M. Nieto-Vesperinas and N. Garcia, Nieto-vesperinas and garcia reply: Phys. Rev. Lett., vol. 91, no. 9, p. 099702, August 2003.

[38] Manuel Nieto-Vesperinas, “Problem of image superresolution with a negative-refractive-index slab,” J. Opt. Soc. Am. A, vol. 21, no. 4, pp. 491-498, April 2004.

[39] David R. Smith, David Schurig, Marshall Rosenbluth, Sheldon Schultz, S. Anantha Ramakrishna, and John B. Pendry, “Limitations on subdiffraction imaging with a negative refractive index slab,” Applied Physics Letters, vol. 82, no. 10, pp. 1506-1508, 2003.

[40] Zhaowei Liu, Nicholas Fang, Ta-Jen Yen, and Xiang Zhang, “Rapid growth of evanescent wave by a silver superlens,” Applied Physics Letters, vol. 83, no, 25, pp. 5184-5186, 2003.

[41] W. Yang, J. O. Schenk, and M. A. Fiddy, “Revisiting perfect lens: Negative refraction does not make a perfect lens,” arXiv.org:0807.1768, 2009.

[42] Weiguo Yang, J.O. Schenk, and M.A. Fiddy, “Revisiting the perfect lens with loss,” In IEEE SoutheastCon 2010 (SoutheastCon), Proceedings of the, pp. 302-304, March 2010.

[43] Weiguo Yang and Michael A. Fiddy, “Impact of surface current on perfect lens,” In IEEE SoutheastCon 2013 (SoutheastCon), Proceedings of the, April 2013.

[44] J. D. Jackson, *Classical Electrodynamics*, John Wiley & Sons, 2nd edition, 1975.

[45] Roger Harrington, *Field Computation by Moment Methods*, IEEE Press, 1993.

[46] Walton C. Gibson, *The Method of Moments in Electromagnetics*, Taylor & Francis Group, 2008.

[47] I. S. Gradshteyn and I. M. Ryzhik, *Table of Integrals, Series, and Products*, Academic Press, Elsevier, 7th ed. edition, 2007.

[48] Yun-Song Zhou, Huai-YuWang, and HaiWang, “Zero refraction in natural materials and the mechanism of metal superlens,” EPL (Europhysics Letters), vol. 98, no. 6, p. 67005, 2012.

DOI: 10.5963/JBAP0403003