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Sub-wavelength imaging with a left-handed material flat lens

Michael W. Feise, Yuri S. Kivshar *

Nonlinear Physics Centre and Centre for Ultra-high bandwidth Devices for Optical Systems (CUDOS), Research School of Physical Sciences and Engineering, Australian National University, Canberra, ACT 0200, Australia

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Abstract

We study numerically, by means of the pseudospectral time-domain method, the unique features of imaging by a flat lens made of a left-handed metamaterial that possesses the property of negative refraction. We confirm the earlier finding that a left-handed flat lens can provide near-perfect imaging of a point source and a pair of point sources with clear evidence of sub-wavelength resolution. We illustrate the limitation of the resolution in the time-integrated image due to the presence of surface waves.

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The unique properties of left-handed (LH) materials [1], i.e., materials with simultaneously negative real parts of the dielectric permittivity ϵ_r and the magnetic permeability μ_r (which can also be described by a negative index of refraction), allow focusing of electromagnetic waves by a flat slab of the material; this effect is in sharp contrast to conventional optical lenses with a positive refractive index that need to have curved surfaces to form an image. Recently, Pendry [2] argued that a slab of a lossless LH material with $\epsilon_r = \mu_r = -1$ should behave as a perfect lens enabling one to obtain an ideal image of a point source through the reconstitution of the evanescent wave components. While recent experiments confirmed the main features of negative refraction [3,4], the question of near-perfect imaging of a flat lens and near-field focusing has remained highly controversial [5], and is severely constrained because of large dissipation and anisotropy in the metamaterial. Nevertheless, several studies showed that nearly-perfect imaging should be expected even under realistic conditions when both dispersion and losses of the left-handed material are taken into account [6–10].

* Corresponding author.
E-mail address: ysk124@rsphysse.anu.edu.au (Y.S. Kivshar).
URL: http://www.rsphysse.anu.edu.au/nonlinear/.

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In this Letter, we re-visit the problem of nearly perfect imaging by a flat lens made of a left-handed metamaterial and study numerically, by use of the pseudospectral time-domain method, imaging by a flat lens made of this material. In order to study the amplification of the evanescent waves, we compare the wave-vector spectra of the field at the image plane in the case with and without the LH slab. We confirm the earlier finding that a left-handed flat lens can provide near-perfect imaging of a point source [7] and a pair of point sources with clear evidence of sub-wavelength resolution. In addition we consider the time-resolved and time-integrated Poynting vector at the source frequency which behaves equivalently to the time-integrated intensity that may be relevant in lithography applications.

We model an electrical line current source in front of a slab of LH material embedded in free space, as shown in Fig. 1. The system is translationally invariant in the z direction and is treated as two-dimensional. The simulations are performed in TE polarization ($H_x, H_y, E_z \neq 0$). In the y direction the system is considered open, as achieved through reflectionless absorbing boundaries, while the x direction is taken as periodic. Because of this the simulation essentially uses an infinite slab and an array of sources.

It has been shown that a material with left-handed character can only be achieved through dispersion [1]. Therefore, the LH material is assumed to have lossy Drude characteristics in both electric permittivity and magnetic permeability [2], given by

$$\varepsilon_r(\omega) = 1 - \frac{\omega_{pe}^2}{\omega(\omega + i\gamma_e)}, \tag{1}$$

$$\mu_r(\omega) = 1 - \frac{\omega_{pm}^2}{\omega(\omega + i\gamma_m)}. \tag{2}$$

Here ω_{pe}, ω_{pm} are the plasma frequencies and γ_e, γ_m are the collision frequencies of the electric and magnetic properties, respectively. To simplify and to impedance match the slab to free space, we take $\omega_{pe} = \omega_{pm} = \omega_p$ and $\gamma_e = \gamma_m = \gamma$. The material parameters are chosen to give a refractive index with real part $\mathrm{Re}(n) = -1$ at frequency $f_0 = 15$ GHz ($\omega_0 = 2\pi f_0$). For this we use $\omega_p = 2\pi\sqrt{2} f_0$. The collision frequency is $\gamma = 2\pi \times 4.5$ MHz, which results in $\varepsilon_r(\omega_0) = \mu_r(\omega_0) = -1 + 0.0006i$.

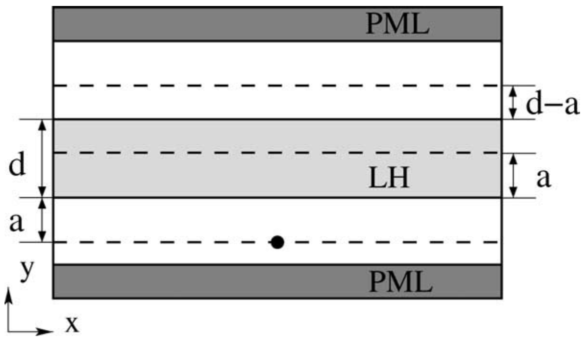

Fig. 1. Schematic view of the model system. A current source is placed in front of a LH slab. In y direction the system models an open domain through the use of reflectionless absorbing boundaries (PML), while it is periodic in the x direction. The solid dot indicates the source location while the dashed lines denote the observation planes, i.e., the source and image planes.

We directly simulate the field propagation based on Maxwell's equations, using the pseudospectral time-domain method [11]. In this method all field components are sampled at the same spatial location which avoids ambiguities of the material interfaces [12] inherent in the usual finite-difference time-domain method [13,14], and the problems caused by transition layers at the interfaces [15]. The domain walls in the y direction are covered with a uniaxial perfectly-matched layer (PML) [16–18] boundary to simulate an open domain. In the x direction the system is periodic. The material constitutive relations are implemented using the auxiliary differential equation method [19].

The current source is turned on slowly using a temporal dependence $(1 - e^{-t/\tau})\sin(\omega_0 t)$, with a turn-on parameter $\tau \approx 22/f_0$, to reduce its band width and allow the system to reach steady-state faster.

The simulation uses a time step of $\Delta_t = 29.2873$ ns and a spatial step size of $\Delta_x = \Delta_y = \lambda_0/100 = 0.199862$ m; λ_0 is the free-space propagating wavelength at frequency f_0. The simulation size is 1024×128 and is iterated for 600000 time steps, i.e., 2635 periods, to ensure steady-state.

It has been shown that a slab of LH material with parallel sides should focus propagating [1] and evanescent [2] waves. Thus, if the slab thickness d is greater than the distance a between the object (source) and the front face of the slab, then one expects an image to form inside the slab, a distance a from the front face, as well as behind the slab, a distance $d - a$ from the back face, as indicated in Fig. 1.