Optik 123 (2012) 147–151

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Novel TMM for analyzing evanescent waves and optimized subwavelength imaging in a multilayer structure

M. Parvinnezhad Hokmabadi*, A. Rostami

Photonics and Nanocrystal Research Lab (PNRL.), University of Tabriz, Tabriz 51664, Iran

ARTICLE INFO

Article history:
Received 30 October 2010
Accepted 12 March 2011

Keywords:
Metamaterial
Metal-dielectric
Subwavelength imaging
TMM
OTF

ABSTRACT

Here, we report the best configuration for metal-dielectric multilayer structure that recently has been used for sub-wavelength imaging beyond the diffraction limit. We have used Genetic Algorithm (GA) to achieve the best optical transfer function (OTF) calculated by a novel Transfer Matrix Method (TMM) for evanescent waves, to find optimized configuration of the structure for sub-wavelength imaging. Our optimized configuration composed of Ag–GaP with 10 nm thickness for both layers and air as the surrounding medium, shows 0.05 λ imaging resolution with 83.82% contrast at 545 nm wavelength. Also, we show that in photolithographic applications if imaging and object layers are replaced by a photoresist and quartz respectively instead of air, 0.03 λ resolution can be obtained. In contrast to the other works, we have mathematically obtained a structure that exhibits better resolution in a visible wavelength in spite of thinner layers thickness by regarding fabrication difficulties.

1. Introduction

In the world that promotion depends on technological advances, researchers are following the way to manipulate structural components of materials to enhance their function. This indicates that high resolution photolithography is required to fabricate electronic products as small as possible. In addition, with the advancement in nanotechnology and biological sciences, demand for high resolution microscopes is increasing. These needs could be responded by a sub-wavelength imaging system. Unfortunately conventional imaging systems such as conventional lenses, have a major limit that hinder to access these goals. These systems can not provide images from fine features of an object smaller than half the wavelength of the light. This is the fundamental limit of optics that Abbe found in 1873 [1]. In fact, high spatial frequencies comprising fine information of the object are carried by evanescent waves, which decay in the far field of the object and exist only in the near field of it and hence these fine features can not be collected and imaged by conventional lenses.

Among many attempts to overcome this fundamental limit, in 2000 Pendry proved that a Metamaterial slab which Veselago had shown that it is able to focus light in two focal points [2], can also focus evanescent waves of the object and hence can provide sub-wavelength images [3] by excitation of plasma modes at the interface between the metal and dielectric. However one of the major flaws of Pendry's perfect lens was its large thickness. In [4] Pendry and Ramakrishna suggested a multilayer structure of metal-dielectric instead of a single slab of metal to reduce losses in the lens due to its large thickness. Recently many researches in this area have been focused on metal-dielectric multilayer structures or similar structures and methods to enhance the near field and far field imaging [5–11]. All of these efforts follow the directions to find a way to reduce the loss or loss effect on imaging in these lenses.

In this work, we want to find the best configuration for the metal-dielectric multilayer structure, mathematically to see how far we can improve its function by considering fabrication limits. We have utilized GA to find the best configuration of the metal-dielectric multilayer structure having optimized OTF which is calculated by a novel TMM for evanescent waves. We have used GaP as the dielectric, Ag as the metal and air as the surrounding medium in this case. We show that 0.05 λ resolution with 83.82% contrast for the proposed structure at 545 nm wavelength can be obtained. Also, we show that if we use photoresist as the imaging layer and quartz as the first or mask layer which information is written on it by Cr, 0.03 λ resolution at the same wavelength can be obtained. We have considered $\exp(j\omega t)$ for all waves time dependence. In the following sections detailed discussions about OTF calculation by the novel TMM, applying GA to TMM, results and conclusions are presented.

2. OTF calculation by novel TMM

In this section, we describe how OTF can be calculated in a multilayer structure for evanescent waves. First, we examined the

* Corresponding author.
E-mail address: m.parvinnezhad@ymail.com (M.P. Hokmabadi).

0030-4026/$ – see front matter © 2011 Elsevier GmbH. All rights reserved.
doi:10.1016/j.ijleo.2011.03.013

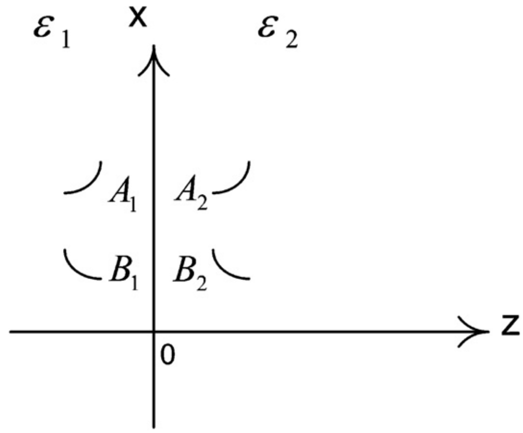

Fig. 1. Reflection and transmission of an evanescent wave at interface between two semi-infinite media.

structure presented in [8] using TMM for propagating waves in [16] and no growth for parallel polarized evanescent waves was observed which has no correspondence with [8]. So, we concluded that the dynamic matrix in [16] can be applied only for propagating waves therefore a new dynamic matrix for evanescent waves in a multilayer structure is needed.

Consider the single interface between two semi-infinite media (see Fig. 1). The wave vector of the incident wave is in x–z plane and x component of it has a large value than each medium wave number so that the wave is evanescent in z direction and just propagating in x direction. The structure is invariant in x and y direction so that we have $\partial f/\partial y = 0$ and $\partial f/\partial x = -jk_x$ which f is representative for the electric and magnetic fields. Upward curves in Fig. 1 indicate growing waves and downward curves indicate decaying waves near the interface.

By solving Maxwell's equations for TE and TM modes the corresponding evanescent modes in this structure are given as follows.

For TM polarization case:

$$H_{iy} = A_i \exp(k_{iz}z - jk_{ix}x) + B_i \exp(-k_{iz}z - jk_{ix}x) \quad (1)$$

$$E_{ix} = j\frac{A_i k_{iz}}{\omega\varepsilon_{ri}\varepsilon_0} \exp(k_{iz}z - jk_{ix}x) - j\frac{B_i k_{iz}}{\omega\varepsilon_{ri}\varepsilon_0} \exp(-k_{iz}z - jk_{ix}x) \quad (2)$$

$$E_{iz} = -\frac{A_i k_{ix}}{\omega\varepsilon_{ri}\varepsilon_0} \exp(k_{iz}z - jk_{ix}x) - \frac{B_i k_{ix}}{\omega\varepsilon_{ri}\varepsilon_0} \exp(-k_{iz}z - jk_{ix}x) \quad (3)$$

For TE polarization case:

$$E_{iy} = A_i \exp(k_{iz}z - jk_{ix}x) + B_i \exp(-k_{iz}z - jk_{ix}x) \quad (4)$$

$$H_{ix} = -j\frac{A_i k_{iz}}{\omega\mu_0} \exp(k_{iz}z - jk_{ix}x) + j\frac{B_i k_{iz}}{\omega\mu_0} \exp(-k_{iz}z - jk_{ix}x) \quad (5)$$

$$H_{iz} = \frac{A_i k_{ix}}{\omega\mu_0} \exp(k_{iz}z - jk_{ix}x) + \frac{B_i k_{ix}}{\omega\mu_0} \exp(-k_{iz}z - jk_{ix}x) \quad (6)$$

where $E, H, \omega, \varepsilon_r, \varepsilon_0$ and μ_0, are the electric field vector, the magnetic field vector, the incident wave frequency, the relative permittivity of medium, the permittivity and permeability of free space respectively. Also, i stands for i'th medium, $k_{iz} = (k_{ix}^2 - k_0^2\varepsilon)^{1/2}$, which k_0 is free space wave number, A_i and B_i are the coefficients of the growing and decaying surface waves at z direction and x, y, z letters indicates to x, y, z components of the fields.

Now, we can apply boundary conditions which are the equality of tangential components of the electric and magnetic fields at the interface $z = 0$. By applying boundary conditions, we can find the equality of x components of the wave vector in each medium and also,

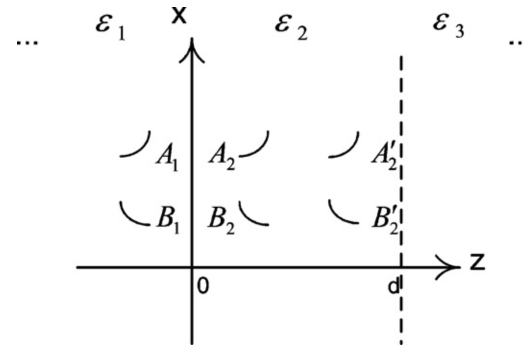

Fig. 2. Reflection and transmission of an evanescent wave in a multilayer structure.

$$D(1)\begin{bmatrix} A_1 \\ B_1 \end{bmatrix} = D(2)\begin{bmatrix} A_2 \\ B_2 \end{bmatrix}, \quad (7)$$

which $D(i)$, $i = 1, 2$ is the dynamic matrix which is defined for TM (p) and TE (s) polarization respectively.

$$D_p(i) = \begin{bmatrix} 1 & 1 \\ \dfrac{k_{iz}}{\varepsilon_{ri}} & -\dfrac{k_{iz}}{\varepsilon_{ri}} \end{bmatrix} \quad i = 1, 2 \quad (8)$$

$$D_s(i) = \begin{bmatrix} 1 & 1 \\ -k_{iz} & k_{iz} \end{bmatrix} \quad i = 1, 2 \quad (9)$$

Clearly these dynamic matrixes are different from those in [16] which show why the method in [16] does not apply for evanescent waves.

Now the multilayer structure illustrated in Fig. 2 is considered. In addition to dynamic matrixes, to completely analyze the structure we should also find propagation matrixes. The propagation matrix for both TE and TM polarization is obtained in the following form:

$$P_i = \begin{bmatrix} \exp(k_{iz}d) & 0 \\ 0 & \exp(-k_{iz}d) \end{bmatrix} \quad (10)$$

$$\begin{bmatrix} A_2 \\ B_2 \end{bmatrix} = P_i \begin{bmatrix} A'_2 \\ B'_2 \end{bmatrix}, \quad (11)$$

which shows the growing wave "A_2" decays by traveling distance "d" and converts to "A'_2" and "B'_2" decays and converts to "B_2" in the same manner.

Now by having dynamic and propagation matrixes one can proceed to analyze evanescent waves in a multilayer structure. To test the novel TMM for evanescent waves, we simulated the structure presented in [8] and observed complete agreement.

3. Applying GA to TMM

After calculating OTF, we applied GA to obtain the best configuration for superlens which gives the best imaging resolution. We optimized the multilayer structure composed of metal and dielectric layers in both five and four controllable parameters cases. Four controllable parameters procedure is described first.

In four controllable parameters optimization case, the multilayer structure, that we are going to optimize as a near-field superlens, has been composed of alternative layers of GaP as dielectric and Ag as metal. We have used the Drude model for Ag with $\omega_p = 1.37 \times 10^{16}$ rad s^{-1} as the plasma frequency and