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Optical superlens imaging system for near field nanolithography

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ABSTRACT

It has been proposed that a planar silver layer could be used to project a super-resolution image in the near field when illuminated near its plasma frequency. The planar silver layer is called as a superlens. In this paper, we design a superlens structure for nanolithography purpose. The imaging comparisons of single and layered silver/dielectric stacks are made. The design details of the superlens structure are presented. An experiment for demonstrating the focusing effect of the silver layer is performed which shows the superlens supports the imaging of a grating with 1 μm pitch at an exposure source with 365 nm wavelength.

1. Introduction

Negative refraction of electromagnetic waves, initially proposed by Veselago in the 1960s [1], has attracted strong research interests. Materials with simultaneously negative dielectric permittivity and magnetic permeability are known as left-handed media (LHM) [2]. It has been demonstrated that a slab of uniform LHM with permittivity $\varepsilon = -1$ and permeability $\mu = -1$ is capable of capturing both the propagating and evanescent waves emitted by a point source placed in front of the slab and refocusing them into a perfect point image behind the slab [3]. While the focusing effect of propagating waves can be appreciated from a familiar picture of rays in geometric optics, it is amazing that perfect recovery of evanescent waves may also be achieved via amplified transmission through the negative-index slab. The concept provides very promising applications in high resolution imaging and lithography [4].

Unfortunately, a true LHM operating at optical frequencies is difficult to find. Pendry proposed that for the appropriate illumination wavelength and polarization a slab of silver could be used as a negative refraction material, as long as it was much thinner than the wavelength of light employed [3]. Much simulation work has been done to explore the ability of a planar silver slab to image an electromagnetic source. Based on predictions of greatly improved resolution, Fang et al. [5] experimentally demonstrated that a 60 nm half-pitch object can indeed be resolved with $\lambda/6$ resolution with the implementation of a silver slab with $\lambda = 365$ nm illumination wavelength, which is well below the diffraction limit. Blaikie and Melville [6] used single and double-layer planar silver slabs for near-field optical nanolithography. Their experiments showed that transmission can be increased by lamination of the silver in the double-layer structure, but improvements in resolving power were not clearly evident.

In this paper, we numerically analyze the imaging system with single and multiple silver layers, and then design an imaging system for the purpose of nanolithography. Finally, preliminary experimental result is presented.

2. Optical superlens imaging system

Fig. 1 shows the physical model of a superlens system for near-field optical lithography. At a distance f_1 beneath the exit plane of the grating there is a silver layer of thickness h. The presence of this layer is predicted to cause a sub-diffraction-limited image of the mask pattern to be formed at a distance f_2 below its bottom surface (see ray diagram). Subwavelength mask structures are to be imaged through the superlens recorded on the opposite side in photoresist. The system uses a chrome grating mask and vacuum arrangement to ensure intimate contact between mask and substrate to achieve maximum resolution. Additional dielectric spacer and silver lens layers are then deposited to form the superlens structure. The first spacing layer has two functions: providing a means of spacing the silver from the mask, and planarizing the chrome mask to smooth out the uneven topology before the silver lens layer is deposited. Poly-methylmethacrylate (PMMA) is chosen as the material of the first spacer. Silica (SiO_2) was the choice for the second spacing layer material for good adhesion of the planar lens and avoiding the contaminant of the photoresist. Even though there is a slight mismatch of planar lens and surrounding material, it is numerically shown that such an asymmetric lossy superlens still

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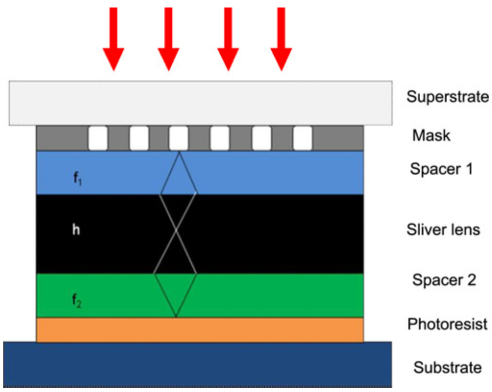

Fig. 1. Schematic view of the optical superlens imaging system.

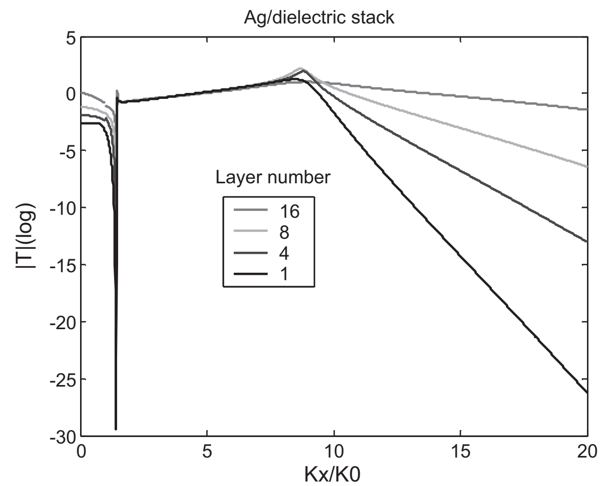

Fig. 2. The transmission as a function of transverse wave vector for various silver layers.

supports the efficient coupling of the evanescent fields between two surfaces of the silver film [7]. In order to match the real part of silver complex dielectric constant with the surrounding dielectric materials, illumination wavelength $\lambda = 365$ nm is determined at which the permittivity of silver is $-2.4012 + i0.2488$.

In principle, these thicknesses should meet the relation, $f_1 + f_2 = h$, where f_1 is object–silver distance, f_2 is silver–image distance, and h is the thickness of the silver slab. Due to the slight difference of the refractive indices between the superlens and surrounding materials, however, we have to reconfigure the system. The key to the reconfiguration is to carefully select the thicknesses of the planar lens and spacers in order to maximize the enhancement of evanescent waves.

3. Design of the superlens structure

3.1. Determination of the silver layer number

In order to evaluate the imaging performances of single and layered silver/dielectric stack, the transmission as a function of the transverse wave vector is plotted in Fig. 2. The transmission coefficient for TM waves is calculated based on the characteristic matrix method [8]. The total slab width is maintained in each case, while the number of individual layers varies. The thickness ratio of the silver and dielectric layers is 2:1 and the silver thickness is 10th of the

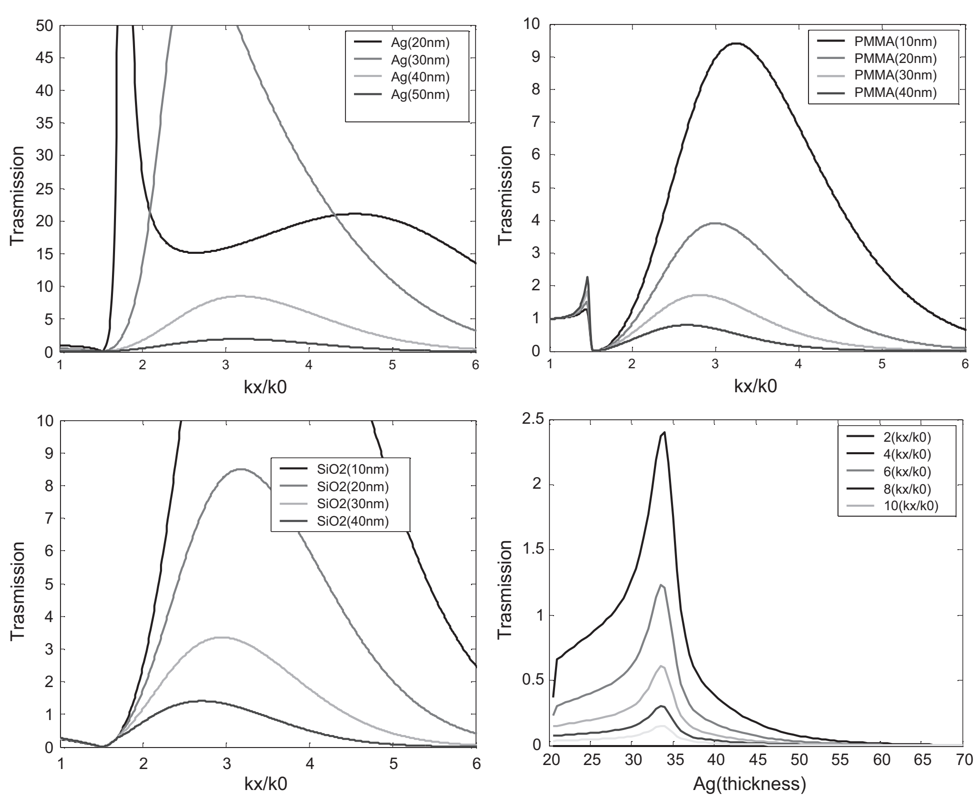

Fig. 3. The transmission of various superlens structure configurations. (a) Both PMMA and SiO_2 thickness fixed at 20 nm and silver thickness varying from 20 to 50 nm in 10 nm step. (b) Silver and SiO_2 thickness fixed at 30 nm and 20 nm, respectively, and PMMA thickness varying from 10 to 40 nm in 10 nm step. (c) Silver thickness and PMMA thickness fixed at 30 nm and 20 nm, respectively, SiO_2 thickness varying from 10 to 40 nm in 10 nm step. (d) Transmission for different wavenumbers with varying silver thickness from 20 to 70 nm in 5 nm step.