Research Report

Transmission through Metal-dielectric Hole Array and Applications to Optical Devices

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Report received on May 10, 2013

ABSTRACT Transmission phase control and spectral filtering through a stacked metal-dielectric sub-wavelength hole array (SHA) are presented. Laterally propagating surface plasmon polaritons are closely related to transmission through an SHA, and the periodicity of the holes and hole shape affect the transmission properties. In this article, we present our recent activities on transmission through an SHA and applications to optical devices. Three topics are presented: a color filter, transmission phase control, and wavefront control, which were reported in "Appl. Phys. Lett. 98, 093113 (2011)", "Opt. Express 20, 16092 (2012)", and "Opt. Express 21, 6153 (2013)", respectively. A red-green-blue (RGB) color filter is achieved using aluminum, due to its high plasma frequency and compatibility with the lithographic process. The transmission phase through the SHA can be controlled using a two-dimensional geometric SHA design and gradual change in the hole shape produces an inclined wavefront for one-dimensional beam steering.

KEYWORDS Optics, Plasmonics, Metamaterials, Sub-wavelength Structures, Nanostructure Fabrication

1. Introduction

The passage of light through a single metallic sub-wavelength hole array or a stacked metal-dielectric sub-wavelength hole array (SHA) has been intensively studied over the past decade.(1-4) Transmission through such metallic holes is achieved via interaction between the incident light and laterally propagating surface plasmon polaritons (SPPs),(5) and this unique transmission is referred to as extraordinary optical transmission (EOT). There have been many reports on the EOT transmission mechanism.(6-8) In addition to the EOT of a single metallic hole array film, transmission through a multi-stacked metal-dielectric hole array, which is known as fishnet structure, has been reported to exhibit a negative refractive index.(9,10) Transmission through such single or multi SHA films has been explained mainly in terms of two types of laterally propagating SPPs.(11,12) One type is an outer SPP of which the electromagnetic field is localized at the metal-dielectric interface, and the other type is a gap SPP(13) of which the electromagnetic field is confined between the metal films. Transmission through an SHA is now recognized as a combination of laterally propagating SPPs excited by the periodic hole array and localized hole resonances.(14,15) In this paper, we introduce our recent activities(16-18) regarding transmission through an SHA and applications to a color filter and optical beam steering device.

2. Plasmonic Color Filter(16)

We have reported a red-green-blue (RGB) plasmonic color filter using Al in Ref. 16. Al and Ag have a high plasma frequency(19); therefore, these two metals are good candidates for a plasmonic blue color filter. In addition, Al is compatible with the CMOS process; therefore, Al is the best material for the development of an image sensor with a plasmonic color filter.(16,20) Transmission color control can be realized via selection of the perioidicity and shape of holes. A 150 nm thick Al plasmonic color filter was fabricated on a fused silica substrate using electron beam lithography and a dry etching technique. Transmission spectra through the Al color filter were measured using a microscope spectrometer with an incoherent light source. **Figure 1** shows optical microscope images of plasmonic color filters with different periodicity and hole shapes. The side-lengths of the squares and triangles, and the diameters of the circle were set at half the length of the periodicity. The hole periods of the hole arrays that correspond to the color bars are given beside the micrographs. By controlling the periodicity and hole shape, color control could be realized, and an RGB plasmonic color filter was achieved. We have also confirmed polarization independent transmission through a hexagonal lattice plasmonic color filter due to the symmetric arrangement of the lattice.

3. Transmission Phase Control with Two-dimensional Geometric SHA Design(17,18)

SHAs can be applied to spectral filtering, but also to control the phase of transmitted light, because coupling between light and the laterally and resonantly propagating waves leads to a phase shift. Our target is to achieve a flat wavefront control element using SHA, which is achieved based on the two-dimensional geometric design of an SHA unit-cell and the systematic variation of the structures. In this section, we introduce the concept of transmission phase control for an SHA unit cell structure.

The resonance frequencies, where incident light and laterally propagating SPPs can be coupled, can be extracted from a dispersion diagram of the SPPs and the reciprocal lattice vector. **Figure 2**(a) presents a dispersion diagram for insulator-metal-insulator-metal-insulator (IMIMI) layers. The dispersions of the outer and gap SPPs are indicated by solid and dashed lines, respectively. Normal incident y-polarized light is coupled to the SPPs by the generation of a grating momentum from the periodic hole array at energies of 0.83 eV for an outer SPP and 0.65 eV for a gap SPP. The transmission amplitude and phase around the frequencies that correspond to these resonances will now be discussed by comparing the results of numerical calculations (Figs. 2(b) and (c)). Several key features can be noted from the calculated transmission spectra and phase. Firstly, high transmittance and a significant phase shift occur near the resonance frequencies of 0.83 and 0.65 eV. Therefore, the SHA is suitable for transmission phase control. Secondly, there is a clear influence of the hole shape on the transmitted phase. For a narrow SHA ($wx = 0.4a$), the phase is rapidly shifted compared to that for a wide SHA ($wx = 0.6a$). Thus, the dependence of the phase on the frequency (dispersion) is stronger for a narrow SHA. The dispersion can therefore be tuned by varying the side lengths of the rectangular holes that are normal to the polarization direction.

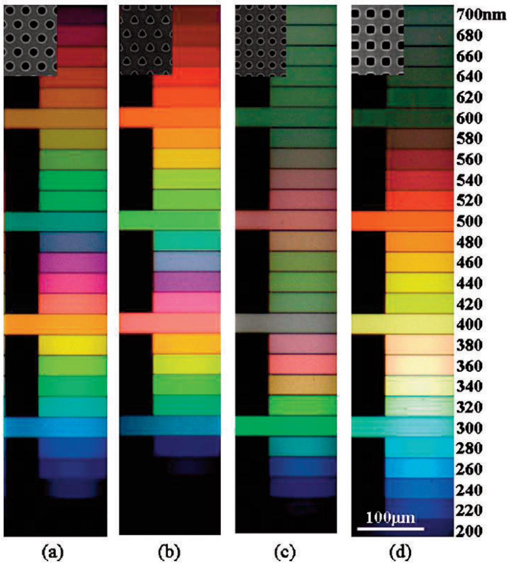

Fig. 1 Optical microscope images of Al color filters with (a) circular holes arranged on a hexagonal lattice, (b) triangular shaped holes, (c) circular holes arranged on a square lattice, and (d) square holes. The array periods are given beside the micrographs.

To experimentally demonstrate transmission phase control through an SHA, rectangular hole SHAs with two 40 nm thick Al layers and three 50 nm thick SiO_2 layers were fabricated. Transmission spectra were measured using a microscope spectrometer with an incoherent light source, and the transmitted phase was evaluated using an in-house-built interferometric microscope (**Fig. 3**). This microscope produces an interferometric phase image consisting of bright and dark fringes superimposed on a typical microscopic image. The phase from the SHA is determined by comparing the interferometric fringe of the target structure to a known dispersion region. The experimental results for the transmission amplitude and phase were in good agreement with those calculated.

4. Wavefront Control Using an SHA with Variable Hole Shapes (17,18)

To realize an inclined wavefront, a gradual and linearly varying transmission phase is required. As described in Sec. 2, the phase produced by a uniform SHA can be controlled by changing the length of the sides normal to the polarization direction. Thus, as described in Ref. 21, the basic geometric unit for enhanced transmission is a linear chain of sub-wavelength holes along the polarization direction. Therefore, an SHA with periodicity along the polarization direction and gradual variation of the rectangular hole shapes normal to the polarization direction has the potential to enable one-dimensional beam steering. To simulate the inclined wavefront produced by an SHA, a numerical calculation for an 11-hole array was performed for the structure depicted in Fig. 3(a). Normal incident y-polarized light and

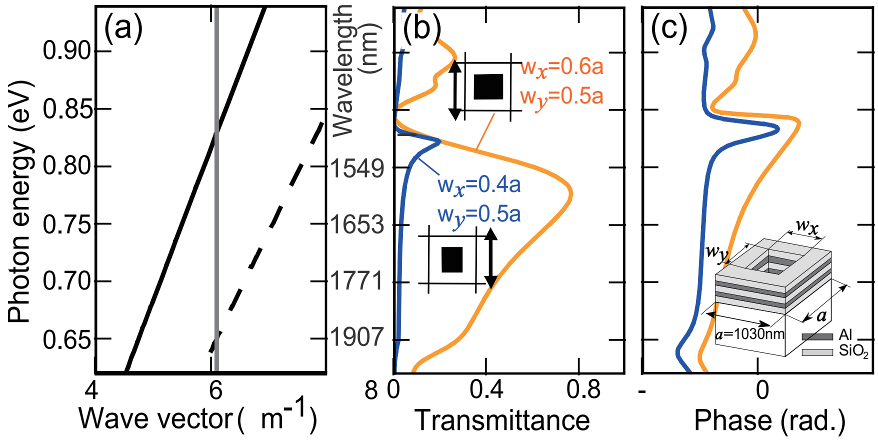

Fig. 2 (a) Dispersion of an IMIMI structure for outer (solid line) and gap (dashed line) SPPs. The gray vertical line represents the reciprocal lattice vector for periodic holes with y-polarized normal incident light. (b) Numerically calculated transmittance. The double-headed arrows indicate the incident polarization direction. (c) Numerically calculated phase relative to that in a vacuum layer with the same thickness as the SHA. The inset represents the unit-cell structure of a rectangular holed SHA.

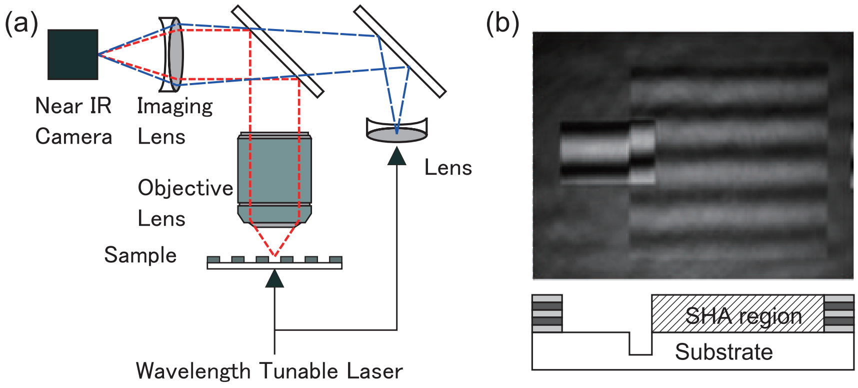

Fig. 3 (a) Experimental setup for the interferometric microscope. (b) Transmission interferometer image of an SHA.

periodic boundary conditions along the y-axis were assumed. The structure has gradually varying hole shapes along the x-axis. **Figure 4** represents the phase of E_y in the xz-plane. In the region outlined by the dashed line, 11 rectangular holes are aligned that become increasingly wider from the left to the right. Figure 3(b) shows that the outgoing wavefront can be tuned from almost flat at 0.832 eV to oblique at 0.810 eV. Thus, the numerical simulation confirms the possibility of producing an inclined wavefront with a transitional SHA. Wavefront control using the SHA with variable hole shapes was experimentally confirmed. **Figures 5**(a)-(c) show SEM micrographs of the fabricated structure for 1D beam steering and Figs. 5(d)-(f) show interferometric phase images through the structure. Wavefront control through the transition region of the SHA was experimentally

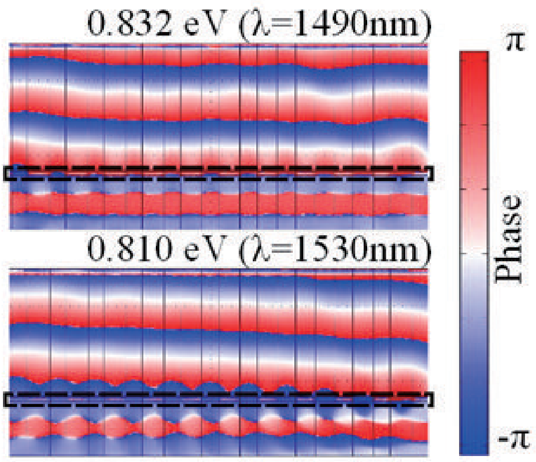

Fig. 4 Numerical results for the phase in the transition region.

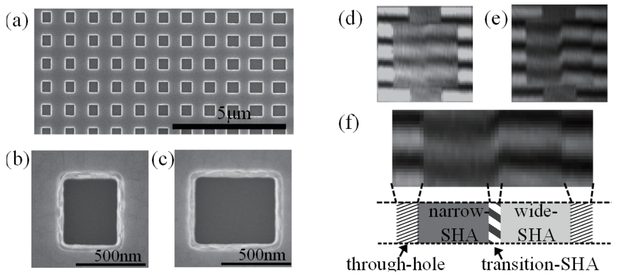

Fig. 5 (a)-(c) SEM micrographs of the fabricated SHA. (a) Transition region where the rectangular holes are gradually varied in shape. (b) Top view of a narrow SHA (*wx*=0.4a). (c) Top view of a wide SHA (*wx*=0.6a). (d)-(e) Interferometric images of the fabricated structure at a frequencies of (d) 0.827 and (e) 0.810 eV. (f) Magnified portion of (e) and the corresponding region in the fabricated structure.

confirmed from almost flat (Fig. 5(d)) to oblique (Figs. 5(e) and (f)) wavefronts.

5. Summary

Our recent activities on transmission through SHA and applications to optical devices were introduced using three recent results. Firstly, an Al plasmonic RGB color filter was presented. Al has high plasma frequency and is compatible with the CMOS process, so that this material can be applied to an RGB color filter on an image sensor. Secondly, the applicability of an SHA to a transmission phase control element was experimentally verified. Laterally propagating SPPs excited by the periodic nanohole array play an important role in light transmission through an SHA. The transmission amplitude and phase were significantly changed around the resonance frequencies, which were determined mainly by the periodicity of the SHA and the hole shape. Thirdly, an inclined wavefront for beam steering was achieved using an SHA with a gradually changing hole shape. We consider that a practical transmission control element using an SHA can be realized with continuous investigation of SHAs, and this work will contribute to the metamaterial community and future applications.

Acknowledgments

All samples were fabricated by A. Miura with technical support from M. Ochiai, D. Tsuya, and N. Ikeda of the National Institute for Materials Science (NIMS). D. Inoue, T. Nomura, and T. Matsui simulated and designed the devices, and T. Matsui. and A. Miura measured the optical properties of the devices. H. Fujikawa and K. Sato supervised the project.

The authors would like to thank H. T. Miyazaki (NIMS), Y. Sugimoto (NIMS), M. Hangyo (Osaka Univ.), M. Ozaki (Osaka Univ.), and K. Asakawa (Univ. of Tsukuba) for fruitful discussions. This work was supported in part by the New Energy and Industrial Technology Development Organization (NEDO) and the Nanotechnology Innovation Station of the NIMS in Japan.

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Fig. 1
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Figs. 2, 4 and 5
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