Vacuum 107 (2014) 284–290

Contents lists available at ScienceDirect

Vacuum

journal homepage: www.elsevier.com/locate/vacuum

Numerical and experimental studies on sub-wavelength focusing in nano-slit arrays of metallic stripes with variable widths

Da Ye Seo, Seungho Park*

Department of Mechanical and System Design Engineering, Hongik University, Seoul, Republic of Korea

ARTICLE INFO

Article history:
Received 4 October 2013
Received in revised form
17 February 2014
Accepted 27 February 2014

Keywords:
Nano-slit array
Sub-wavelength focusing
Surface plasmon polariton
Gold thin-film
Metallic stripes with variable widths

ABSTRACT

We simulated the distributions of light energy transmission through metallic nano-slits for the optimal design of nano-lens structures and observed experimentally the light focusing effect from the nano-lens array. Contrary to reported research where the dielectric slit sizes are controlled, the current design is based on the distributions of metallic claddings of different sizes. The nano-focusing is generated by the surface plasmon polariton (SPP) effect that is known to overcome the diffraction limit and to induce sub-wavelength focusing. SPPs are collective electron charge oscillations in metallic nano-slits that can be excited by electromagnetic waves, amplifying near-field optical waves at resonance. Here, intensity amplifications in near-fields are maximized for a given light source, mainly based on various distributions of metallic claddings of different sizes in an array. For experimentation gold nano-slit arrays designed from the numerical optimization were fabricated through the lift-off process and confirmed by observations in SEM and confocal microscopes. The SPP effect in nano-slit lenses was explored by light focusing on light-sensitive papers macroscopically and by light transmission microscopically using a dispersive Raman spectrometer in scattering mode.

1. Introduction

The surface plasmon polariton (SPP) is a surface electromagnetic (EM) wave with a collective oscillation of the electrons, which is confined to the near vicinity of the dielectric–metal interface, leading to an enhancement of the electromagnetic field at the interface or resulting in extraordinary sensitivities to surface conditions. Due to its EM field confinement and enhancement at a metal/dielectric interface, the SPP has started to be investigated seriously in various areas of nanoscale science and engineering recently. Current and possible applications will be found in optical interconnections in chips, optical data storages, optical detectors, surface plasmon resonance sensors, organic light-emitting diodes, solar cells, and so on [1–7].

A prism coupled with a thin metallic film, known as the Kretschmann–Raether configuration, permits the precise measurements of the surface-plasmon resonance (SPR) to estimate the optical properties of a dielectric medium to be monitored, leading to the development of various chemical and bio-sensors. Even a small variation in the refractive index of the medium resulting from physical, chemical, or biological reactions can be monitored and understood by the changes of total internal reflection and SPR through the measurements of the intensity and the phase of reflected light in the configuration [8–12].

Among various aspects of the SPP, the extraordinary optical transmission (EOT) from a single sub-wavelength metal hole were revisited due to the recent interest in the transmission of a one-dimensional array of sub-wavelength metallic slits, since the SPP can be exploited to overcome the limits of the conventional diffractive optics [13–17]. According to the classical aperture theory, the Bethe theory, the light is diffracted isotropically and evenly when the light of wavelength λ falls on a sub-wavelength aperture (diameter $d < \lambda$) and its intensity decays as $(d/\lambda)^4$ [18]. Efficiencies of the EOT from sub-wavelength holes in a metallic film, however, could be increased up to several orders of magnitude greater than that predicted by the classical theory.

In order to realize the beam focusing and collimating, Sun and Kim [19] proposed a metallic lens consisting of a nanoslit array formed on a metal layer with tapered film thickness, opening up the possibility of creating metallic lenses. Goh et al. [20] showed that the phase of transmitted light through devices consisting of arrays of spatially varying near-resonant slits could be controlled by varying the structural geometry and incident wavelength. Kim and Lee [21] investigated the unidirectional SPP excitation on single

* Corresponding author.
E-mail address: spark@hongik.ac.kr (S. Park).

http://dx.doi.org/10.1016/j.vacuum.2014.02.025

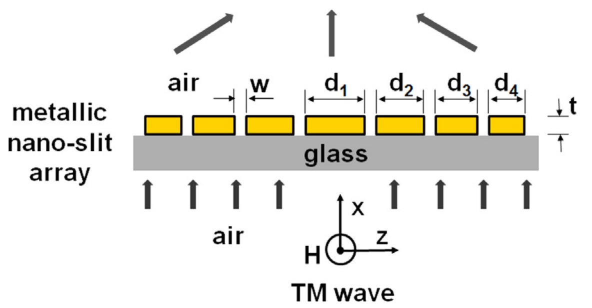

Fig. 1. Schematic diagram of the metallic nano-slit array with variable cladding widths.

slits with oblique backside illumination and Chen et al. [22] proposed a method to modulate phase using variant square holes in a metallic film based on a fundamental mode approximation model.

Shi et al. [23] proposed a type of metallic double nano-slit with different widths that could control the position of Young's interference fringes through modulating the slit-width differences and film thicknesses. They demonstrated that the shift of the interference orders was mainly due to the additional phase retardation produced by the surface plasmon mode in slits with different widths. Bian et al. [24] showed that the transmission of light through a slit-doublet structure milled in a metal film was considerably enhanced by introducing a wide collection cavity. Two types of interference patterns on the output surface (the periodic single peak and the periodic double peaks profile), were observed by varying the thickness of the double slits.

Ishii et al. [25] designed arrays of nano-slits to focus either TM- or TE-polarized light, acting as concave lenses for the orthogonal polarization of incident light. These compact and simple lenses could find applications in optical probing and sensing. Thongrattanasiri et al. [26] and Ishii et al. [27] suggested sub-wavelength slits combined with hyperbolic metamaterials (HMMs) and showed that diffractive nature in an HMM was directional compared to that in free space and focusing with a sub-wavelength spot size was possible utilizing this unique feature.

The main objectives of this study are to realize a metallic nanolens consisting of a nano-slit array and to obtain the design for maximization of focused intensity through numerical predictions and experimental measurement. We simulated extensively the distributions of light energy transmission through metallic nanoslits for the optimal design of nano-slit structures which were dependent on the wavelengths of incident light and dielectric slit-widths as well. The optimization was based especially on the intensity amplification depending on non-uniform distributions of metallic claddings of various widths in array indicated by different values of d_i, as illustrated in Fig. 1. By contrast, research available in the literature has been mainly focused on the effects due to double slit structures [16,23], non-uniform slit-sized array [20,27,28], oblique incidence of light [21,29] on the slit structure, various geometric structures in the metallic cladding [19,22,30–32] such as holes, grooves, and tapered slits, various materials for the dielectric insulator [26,27], temperature dependence of the SPR [33], phase modulation of SPPs by surface relief dielectric structures [4,34,35], or, depth-tuned structures [36]. For experimental measurements gold thin-films were deposited on glass and nano-slit arrays designed from the numerical calculations were fabricated through the lift-off process. The SPP effects in nano-slit lenses were seen from burn marks spotted on light-sensitive papers due to light focusing and by measurements of transmission using a dispersive Raman spectrometer in scattering mode.

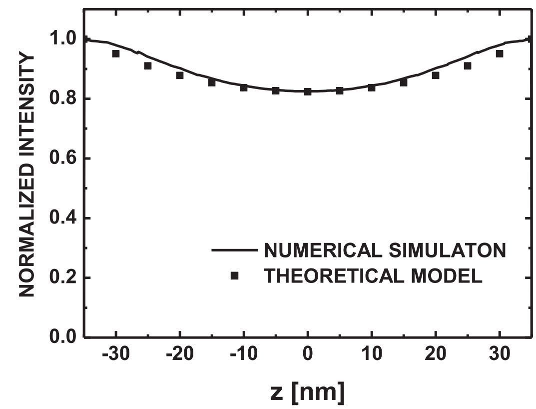

Fig. 2. Comparison of intensity distributions of light propagating through a MIM structure between theoretical and simulation models.

2. Simulation and experimental models

2.1. Simulation

To obtain the optimal design of the nano-slit array for subwavelength-focusing in the near-field prior to its fabrication and experimentation, we carried out numerical simulations for numerous designs of the slit-metal cladding structures, as shown in Fig. 1.

Preliminary to conducting the major simulation in this study, intensity distributions estimated from the numerical simulation were compared to the theoretical solutions for a wave propagating in a simple structure: a metal–insulator–metal (MIM) waveguide. Assuming that the metallic claddings were larger than twice the skin depth and the dielectric nano-slit was long enough to be considered as one-dimensional, the propagation of light through the nano-slit could be understood by that occurring through a parallel plate waveguide. The dispersion relation for the plasmonic mode correspondent to only TM-polarized light at a planar metallic interface is given as [25,37],

$$\tan\text{h}\ k_1 a = -\frac{\varepsilon_d k_2}{\varepsilon_m k_1}, \tag{1}$$

where a ε_d, and ε_m are the half-width of the dielectric core, the permittivities of the metallic cladding and the core, respectively. Here, $k_1 = \sqrt{\beta^2 - \varepsilon_d k_0^2}$ and $k_2 = \sqrt{\beta^2 - \varepsilon_m k_0^2}$ with $k_0 = 2\pi/\lambda$, the wave-number for the free-space wavelength λ and β, the propagation constant that can be obtained from the dispersion relation given in Eq. (1).

The intensity of light propagation through the nano-slit ($-a<z<a$) can be described by the average values of the Poynting vector, based on TM polarization is correlated as,

$$< S_x > = \frac{\text{Re}\left(\frac{\beta}{k_o \varepsilon_d}\right)}{2c\varepsilon_o} \frac{\{\exp[-2\text{Re}(k_2)a - 2\text{Im}(\beta)x]\}\cdot\{\cos\text{h}[2\text{Re}(k_1)z] + \cos[2\text{Im}(k_1)z]\}}{\cos\text{h}[2\text{Re}(k_1)a) + \cos(2\text{Im}(k_1)a]}. \tag{2}$$