Lasers in Manufacturing Conference 2015

Direct Laser Beam Interference Patterning for Fabrication of Plasmonic Hole Arrays

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Abstract

Periodic arrays of apertures in thin metallic films act as metamaterials with interesting properties such as extraordinary transmission due to surface plasmon resonances and can be applied as biosensors or filters of electromagnetic radiation. We have tested the Direct Laser Beam Interference Patterning (DLIP) technique as a tool for the fabrication of the periodical hole' arrays in thin metal films using picosecond laser pulses. A novel scanning technique allowed the production of uniform patterns in the tens of square millimetres sized areas. Such device areas are sufficient for most applications. Properties of the hole' array depend on the shape of the hole and the lattice structure. The shape of the hole was controlled by adjusting irradiation fluence and by introducing sample translation between laser exposures. The lattice structure was adjusted using a certain number of interfering beams. Reflectance measurements of the DLIP patterned samples show reflectance dips corresponding to the extraordinary transmission. The reflectance modulation depth strongly depended on fabrication parameters. Longer pulse duration may be favourable to avoid sub-period irregularities in the ablated structures.

Keywords: Direct Laser Beam Interference Patterning; plasmonic hole arrays

1. Introduction

Perforated metal films on dielectric substrates provide some useful properties. Periodical structure in the metal allows coupling between the surface plasmon polaritons (SPP) and incoming light waves. This results in the enhanced transmission in certain spectral regions. Such effect is often referred to as “extraordinary”

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or “anomalous” optical transmission. This phenomenon may result in the applications for chemical sensors (D’Apuzzo, et al., 2015) or plasmon-enhanced spectroscopy (Lesuffleur, et al., 2007).

The reported methods for plasmonic hole arrays fabrication include optical lithography (Diwekar, et al., 2007), electron beam lithography, focused ion beam milling (FIB) (Ebbesen, et al., 1998), interference lithography (Menezes, et al., 2012). FIB is probably the most widely used fabrication method, as it offers highly accurate structuring with the precise array geometry and the hole’ shape control. However, the large-area patterning of small-size structures takes long time. The fabrication time can be reduced using such methods as optical lithography or interference lithography. However, they require several consecutive processing steps. Direct Laser Beam Interference Patterning (DLIP) method combines fast and flexibility in a one-step process (Nakata, et al., 2014).

In this paper, we investigate DLIP as a tool for flexible structuring of the plasmonic hole’ arrays for the infrared spectral region. DLIP combined with the sample translation between laser exposures method (Indrišiūnas, et al., 2013) allowed flexible control of the hole shape. A novel scanning technique permited the production of uniform patterns in the tens of square millimetres sized areas. Such device areas are sufficient for most applications. Properties of the hole’ array depended on the shape of the hole and the lattice structure. The form of the hole was controlled by adjusting the laser fluence and by introducing sample translation between laser exposures. The lattice structure was adjusted by selecting appropriate number of interfering beams. Combined, these methods provide fast, flexible and cost effective tool for the fabrication of the plasmonic hole’ arrays.

2. Experimental

50 nm-thick aluminium layers on silicon and sapphire substrates were patterned, using the 4- and 6-interfering beam configurations. The laser beam was split into the required number of beams using diffractive optical elements. Beams were collected on the sample using a confocal imaging lens system. Experiments were conducted using the picosecond laser Atlantic HE (Ekspla, pulse duration 300 ps, repetition rate 1 kHz, wavelength 532 nm). The 25 mm^2 size areas of the uniform pattern were formed by ensuring accurate overlap of the interference spots. Periodicity of the ablated pattern was fully retained in the overlap areas. The 86% overlap of the interference spots was utilised to ensure pattern uniformity and avoid any pattern irregularities due to the Gaussian shape intensity distribution in the interference spot.

3. Results

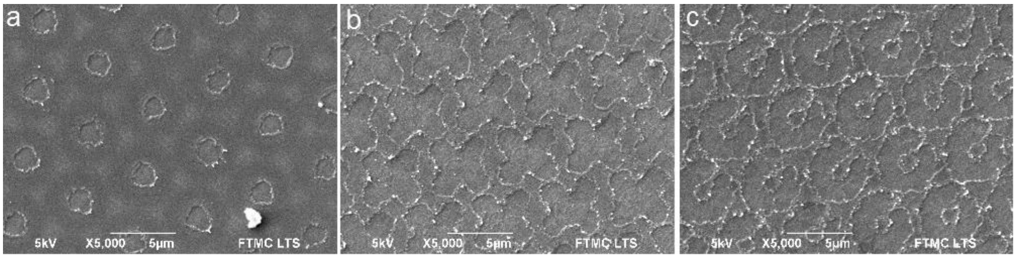

Fig. 1. Hole’ arrays ablated in 50 nm-thick aluminium films on a sapphire substrate.

The hole’ arrays with the 3.35 µm period rectangular and 5.44 µm period hexagonal symmetry were fabricated using four and six beam interference intensity distributions. The reduced period structures (1.68 µm for four beam and 2.71 µm period for six beam arrangements) were fabricated using the sub-period sample translation between several expositions. Using this approach, the structures with different hole shapes were also fabricated (Fig. 1). The cross and split-ring shape holes were ablated using the sub-period sample translation between expositions using the six-beam interference intensity distribution.

SPP resonance wavelengths λ_R can be evaluated from (Ebbesen, et al., 1998):

$$\lambda_R = \frac{P\left(\sqrt{\frac{\varepsilon_d \varepsilon_m}{\varepsilon_d + \varepsilon_m}} - \sin(\Theta)\right)}{\sqrt{i^2 + j^2}} \qquad (1)$$

where Θ is the irradiation angle of incidence, P is the structure period, i and j are integers denoting SPP resonance mode, and ε_m and ε_d are metal and dielectric permittivities, respectively. The extraordinary transmission peaks of the fabricated structures were evaluated to be in the mid-infrared spectral range.

Reflectance spectra of the patterned samples were measured at the 25° angle of incidence. The reflectance spectra of the 3.35 µm period square symmetry hole array on silicon substrate are presented in Fig. 2 a). Reflectance dips corresponding to five SPP resonance modes are apparent. By changing the hole' diameter (irradiation fluence,) depth of the reflectivity dips was changed. Also, positions of the peaks slightly shifted to the longer wavelengths when the used fluence increased. The shallow reflectance dips show the poor quality of the structure. The quality was reduced due to ablation of the silicon substrate and formation of aluminium ridges in the vicinity of melted silicon regions. Furthermore, ablation using long picosecond laser pulses leads to the irregular metal edges and variation of the hole' shape. After reduction of the structure period, only (1,0) mode remained. Such result may arise due to the close packing of ablated holes that increased surface corrugation between them.

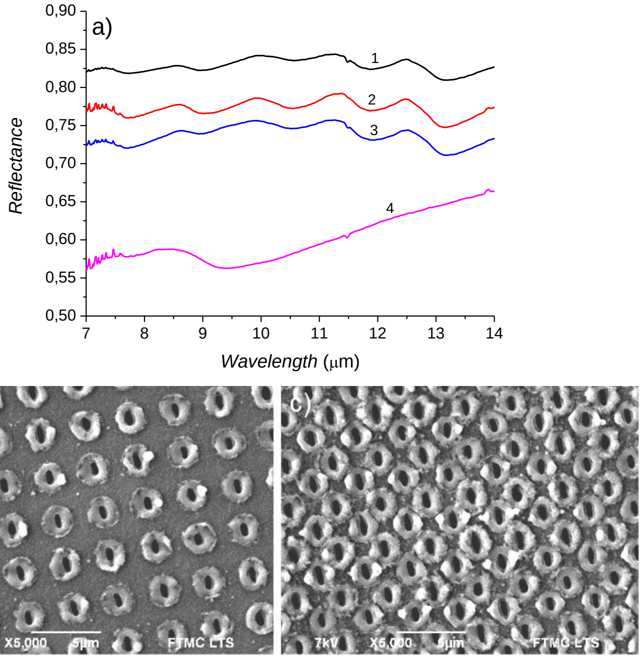

Fig. 2. Reflectance spectra of hole arrays (a) fabricated in 50 nm-thick aluminium film on a silicon substrate using 1 J/cm^2 (1), 0.96 J/cm^2 (2), 0.92 J/cm^2 (3) fluencies and 3.35 µm structure period and 1 J/cm^2 fluence and 1.68 µm structure period (4). SEM images of the 3.35 µm (b) and 1.68 µm (c) period structures, fabricated using 1 J/cm^2 fluence.

Reflectance spectra of structures fabricated on the aluminium film on the sapphire substrate (Fig. 3) show that reflectance dips are deeper compared to the structures fabricated on the silicon substrate. This indicates the better structure quality than using silicon substrates. Reduction of the structure period, caused a shift of the reflectance dips to the shorter wavelengths, as expected. However, reflectance dips became wider and shallower. The high pulse number per spot (Fig. 3 a) curve 3) deteriorated the structure quality due to the formation of particles from melted metal (Fig. 3 c)) and reflectance spectra did not show well-defined dips.

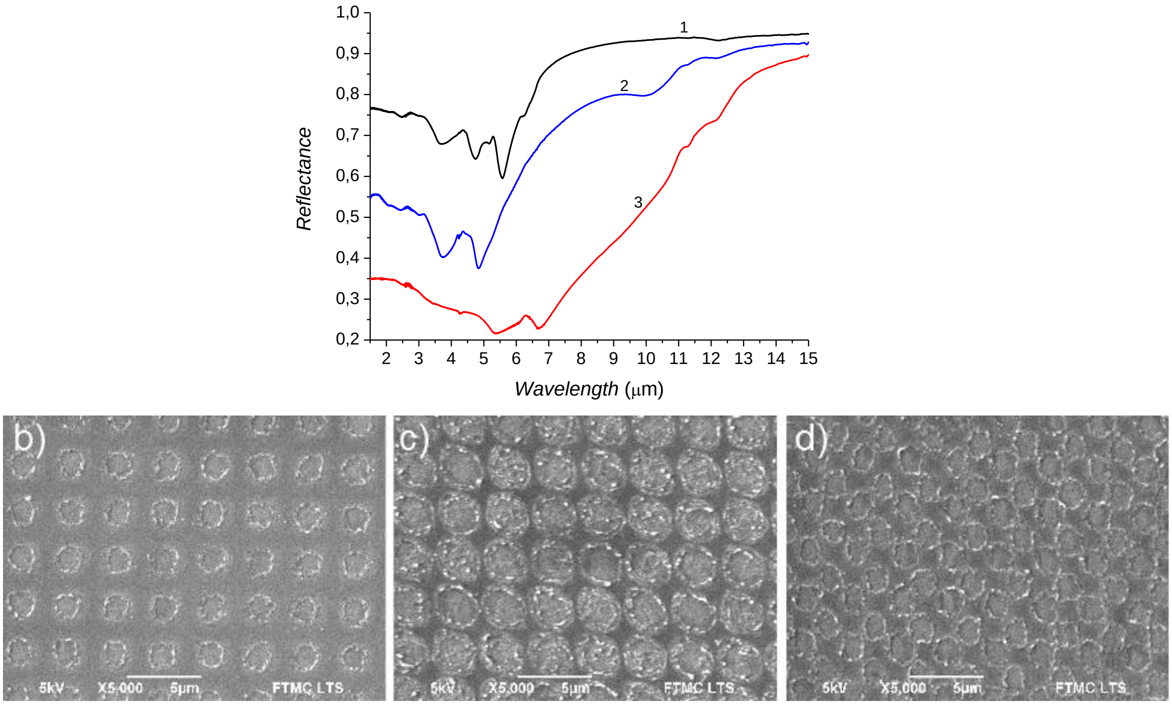

Fig. 3. Reflectance spectra of hole arrays (a) fabricated in 50 nm-thick aluminium film on a sapphire substrate using 1 J/cm^2 fluence and the different number of pulses and structure periods: 1 pulse, 3.35 μm period (1), 50 pulses, 3.35 μm period (2), 1 pulse, 1.68 μm period (3). (b), (c) and (d) show SEM images of the structures corresponding to the reflectance lines 1, 2, and 3, respectively.

4. Conclusion

In conclusion, DLIP patterning technique allows producing perforated metallic structures for plasmonic applications. Reflectance measurements of DLIP patterned samples show a strong dependence of reflectance modulation depth on the fabrication parameters. The high pulse number per spot or close packing of holes next to each other leads to the reduced modulation depth due to the formation of disordered molten metal droplets and metal film corrugations between the holes. Longer laser pulses may be preferable for ensuring the high modulation depth.

Acknowledgements

The project VP1-3.1-ŠMM-08-K-01-009 is financially supported by the National Program “An improvement of the skills of researchers” under the supervision of Lithuanian Ministry of Education and Science.

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