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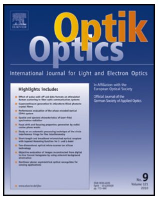

Original research article

Inscription of sub-wavelength gratings with different periods based on asymmetric metal-cladding dielectric waveguide structure

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ABSTRACT

A method of fabricating sub-wavelength gratings with different periods by employing an asymmetric metal-cladding dielectric waveguide structure is proposed. Theoretical analyses of the dispersion curves of the waveguide modes and the period dependences of the sub-wavelength gratings fabricated by this method are presented herein. The results of simulations performed using the finite element method to determine the distributions of the interference fields of the waveguide modes are also discussed. The sub-wavelength gratings with various different periods can been produced using this method by changing the thickness and refractive index of the photoresist, as well as which of the waveguide modes is excited and employed. The proposed nanolithography method of fabricating sub-wavelength gratings is advantageous because of its low cost, its simplicity, and, in particular, its ability to produce gratings with various periods.

1. Introduction

Sub-wavelength gratings are in high demand for use in a wide range of devices such as polarizing beam splitters [1,2], polarizers [3], reflectors [4–6], blazed gratings [7], filters [8], sensors [9] and so on [10]. Thus, the fabrication of sub-wavelength gratings is an interesting and important research area. Lithography techniques [11] have always been the methods most commonly used to fabricate gratings. These techniques include electron beam lithography [12], focused ion beam writing [13], X-ray lithography [14], extreme ultraviolet lithography [15], and zone-plane-array lithography [16–19], among others. However, drawbacks such as high cost, complexity, and resolution limitations resulting from diffraction have prevented the widespread use of these methods to fabricate sub-wavelength gratings. Recently, plasmonic nanolithography [20–22] has attracted significant attention in nanolithography investigations. Yang et al. [23] generated a sub-wavelength grating with 350 nm period and 100 nm linewidth by surface plasmon polariton interference based on a hyperbolic metamaterial multilayer structure and a 700-nm-period Al grating mask. Liang et al. [24] proposed and demonstrated a hyperbolic metamaterial composed of SiO_2/Al films that squeezes out bulk plasmon polaritons (BPPs) to produce sub-wavelength interference patterns. In the experiment, Au grating masks were used for BPP excitation. The hyperbolic metamaterial structure and grating masks can be employed to fabricate sub-wavelength gratings, but the hyperbolic metamaterial structure production processes are complex and the periods of the resulting sub-wavelength gratings are difficult to change. In addition,

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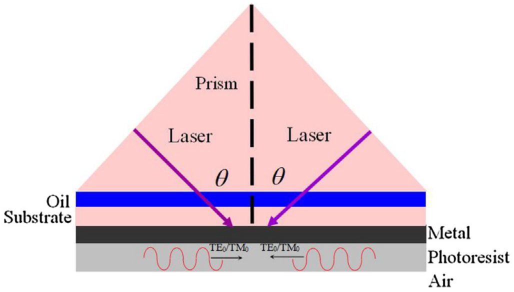

Fig. 1. Schematic of zeroth-order mode interference nanolithography configuration based on asymmetric metal-cladding dielectric waveguide structure.

metal-dielectric and metal-dielectric/insulator-metal (MDM/MIM) waveguide structures [25,26] can also be used for nanolithography. Based on the amplification of evanescent waves in an MIM cavity, a dense grating with 22 nm half-pitch [27] and nanocharacters with about 50 nm line width and dense lines with 32 nm half-pitch resolution [28] have been proposed and demonstrated. Compared with metal-dielectric waveguide structures, the fabrication of MDM/MIM waveguide structures is expensive and complex.

Based on an asymmetric metal-cladding dielectric waveguide structure, we previously proposed and demonstrated sub-wavelength grating inscription by utilizing a waveguide mode interference lithography technique, which is a type of maskless nanolithography [29,30]. In this letter, a method of fabricating sub-wavelength gratings with different periods, namely, zeroth-order mode interference nanolithography, is proposed and discussed in detail. The prism coupling method and a 325 nm laser beam are used to excite the TE_0 and TM_0 waveguide modes existing in an asymmetric metal-cladding dielectric waveguide structure. Due to its advantages of low cost, simplicity, and, in particular, ability to produce gratings with various periods, the proposed nanolithography technology would reduce the cost of producing sub-wavelength gratings and provide a theoretical reference that could be employed when it is necessary to fabricate a grating with a certain period.

2. Theoretical analysis

Fig. 1 presents a schematic of the zeroth-order waveguide mode interference nanolithography configuration that is based on an asymmetric metal-cladding dielectric waveguide structure consisting of an Al film, a photoresist film, and air, which is similar to that in Ref. 29. Two laser beams with identical intensities and polarizations irradiate the waveguide structure at the excitation angle θ of the TE_0 or TM_0 mode. The interference of the TE_0 or TM_0 waveguide modes excited in the photoresist layer by the two laser beams generates an electromagnetic field distribution with a sub-wavelength period. After the exposure and developing processes, the sub-wavelength dielectric grating is fabricated on the metallic film, which is coated on substrate glass that has the same refractive index as the coupling prism.

The eigen-equations for the TE_0 and TM_0 waveguide modes are presented as Eqs. (1) and (2), respectively [31]:

$$\kappa_2 d = \arctan\left(\frac{\alpha_3}{\kappa_2}\right) + \arctan\left(\frac{\alpha_1}{\kappa_2}\right), \tag{1}$$

and

$$\kappa_2 d = \arctan\left(\frac{\varepsilon_2\alpha_3}{\varepsilon_3\kappa_2}\right) + \arctan\left(\frac{\varepsilon_2\alpha_1}{\varepsilon_1\kappa_2}\right), \tag{2}$$

where ε_1 is the permittivity of the metal film. Since the imaginary part of ε_1 is much less than its real part, it is often convenient to neglect the imaginary part in the analysis. ε_2 and ε_3 are the permittivities of the photoresist and air, respectively, and d is the photoresist thickness. κ_2, α_1, and $\alpha_3$can be expressed as

$$\begin{cases} \kappa_2 = \left(k_0^2\varepsilon_2 - \beta^2\right)^{1/2} \\ \alpha_1 = \left(\beta^2 - k_0^2\varepsilon_1\right)^{1/2} \\ \alpha_3 = \left(\beta^2 - k_0^2\varepsilon_3\right)^{1/2} \end{cases}. \tag{3}$$

Here, β is the propagation constant and $k_0 = 2\pi/\lambda$is the wave number in a vacuum of the light emitted by the exciting laser.

For Eqs. (1) and (2), the allowed range for the effective refractive index n_{eff} should satisfy

$$\sqrt{\varepsilon_3} < n_{eff} = \beta/k_0 < \sqrt{\varepsilon_2}. \tag{4}$$

For TM_0 waveguide modes, when the allowed effective refractive index is larger than $\sqrt{\varepsilon_2}$, the eigen-equation becomes:

$$\alpha_2 d = -ar\tanh\left(\frac{\varepsilon_2\alpha_1}{\varepsilon_1\alpha_2}\right) - ar\tanh\left(\frac{\varepsilon_2\alpha_3}{\varepsilon_3\alpha_2}\right), \tag{5}$$