Optics Communications 311 (2013) 33–37

Contents lists available at ScienceDirect

Optics Communications

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

Investigation of inverse polarization transmission through subwavelength metallic gratings in deep ultraviolet band

Guoguo Kang [a,b,*], Jianjie Dong [b], Ismo Vartiainen [c], Pertti Paakkonen [a], Jari Turunen [a]

[a] Institute of Photonics, University of Eastern Finland (Joensuu Campus), PO Box 111, FI-80101 Joensuu, Finland
[b] School of Optoelectronics, Beijing Institute of Technology University, Beijing 100081, China
[c] Paul Scherrer Institute, 5232 Villigen PSI, Switzerland

ARTICLE INFO

Article history:
Received 26 May 2013
Received in revised form
28 July 2013
Accepted 15 August 2013
Available online 28 August 2013

Keywords:
Polarization control
Subwavelength metallic grating
Waveguide
Deep ultraviolet

ABSTRACT

Inverse polarization transmission of light, with the TE transmittance η_{TE} largely exceeding the TM transmittance η_{TM}, through subwavelength metallic gratings at certain wavelength in deep ultraviolet band is theoretically investigated. By using the Fourier modal method and the planar waveguide theory, we show that the light transmission involves both the surface plasmon and the low-loss waveguide modes. Strong coupling of the incident wave to surface plasmon polariton results in the minimum in TM transmittance, whereas the coupling to the low-loss mode leads to the TE transmittance maximum. The established physical mechanism is sufficient to explain the inverse polarizing phenomenon observed in aluminum grating at the wavelength of 193 nm, which may lead to important applications such as effective and compact polarizer used in DUV lithography.

1. Introduction

The form birefringence of subwavelength structures [1] has invoked much interest since its discovery. For a long time, it has been well known that the metallic grating with its period much smaller than the wavelength of incident light, transmits the TM polarization, i.e., polarized light that has an electric field vector perpendicular to the grating slits, but reflects and absorbs the TE polarization. Such short-period metallic gratings support the lowest TM mode, but cut off fundamental (guided) TE mode. Based on the strong form birefringence of metallic gratings, many important polarization-control devices, such as linear polarizers [2], polarization beam splitters [3], and radial polarizers [4], are widely used in the infrared and microwave region and recently in visible, due to the huge progress in nanofabrication technologies. However, some experiments in recent publications demonstrated an inverse polarization transmission (IPT) through subwavelength metallic gratings, i.e., with the TE transmittance η_{TE} largely exceeding the TM transmittance η_{TM}, in visible [5,6] or even deep ultraviolet (DUV) band [7]. The inverse polarizing effect of subwavelength metallic gratings found in DUV band is most inspiring. Because a grating with the period close to the DUV wavelength (say, with period ~200 nm) can be easily realized by using the current nanofabrication technologies, compact DUV polarizers, polarization beam splitters, etc., taking the place of bulk crystals, are approaching practical applications.

Although the IPT has been demonstrated experimentally in the DUV band, its underlying physics is less understood. Here, we attack the physical mechanism of the IPT phenomenon by exploring the interaction of polarized light and subwavelength metallic gratings (SWMGs). The main processes which accompany the TM incidence onto a metallic grating include: (i) transformation of the incident wave into the low-loss waveguide modes and into the surface plasmon polaritons (SPPs) on the entrance side of the grating, (ii) propagation and reflection of the waveguide modes within the grating region, and (iii) transformation of the waveguide modes to the surface plasmons and the zero-order transmitted wave on the exit side of the grating. As for TE illumination, the absence of SPPs simplifies the propagation process: the TE transmittance largely depends on the coupling strength of incident wave to TE waveguide mode. By calculating the propagation constants of the modes excited in the grating region, we first divide the modes into the propagating and inhomogeneous ones. Rigorous calculations show that both the TE and TM propagating (low-loss) modes do exist in the grating slits and should propagate without significant decay if they are effectively excited. In the second step, we calculate the weights associated with different modes to find out which are dominant in the grating region. As expected, the effectively excited TE guided mode with the largest weight leads to the high transmittance, whereas the excitation of SPP mode at the input interface prevents effective coupling of light to the TM guided mode, causing the suppressed TM transmission. The forthcoming detailed modal analysis of inverse polarization

* Corresponding author at: University of Eastern Finland (Joensuu Campus), Department of Physics and Mathematics, Institute of Photonics, PO Box 111, 80101 Joensuu, FIN-80101 Joensuu, Finland. Tel.: +358 404474385.
E-mail address: kangguoguo@gmail.com (G. Kang).

0030-4018/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.optcom.2013.08.048

transmission through subwavelength metallic gratings will eventually lead us to uncover the physics behind the phenomenon.

2. Modes in an IPT metallic grating

Fig. 1 shows the subwavelength metallic grating with period $d=176$ nm, slit width $g=88$ nm, ridge width $b=88$ nm, and grating depth $h=180$ nm. When illuminated by the DUV light with wavelength $\lambda=193$ nm, the grating exhibited the pronounced IPT phenomenon [7]. To understand the cause of it, we start our investigation with the modal expansion. Note that the IPT grating has width of the ridges b considerably larger than the skin depth of the metal, so the propagating grating modes are very similar to the modes of an isolated metal-insulator-metal (MIM) waveguide. Like the waveguide modes in an isolated slit, the grating modes are characterized by their propagation constants β, which can be determined directly by using methods such as Fourier modal method (FMM) [8].

In the air and substrate regions, the fields can be expressed as Rayleigh expansions. In the grating region, Maxwell's equations should be solved with appropriate periodic boundary conditions to obtain the grating modes. The total electromagnetic field therein can be written as a linear superposition of these modes

$$\begin{bmatrix} E_y(x,z) \\ H_y(x,z) \end{bmatrix} = \sum_{q=0}^{\infty} \begin{bmatrix} E_q(x) \\ H_q(x) \end{bmatrix} [a_q^{+} \exp(i\beta z) + a_q^{-} \exp(-i\beta z)], \quad (1)$$

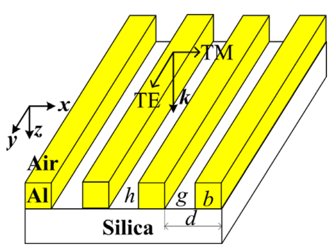

Fig. 1. Schematic of the subwavelength metallic grating.

where q is the order of mode, β is the propagation constant of the qth mode, $\alpha_q^{\pm}$ are the weights associated with the qth mode travelling in positive and negative z direction, $E_q(x)$ and $H_q(x)$ are the lateral field distributions of the qth mode for TE and TM polarization, respectively. Inside the grating region, the field continuity conditions at the boundaries between the ridges and grooves lead to a dispersion equation [9] for β, which can be written as for TE-polarized illumination

$$f_{\mathrm{TE}}(\beta) = \cos(k_x^b b)\cos(k_x^g g) - \frac{(k_x^b)^2 + (k_x^g)^2}{2k_x^b k_x^g}\sin(k_x^b b)\sin(k_x^g g) = \cos(k_x^{in} d) \quad (2)$$

for TM-polarized illumination

$$f_{\mathrm{TM}}(\beta) = \cos(k_x^b b)\cos(k_x^g g) - \frac{(\varepsilon_g k_x^b)^2 + (\varepsilon_b k_x^g)^2}{2\varepsilon_b \varepsilon_g k_x^b k_x^g}\sin(k_x^b b)\sin(k_x^g g) = \cos(k_x^{in} d) \quad (3)$$

with

$$k_x^{in} = k_0 \sin\theta_{in} \quad (4)$$

$$k_x^b = \sqrt{\varepsilon_b k_0^2 - \beta^2} \quad (5)$$

$$k_x^g = \sqrt{\varepsilon_g k_0^2 - \beta^2} \quad (6)$$

$$\varepsilon_b = n_b^2, \quad \varepsilon_g = n_g^2 \quad (7)$$

where k_x^{in}, k_x^b and k_x^g are the x-component of propagation constant in the incident medium, grating ridge and groove, respectively. The rightmost part of Eqs. (2) and (3), i.e., $\cos(k_x^{in} d)$ contains the incident angle and wavelength, representing the incidence conditions. The solutions of Eqs. (2) and (3) give the complex value of β in the form $\beta=\beta'_\nu + i\beta''_\nu$, where the index ν numerates the modes in the order of increasing β''. Modes with large β''_ν are evanescent, and those with small β''_ν propagate along the z-direction. The effective index of the evanescent modes determines how fast their amplitude decreases with increasing groove depth. In case of

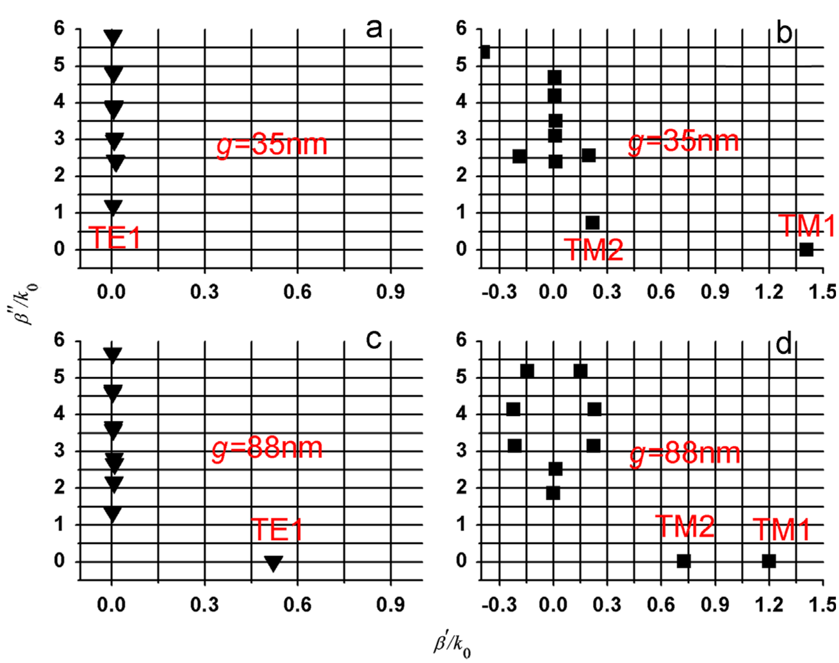

Fig. 2. Normalized propagation constants β of (a) TE and (b) TM modes for an Aluminum grating with $g=35$ nm. (c) TE and (d) TM modes for the grating with a larger slit width $g=88$ nm. Other fixed parameters are: $d=176$ nm, $\lambda=193$ nm, $n_i=n_g=1$, $n_b=0.01434+2.29657i$, and $\theta_{in}=0^{\circ}$.