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PHOTONICS AND NANOSTRUCTURES Fundamentals and Applications
Photonics and Nanostructures – Fundamentals and Applications 11 (2013) 109–114
www.elsevier.com/locate/photonics

Energy transfer channels at the diffraction-anomaly in transparent gratings and applications in sensors

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Received 23 December 2011; received in revised form 1 April 2012; accepted 3 November 2012
Available online 6 December 2012

Abstract

Diffraction anomaly corresponds to an energy re-distribution in the reflected and transmitted light beams and in different diffraction orders of a grating, which leads to sharp modulations on the transmission and reflection spectra. In gratings sitting on a transparent substrate, this portion of the energy is actually transferred to channels separated from the reflected and transmitted beams. These channels are based on multiple degenerated diffraction processes at the same wavelength as the diffraction anomaly. The spectroscopic response of these channels is sensitive to the change in the environmental refractive index and can be utilized in sensor devices.

Keywords: Diffraction grating; Rayleigh anomaly; Sensor

1. Introduction

Abrupt spectral changes may be observed as the incident light beam is diffracted by a grating into grazing orders, which are generally recognized as the Rayleigh anomalies [1–3]. In this case, the diffraction induces surface evanescent waves that are coupled with other orders of diffraction and the transmitted and reflected beams. Thus, when one of the diffraction orders becomes evanescent, the corresponding energy will be redistributed among these energy flow channels. The relations between the properties of the evanescent surface wave and the structural parameters of the grating are quite intricate. Clear understanding and precise characterization of these relations will be very helpful for tailoring the light energy flow in photonic structures. Furthermore, the corresponding photophysical functions may be multiplied if combined with other mechanisms. Fabricating the gratings on a layer of waveguide produces the so-called waveguide-grating structures (WGS) [4] that may be used as narrow-band filters [5], optical switch [6], polarizers [7,8], or sensors [9]. One can investigate the photophysics related to the coupling between the photonic and plasmonic resonance modes and improve the stability of the device by using metallic materials to construct the grating structures [10–13].

In this work, we investigate experimentally multiple diffraction processes that are degenerated at the wavelength of the diffraction anomaly in a classical transparent grating, which are considered as different possible transfer channels for the same amount of energy of the incident light. The corresponding

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1569-4410/$ – see front matter
http://dx.doi.org/10.1016/j.photonics.2012.11.002

spectroscopic response of these processes is found sensitive to the environmental changes in refractive index and the device may be used to explore sensors.

2. Photophysical mechanisms involved in the energy transfer channels degenerate at the diffraction anomaly

Three different channels are demonstrated in Fig. 1(a) in addition to the reflected and transmitted beams for the energy transfer at the wavelength of the diffraction anomaly that is excited by a collimated light beam incident onto the grating at an angle of θ_i and diffracted into grazing orders. Fig. 1(b) shows the atomic force microscopic image of the grating structures used in the experiments, which are made of photoresist on a glass plate with an area of 15 mm × 15 mm and a thickness of about 1.1 mm. This photoresist grating has been fabricated using the conventional interference lithography technique, where a He–Cd laser at 325 nm provides the UV light and S1805 photoresist from Rohm & Haas is used as the recording medium. The photoresist is spin-coated onto the glass substrate at speed of about 2000 rpm so that the photoresist layer has a thickness of about 200–300 nm before the exposure and the development processes. The photoresist grating has a period of about 340 nm and a modulation depth of more than 100 nm.

Channel ❶ actually corresponds to the light-trapping process in the micro-cavity based on the distributed feed-back (DFB) mechanism through Bragg diffraction. The surface-emitting mode normal to the substrate is actually the diffraction of the trapped light in the DFB cavity, which is designated as channel ❷. The diffraction anomaly actually takes place at the same wavelength as the diffraction into the substrate, which is totally reflected by the bottom of the substrate and diffracted again by the top grating into beam ❸. The diffraction into beam ❸ is based on the same condition as that into the substrate for the incident beam at θ_i. Therefore, beam ❸ is parallel to the reflected beam can be used to measure the wavelength of the diffraction anomaly. Thus, at the wavelength of diffraction anomaly, part of the light energy flows into channel ❶ and the other part into the substrate to excite the diffraction into channel ❸. However, channel ❶ involves an unstable state, where the corresponding light energy relaxes through further diffraction into channel ❷ and through scattering and absorption in the grating itself. Channel ❷ is actually an extending process of channel ❶.

The diffraction anomaly or Rayleigh anomaly is defined by the diffraction perpendicular to the grating

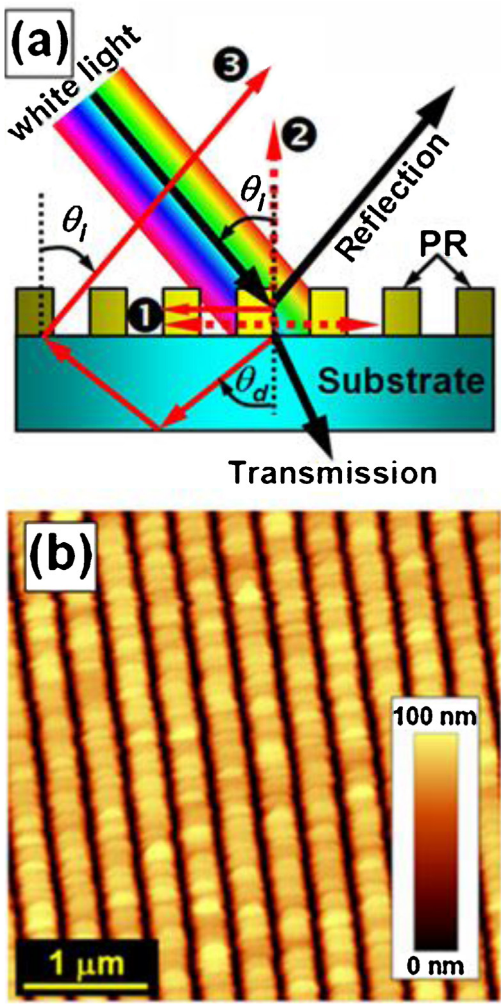

Fig. 1. (a) Schematic illustration of the diffraction channels to which the light energy of the diffraction anomaly is transferred; (b) the atomic force microscopic image of the photoresist (PR) grating.

normal. Assuming an incident angle of θ_i of the white light from air, the condition for the diffraction anomaly is written as:

$$\Lambda \sin\theta_i + n\Lambda = \lambda, \quad (1)$$

where n is the refractive index of the environment and n equals 1 when the grating is located in air, Λ is the grating period, and λ is the corresponding wavelength of the incident light. In this work, due to the small grating period ($\Lambda = 340$ nm), only the first-order diffraction process is included in Eq. (1) for the wavelengths in the visible spectral range. It should be noted that the white light is incident from air into the environment of the grating and the practical incident angle onto the grating is $\theta' = \sin^{-1}(\sin\theta_i/n)$, therefore, we always have $n \sin\theta' = \sin\theta_i$ and the first term on the