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Bypassing and cutting through 1D photonic crystals by ultra-shallow wet-etched resonant gratings

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Abstract

The electromagnetic field in subwavelength resonant diffractive optical elements is so concentrated that a very shallow surface corrugation obtained by wet chemical micro–nano-etching is sufficient to give rise to high contrast diffraction effects allowing a high wavelength-, polarization- or transverse-mode-selectivity which is not achievable by conventional diffractive elements. Two examples of polarizing laser mirrors at both extremes of the optical spectrum with wet-etched grating bypassing and cutting through the 1D photonic crystal are demonstrated.
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Keywords: Wet etching; Resonant grating; Photonic crystal; Multilayer mirror; Radial polarization

1. Introduction

The development of micro–nanostructuring in diffractive optics, and more generally in microoptics, owes much to the steady and so far predictable development of microelectronics towards ever smaller feature sizes. The technologies used in microelectronics which can be borrowed by microoptics include lithography (either by direct e-beam writing or by step and scan), etching and deposition of silicon-based layers, such as amorphous silicon, silicon oxide (SiO_2), silicon oxinitride (SiON) and silicon nitride (Si_3N_4), and more recently, high-*k* gate oxides, such as Hafnium and Tantalum oxides (HfO_2 and Ta_2O_5) [1]. Well-documented Reactive Ion Etching (RIE) processes and related equipment have been developed for silicon-based substrates and layer materials [2], whereas high refractive index metal oxide layers can be etched by Reactive Ion Beam Etching (RIBE) [3], which combines chemical etching and the kinetic energy of an ion beam to remove the non-volatile products of the reaction. This is a complex process with a large number of parameters and high processing costs. Metal layers can be etched by chlorine RIE [4]; this is a well-developed technology, but it requires strict safety precautions and costly infrastructure.

Isotropic wet etching for microstructuring objectives in microelectronics was abandoned long ago for its incapability of matching with the demands on the characteristic dimension (CD), the sidewall etching spoiling the resolution needed by today's photolithography. Wet etching is currently mainly used in microelectronics for anisotropic shaping of single-crystal silicon and removal of relatively large areas of metal and dielectric layers. Wet microetching has found limited use in diffractive optics either since vertical

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walls are often required and sidewall etching would further limit the angular aperture of the element as the typical depth of fused quartz-based transmission diffractive optical elements (DOE) is roughly between half and one operation wavelength.

However, there is currently an emerging field within diffractive optics where wet microetching is bound to play an important role as an alternative manufacturing technology to dry etching. This field concerns resonant diffractive elements, and more particularly, diffraction gratings, where the surface corrugation is located in the field of an electromagnetic surface wave. This surface wave can be that of a plasmon propagating at a metal–dielectric interface [5] or a guided [6] or leaky mode [7] of a dielectric layer or multilayer. Fig. 1 illustrates one resonant grating structure with the transverse field of the surface wave involved which is here a true waveguided mode. The mechanism of operation and typical effects of one type of resonant element (a resonant mirror) are symbolized in Fig. 2. In this case, the grating couples an incident wave to the surface wave, which acts as an energy reservoir. The surface wave propagates over some distance along the corrugated surface and then re-radiates away into the incident and transmission media, where it interferes with the component of the field that was not coupled to the surface wave, giving rise to interference effects whose contrast, destructive or constructive character are determined by the optogeometrical parameters of the structure [8]. It is of particular interest that the diffraction effects can be made highly selective with regard to wavelength, angle and polarization, unlike in standard non-resonant corrugations, the selectivity of the created interference effects being conferred by the surface wave itself. From a photonic crystal point of view, the resonant gratings sketched in Fig. 1, sometimes named 2.5D photonic crystals if composed of holes instead of lines [9], are 1D waveguide mode photonic crystals operating according

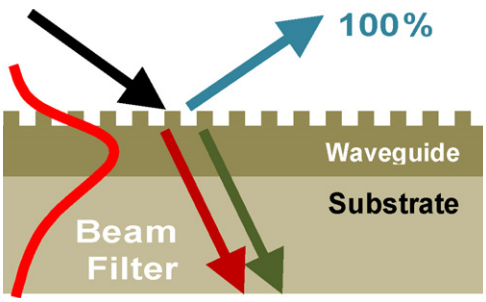

Fig. 1. Resonant reflection of a free-space wave from a grating waveguide upon mode coupling (transverse electric field profile of the TE_0 mode and wavelength selectivity represented).

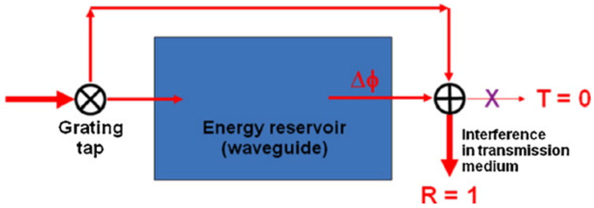

Fig. 2. Symbolic representation of the operation of a waveguide grating resonant mirror: the grating splits the incident field into a 1st order coupled waveguide mode field with energy accumulation then outside re-radiation, and the 0th order transmitted field. The latter and the former recombine in the transmission half-space with design-adjusted relative amplitude and phase for destructive interference, ensuring 100% reflection theoretically.

to the intraguide 2nd grating order, addressed by the incident free space wave via the 1st grating orders. However, the photonic crystal representation is here less meaningful physically than a coupled wave phenomenology since the lateral modal field confinement is weak as will be seen in the two examples where the grating permits to bypass or cut through the stop-band of the 1D photonic crystal of a dielectric multilayer. What matters most in the scope of the present paper is that the electromagnetic field of the surface wave can be so strong that highly selective control over the contrast of the said interference in the incident or transmission media can be achieved using a very shallow corrugation whose depth is between one tenth and one hundredth of the period depending on the refractive index of the corrugated layer material. This arises because the strength of a resonant grating is the product of three factors: the corrugation height h, the normalized modal field strength in the corrugation, and the permittivity difference between groove and ridge [10]. Interest in ultra-thin gratings has also been fuelled recently by demonstrations of such gratings with engineered subwavelength gold V-shaped structures forming so-called metasurfaces giving rise to phase discontinuities by means of surface steps height of no more than one hundredth of a wavelength [11]; this is presently made by a lift-off technique and could easily be wet etched.

The etching of such shallow features is difficult to achieve using a dry chemistry process involving a plasma or reactive ion beam: as the etching rate is usually rather high, the depth and uniformity of the corrugation relief is determined by the very first seconds of a short process where the plasma is unstable and non-uniform. This is where wet microetching offers a solution: although such resonant gratings are often ‘‘zeroth order elements’’, and thus subwavelength, i.e., clearly submicron in visible and near-IR applications, the required aspect ratio of the corrugation is so small

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