New Resonant Diffraction Phenomenon from Silicon Grating Waveguide

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ABSTRACT

The excitation of a grating waveguide mode from a high-index incidence medium by means of the +1st and -2nd diffraction orders of the grating in the neighbourhood of the -1st order Littrow condition causes a lossless 100% isolation switching between the propagative 0th and -1st reflected orders upon a wavelength or angular scan under the condition that all orders in the low-index transmission medium are evanescent. This purely reflective diffractive effect only occurs if the excited mode effective index is larger than 3. Considering that the waveguide is corrugated, silicon and related microstructuring technologies is thus the adequate implementation material. This new resonant diffraction effect can be used for wavelength and angular control, and biochemical sensing.

Keywords: Grating waveguides, resonant diffraction, mode coupling, silicon photonics

1. INTRODUCTION

Since the mid-eighties a number of resonant diffraction effects have been found, theoretically analysed, experimentally demonstrated, and used in industrial application. "Resonant diffraction" is a process whereby an incident free-space wave impinges onto a waveguide associated with a periodic corrugation or index modulation, gets synchronously coupled and partially trapped into a mode of the waveguide by a diffraction order of the grating, then re-radiated into the adjacent sub- and superstrates where a possibly high contrast interference occurs with the uncoupled 0th diffraction orders. This process is often referred to as a Fano resonance. The best known and most used effect is that of resonant 0th order reflection [1] implemented in a number of biochemical sensors [2]. More recently, ultra-narrow 100% resonant reflection under normal incidence from a high contrast binary grating was disclosed [3] and analysed [4]; it still requires an intelligible phenomenological analysis. The coupled mode needs not be a truly guided mode: high, possibly 100% -1st order diffraction efficiency can be obtained by the grazing excitation of a leaky mode, and the interferential cancellation of the 0th reflected order [5].

It is paradoxically as an outcome of the study of a plasmonic effect that the insight came for the lossless, purely dielectric reflective switching effect presented here. A switching effect between the 0th and -1st reflected orders was observed from the periodically undulated surface of a metal surface [6]; this high contrast effect occurred for the TM polarization in both angular and wavelength spectra in the neighbourhood of the -1st order Littrow condition. At either side of the Littrow angle θ_L where the -1st order efficiency is maximum, its efficiency suddenly drops to 0 where the 0th order reaches a high maximum. This occurs if the wavelength/period ratio λ/Λ is such that the +1st grating order couples the incident wave to the forward-propagating plasmon, and its -2nd order to the backward-propagating plasmon.

This switching effect between 0th and -1st reflected orders exhibits high contrast under the condition that the sole 0th and -1st orders have a propagative character in the incident medium and that the transmitted orders are forbidden. The last condition is inherently satisfied if the surface wave is a surface plasmon at a metal surface. It can also be satisfied as shown in Ref [7] if the surface wave is the TE or TM mode of a mirror-based dielectric slab grating waveguide. The purpose of the present contribution to the field of high-contrast resonant diffractive phenomena is to disclose yet another, strictly lossless version of the same switching principle that forbids the propagation of transmitted orders without mirror, and which lends itself to a particularly simple monolithic implementation: all possible transmitted orders are evanescent, i.e., they all experience total internal reflection.

2. THE COUPLING MECHANISM

The above condition imposes the refractive index n_i of the incident medium to be larger than that of the transmission medium, n_t, the incidence angle θ_i to be larger than the critical angle $\theta_C = \arctan(n_i/n_t)$, and the grating vector $K_g = 2\pi/\Lambda$ to point outside the half-circle of radius $k_0 n_t$ ($k_0 = 2\pi/\lambda$) in the Ewald circle representation of Fig. 1. The dielectric grating waveguide of refractive index n_g, thickness w, and period Λ is placed monolithically at the basis of the incident medium as suggested by the inset of Fig. 1 that shows the cross-section of the coupling structure. Analogously to the plasmonic functional structure of Ref. [6], the central angular operation point is set to be the -1st order Littrow angle θ_L given by $\sin\theta_L = \lambda/(2n_i\Lambda)$. Figure 1 summarizes in the spatial frequency domain the coupling mechanisms involved in the switching effect between the reflected 0th and -1st grating orders at constant wavelength in the case $3K_g > 2k_0n_e$ where n_e is the effective index of the waveguide mode excited by the grating +1st and -2nd diffraction orders in the forward and backward directions resp. (propagation constant k_0n_e).

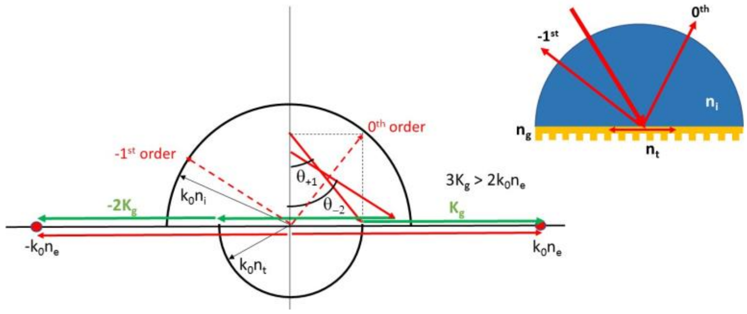

Figure 1 Ewald circles in the spatial frequency domain illustrating the conditions on the incidence angle in the medium of high index n_i for the total reflection of all diffraction orders while the +1st and -2nd grating orders excite the forward and backward propagating waveguide mode. The inset is an example of a monolithic device in the direct space.

To forbid the 0th (resp. -1st) transmitted order to have a propagative character without mirror, the incidence angle θ_{+1} (θ_{-2}) ensuring the excitation of the forward (backward) propagating mode via the +1st (-2nd) grating order must satisfy the condition $n_i \sin\theta_{+1} \geq n_t$ (resp. $n_i \sin\theta_{-2} \leq \lambda/\Lambda - n_t$). Setting θ_{+1} and θ_{-2} at their above limit, their relationship with the Littrow angle θ_L is :

$$\sin\theta_{+1} + \sin\theta_{-2} = 2\sin\theta_L \qquad (1)$$

For any incidence angle θ_i within the above limits in the high index incident media, the angle θ_{-1} of the propagative reflected -1st order is:

$$\sin\theta_{-1} = \lambda/(n_i\Lambda) - \sin\theta_i = 2\sin\theta_L - \sin\theta_i \qquad (2)$$

with the condition $\sin\theta_{-1} \geq n_t/n_i$ to ensure the evanescent character of the transmitted -1st order. Expressions (1) and (2) imply that $\theta_{-1} = \theta_{+1}$ when $\theta_i = \theta_{-2}$ and θ_{-2} when $\theta_i = \theta_{+1}$.

The expected switching effect between the reflected 0th and -1st orders as sketched in the angular domain in Fig. 2c) was analysed by a coupled wave formalism. This was accomplished in Ref. [8] where the coupled surface wave is the TM plasmon mode at a periodically undulated metal-dielectric interface. This theoretical model revealed that the switching in the angular domain between a -1st order maximum at the Littrow angle and its cancellation and 0th order maximum at two neighbouring angles at either side of the latter is a result of destructive and constructive interferences between +1st and -2nd order coupled forward and backward propagating plasmon modes re-radiating back into the incidence medium, the 3rd order of the rather deep grating coupling the two plasmon modes to each other. The same mechanism operates here. There is a limitation, however: looking back at Fig. 1, k_0n_e is about as large as $3k_g/2$. Yet K_g must be at least as large as k_0n_t to forbid all transmitted orders to have a propagative character. Consequently, k_0n_e must be at least as large as $3k_0n_t$, thus n_e at least as large as $3n_t$. n_t is no less than 1 with air (1.33 in the case of a biosensor with a water solution). Therefore, n_e must be at least as large as 3 (4 with a water analyte) which implies that high refractive index semiconductors only are appropriate as the grating waveguide material; silicon above its gap is the ideal choice for manufacturing reasons whereas germanium or amorphous silicon can be considered with a water analyte.

3. LOSSLESS MIRRORLESS SWITCHING DEVICE

The definition of the operation point of a lossless, mirrorless diffractive switch between 0th and -1st reflected orders is here made on an experimental model (ref. inset of Fig. 1) at 1500 nm wavelength composed of a 1.45 index silica incidence medium, a silicon slab waveguide of 3.5 index and thickness w_g topped with a binary silicon grating of 0.5 duty cycle, period Λ, and depth h. The transmission medium where all transmitted orders are evanescent is air, $n_t = 1$. The polarization is TE, but can well be TM too. In a first step the desired Littrow angle and angular range are chosen which sets the period. Next step is a 2D optimization of the 0th and -1st order efficiency to find the grating depth and waveguide thickness. Figure 2 shows the outcome of the search process: a) and b) sketch the diffraction efficiency in false colours in the (Λ,θ) plane of the 0th and -1st reflected orders; c) is its cross-section at Λ = 688 nm illustrating the switching effect in the angular domain. The field at the 0th order maxima has the symmetry of the TE_0 mode; that at the Littrow angle is a hybrid mode.

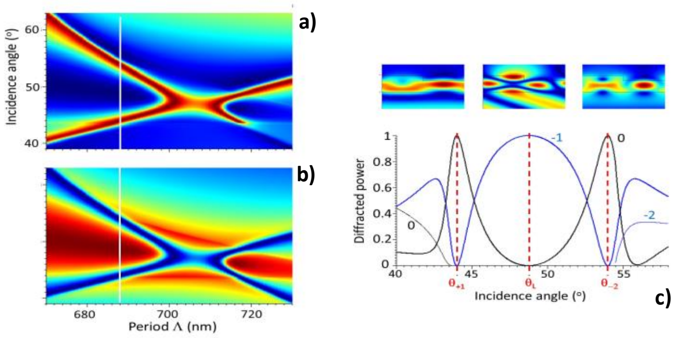

Figure 2 General (Λ,θ) chart of a device with $n_i = 1.45$, $n_g = 3.5$, $n_t = 1$ at $\lambda = 1500$ nm and $w_g(\lambda) = 330.26$, $h(\lambda) = 143.49$ nm. a) 0^{th} order, b) -1^{st} order. c) Angular scan at period $\Lambda = 688$ nm (Littrow angle $\theta_L = 48.75°$) of 0^{th} and -1^{st} orders (thin lines: transmitted propagating -2^{nd} and 0^{th} orders). The field mappings represent the resonant transverse electric field modulus at angles θ_{+1}, θ_L and θ_{-2}.

4. WAVELENGTH (DE)MULTIPLEXER APPLICATION

The presentation will describe the implementation of the resonant effect in different functional devices. We will limit ourselves here to a nearly 100% efficiency two-wavelength demultiplexing scheme. Figure 3 is the angular scan of the 0^{th} order of a smaller wavelength λ_m, and of the -1^{st} order of a larger wavelength λ_n in the same structure. The inset of Fig. 3 shows that both wavelength channels impinge from the silica incident medium under the same angle θ_{mn}, the λ_m channel is totally reflected whereas the λ_n channel is close to 100% diffracted in direction θ_{n-1} slightly off the Littrow angle. Conversely, two angularly separated incident channels under angles θ_{mn} and θ_{n-1} are efficiently superposed in direction θ_{mn}.

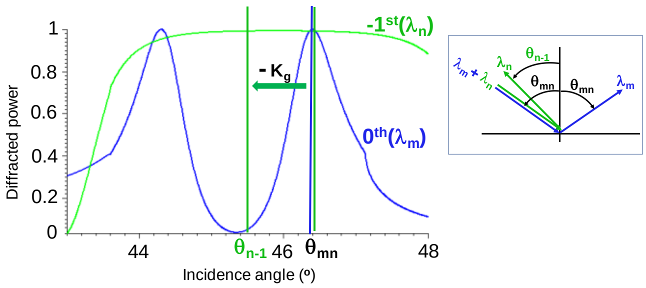

Figure 3 Angular spectra at $\lambda_m = 1510$ nm and $\lambda_n = 1525$ nm with $\Lambda = 732$ nm, $w_g = 275.264$ nm, $h = 279.3$ nm. The λ_m channel is reflected forward. The λ_n channel is diffracted back by the -1^{st} order grating constant $-K_g$ under the angle θ_{n-1}.

5. CONCLUSION

The new, non-Fano, lossless resonant diffraction phenomenon disclosed relies upon above-gap semiconductor grating waveguide mode coupling and high-contrast constructive/destructive interference in the incidence medium.

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