Angularly robust resonant reflection from corrugated slab waveguide by mode coalescence

O. Parriaux, Y. Jourlin, S. Tonchev#, A. Tishchenko, F. Lacour$

Laboratoire H. Curien UMR CNRS 5516, Lyon University at Saint-Etienne, France
Institute of Solid State Physics, Bulgarian Academy of Sciences, Sofia, Bulgaria
$Eurofarad, ZAE du Chêne Saint-Fiacre, 77600 Chanteloup-en-Brie, France
parriaux@univ-st-etienne.fr

***Abstract*—Mode coalescence in a double-sided corrugated high-index dual-mode slab waveguide suppresses the spectral splitting of the normal incidence resonant reflection peak upon an angular offset. The resulting angular robustness enables this polarization- and wavelength-selective reflection effect to be used to optically process free-space light beams emitted by low coherence sources.**

Keywords- *Slab waveguide, Grating, Resonant reflection*

I. Introduction

Since its discovery in 1985 and the explanation of its mechanism [1], resonant grating reflection has been used with beams of high spatial coherence. The reflection peak width is of the order of one nanometer and the peak position is very sensitive angularly. There have been attempts to broaden the angular spectrum by enhancing the second order intra-guide coupling coefficient by tailoring the duty cycle of a corrugation or by means of a doubly-periodic grating [2]. These designs can however not achieve resonant reflection of a wide bandwidth, wide angular spectrum beam like that of a lensed LED for instance which would be very useful for a number of low-end applications such as coarse WDM.

We report here on a waveguide grating which under normal incidence achieves a polarization selective reflection peak of wide spectrum and moreover exhibits high angular robustness preventing the formation of the reflection dip in the spectrum of rays impinging slightly off-normal which preclude the reflection of a whole light beam of non-zero angular aperture.

II. Angularly robust resonant reflection

A remarkable property of double-sided corrugated slab waveguides of very high index propagating a second mode close to its cut-off - here the TE_1 mode - is to exhibit a coalescence of the fundamental TE_0 and TE_1 modes as the corrugation depth increases. This is illustrated in Fig. 1 where an amorphous Silicon (α-Si) slab waveguide of index 3.7 on a glass substrate is given a thickness large enough, t = 130 *nm*, to propagate the TE_1 mode at 850 *nm* wavelength λ. The curves correspond to different sinusoidal undulation amplitudes *d*. The abscissa is the grating period Λ in a numerical experiment at constant wavelength and waveguide thickness *t* under normal TE incidence. The ordinate is the reflection coefficient. As expected, a shallow grating of

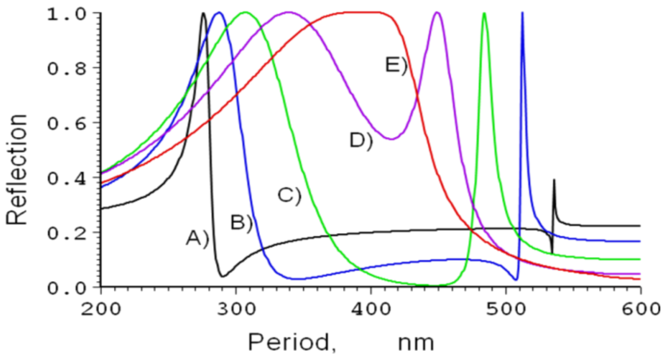

Figure 1. Normal incidence TE reflection spectra of double-sided sinusoidally undulated dual-mode a-Si slab waveguide versus period with grating depth parameter *d = 30, 60, 90, 120, 140 nm* in curves A, B, C, D, E.

increasing period couples the TE_0 mode first, then the TE_1 mode with the resulting narrow reflection peaks. The effective index of the modes is given as $n_e = \lambda/\Lambda$. Increasing the grating depth brings the two effective index closer up to *d = 140 nm* where the two modes have coalesced in a single resonance. As from here, the reflection spectrum is calculated with a grating depth leading to mode coalescence. Spectrum A) of Fig. 2 exhibits a wide reflection plateau of close to 100% reflection. Thus, all spectral components of a relatively wide spectrum light beam experience close to 100% reflection.

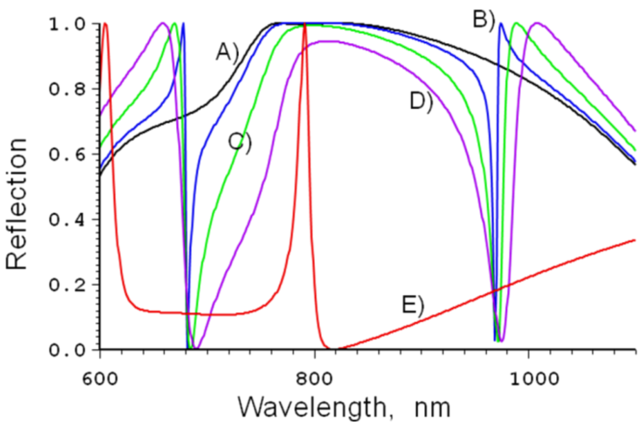

Figure 2. Reflection spectra of 130 nm thick a-Si waveguide with 333 nm period, 120 nm deep double undulation. Curves A, B, C, D are for TE incidence under angles 0, 5, 10, 15 degrees, curve E for TM normal incidence.

The other curves correspond to a tilted incidence in the incidence plane. Remarkably, the wavelength spectrum remains essentially unchanged up to an incidence angle of 15 degrees which roughly corresponds to the angular width of a lensed LED. Consequently, the designed structure represents a high contrast resonant mirror for polarized incoherent light sources of the LED type. Adding to this curve E) representing the TM reflection in the very same element, one has realized an angularly and spectrally robust high contrast polarizer.

A phenomenological vision is given of the coalescence which only takes place if the waveguide/substrate index ratio is larger than about 2. Going back to curve A) of Fig. 1 corresponding to a shallow grating, one realizes that a grating which would couple a normally incident wave to the TE_1 mode of effective index close to the substrate index would also couple the TE_1 mode to the TE_0 mode of effective index close to 3. Furthermore, the intraguide coupling coefficient between TE_0 and TE_1 modes as the overlap integral of the transverse modal electric field in the undulated parts of the slab is very large since the parity of the field of the TE_1 mode and that of the dielectric perturbation which the double-sided undulation represents is odd. The free-space wave and mode coupling condition is thus characterized by a high degree of synchronism and a large coupling coefficient. Going away from this very specific condition, for instance by using a high index oxide waveguide (eg TiO_2, diamond or ZnS), or even by increasing the a-Si waveguide thickness, thus modifying the effective index ratio and the synchronism condition between TE modes, suppresses the coalescence effect. It is therefore a remarkable coincidence that in this spectral range between 700 and 1000 nm are found the cheapest and most efficient LED light sources, high responsivity silicon-based photodetectors, and where the so well controlled a-Si technology of solar cells is for optical purpose a unique very high index and highly transparent material - to the dismay of photovoltaics. This situation is not so unique beyond the Si-gap where a number of transparent high index semiconductors exist, in particular in the far IR where such angularly robust polarization splitter may be very useful.

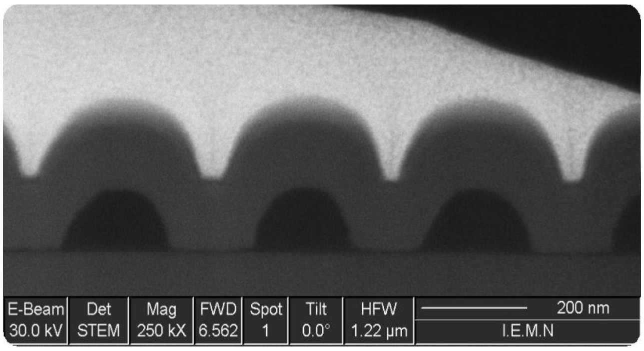

Figure 3. SEM picture of a FIB slice of rounded photoresist lines on glass substrate with 130 nm thick a-Si slab waveguide.

Usual polymer-based polarizers do have a large spectral width and a wide angular aperture with high extinction in the range of -40 dB. They however do not withstand the temperature conditions that prevail in most industrial systems. The functionality demonstration of the above design was made in the form of a binary corrugated photoresist layer on a glass substrate with a conformal a-Si layer on top. The photoresist layer was then post-backed to withstand the a-Si deposition conditions at 150 degree C. Figure 3 is the SEM picture of a FIB slice of the structure showing a very uniform silicon coverage and a perfect resist/silicon interface. The reflection spectrum is close to the modelling expectations as shown in Fig. 4. Accepting a 5% degradation of the TE reflection, the angular acceptance is ±15 degrees.

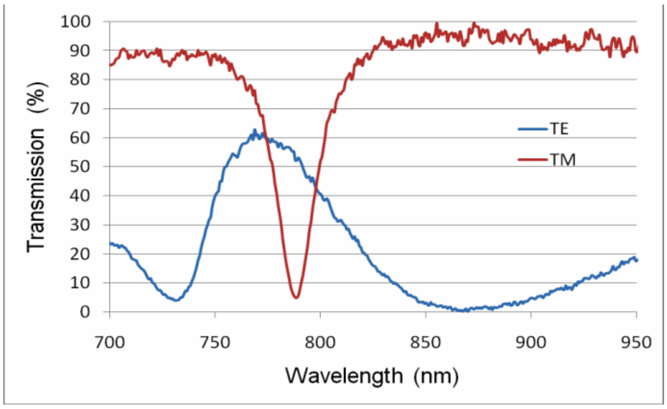

Figure 4. Measured TE and TM reflection spectra under normal incidence on the a-Si grating waveguide of Fig. 3.

III. CONCLUSION

A property of mode coalescence was identified in high index dual-mode waveguides whereby a deep corrugation makes the two modes to coalesce in a single waveguide resonance which is angularly robust and can be at the basis of a family of resonant optical elements processing low temporal and spatial coherence light beams. The demonstrated optical function is a wide band polarizer using the unique properties of an amorphous silicon waveguide fabricated by the highly reliable solar cell technology. This is a breakthrough in that optical waveguide resonances with their inherent selectivity characteristics can act with high contrast on a beam of high NA and large bandwidth.

REFERENCES

[1] G. A. Golubenko, A. S. Svakhin, V. A. Sychugov, and A. V. Tishchenko, “Total reflection of light from a corrugated surface of a dielectric waveguide,” Sov. J. Quantum Electron. **15** 886–887 (1985).

[2] F. Lemarchand, A. Sentenac, E. Cambril and H. Giovannini, "Study of the resonant behaviour of waveguide gratings: increasing the angular tolerance of guided-mode filters," J. Opt. A: Pure Appl. Opt. **1** 545-551 (1999).

[3] U. Kroll, J. Meier, and A. Shah, “Hydrogen in amorphous and microcrystalline silicon films prepared by hydrogen dilution”, J. Appl. Phys., **80** 4971-4975 (1996)