

# INDEX MODULATION BRAGG GRATINGS DIRECTLY IMPRINTED ON SOL-GEL LAYERS.

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## ABSTRACT:

Among the fabrication techniques of integrated optical devices, the sol-gel chemistry is now performant enough to make thin films of transparent materials with controlled purity and composition, at low temperature. Semi-mineral semi-organic solutions allow dip coating followed by low temperature baking to deposit vitreous films up to eight micrometers thick which are free from cracks. A local polymerisation process through UV exposure enables hybrid components compatible with electronic planar silicon or III-V components.

This UV imprinting method is used here to make index modulation gratings with use of a holographic equipment as an alternative of the use of a costly phase mask. Gratings have been imprinted on various sol-gel films : single layer, with a protective coating, and/or with an insulating buffer layer from the substrate which is silicon and glass.

Diffraction magnitude is measured in the various cases (6% for 1-order is presently obtained), as well as analysis and computer simulations are performed. Wavelength filters are experimented and studied. This shows the potential of this low cost technology in integrated optics, for application in telecommunications.

**Keywords :** integrated optics, gratings, sol-gel process, inorganic/organic hybrids,

## INTRODUCTION.

The cost effectiveness and the advantages of sol-gel processed devices compared to conventionally processed photonic devices have been widely reported in the recent years<sup>1</sup>. Though the significant commercial introduction remains to be done, especially in Europe, the ease of preparing transparent materials with competitive optical properties should help us to project that such devices eventually could be commercially important. This could be emphasized by the development of new strategies based on wet process, low temperature sol-gel chemistry, to make materials from organic and mineral precursors.

Pure mineral materials made by the sol-gel process can be doped at high temperature with rare earth<sup>2,3</sup> opening the route to the fabrication of active devices, for instance as an alternative to amplifying Erbium doped fibers. A significant thickness (several microns) needed for optical circuits is hard to obtain (many coatings) and the drawing of the optical circuits (3-D channel waveguides) require costly operations similar to the ones used in semiconductor technology. Polymers are also an attractive alternative to make

optical components, their limitations are derived from their mechanical fragility, their low resistance over a long period : oxidation reducing transparency, but they are very cost effective.

Our research in developing optical components is based on the choice of the synthesis of organic-inorganic precursors which offers a large potential<sup>4</sup> and thus wet chemical routes to provide the multifunctionality required for optical devices. The fundamental advantage of this is simplified fabrication which consists of a few steps achievable with a limited amount of equipment. The first step is the preparation of a solution of organosilicate with a methacrylate group, organozirconate precursors and a photoinitiator(see ref <sup>5</sup>). The coatings are then deposited by the dipping technique on a substrate, the thickness can reach 8  $\mu\text{m}$  in one layer, thus eliminating a major drawback of former sol-gel thin films (limited thickness). Then, thanks to the photoinitiator, the layer is photopolymerizable and allows a simple method to achieve a local refractive index change necessary to implement optical guiding and other functions. Among other qualities, the refraction index (1.479) is close to that of silica glass fibers, thus limiting as well as the obtained thickness, coupling losses when considering waveguides and optical fibers. Also, hybrid components compatible with electronic planar silicon or III-V components can be made because of the low temperatures involved in the process.

Low loss waveguides have been achieved (<0.1 dB/cm at 1.55  $\mu\text{m}$ ) for use in the telecommunication window, in particular with the addition<sup>6</sup> of a cover coating (2.5  $\mu\text{m}$  sol-gel coating transparent to UV, scratch resistant and same index) and a buffer layer (layer without photoinitiator) deposited prior to the guiding layer. Based on this three layer structure, planar waveguides, channel waveguides as well as directional couplers, power splitters, Mach Zehnder have been made<sup>7</sup>.

If many basic functionalities in optical circuits are based on combined three dimensional waveguides, gratings appear as parallel necessary components to insure functions like wavelength filtering , reflection, out of plane connections ....The work here focuses on the direct printing of gratings within the sol-gel structures.

## GRATING FABRICATION

Relief type gratings<sup>8-9</sup> need additional operations which reduce the main advantage of sol-gel layers : its low cost. Also, dimensions of gratings working with visible or infrared lights (such as wavelengths used in communication systems) need costly specific mask for each wavelength. In the parallel polymer technology, the fabrication of tilted gratings has been reported<sup>10</sup>.

Index modulation gratings take direct advantage from the easy way to locally modify the refractive index. Three methods can be applied with sol-gel layers :

- The exposure through a mask gives good performances but is limited to large grating period ( $\gg 1 \mu\text{m}$ ).
- The exposure through a phase mask in contact with the layer, which gives through diffraction a period equal to half the one of the mask. This method is used in particular to imprint gratings on optical fibers<sup>11-12</sup>. This method is used on polymers<sup>13</sup> and on sol-gel layers<sup>14</sup>.
- The holographic method, which gives ideally equal periods without the use of a mask. The equipment is similar to the one used to imprint photoresist in semiconductor technology. Our set up was formerly used to make Bragg gratings in a distributed Bragg reflector (DBR) laser diode described in reference <sup>15</sup>. The period adjustment as well as the uniformity on a surface in the order of 5  $\text{cm}^2$ , the limitations of the equipment, the related optical theory, are also studied in the given reference. Figure 1 gives a schematic view of the equipment.

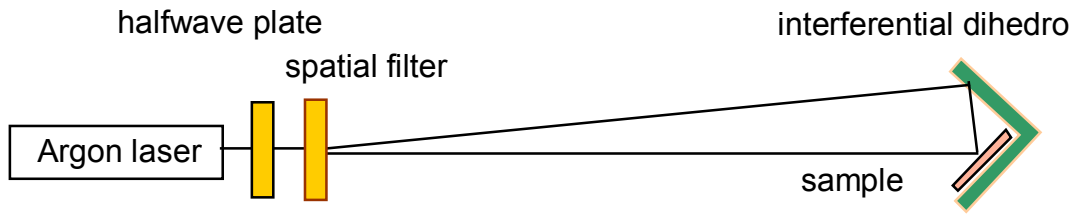


Figure 1: Set up to imprint a grating through UV exposure.

The interferential system is based on a reflecting dihedron, the sample, placed in the dihedron, receives a direct beam interfered with a reflected beam. The laser source (Argon laser, wavelength = 363 nm, power 1.8 mW) produces a polarized beam which is enlarged (the diameter is about 3 cm at the level of the dihedron). A half wave plate induces a 90 ° polarisation rotation to get a linear horizontal polarisation. The dihedron is placed about 1 m from the source to get approximate plane waves. Its reflecting mirror is treated to get optimal reflectivity for U-V light (200-400 nm).

The value of the differential index  $\Delta n(x)$  will have an approximate sine distribution only if the exposure time is in the limited linear part of the polymerisation/exposure curve, it will have more likely a saturated on one side sine function. The polymerisation/exposure curve is strongly not linear and the subsequent refractive index change  $\Delta n$  can be fitted by a formula like :

$\Delta n(E) = \Delta n_{\max} (1 - \exp(-E^2/ E_0^2))$  where E is the received energy proportional to the exposure time and UV light intensity. Other formulas might be found in literature<sup>16</sup>.

The two interfering beams are presently adjusted to strike the sample with the same incident angle (around 20°).

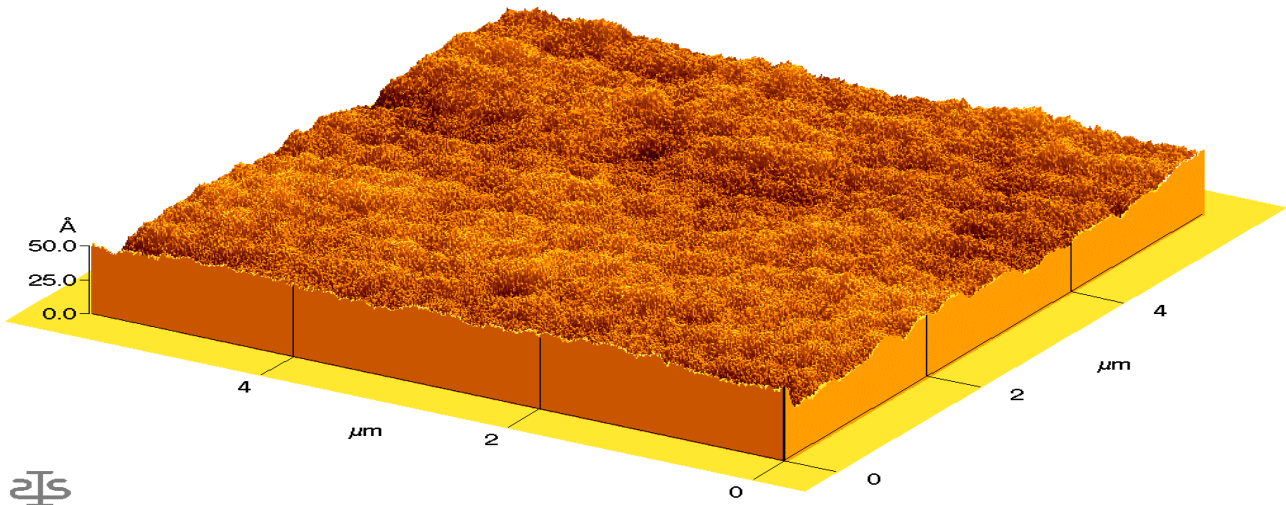


Figure 2 : AFM picture showing the poor relief perturbation of the gratings.

The printing without mask also yields a pure modulation index profile, as shown in AFM picture. On the opposite, phase masks, because they are in contact during printing with the mask show a relief modulation.

## DIFFRACTION EVIDENCE

A Littrow experiment with a Helium-Neon laser is used to show an effective diffraction. As shown in figure 3, the Littrow incidence angle is obtained when one of the reflected 1-order -1 order beams are coincident with the incoming beam.

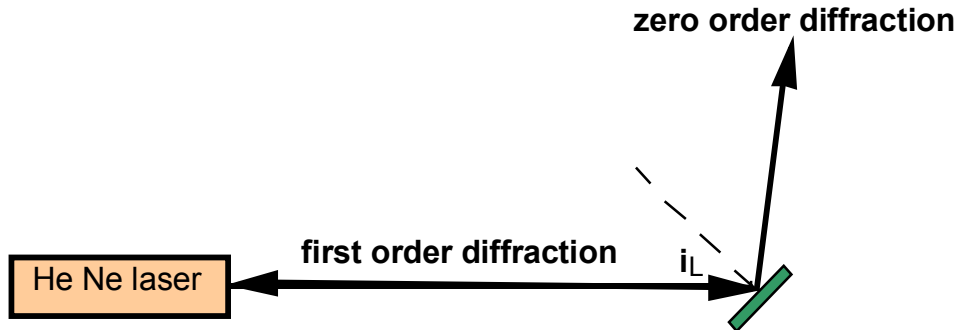


Figure 3 : Littrow experiment allowing a precise evaluation of the grating period.

The incidence angle  $\theta$ , the diffraction angle  $\theta'$ , the order  $K$ , the grating period  $\Lambda$  and the wavelength in free space  $\lambda$  are linked with the formula :

$$\Lambda = \frac{K \lambda}{(\sin \theta + \sin \theta')}$$

It gives the opportunity to check the printed period, through the measure of the Littrow angle ( $\theta = \theta'$ ). Through successive corrections, the period  $\Lambda$  can be adjusted with a precision of a few Angstroms.

Although our sol-gel layers are regularly deposited on Silicon substrates. The main reason for this is the ease to cleave samples and thus avoiding the polishing step necessary with other kind of substrates. Also, it prepares the investigation of hybrid components optical and electronic, that the sol-gel process enables because of the low temperatures involved. Gratings printed on layers deposited on pyrex glass were also tested but no reflection at order one was visible with the Littrow experiment. This illustrates the role of the reflection of the beam at the interface layer substrate, before and after crossing the layer in which the refractive index, thus the optical path is modulated.

According to computer simulations, the Littrow incidence is a maximum, as it is shown in figure 4. In this case the incidence angle varied around the theoretical Littrow angle :  $47.5^\circ$  both experimentally and through a numerical simulation giving the diffraction efficiency for each order (reflected and transmitted). In the simulation, the grating was defined as a step index modulated grating . Of course, the efficiency depends on the refractive index change between the two zones (exposed and not exposed) in each period. The accordance between the two curves (experiment and computation) is a measure of the evaluation of the refractive index.

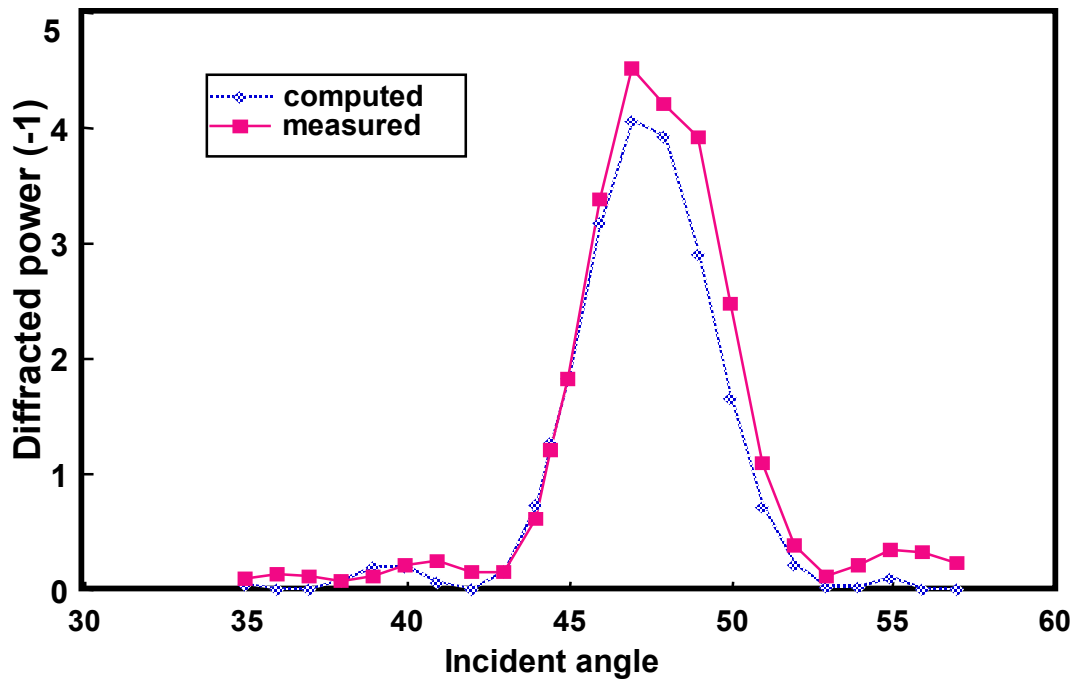


Figure 4 : Diffraction efficiency measured and computed at -1 order in reflection around the Littrow angle.

Because of this maximal reflection at the Littrow angle which depends on the wavelength, a filter may be built without a change in the grating period. Figure 5, gives the intensity of the reflection for two incident angles (corresponding to Littrow's angles for 632 nm and 553 nm). One can imagine a filtering device with multi wavelength signal impinging at several incident angles, and reflected back in directions depending on the wavelength.

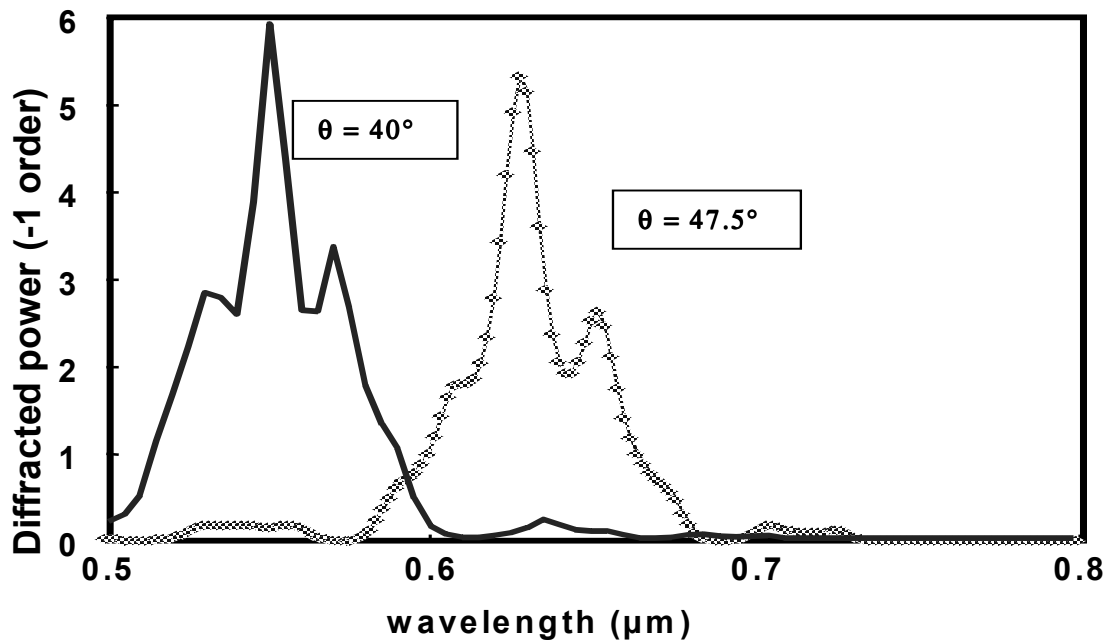


Figure 5 : Diffracted power at -1 order for two incident angles as a function of wavelength.

## GRATING FILTERS

With an incident light in the grating plane, the grating is essentially a narrow band rejection filter with a maximum for a central frequency  $\lambda$  when the grating period is half the wavelength in the material.

This can be computed in TE and TM modes by an evaluation of the transmitted and reflected fields at each change of the refractive index, through complex matrix multiplication.

Figure 6 shows the influence of the modulation profile : There is only a 3% loss in the maximum (95% instead of 98%) with a sine profile in comparison with a step profile . The higher index is 1.49 while the lower index is 1.48. Zones are of equal width 260.9 nm, this corresponds to a central wavelength of 1.55  $\mu\text{m}$ . The reflection is shown after 400 periods, which is much less than that the grating length (about 2 cm) allows.

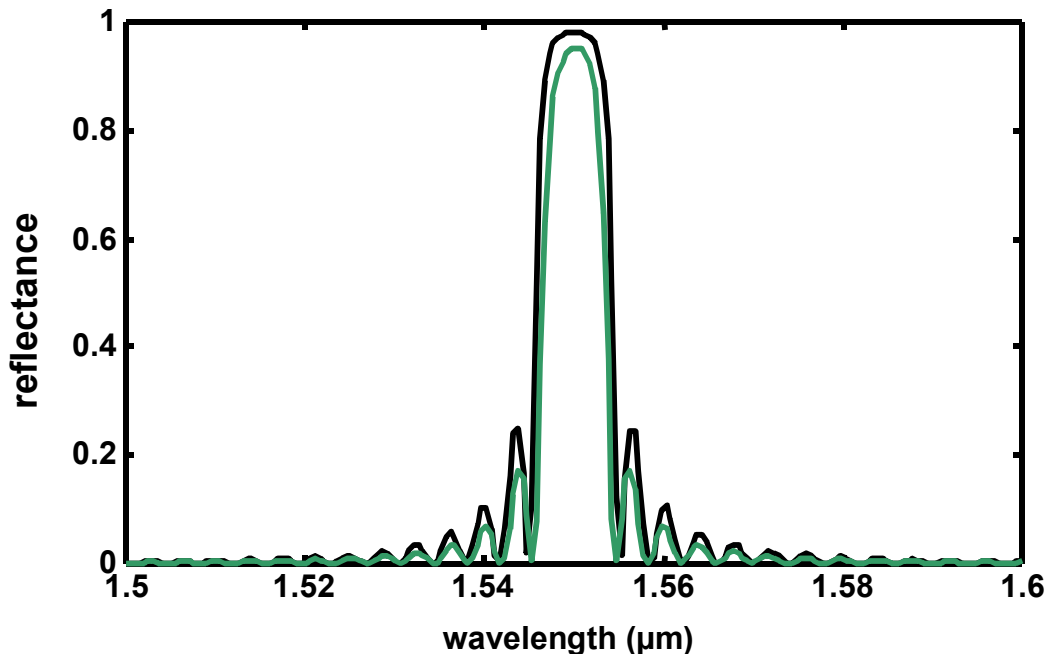


Figure 6 : Comparison of modulation profiles sine (grey line) and step (dark line) for the reflected power with a grating of 400 periods, adjusted for maximum rejection at 1.55  $\mu\text{m}$ .

The refractive index change is estimated to be about  $\Delta n = 0.01$  in our sol-gel gratings. Higher index changes have been obtained with waveguides under direct exposure under a UV Hg vapour lamp (up to  $\Delta n = 0.03$ ), An excimer laser would probably also give a higher change. Also a combination of a channel waveguide and a grating requires a double level of exposure. With an increase of the index change to  $\Delta n = 0.02$ , the maximum is higher (200 periods are enough to get 98 % of reflection), but the bandwidth is doubled as one can see in figure 7.

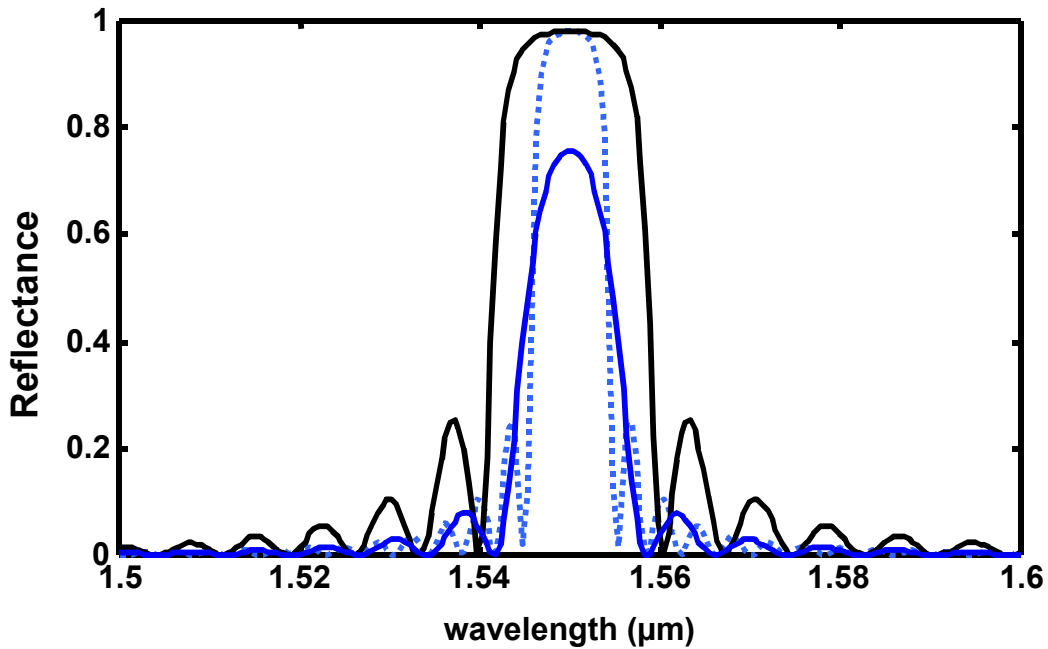


Figure 7 : Influence of the refractive index change  $\Delta n(x)$  on the bandwidth. The bandwidth is halved, when the index change is halved (grey lines), but the reflected power is also reduced (75 % instead of 98%), this is easily compensated by the number of periods (dashed line).

A low index change for the modulation profile enables to print a grating perpendicularly over a channel waveguide printed at a saturated level of photopolymerisation. Presently the printing of the gratings induces a modification of the effective index in the whole layer : a planar waveguide appears. Because our gratings are printed in the central layer of our three layer structure (cover, guide, buffer), a remedy should be to slightly increase the index of the layers which cannot be photopolymerised.

## CONCLUSION

Sol-gel processing offers attractive possibilities for passive waveguides and devices. Gratings which have to play an important role in integrated optics can be also directly imprinted on sol-gel layers without chemical or high thermal process. This should enable the fabrication of optical devices on one hand compatible with fiber use, and on the other hand compatible with integration with electronic devices.

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