Laser trimming of thin-film filters

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ABSTRACT

The use of a photosensitive material for manufacturing the spacer of bandpass thin-film filters is a very attractive way for enabling the post-processing of such devices with the help of a light beam, either to correct with a high accuracy the consequences of some deposition errors on the filter properties (central wavelength out of specifications, inadequate spatial uniformity) or to create entirely new filtering devices with controlled spatial properties (for instance, variable filters with arbitrary profile). A theoretical presentation of the main problems arisen by such a laser trimming will be done, first for bandpass thin-film filters but also for multiple-cavity Solid Spaced Etalons (SSE). After a comprehensive analysis of the possible materials which can be selected for such an application, we will conclude our presentation by the description of the first experimental results obtained by our team in this new field, including a rapid presentation of the dedicated control means needed by this spatially localized approach of a filtering device.

Keywords: thin-film filters, Solid-Spaced Etalons, photosensitive materials

1. INTRODUCTION

Today, more than 70% of the world's analog semiconductor companies are using laser-based trimming to enhance circuit performance, boost yields, speed time-to-market, and ensure higher profitability in thin film semiconductor and silicon manufacturing [1]. Lasers can be used to trim thick film resistors, thin film resistors and capacitors. In the case of resistors, for instance, laser trimming replaces the need for SOT (Select-On-Test) or potentiometers, and offers attractive improvements over abrasive trimming like higher speed, greater accuracy and lower running costs. Passive trimming refers to altering a resistor or a capacitor to a specific value, while active trimming, also known as functional trimming, is used to lock a circuit parameter to a target value, as voltage, current or frequency [2]. At the figure 1a is represented the structure of laser adjustable surface mount multi-layer ceramic capacitor (MLCC) intended for active trimming applications in various RF circuits [3]: the surface electrode interacts with internal buried electrodes and determines the initial capacitance prior to trimming. As indicated at the figure 1b, the capacitance decreases as the surface electrode is removed by vaporizing it with a controlled laser beam (for instance, 6 watts Q-switched 1064nm Nd:YAG laser, with a spot size of 40-50μm).

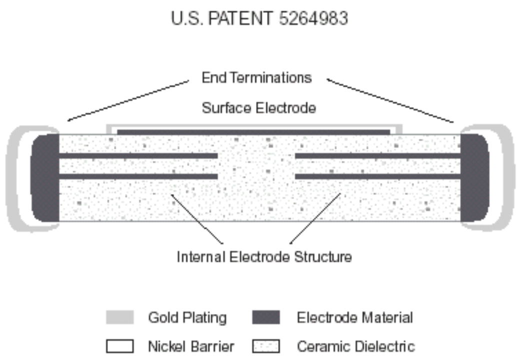

Figure 1a – Structure of a laser adjustable MLCC (from [3])

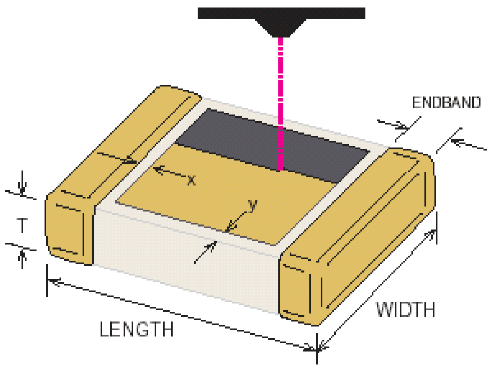

Figure 1b – Laser trimming process (from [3])

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This laser trimming approach has been widely used by the optics community since the beginning of the 90's, either for optimizing the performance of a four-port bandpass filter fabricated in a single-mode photosensitive Ge-doped planar waveguide [4], or for achieving a wavelength-insensitive biasing of an electro-optic polymer intensity modulator [5] or also for both tuning wavelength responses of planar lightwave circuits and canceling their intrinsic birefringence [6]. In all these examples of application, the laser beam is used not in an ablation or engraving mode but to modify the refractive index of a photosensitive material (mainly Ge-doped silica) used for the manufacturing of a waveguide. More recently, the same kind of approach has been applied to compensate, by UV photobleaching, systematic manufacturing deviations of 2-dimensional photonic crystals structures formed by a square lattice of holes (lattice constant 500nm, hole radius 150nm) deeply etched into a photosensisitive polymeric slab waveguide [7].

It is well known that the spectral properties of a thin-film filter are directly defined by the thicknesses and the refractive indexes of its various layers. It is well known too that some layers inside the stack are particularly critical with respect to the final performances of the filter and that a manufacturing error occurring on one of these layers can induce some drastic changes in the filter spectral profile. As an example, the central wavelength λ_0 of a single cavity narrow bandpass filter is mainly defined by the optical thickness nt_{sp} of its spacer, and any change of this quantity induces a correlative change of the central wavelength of the filter, in accordance with the general relation [8]

$$\frac{\Delta\lambda}{\lambda_0} = \kappa \frac{\Delta(nt_{sp})}{nt_{sp}}$$

where κ is a positive coefficient, typically comprised between 0.3 and 1, and whose exact value is connected to the structure of the filter. As a consequence, if our spacer is photosensitive, we can modify locally the value of the central wavelength of the bandpass filter by focusing in the volume of this "active" spacer a laser beam with the required wavelength, spot size and fluence. By sweeping this laser beam at the surface of the filter, we can adjust very accurately the spatial dependence of the spectral properties of our filtering device, either to reach the same performance on the whole component surface or to define a complex pattern adapted to a specific application.

The main objectives of this paper are first to perform a theoretical analysis of this new concept for bandpass thin-film filters and multiple-cavity Solid Spaced Etalons (SSE) and second to assess in a preliminary way its experimental feasibility.

2. PHOTOSENSITIVE THIN-FILM FILTERS

Let us consider a single-cavity narrow bandpass filter [$(HL)^5H$ – 8P – $H(LH)^5$] deposited at the surface of a silica substrate, where H (respectively L) is a quarter-wavelength layer manufactured with a high (respectively low) index material and 8P a photosensitive spacer whose optical thickness is equal to two times the design wavelength, chosen here equal to 1550nm. The refractive index of the low index and photosensitive materials are assumed to be identical before laser trimming, with the same spectral dependence as the bare fused silica, i.e.

$$n_P(\lambda) = n_L(\lambda) = n_{SiO_2}(\lambda) = \sqrt{1+\lambda^2\left[\frac{0.696}{\lambda^2-0.068^2}+\frac{0.408}{\lambda^2-0.116^2}+\frac{0.897}{\lambda^2-9.896^2}\right]}$$

where λ is expressed in microns. This hypothesis is allowed since a possible candidate as photosensitive material is Ge-doped silica. We assume besides that the high index material is tantalum pentoxide deposited by Dual Ion Beam Sputtering, with the following refractive index dispersion

$$n_{Ta_2O_5}(\lambda) = 2.085 + \frac{0.017}{\lambda^2} + \frac{0.0016}{\lambda^4}$$

where λ is again expressed in microns. Moreover let us suppose that the refractive index of our photosensitive layer can be modified by illuminating it with the second harmonic of a Nd:YAG laser (λ @ 532 nm) and that this local change can be described by the following classical relationship

$$n_P(F,\lambda) = n_P(\lambda) + \Delta n_0 \cdot [1 - e^{-F/F_0}]$$

where F is the value of the laser fluence into the layer, F_0 a fluence level characterizing the photosensitivity of the spacer material and Δn_0 the maximum achievable refractive index change in this material. This laser fluence is obviously proportional to the intensity I of the local electric field (i.e. its square modulus).

In a first step, we will assume that the absorption can be neglected at any wavelength for all the materials used in the stack. In this case, before any kind of laser trimming, the spectral transmittance of the filter in a wide spectral range including the design wavelength (1550nm) and the trimming wavelength (532nm) is described by the left side graph of the figure 2.

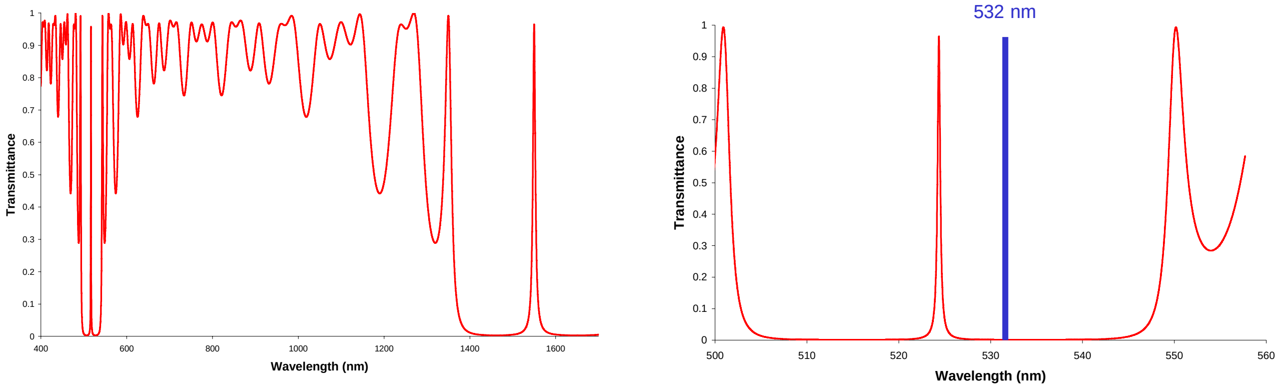

Figure 2 – Spectral transmittance of the filter before laser trimming

On the right side graph of the same figure, we have selected a smaller spectral range around 532nm in order to highlight the behavior of the filter at the trimming laser line: for this specific wavelength, we observe first that the reflectance of each mirror stack is high and second that the filter is out of resonance. It means that the effective value of the intensity of the electric field into the photosensitive layer will be greatly reduced with respect to the outside one. By using the classical matrix formalism of the thin-film optical filters [9], we are able to compute, at any wavelength, the ratio of these two quantities (i.e. the local laser intensity divided by the incoming one) inside each elementary layer of the stack, and especially into the spacer. The figure 3 gives the result of such a computation at 532nm (the origin of the physical thicknesses is chosen on the surface of the substrate).

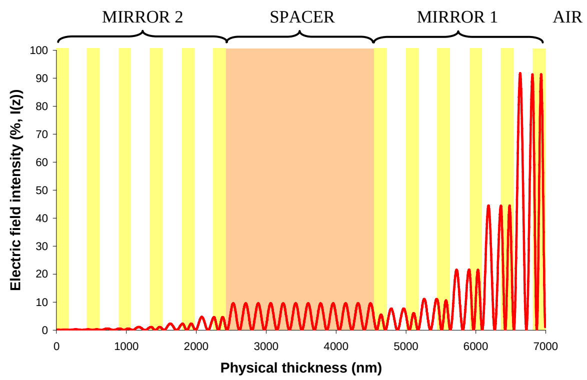

Figure 3 – Spatial variation of the ratio between the laser fluence inside the stack and the incoming one @ 532nm

This graph shows two important features for the repartition of the effective laser intensity inside the spacer: first, a sine modulation with a spatial period equal to $\lambda_0 / 2n_P$ and second a significant reduction of the mean value of the field intensity which in our case remains smaller than 5% of the incoming one. It means that after laser processing at 532nm, the refractive index of the spacer will be slightly increased and modulated (with amplitude typically less than few 10^{-3}). Additional simulations show that such a modulation has no direct effect on the shape of the spectral profile of our bandpass filter around the design wavelength. At the opposite, the increase of the mean value of the refractive index of the spacer induced by the laser trimming has a direct impact of the central wavelength of this filter. The key parameter for evaluating the efficiency of a thin-film filter trimming is then the mean value of the intensity of the laser field inside the active layer.

In our case, this efficiency is quite bad, but an increase of the trimming duration is enough to correct that. However, we can try to optimize this situation, and in this goal, we have computed the variation of the mean value of the field intensity with respect to the wavelength of our trimming laser.

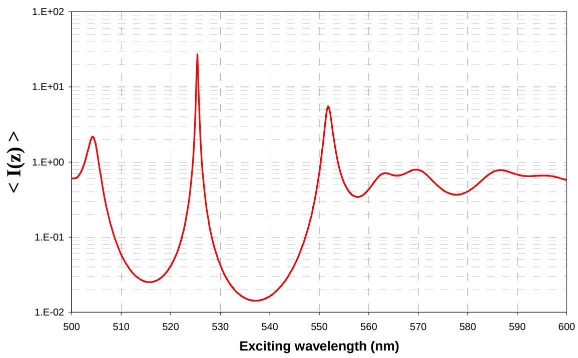

Figure 4 – Spectral dependence of the ratio between the mean value of the intensity of the field inside the spacer and the incoming one

At the wavelength corresponding to the harmonic of the bandpass filter (i.e. 525.4nm and not 516.7nm because of the dispersion of the layers materials), we observe, as expected, a great amplification of the field intensity (about 25), while at 532nm the same field intensity is attenuated by nearly 50. We can also notice the presence of two additional amplification peaks around 552nm and 503nm and the quite stable behavior of this ratio from 560nm up to 600nm. Our first idea would be obviously to center the dominant amplification peak at the wavelength of the laser line used for the spacer trimming, or in other words to reach a resonant behavior of our bandpass filter simultaneously at 1550nm and 532nm. That can be achieved quite easily, for instance by replacing the initial design of the thin-film mirrors [i.e. $H(LH)^5$] by the following one

0.070H – 0.934L – 0.567H – 1.544L – 1.691H – 0.240L – 0.998H – 0.971L – 0.979H – 1.010L – 1.011H – 1.042L – 1.002H

With such an optimized design, the amplification coefficient at the laser line reaches nearly 20, which will be naturally very attractive in terms of laser power and/or overall duration of the trimming process. Nevertheless, we have to stress here that the refractive index change associated to this photosensitivity mechanism will progressively detune this resonance: the full-width at half-maximum of the peak at 532nm is indeed about 1 nm, which limits the efficiency range of this amplification mechanism to refractive index changes less than 2.10^{-3}. This is obviously small but remains however attractive.

From the start, we made the assumption that the absorption can be neglected in all the materials, either classical or photosensitive. That is allowed when the trimming wavelength is around 532nm, but becomes totally wrong when the processing laser is for instance a KrF one (laser line at 248nm). In a first step, let us suppose that only the spacer is absorbing, with an imaginary part of the refractive index k comprised between 0.1 and zero. When the absorption remains small ($k < 10^{-4}$), the repartition of the intensity of the electric field inside the spacer is identical to the one of the non-absorbing case. When the absorption becomes moderate ($10^{-4} < k < 10^{-2}$), we are still observing a modulation of the intensity of the field inside the spacer, but with a mean value which decreases towards the substrate. At the end, when the absorption is high, the modulation disappears while the field continuously decreases along the spacer, with an exponential shape. The same kind of computation can be performed by taking into account a possible absorption of the standard H and L layers at the 248nm laser line, with roughly the same conclusions.

To summarize all these results, we plotted at the figure 5 the evolution of the mean value of the intensity of the electric field inside the spacer at 248nm (expressed in incoming field intensity units) with respect to the extinction coefficient k of the photosensitive spacer at the same wavelength. Two specific cases are analyzed, the first one with no absorbing mirrors and the second one with absorbing mirrors ($k = 10^{-3}$ for all the layers). In any case, we can see that the trimming process remains feasible, with obviously an increase of the required processing time in case of absorbing materials.

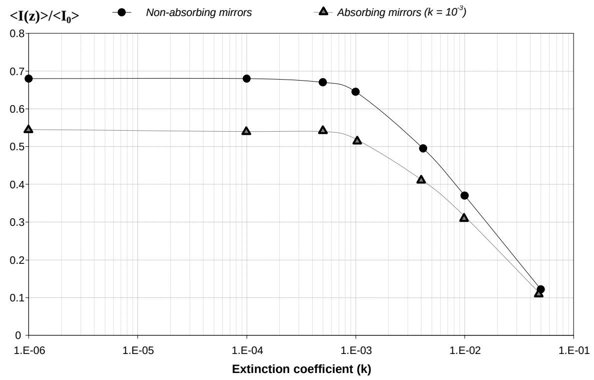

Figure 5 – Evolution of the mean value of the intensity of the field inside the spacer (divided by the incoming one) versus the extinction coefficient of the photosensitive material

As a conclusion of the first part of this paper, we can stress that the trimming of the central wavelength of a narrow bandpass filter is always possible with an acceptable efficiency, even if the materials used for the manufacturing of the component are slightly absorbing. Moreover, the relative shift of the central wavelength is less or equal to the relative refractive index change of the photosensitive spacer, which limits the achievable modifications to few per mille.

3. PHOTOSENSITIVE DOUBLE-CAVITY SOLID-SPACED ETALONS

The use of Solid-Spaced Etalons (SSE) is an attractive way for achieving narrow-bandpass filters, especially in terms of number of layers required to reach a given bandwidth [10, 11]. This filtering component combines two or more elementary Fabry-Perot cavities, including each a high quality thin transparent wafer (thickness comprised between 25 and 500 microns, parallelism about one arc second) coated on both sides with few alternated layers (typically between 3 and 9): the efficiency of the filtering is indeed provided more by the high value of the interference order inside the cavity than by the high reflectivity of the thin-film mirrors. The spectral transmittance of each cavity is characterized by a regular grid of peaks with close unity transmission, whose position and pitch (the Free Spectral Range) are mainly defined by the optical thickness of the wafer. By coupling through a specific quarter-wavelength layer two separate SSE's with different optical thicknesses (for instance two silica wafers having mechanical thicknesses respectively equal to 100 and 140 microns), we superpose two spectral transmission grids with different FSR's which will perfectly coincide for an unique wavelength in a given spectral range: it is the so-called self-filtering mechanism.

To illustrate this approach, let us consider the double-cavity SSE centred at 1550nm and defined by the following formula

[HLHLH – 376L – HLHLH] – L – [HLHLH – 530P – HLHLH]

in which the first cavity is a 100μm silica wafer, the second one a 150μm photosensitive plate (for instance Ge-doped silica) and the alternated layers silica and tantalum pentoxide deposited by Dual Ion Beam Sputtering. The spectral transmittance of this SSE filter in the telecommunications C-Band is shown on the left side of the figure 6.

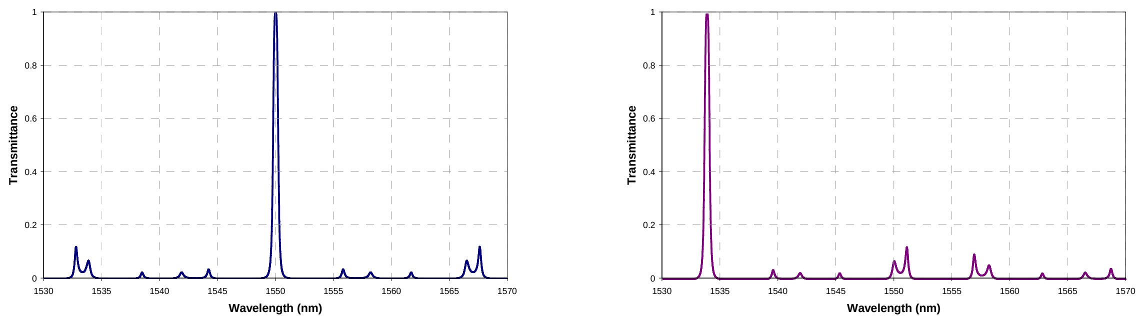

Figure 6 – Spectral transmittance of the photosensitive double-cavity solid-spaced bandpass filter before and after laser trimming

Let us suppose now that the second cavity be locally illuminated by a trimming laser, to induce a slight increase of its optical thickness from 530 $\lambda_0/4$ to 530.375 $\lambda_0/4$, while the first one remains unchanged. The transmittance grid of the first cavity is then slightly shifted, which moves sharply the coincidence wavelength between both grids to a new value (1533.85nm instead of 1550.00nm), as shown on the right side of the figure 6. It means that, by this way, we have obtained a great amplification of the trimming mechanism (about 15 times), since a refractive index change of 10^{-3} (i.e. about 7.10^{-4} in relative) is sufficient to induce a wavelength shift of more than 16nm (i.e. about 10^{-2} in relative). The same kind of amplification mechanism was yet used by our group to increase the tunability range of tandem silica/silicon SSE configuration [11].

By using no more one, but two photosensitive wafers in our tandem SSE configuration, we are able to reach any wavelength in a given spectral range. This very attractive property can be used for developing for instance a staircase optical interference filter, i.e. a bandpass filter whose central wavelength varies along a given direction by discrete steps, as shown at figure 7a.

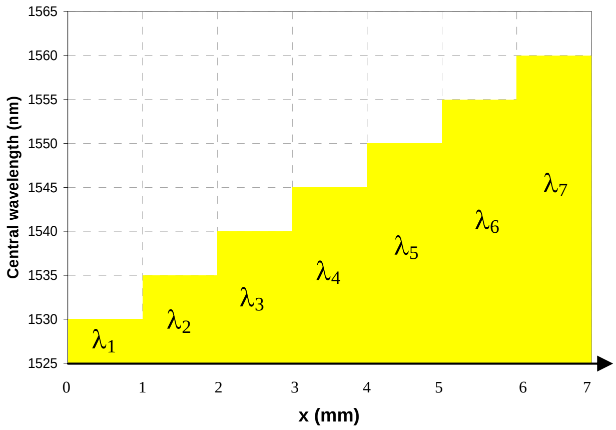

Figure 7a – Spatial profile of a 2-cavity SSE staircase optical interference filter

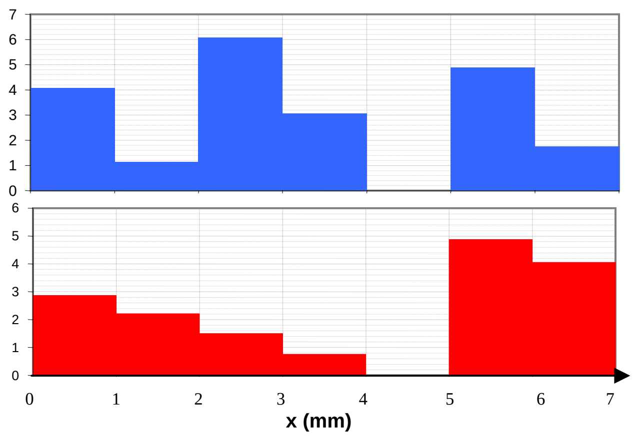

Figure 7b – Spatial profile of the refractive index changes (units 10^{-3}) applied in each SSE

Let us suppose that we use the same double-cavity SSE as defined before, but with photosensitive spacers for both cavities. The staircase optical interference filter defined at the figure 7a includes 7 zones, and for each of these zones, we have to achieve a dedicated shift of the transmittance grid associated to each SSE, in order to lock one of their peaks on the specific wavelength defined by the profile. So, for the fifth zone, the central wavelength shall be equal to 1550nm, which is precisely the nominal position of one of the transmittance peak for each of the two grids: then, as indicated at the figure 7b, we do not have to produce any kind of refractive index change for this fifth zone in each SSE. At the opposite, for the first zone, the achievement of a 1530nm value for the coincidence wavelength requires two specific refractive index changes in each SSE: 4.08 10^{-3} in the first one (whose initial optical thickness was equal to 376 $\lambda_0/4$) and 2.86 10^{-3} in the second one (whose initial optical thickness was equal to 530 $\lambda_0/4$). It is important to stress here that this kind of filter programming requires an achievable maximum refractive index change Δn_0 about 6.10^{-3}.

Let us suppose now, as before for the thin-film filter configuration, that the trimming wavelength be not absorbed by the spacer (for instance by using a laser line at 532nm). The simplest way for achieving the required refractive index change is then to illuminate the SSE wafer with the trimming laser before the mirror deposition. However, the standing wave generated by the partial reflection of the incoming beam on the rear face of the wafer will induce the growing of a Bragg reflector rightly centered at this trimming wavelength. Again, as for the thin-film configuration, this refractive index sine modulation will do not have any kind of impact on the spectral properties of the SSE around the design wavelength (1550nm), but this time, due to the large thickness of the cavity, it will progressively decrease the efficiency of the trimming mechanism during the laser processing. A possible solution to overcome this difficulty would be to use dedicated thin-film mirrors, which have simultaneously a high reflectivity at the design wavelength and an antireflective behavior at the trimming wavelength (in order to avoid the appearance of the unwanted standing wave into the spacer) and to perform the laser processing of the wafers after deposition of these mirrors. If we assume at the end that the trimming wavelength is absorbed by the SSE (for instance by using a 248nm KrF laser line), the intensity of the electric field will decrease inside the spacer, which will cancel almost automatically this standing wave problem: however, as before, the use of mirrors having an antireflective behavior at the trimming wavelength would allow to achieve the trimming of the filter at the end of its manufacturing process and with a slightly increased efficiency.

4. PHOTOSENSITIVE MATERIALS

The choice of a photosensitive material as a part of an optical interference filter (either as thin-film spacer or SSE wafer) shall take into account a lot of constraints, i.e.

- the amount of losses in this material shall be very small at the design wavelength (typically characterized by an extinction coefficient less than few 10^{-4}), these losses being associated either to absorption or to scattering
- the material shall be compatible with a polishing process (in case of SSE) or with a deposition process (in case of thin-film spacer). The polishing process shall guarantee a very low surface roughness (super-polishing) and a very good parallelism (less than one arc second), while the deposition process shall maintain the chemical composition of this material in order to keep its photosensitive behavior (for this point of view, a ion beam sputtering process seems very attractive)
- the long-term stability of the nominal refractive index of this material (and of its refractive index changes induced by the trimming process) shall be very high, in order to avoid any kind of spontaneous evolution of the spectral properties of the processed filter with time
- the maximum refractive index change achievable through the laser trimming process shall be as high as possible (5.10^{-4} is absolutely required and 10^{-2} would be perfect)
- the trimming wavelength shall be, if possible, a standard laser line not included into the spectral range defined for the final use of the filter (in order to avoid unwanted evolution of its response); the absorption of the material at this wavelength shall be a tradeoff between the efficiency of the refractive index change and the thickness of the material in which this change is induced.

Among all the possible candidates, we have selected some especially attractive materials, as the PhenantreneQuinone-doped Poly(Methyl MethAcrylate) or PQ:PMMA [12], the lead silicate glasses [13], the PhotoThermoRefractive or PTR glass [14] and the Germanium-doped silica glasses [15-18]. We have summarized at the table 1 the main features of all these materials.

Material	Cut-off wavelength	Wafer quality	Thin-film deposition	Trimming wavelength	Maximum Δn
PQ:PMMA	550nm	Medium	No	488 – 532nm	10^{-4}
Lead-silicate glasses	400nm	Good	No	266nm	up to 0.2
PTR glass	500nm	Good	No	325nm	10^{-3}
Corning PR glass	400nm	Very good	No	248nm	5.10^{-4}
Ge-doped silica	300nm	Very good	Yes	248nm or 330nm	few 10^{-3}
SGBN glass	300nm	Poor	Yes	248nm	up to 3.10^{-2}

Table 1 – Main features of some photosensitive materials

The four first materials can be used only for manufacturing photosensitive SSE, while the two last ones can be deposited as thin-films through PECVD [16] or sputtering [18]. The acronym SGBN is the name given by the Politecnico di Torino [17, 18] to a silica glass co-doped with Germanium (20mol.%), Boron (9mol.%) and Sodium (20mol.%), and which can be used as sputtering target.

The PQ:PMMA does not satisfy the long-term stability requirement expressed before, while the PTR glass requires a baking operation to reveal the refractive index changes induced by an illumination at 325 nm. The absorption of the lead-silicate glasses to the 266nm laser line is extremely high which restricts the trimmed thickness to few microns. They are the reasons for which we started our experimental confirmation of the theoretical schemes developed in section 2 and 3 by the Corning photorefractive glass, which is in fact a hydrogen-loaded germanium-doped silica glass [15].

5. FIRST EXPERIMENTAL RESULTS

To assess and quantify the effect of a laser trimming on the refractive index of photosensitive thin films or etalons, we have decided to develop a dedicated optical test bench [19, 21], which can locally either measure the central wavelength of a thin-film narrow bandpass filter or determine in a absolute way the optical thickness of a transparent window. This optical bench is represented at the figure 8.

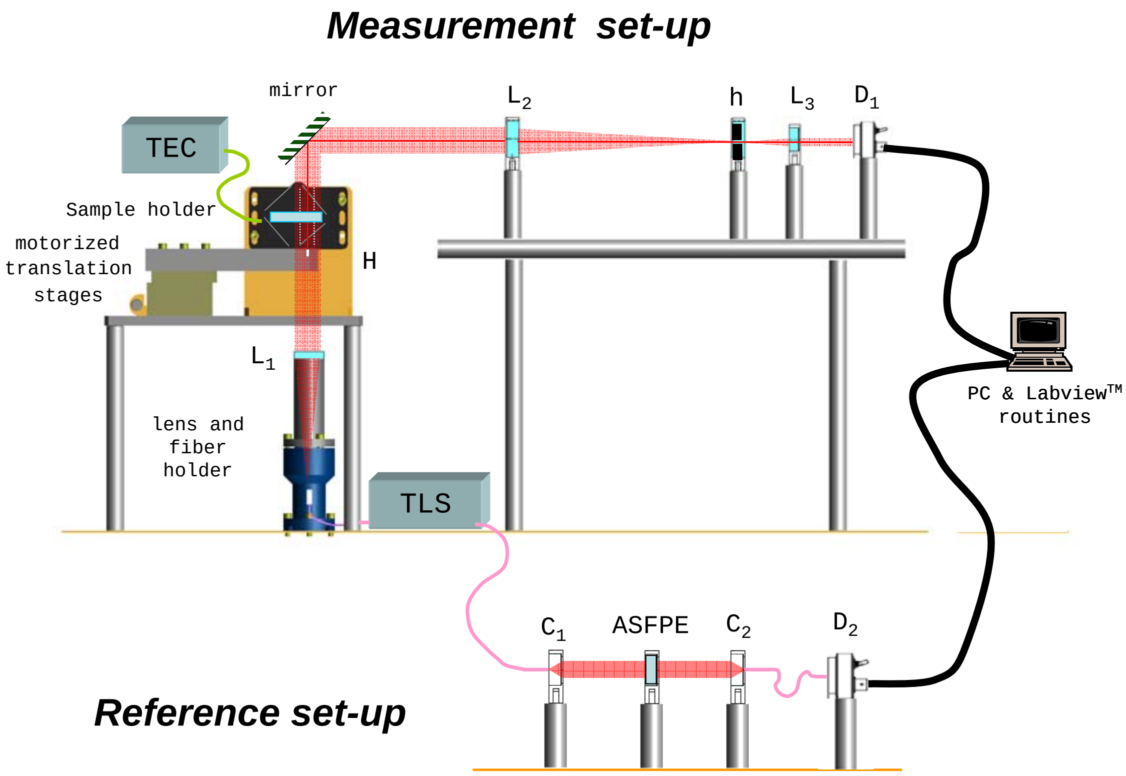

Figure 8 – Optical test bench dedicated to the study of the photosensitivity of thin-films and etalons

The light source is an EXFO FLS-2600 tunable laser source (TLS), which delivers into a singlemode fiber a 2mW laser line whose wavelength can be continuously scanned between 1520nm and 1570nm. The divergent light beam emitted by this fiber is collimated with a 120 mm focal length lens L_1, while a low section diaphragm (diameter selectable from 100 microns to 1mm) is used to define a small illuminated area at the surface of the sample. By moving this diaphragm with the help of two motorized translation stages, it is possible to displace this area inside the 25mm diameter collimated beam and to perform then a fine mapping of the spectral transmittance of the sample. In this goal, the light power transmitted by the sample is imaged onto an InGaAs photodiode D_1, followed by a low-noise trans-impedance amplifier and a 16bits analog-to-digital converter. All these items (tunable laser source, translation stages, numerical data delivered by the detection system) are driven and processed by a dedicated PC.

In order to avoid possible drifts in the wavelength values produced during a given laser sweep, the monitor output of the tunable source is launched towards a reference set-up which includes a sealed air-spaced Fabry-Perot etalon (ASFPE), with a constant free spectral range (FSR) of 100GHz and a thermal stability of about 10pm/°C. The recording of the spectral transmittance function of this ASFPE is used to calibrate the wavelength scale of each laser scan with accuracy better than 10pm. Moreover, the sample is installed into a temperature-stabilized holder associated to a Peltier thermoelectric controller (TEC), which permits to regulate the temperature of this sample with stability better than 0.02°C.

To study the photosensitivity of a thin-film material, we have to use it as the spacer of a narrow-bandpass filter: the recording of the transmittance function of this filter with our test bench will permit to extract with a high accuracy (few pm) the value of its central wavelength λ_0 and to determine through a mapping the variations of this parameter at the surface of the sample. By comparing these mapping results before and after illumination by different laser fluences, we are able to locally quantify the refractive index changes of the spacer by using the proportionality relation defined in the section 2 and by numerically computing the κ factor. The wavelength stability of our set-up (i.e. few pm) permits to identify refractive index changes as low as 5.10^{-6}.

For photosensitive etalons, the problem is quite the same, while the recording of the spectral transmittance function (in fact, the channeled spectrum of the window) in the whole tuning range of the laser source is used to extract the optical thickness of the wafer in each point of the sample surface. Again, by comparing the optical thickness data recorded before and after laser illumination, we are able to identify possible refractive index changes, in this case with a resolution about 10^{-6} (this improvement is simply due to the increased thickness of the photosensitive material).

The qualification of our set-up has been first achieved with a material whose photosensitive properties are well known, i.e. a commercial photosensitive polymer called CROP (Cationic Ring Opening Polymer) which has been developed for holographic data storage applications [20]. The measured maximum refractive index change Δn_0 is about 4.10^{-3}, while the characteristic fluence F_0 is close to 30 mJ/cm² @ 525 nm [21]. To assess the performances of our set-up in a more realistic configuration, we decided then to use a 1mm-thick window manufactured with the Corning photorefractive glass [15] and to submit it to a pulsed illumination at 248nm (square spot, 1mm side, singleshot fluence about 100 mJ/cm²), with a gradually increase of the number of pulses seen by the sample at different locations: 1 – 10 – 100 – 1000 – 5000 – 10000 (two locations) – 50000. By comparing the results of the optical thickness measurements performed before and after this laser processing, we can extract the effect of the KrF laser illumination on the refractive index of the Corning PR glass, by assuming a constant change in the thickness of the sample (no absorption of the trimming laser). The results are presented at the figure 9 (left side, the mapping data (square surface, 6mm side, diaphragm diameter 200 µm, x and y pitch 200 µm; right side, the photosensitivity curve, expressed in refractive index changes versus the number of laser pulses).

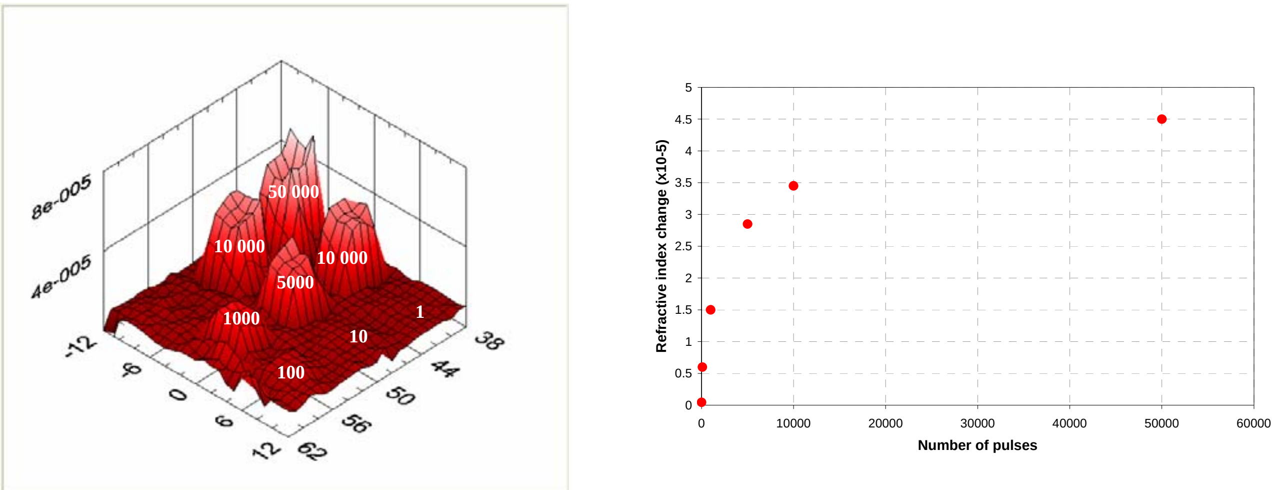

Figure 9 – Experimental results of the photosensitivity studies performed on a Corning Photorefractive Glass @ 248 nm

We can see first that the performances of our set-up are in perfect accordance with our objectives and, second, that the induced refractive index change seems for this material much lower than expected (typically 5.10^{-5} instead of 5.10^{-4}). This last result is difficult to explain at this time and has to be confirmed by further experiments.

6. CONCLUSION

The use of photosensitive materials as spacers of thin-film filters and/or solid-spaced etalons is a very attractive way to permit the spatial patterning of the spectral transmittance function of these narrow-bandpass filters, either to correct always possible manufacturing errors or to create entirely new filtering devices. The identification of the most efficient materials remains nevertheless a big challenge, as well as the selection of the trimming wavelength and the choice of the type of laser-matter interaction: direct absorption, two-photon absorption or even multi-photon processes associated to ultra-short laser pulses. The main advantage of this last solution, yet used for the direct writing of optical waveguides [22], would be obviously the possibility to use standard materials (as for instance, silica).

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