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Janis Zideluns, Fabien Lemarchand, Frederic Lemarquis, Detlef Arhilger, Harro Hagedorn, et al.. Multi-witness glass monitoring strategy for two-cavity thin-film Fabry-Perot filters. *Optics Continuum*, 2024, 3, 10.1364/optcon.533681 . hal-04758484

HAL Id: hal-04758484

<https://amu.hal.science/hal-04758484v1>

Submitted on 29 Oct 2024

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Multi-witness glass monitoring strategy for two-cavity thin-film Fabry-Perot filters

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Abstract: Narrow bandpass thin-film filters are frequently used for many applications that require frequency filtering. Although various designs and approaches have been studied in past decades, they still present serious challenges regarding deposition. Especially, as the required passband of the designs becomes narrower, the accuracy needed on layer thicknesses increases involving more difficulty to control the layers during deposition. This paper presents a multi-witness glass monitoring strategy for narrow thin film Fabry-Perot filter deposition.

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1. Introduction

Fabry-Perot filters are probably the most popular designs for narrow bandpass filters. The basic thin-film structure consists of a cavity layer surrounded on both sides by highly reflecting mirrors. In order to achieve constructive interference, and consequently a maximum transmittance for the filter's centering wavelength, the optical thickness of the cavity must be equal to an integer number of half of this centering wavelength (half wave layer). Moving away from this wavelength, light undergoes destructive interference, transmittance reduces towards zero, and the filter exhibits a bandpass profile. To ensure high transmittance in the bandpass, mirrors are generally dielectric rather than metallic, because the maximum transmittance is limited by absorption in the mirrors [1,2]. To obtain an almost square-shaped bandpass profile (flatter transmission in the bandpass and abrupt transitions with the rejection bands), several thin-film Fabry-Perot filters must be combined, all separated by a low index quarter wave layer to allow coherent combination of the cavities [3].

The transmittance profiles of such resonant structures are particularly sensitive to thickness errors. As a result, optical thicknesses (product of refractive index and physical thickness) must be accurately controlled during manufacturing, layer after layer, to ensure a correct final transmittance profile. Therefore, filters are usually formed with quarter wave layers only, while the go-to method for monitoring quarter wave Fabry-Perot filters is turning point monitoring [4–6]. With this method, the layers' deposition is terminated when a transmittance extremum is detected at a control wavelength corresponding to the centering wavelength of the bandpass. This allows an efficient error compensation effect during deposition [7–9]. Because of the strong error self-compensation, the uninterrupted turning point monitoring is the go-to monitoring method for Fabry-Perot filters. However, in the case of narrow band pass filters, turning point monitoring becomes difficult to implement because of the technical limits of standard optical monitoring systems. One of the problematics for monitoring of narrow Fabry-Perot filters is the low transmittance levels measured after deposition of the first cavity mirror. Not only the transmittance can drop below 1% (high reflectance mirrors are required for narrow bandpass) but the transmittance modulation during layer deposition is also very small at this low transmittance level – in such case, measurement noise disturbs the monitoring signal to an extent where monitoring is no longer possible. Another difficulty comes from the spectral width of the

transmitted band when the filter's bandpass starts to take shape during the deposition of the second cavity mirror. The spectral resolution of most *in-situ* measurement systems is not sufficient to measure very narrow bandpass filters. Indeed, even *ex-situ* measurements for Fabry-Perot filters with FWHM (full width at half maximum) within a few tenths of nanometer range is a challenging task because of the spectral resolution of spectrometers. One solution to overcome these two difficulties is to use a laser as light source [10], since it ensures necessary spectral resolution and enough power for very low transmittance measurement. The drawback to this approach is that one needs to heavily modify the existing optical measurement setup and of course the measurement wavelength range is not as flexible as with a standard white light source. In addition, parasitic interferences might appear within the optical path of the measuring beam. In recent years, studies for non-turning point monitoring strategies have been carried out [11–13] but they are either limited to single cavity Fabry-Perot filters or the experimental verification is missing.

Therefore, it is in our interest to find another solution for the monitoring of multi-cavity narrow bandpass filters that would allow us to use existing monitoring setup. To achieve this goal, we studied strategies based on the use of several monitoring witness glasses, that would not allow to benefit from strong error self-compensation. We converged to an alternative approach that both allows to maintain partial error compensation (turning point monitoring is used) and to avoid low transmittance and spectral resolution limits of the *in-situ* measurement systems.

2. Experimental setup

Filters were deposited with a HELIOS 800 plasma-assisted reactive magnetron sputtering deposition (PARMS) coater [14] equipped with an automatic witness glass changer that allows to store all the witness glasses in vacuum. Samples can be heated before the deposition process begins, usually the substrate temperature is raised to 150 degrees and held for 5 minutes. The deposition was carried out at pressures of $\sim 5 \cdot 10^{-3}$ mbar.

The optical and deposition time monitoring was performed with OMS5100. The deposition time (rate) usually is calibrated when first layer of a given filter are deposited. Both the deposition machine and the monitoring system are developed by *Bühler Leybold Optics*. In the HELIOS coater, the samples are placed on a round turntable. There are 12 places for the samples on the table and each of them passes under magnetron, RF ion source and measurement window on each turn. The spectral resolution of the spectrometer can be adjusted; however, one has to find a balance between narrowest possible bandwidth and sufficient signal to noise ratio. For these experiments, bandwidth of 1 nm was set.

Ex-situ characterization of filters was done with *PerkinElmer Lambda 1050 (PE1050)* spectrophotometer with a resolution as low as 0.1 nm. Nb_2O_5 and SiO_2 (reactive deposition using MF-magnetron sputtering from metallic targets) were used as high and low index materials respectively with refractive indexes of 2.395 and 1.488 at 500 nm. Plasma assistance was also used to secure dense and fully oxidized layers. Deposition rates were about 0.4 nm/s for each material. At 500 nm, the thickness of the quarter wave high refractive index layers is 52.2 nm and the one of low refractive index layers is 84.0 nm. D263 glass was used as substrate with refractive index of 1.532 at 500 nm. All materials are considered absorption free at this wavelength. The filter was designed manually by combining classical Fabry Perot cavities in order to match with the requested project performances and the theoretical performance for the filters was calculated with Optilayer software.

3. Method

Use of multiple glasses for monitoring of filters has been proven to be a reliable option to limit the thickness error accumulation [15–17]. By changing the monitoring glass, not only the thickness errors can be reduced, but it can be beneficial to limit the monitoring issues such as sharp peaks

in spectra, low or high transmittance regions, that we have discussed previously [16,18]. The downside is that with changing the monitoring glass, one cannot fully benefit from the error compensation for the whole design. Although the multi-witness glass approach is widely known, to the authors knowledge it has not been successfully tested on Fabry-Perot structures, as this type of filter is strongly associated with the need for un-interrupted error compensation.

The goal of this new multi-witness glass strategy is to avoid reaching the technical limits of monitoring system. For this purpose, our previous experience tells us that the FWHM of a filter should be 5 times wider than the spectral resolution of the setup, that transmittance during the deposition should not be lower than 10%, and that transmittance amplitude change during deposition for a given layer should not be lower than 4% [18]. Using these criteria, we elaborated strategies where the full design is divided into partial (or sub) designs that meet all the requirements listed above.

Let us first considered a single-cavity narrowband filter to illustrate our multi-witness glass approach. The coating design is described in Eq. (1) and centered at 500 nm, where $M11$ represents mirrors consisting of 11 alternated high (H) and low (L) index materials quarter wave layers at 500 nm. For clarity, from now on, we will write the number after M if the mirror starts with a high index layer and before M if the mirror starts with a low index layer.

$$M11\ 2L\ M11 \quad (1)$$

For such a design, it is not possible to operate turning point monitoring with a single witness glass, as the transmittance drops down to 0.87% after the deposition of the first mirror. The maximum change of transmittance during deposition of the cavity layers is only 1% as shown in the monitoring curve - transmittance evolution as function of optical thickness for the centering wavelength - plotted in Fig. 1(a), additionally the FWHM of this filter is ~ 0.5 nm as shown in Fig. 1(b), much too narrow for standard *in-situ* spectrometer.

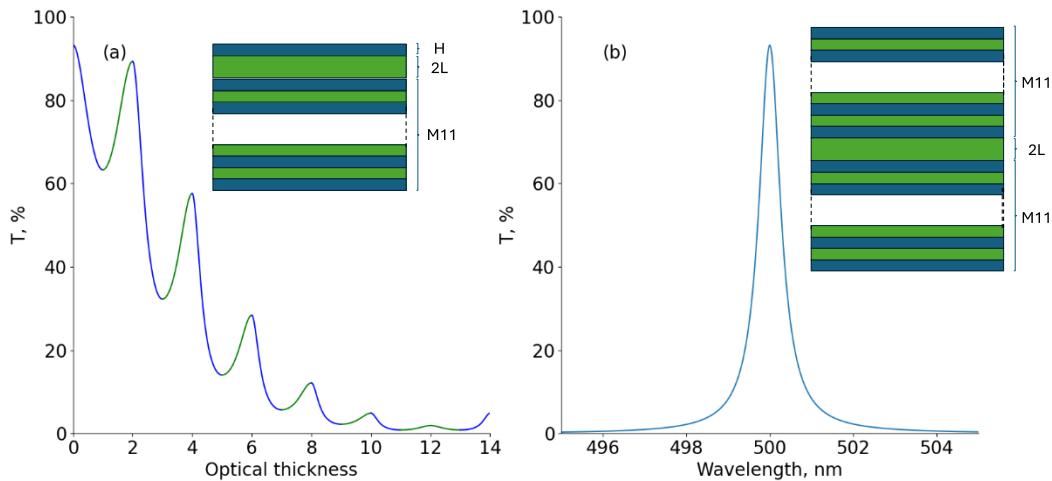


Fig. 1. (a)- illustration and monitoring curve of the first 13 layers for the design in Eq1. Nb_2O_5 layers plotted in blue, SiO_2 in green. (b)- illustration and spectral performance of the filter from Eq. (1).

To overcome these limitations, we further analyzed the monitoring curves. As can be seen, the transmittance of the mirror drops below 10% after the 6th layer. Therefore, for multi witness glass strategy, we decided to separate the first and the last 6 layers from the mirrors surrounding

the cavity. We can re-write the formula as done in Eq. 2 separating six layers from the mirrors.

$$M6 M5 2L M5 6M \quad (2)$$

If we now remove these 6 external layers from both sides of the cavity, we end up with a $M5 2L M5$ Fabry-Perot cavity that is more than 10 times wider than the original filter and that should not present any specific challenge to the monitoring setup. Additional witness glasses are of course required to monitor the external $M6$ and $6M$ mirrors deducted on both sides of the design but, provided that the monitoring setup allows to use the same monitoring glass twice, there is some advantage to monitor these two mirrors on the same separated witness glass. In other words, the second “ $6M$ ” mirror should be monitored on the witness glass that was used to monitor the first “ $M6$ ” mirror. Since $M6 + 6M = M5 2L M5$, this additional witness glass is finally used to monitor a Fabry-Perot structure that also should not present any challenge to the monitoring setup.

The major argument proceeding this way is that one can expect error compensation. Indeed, Fabry-Perot structures are symmetrical stacks, and a thickness error in any layer can be compensated by an adequate thickness change for the symmetrical layer. In that way, the last six layers of the complete design can compensate for errors in the first six layers, as long as they are all monitored on the same witness glass.

The complete monitoring strategy is illustrated in Fig. 2. A first witness glass is used to monitor a Fabry-Perot structure formed with both the beginning and the end of the complete design. A second witness glass is used to monitor a Fabry-Perot structure formed with the central part of the complete design.

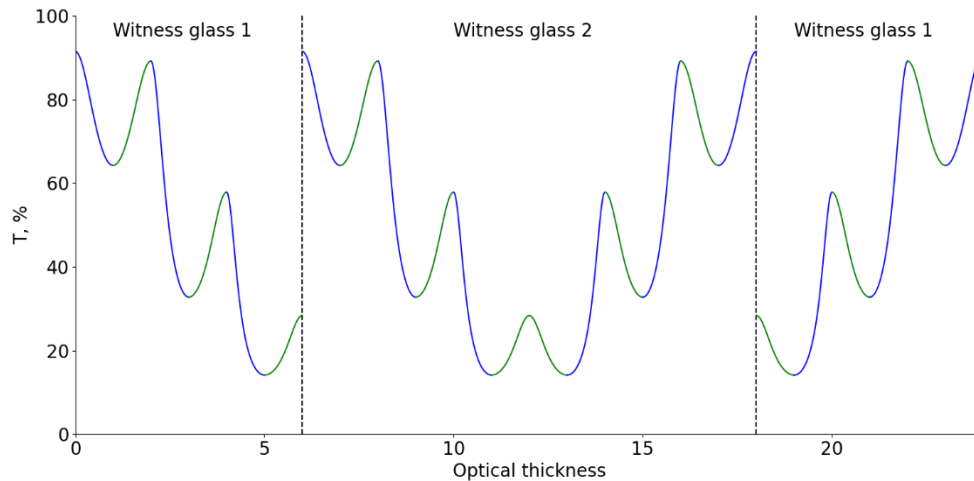


Fig. 2. Monitoring curve of Fabry Perot filter with returning witness glass (layer 18 to 23). Nb_2O_5 layers plotted in blue, SiO_2 layers in green. Dashed lines mark the place where the witness glass is changed.

As can be seen, there are no difficulties from the monitoring point of view with such approach, - the minimum transmittance is 14%, the transmittance amplitude for the cavity layers is 12%, the FWHM of such filters is ~ 9 nm.

4. Experimental verification on a two-cavity Fabry-Perot filter

This Fabry-Perot design division into symmetrical sub-designs can be extended to two-(or more) cavity filter designs. For the fabrication experiment, we selected a two-cavity filter design as

shown in Eq. 3 centered at 500 nm.

$$M11\ 2L\ M11\ L\ M11\ 2L\ M11 \quad (3)$$

The design was divided into sub-designs, each of them being monitored on a specific test-glass as shown in Table 1. Again, the first and last 6 layers of mirrors are separated from the cavities. For this particular design formula, we obtain 4 identical partial designs $M5\ 2\ L\ M5$, and the coupling layer that has to be placed in the middle of the full design. Therefore, the whole filter can be monitored using 4 witness glasses, the first and third control glasses being used twice.

Table 1. Coating sequence for two-cavity filter (Eq. (3)) with returning witness glasses

Coating step	Witness glass	Partial design
1	1	M6
2	2	M5 2 L M5
3	1 (returns)	6 M L
4	3	M6
5	4	M5 2 L M5
6	3 (returns)	6M

The transmittance profiles measured after deposition for each of these witness glasses are plotted in Fig. 3. As we can see, the centering of the bandpass is identical for all of them, and profiles are almost identical for witness glasses n° 2, 3 and 4. The band pass of witness glass 1 is wider than the others because of the additional coupling layer. Because of a too small transmittance evolution during deposition, the coupling layer was controlled by deposition time. Since all layers are quarter wave, they have all the same thickness. Deposition time of these low refractive index material layers was determined by calculating the average deposition time of the five previous low refractive index layers.

Of course, in addition to these four witness glasses used for the monitoring of sub-designs, a fifth one has been placed in the deposition machine and received the full coating given in Eq. 3. This sample was placed closed to the monitoring position where the coater is known to give its best performance in terms of reproducibility. The measured transmittance of the two-cavity filter deposited on the fifth witness glass is plotted in Fig. 4 (a). As can be seen, there is slight shift in central wavelength (~ 0.15 nm) compared to the theoretical value. We compared the experimental result with filters simulated by adding random thickness errors for each layer. With this monitoring approach, we concluded that the equivalent average random thickness errors of each layer is in the range of 0.1-0.2%. In addition, as the sample was relatively large (5×5 cm²), we also measured the transmittance in several places to evaluate the spatial uniformity of the centering wavelength (Fig. 4(b)). The theoretical spectral resolution of the *PE1050* has been set at 0.1 nm, which corresponds to the lowest possible resolution of the system. As the FWHM of this filter is only 0.4 nm, we are not sure that the spectral response is not affected by a spectral resolution problem. The spectral shift of 0.15 nm could even be due to a different wavelength calibration of *in-situ* and *ex-situ* systems or a thermal shift.

In Fig. 4(b) we see that the centering of the filter is not the same across the sample, note that the scale of x axis is 1 nm, and the maximum shift is 0.1 nm.

Most likely, these filters are on the edge of what is possible to achieve with a multiple witness glass strategy, as some mismatch between the two cavities cannot be excluded considering the very high sensitivity of such structures to any kind of error or instability. Additionally, the measured maximum transmittance for the filter is increased by 1.5% when decreasing the spectral resolution from 0.5 nm to the lowest value allowed for the spectrophotometer – 0.1 nm, meaning that we are also on the edge of the characterization capabilities.

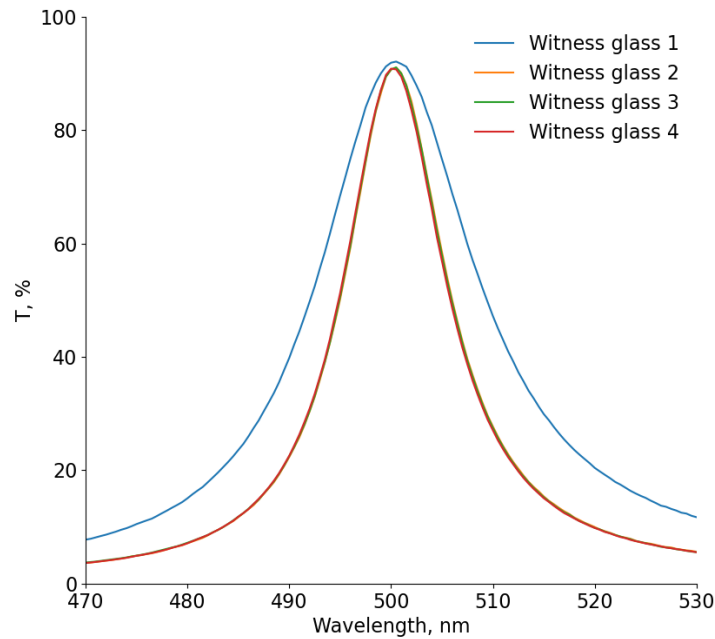


Fig. 3. measured transmittances of the 4 witness glasses of a two-cavity Fabry-Perot filter centered at 500 nm.

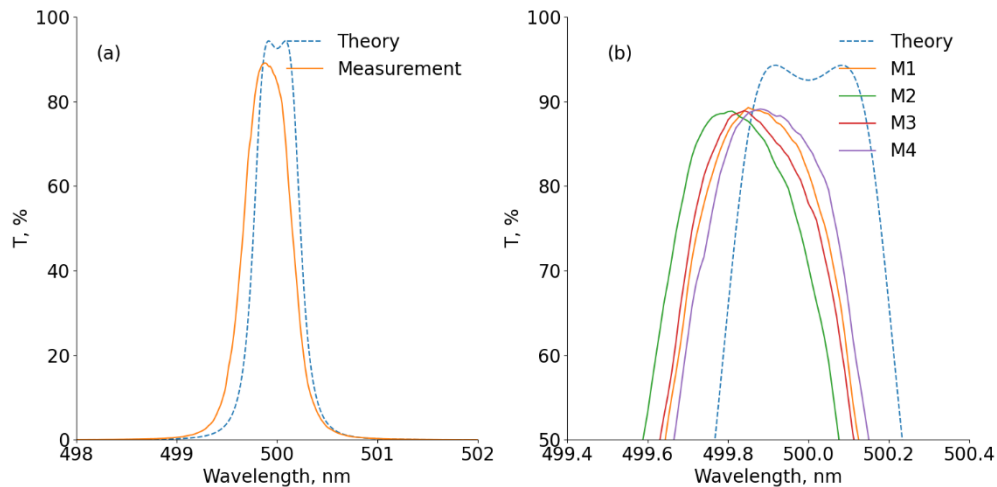


Fig. 4. (a) - Transmittance of the two cavity filter. (b) - Transmittance measurement in multiple places on the glass sample (M-measurement spot).

5. Discussion: error compensation and substrate temperature

Several authors have shown and explained the effect of the error compensation for the Fabry-Perot filters [1,7,19]. The main result is that an error in a layer (either thickness or refractive index deviation from the theoretical value) can be compensated with symmetrical error in another layer and the filters shape, that would be completely distorted otherwise, is maintained. However, error compensation for the experiment described above is possible only for the sub-designs monitored on the 4 witness glasses, but not for the entire filter. Therefore, this result cannot be

related to the strong error compensation associated with uninterrupted turning point monitoring performed along the whole coating design. However, to our knowledge, narrow bandpass two-cavity Fabry-Perot filters cannot be obtained without using turning point monitoring (for example with *time* monitoring). Therefore, we believe that turning point monitoring is necessary for the manufacturing of Fabry-Perot filters, but that the strategy should be chosen to limit random thickness errors caused by measurement noise (so that only small refractive index errors are compensated by the turning point monitoring) leading to the proposed returning witness glass strategy. Additionally, we noticed a higher sensitivity to deposition temperature since we could observe some shift of the centering wavelength between witness glasses used twice for monitoring (namely $n^{\circ}1$ and 3) if the temperature was not identical between the first and second partial deposition. Most probably, uncompensated errors were present on these witness glasses because of material refractive index temperature dependency. For this purpose, we had to modify the deposition process, and more precisely increase the 150°C pre-heating delay from 5 to 15 minutes before deposition, in order to achieve matching centering wavelengths. Therefore, high thermal stability and repeatable coating conditions for all witness glasses is mandatory to deposit filters with such high performance.

6. Conclusions

Using a standard optical monitoring system (based on a white light source and a monochromator), a two-cavity thin film Fabry-Perot filter with a bandwidth that can be considered as too narrow for the monitoring capabilities of such a system has been deposited. This has been achieved by introducing a multi witness glass monitoring strategy. The full design of a two (or more) cavity Fabry-Perot filter is divided into symmetrical sub designs, that from a monitoring point of view, are much wider Fabry-Perot filters. To achieve this, several witness glasses have to be used twice in the monitoring sequence. The individual layer thicknesses are controlled by turning point monitoring, except the coupling layer that has been time monitored.

Considering the close to theoretical transmittance profile we measured, we argue that such a strategy allows at least a correct compensation of random errors by the turning point monitoring, while systematic errors are probably identical for each monitoring witness glass since they are coated with identical sub-designs.

Funding. HORIZON EUROPE Marie Skłodowska-Curie Actions (813159).

Disclosures. The authors declare that there are no conflicts of interest related to this article.

Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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