

# International Conference on Space Optics—ICSO 2012

Ajaccio, Corse

9–12 October 2012

*Edited by Bruno Cugny, Errico Armandillo, and Nikos Karafolas*



## *Narrow-band filters for the lightning imager*

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# Narrow-band Filters for the Lightning Imager

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**Abstract**—The study of lightning phenomena will be carried out by a dedicated instrument, the lightning imager, that will make use of narrow-band transmission filters for separating the Oxygen emission lines in the clouds, from the background signal. The design, manufacturing and testing of these optical filters will be described here.

**Keywords**- optical filters; thin-film coatings, space instruments

## I. INTRODUCTION

An instrument for the analysis of lightning phenomena is under development in the frame of the METEOSAT Third Generation mission [1] of the European Space Agency (ESA). The operation of this lightning imager is based on the detection of the Oxygen line triplet in the clouds. These emission lines are positioned at 777.19, 777.42, 777.54 nm, in a wavelength range narrower than 0.4 nm. The detection of these lines with respect to the background requires the use of very narrow band optical filters, able to transmit the wavelengths of interest and reject the solar radiation out of this band.

Depending on the instrument configuration, the filters could be illuminated with either a collimated or a convergent beam with an angle of incidence in the range  $\pm 5.5^\circ$  in the first case, and a cone semi-angle of  $5.5^\circ$  in the second case. The above mentioned emission lines must be transmitted in all illumination conditions.

Moreover the optical filters should withstand the space environmental conditions expected for this mission, without any shift of the spectral band. Consequently, it is important to use very stable materials in the filter fabrication.

## II. OPTICAL FILTER DESIGN

The filter design is based on both the required filter performance and the filter manufacturability.

### A. Performance Requirements

The filter performance specifications come from the need of selecting the Oxygen emission lines, due to the lightning phenomena, with respect to the background signal due to the solar daylight. That means the in-band transmission should be higher than 80%, in the useful spectrum, and the out-band transmission of the order of  $10^{-4}$ , in the range 300-1100 nm. Moreover, the lightning imager configuration poses additional

requirements on the filter performance. In fact in the case of illumination either with a collimated beam or with a convergent beam, the filter must transmit the signal of interest in the wavelength range 777.14 – 777.59 nm, at all incidence angles between  $\pm 5.5^\circ$ , or even larger angles.

Another requirement that depends on the instrument configuration, is the filter size. Its diameter will be of the order of 100 mm and the optical performance must be maintained over the whole surface.

### B. Filter Design

The above requirements make the filter design rather complicated, in fact at oblique incidence the transmission band is displaced towards shorter wavelengths. Therefore, if a transmission bandwidth of 0.45 nm is chosen for the filter, the wavelengths of interest will be not transmitted at all required angles, owing to the theoretical rules of optical interference in thin films, as reported in the following. Consequently, a transmission bandwidth larger than the useful spectral range would be necessary.

A multiple-cavity dielectric Fabry-Perot filter was chosen for this application with alternating high- and low-index layer materials. Its transmission bandwidth depends mainly on the number of cavities, the number of layers and the refractive index of the layer materials. With the gradual increase of the angle of incidence, the transmittance peak of a typical Fabry-Perot filter moves towards shorter wavelengths and the bandwidth changes, according to the following equations [2] valid for small incidence angles ( $<20^\circ$ ):

- collimated beam with angle of incidence  $\theta$

$$\left(\frac{\delta\lambda}{\lambda_0}\right)_\theta = -\frac{\theta^2}{2\mu^2} \quad \frac{(\Delta\lambda_{0.5})_\theta}{\Delta\lambda_{0.5}} = \left[1 + \left(\frac{\theta^2\lambda_0}{\mu^2\Delta\lambda_{0.5}}\right)^2\right]^{1/2}$$

- convergent beam with semi-angle  $\alpha$

$$\left(\frac{\delta\lambda}{\lambda_0}\right)_\alpha = -\frac{\alpha^2}{4\mu^2} \quad \frac{(\Delta\lambda_{0.5})_\alpha}{\Delta\lambda_{0.5}} = \left[1 + \left(\frac{\alpha^2\lambda_0}{2\mu^2\Delta\lambda_{0.5}}\right)^2\right]^{1/2}$$

where  $\lambda_0$  is the reference wavelength,  $\delta\lambda$  the change in position of the transmittance peak,  $\Delta\lambda_{0.5}$  the half bandwidth of the filter and  $\mu^*$  a sort of effective index of the coating which value is in between the high and the low index of the layer materials.

The higher is the value of  $\mu^*$ , the lower is the performance deterioration. In all-dielectric Fabry-Perot filters, its value approaches the refractive index of the spacer, with increasing the spacer order (the spacer in this type of filters is a layer with optical thickness equal to half-wave of the reference wavelength). For these reasons it is preferable to use the high-index material as spacer and to select such material with the highest possible refractive index.

If  $\theta = \pm 5.5^\circ$  and  $\alpha = 5.5^\circ$ , with the hypothesis that  $\mu^*$  assumes the upper limit value of 2.25 (TiO<sub>2</sub> refractive index at the wavelengths of interest), the minimum shift of the transmission curve can be easily calculated:

- collimated beam:  $\delta\lambda_{\min} = -0.7$  nm
- convergent beam:  $\delta\lambda_{\min} = -0.35$  nm

The real shift of the transmission band towards shorter wavelengths will be in any case higher than these values (because of the lower  $\mu^*$  value). Therefore, with a filter having a bandwidth of about 1 nm (FWHM), the wavelengths of interest (Oxygen triplet) will be not transmitted (80%) at the required angles of incidence, and the filter cannot be used for this application. On further increase of the angle, both the maximum transmittance and the bandwidth deteriorate. This is a theoretical limitation that cannot be overcome thus, depending on the required angles (and the filter design), there will be a minimum acceptable filter bandwidth to allow the operation at oblique incidence.

From these calculations it comes out that a transmission bandwidth of the order of 2 nm could be a convenient solution. In Fig. 1a,b the transmittance at normal incidence of a double-cavity filter with bandwidth  $\Delta\lambda = 2$  nm (FWHM) is shown, as obtained with a multilayer coating of either TiO<sub>2</sub>/SiO<sub>2</sub> or HfO<sub>2</sub>/SiO<sub>2</sub> materials, on a fused silica substrate. The transmittance at oblique incidence of the filter of Fig 1a, is shown in Fig. 2a,b for both a collimated and a convergent beam.

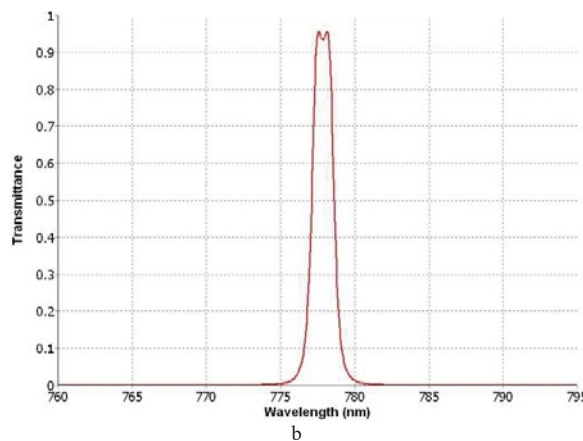
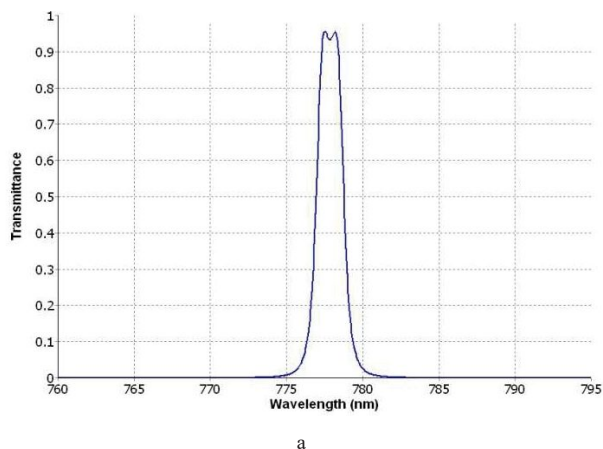


Figure 1. Calculated transmittance of a filter with bandwidth of ~2 nm: a) 43 layers (TiO<sub>2</sub>/SiO<sub>2</sub>) and b) 59 layers (HfO<sub>2</sub>/SiO<sub>2</sub>)

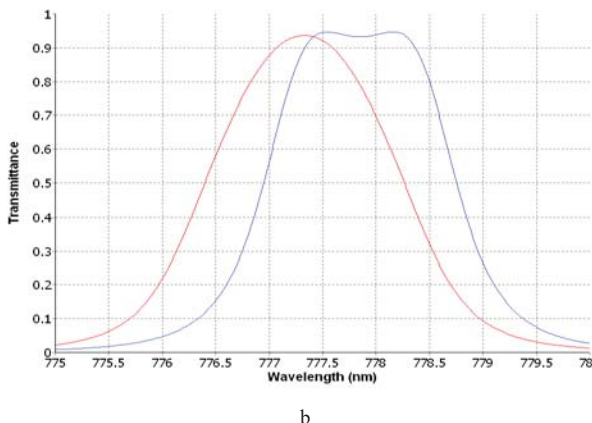
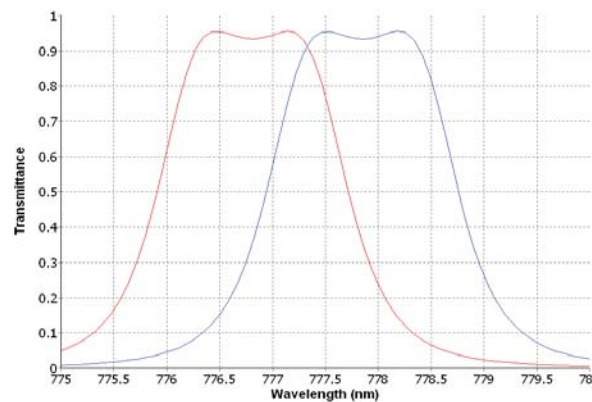


Figure 2. Transmittance of the filter of Fig 1a at oblique incidence in case of: a) collimated beam with an incidence angle of  $\pm 5.5^\circ$  and b) convergent beam with cone semi-angle  $5.5^\circ$  (red), compared to normal incidence (blue)

This filter could be acceptable for the lightning imager application, even though the in-band transmission would be slightly lower than 80%, with a collimated beam. As a consequence, and taking into account manufacturing errors that would worsen the performance with respect to the theory, a further enlargement of the bandwidth appears preferable. A triple-cavity Fabry-Perot filter would have a more rectangular

shape of the transmission band but with a significant higher number of layers, and consequent manufacturing difficulties. The out-band radiation will be rejected by this type of filter only in the range 700-900 nm, thus a proper blocking filter must be added for rejecting the radiation in the whole operating range 300-1100 nm.

### III. FILTER MANUFACTURING

To design the narrow-band filter,  $\text{TiO}_2$  and  $\text{SiO}_2$  have been chosen as high and low-index materials of the multilayer coating [3]. If  $\text{HfO}_2$  is used instead of  $\text{TiO}_2$ , a higher number of layers is needed to obtain the same optical performance (Fig 1b), because of its lower refractive index. However this material could be more stable in the space conditions of use.

All thin-film materials have been deposited by two different techniques: the dual ion beam sputtering and the electron beam evaporation with and without ion assistance. The fundamental difference between thin films deposited by the two techniques is the high density of materials produced by the ion beam sputtering that is due to the surface mobility of the ad-atoms promoted by the energetic sputtered atoms arriving on the substrate. For that reason the ion beam sputtering appears in principle the most suitable method for this application. In thin-film coatings deposited by electron beam evaporation, a significant difference was found depending on the use of ion assistance, as far as the stability of filter performance is concerned. It should be noticed that the material properties could be strongly dependent on both deposition technique and process parameters. This is especially true for  $\text{TiO}_2$ , thus the filter design should be made using the really obtained values of the optical constants of each material.

Taking into account the manufacturing uncertainties, an alternative filter with a lower number of layers with respect to Fig 1a, and bandwidth of 3 nm, was designed. Its transmittance obtained with  $\text{TiO}_2/\text{SiO}_2$  materials, as deposited by ion beam sputtering, is shown in Fig. 3. A bandwidth of 3 nm should ensure a better transmission of the useful signal at all requested incidence angles, taking into account a possible shift of the transmission band either due to a slight non-uniformity of the coating over the filter surface or due to the environmental conditions in space.

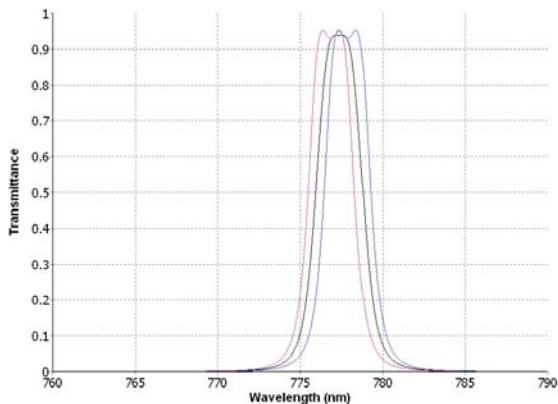


Figure 3. Calculated transmittance of a 35-layer double cavity filter with bandwidth of ~ 3 nm, made of  $\text{TiO}_2/\text{SiO}_2$ , at normal incidence (blue) and oblique incidence with collimated beam (pink) and convergent beam (black)

The filter of Fig. 3 was manufactured by dual ion beam sputtering and the resulting performance is shown in Fig. 4a, as measured by a spectrophotometer Perkin-Elmer Lambda 950. A narrow-band filter with  $\text{HfO}_2/\text{SiO}_2$  was manufactured by electron beam evaporation with ion assistance and its transmittance is shown in Fig. 4b, while in Fig. 4c the spectral transmittance obtained combining this filter with a blocking filter is reported.

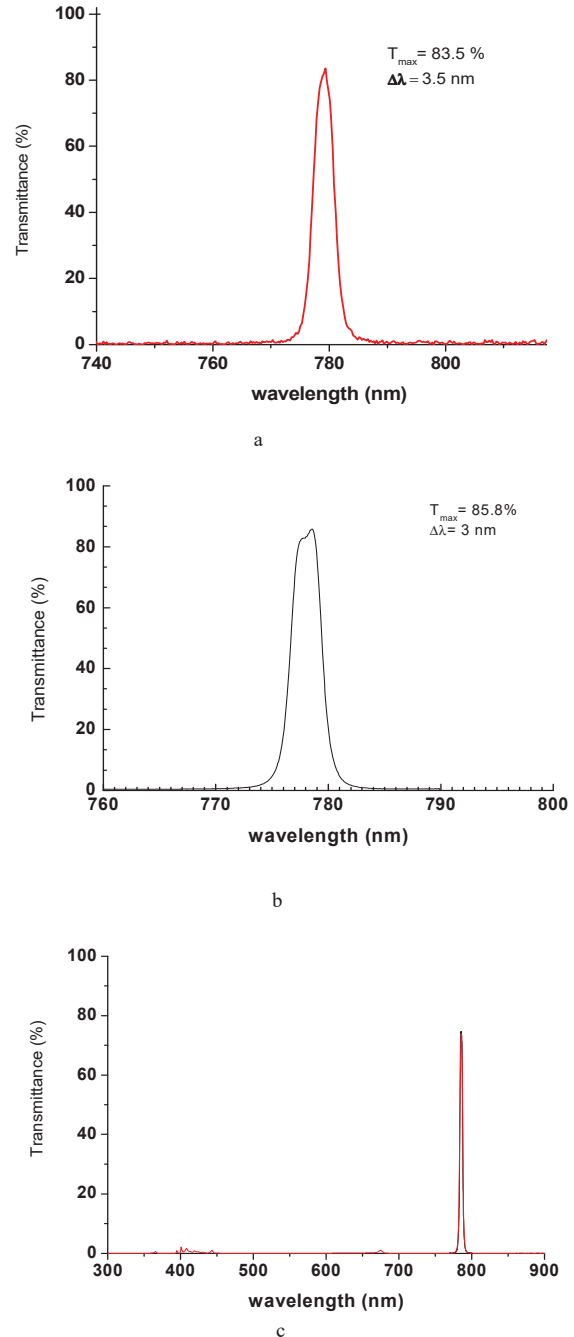


Figure 4. Measured transmittance of: a) 35-layer filter ( $\text{TiO}_2/\text{SiO}_2$ ) deposited by dual ion beam sputtering b) 51-layer filter ( $\text{HfO}_2/\text{SiO}_2$ ) deposited by electron beam evaporation on a fused silica substrate, c) the filter reported in (b) combined with a 70-layer blocking filter.



These narrow-band filters are very sensitive to manufacturing errors, in fact thickness variations of the order of 1% in the coating layers will destroy completely the filter optical performance. To maintain an acceptable transmittance curve, the thickness errors should be lower than 0.1%.

Efforts were made to improve the spatial uniformity of the deposited material, inside the vacuum chamber of the deposition system.

The dual ion beam sputtering plant was initially equipped with a substrate holder of 80 mm diameter. This diameter was then enlarged to 160 mm by modifying the mechanical set up inside the deposition plant. The distribution of deposited material over the substrate surface is shown in Fig. 5, as function of the substrate radius. As can be seen, the initial thickness distribution did not have an acceptable uniformity. Therefore some properly shaped masks were inserted into the plant near to the substrate holder, that was put into rotation with respect to the mask. In this way a more uniform material distribution can be achieved, by regulating the flux of particles arriving onto the substrate. After several adjustments, the variations of film thickness over the substrate surface were significantly reduced, along a radius of 50 mm, as shown in Fig. 5. Further improvements are possible by acting on mask shape and positioning.

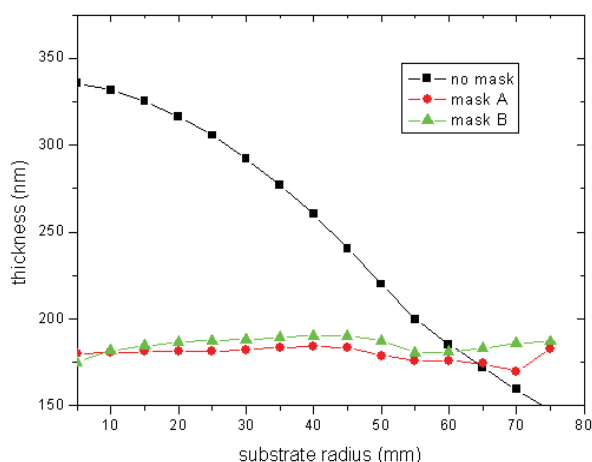


Figure 5. Measured thickness distribution of a thin film, deposited by ion beam sputtering, along the substrate radius

#### IV. ENVIRONMENTAL TESTS

The behavior of evaporated and sputtered filters was analyzed, with respect to their ability to exhibit vacuum-air stability and to withstand space environmental conditions.

Several environmental tests were carried out according to the specific requirements and all tests were successful. The results about thermal cycling and gamma irradiation are summarized here below, while the results of proton irradiation, at different energy levels, are reported in another paper of these Proceedings [4].

#### A. Temperature testing

Temperature testing was performed by a home-made system based on a cryostat “Oxford mod. CF1204” equipped with optical fibers. The temperature of the sample can vary in the range from 30 K to 333 K with a heating or cooling rate that can be defined by the user. Before starting the measurements the cryostat sample chamber was evacuated by a turbo-molecular pump ( $10^{-4}$  Pa). A number of thermal cycles were performed on the narrow-band filters. The filter transmittance was measured before and after the test and even during the thermal cycles.

No variations in the transmittance curve were detected after thermal cycling on a filter made by ion beam sputtering (Fig 6). The transmittance was also measured in vacuum, inside the cryostat by an online spectrometer, during the thermal cycle at: -45 C, +60 C (228 K, 333 K), and room temperature (300 K) both at the beginning and end of the cycle.

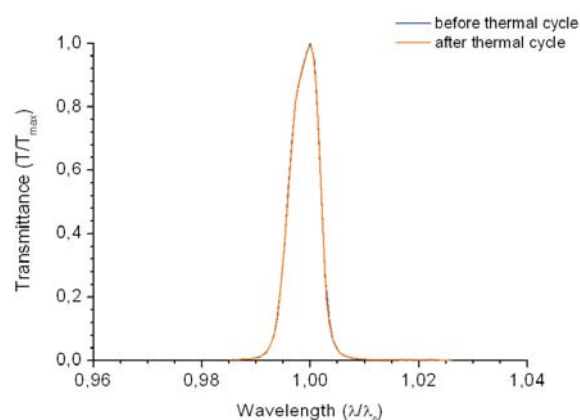


Figure 6. Comparison of the transmittance curves of a narrow band filter measured before (blue) and after (red) the thermal cycle (scales normalized to the central wavelength and the maximum transmittance of the filter before testing)

#### B. Gamma irradiation test

Testing with gamma irradiation of coatings deposited on fused silica substrates, were carried out at the ENEA CALLIOPE plant [5], equipped with a  $^{60}\text{Co}$  source, and transmittance curves were measured before and immediately after irradiation (to avoid recovering effects) by using a Perkin-Elmer Lambda 950 spectrophotometer.

The test was performed both at 50 krad and at 100 krad on a narrow-band filter ( $\text{TiO}_2/\text{SiO}_2$ ) made by ion beam sputtering and the result was a perfect overlapping of the transmittance curve before and after the gamma irradiation, as shown in Fig. 7a. A similar behavior was found on a filter made by electron beam evaporation using different materials ( $\text{HfO}_2/\text{SiO}_2$ ), as shown in Fig. 7b. Thus, it can be concluded that no damage is induced by gamma rays on these filters.

The transmittance curves of the filters used for the environmental tests are not equal to that of the final filter, but the filter structure (number of layers) is representative of the final one, as far as environmental tests are concerned.

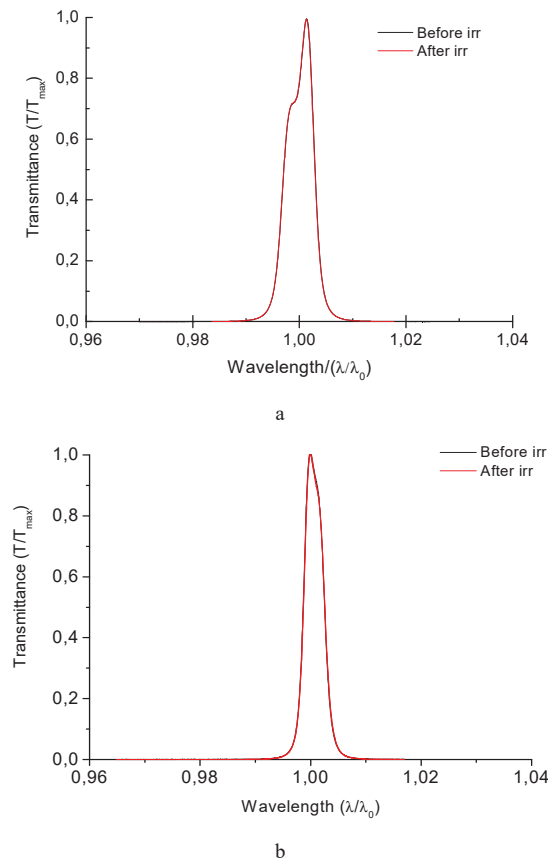


Figure 7. Measured transmittance (normalized scale) before (black) and after (red) gamma irradiation at 100 krad of : a) 35-layer ( $\text{TiO}_2/\text{SiO}_2$ ) filter made by dual ion beam sputtering, b) 51-layer filter ( $\text{HfO}_2/\text{SiO}_2$ ) made by electron beam evaporation

Indeed for a fixed sequence and number of layers of the coating, some slight difference in some layer thickness with respect to the filter design, can cause a significant difference in the spectral transmittance, however the comparison of curves before and after irradiation maintains its validity.

## V. CONCLUSIONS

The narrow-band filters are critical components of the lightning imager. They allow the detection of the Oxygen emission lines, for the analysis of lightning phenomena, by separating these lines with respect to the background signal. Two important characteristics of these filters must be taken into account during the filter design and manufacturing: the required operation with oblique incidence and the large area of the filter itself.

In addition, their performance must be tested in the environmental conditions of space. The narrow-band filters deposited by both dual ion beam sputtering and ion assisted electron beam evaporation showed successful performance in all environmental tests.

## ACKNOWLEDGMENT

This work was performed under ESA-ESTEC contract N. 22577/09/NL/CT "Lightning Imager Large Area Narrow Band Filter Development".

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