Optical filters for space applications

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Optical filters for the use in space instruments must not only satisfy the optical requirements but also contribute to the reduction of mass and size of the instrument itself. Moreover, they must survive in space conditions, specifically at low temperatures and with exposure to irradiation by various particles. Two examples of narrowband transmission filters dedicated to Earth observation are described.

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Optical coatings and filters play a fundamental role in the construction of instruments for space applications[1]. In both Earth-orbiting and interplanetary missions, low-mass and small components are required. To this end, the possibility of fabricating miniaturized optical filters may result in new types of instruments[2]. On the other hand, there are large-area instruments where coatings with a very high uniformity on the component surface are needed. In this case, the weight of the substrate should be reduced as much as possible.

Different types of coatings (filters, mirrors, antireflection coatings, and so on) are required, depending on the specific space mission. Here, only transmission filters developed for Earth observation instruments will be illustrated. More specifically, two types of narrowband transmission filters will be investigated: one with a variable performance over a small-dimension surface, and the other with a highly uniform performance on a large surface. The first filter is dedicated to a small-dimension spectrometer for image spectroscopy; the second filter will be part of an instrument for the investigation of lightning phenomena.

In the following sections, the two filters will be described, and criticalities in the fabrication of both miniaturized filters and large-area coatings will be analyzed. Optical coatings in space must withstand critical environmental conditions and be able to survive cryogenic temperatures and space radiation. Testing of their performance in these conditions will also be reported.

The reduction of mass and size of a spectrometer for space application can be achieved by combining an appropriate optical objective (telescope) with a small optical sensor free of moving parts. A thin-film interference filter, which shows a spatial variation along the coating surface[3] in a distance of few millimeters, combined with a charge-coupled device (CCD) detector, creates a small optical sensor that is able to detect radiation in the whole spectrum of interest. If its transmission band is continuously moved as the position on the substrate is changed, different radiation bands are transmitted at different spatial positions, corresponding to different lines of the array detector. The requirements on the transmittance curve, i.e., the transmittance bandwidth, transmittance peak value, and outband rejection, are taken from the requirements of the European Space Agency Sentinel mission. Their values should respectively be lower than 20 nm, higher than 50%, and lower than 0.5% in the whole operating wavelength range (440–940 nm), as shown in Fig. 1. The optical performance (Fig. 1) is achieved by combining two coatings on the two sides of a glass substrate (Fig. 2(a)). The coating on the back side is a blocking filter needed for achieving the required outband rejection, while the coating on the other side is a narrowband transmission filter. Both coatings have graded thicknesses, as explained in the following text. A picture of the manufactured variable filter is shown in Fig. 2(b); the color stripes are due to the variation of coating thickness along one direction.

The blocking filter is a conventional widepass transmission filter. The narrowband transmission filter is designed by taking into account the wide operating range (ratio between extreme wavelengths higher than 2:1) and the required transmittance bandwidth (15–20 nm). A metal-dielectric coating appears as a suitable choice because it allows wide outband rejection with a

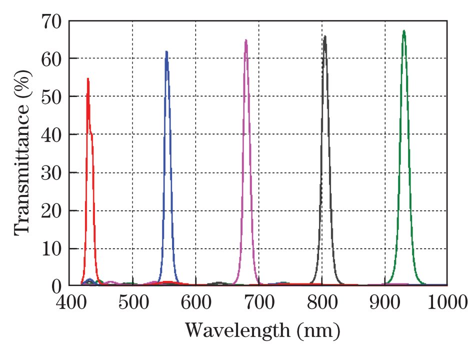

Fig. 1. Calculated transmittance of a variable filter whose peak transmittance is moved by grading the coating thickness.

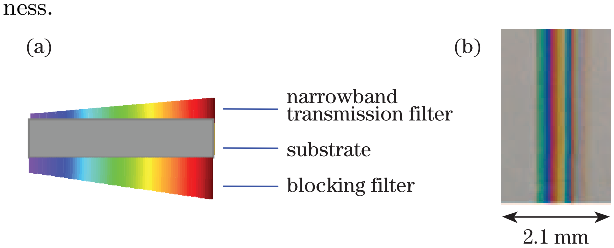

Fig. 2. (a) Lateral scheme of the variable filters on both sides of the substrate; (b) picture of the variable coating over the substrate surface.

limited number of layers. The curves shown in Fig. 1 are obtained with a 21-layer coating that contains 20 alternating layers of dielectric materials (SiO_2 and Ta_2O_5) and a silver layer (70 nm) in a central position. This type of filter is known as an induced transmission filter[4]. The substrate used is glass. Once the filter is designed for the longest peak wavelength (940 nm), the whole spectral performance can be moved to shorter peak wavelengths (Fig. 1) by linearly grading all layer thicknesses.

However, to obtain an acceptable result, this condition must be taken into account during the design process. The performance is not automatically maintained by grading the coating thickness for metal-dielectric coatings. On the contrary, for all dielectric blocking filters, the design is simple. The transmittance curve is almost unchanged when the whole coating thickness is varied, as shown in Fig. 3. The calculated and measured transmittances of a 38-layer (SiO_2, Ta_2O_5) widepass filter are reported. The presence of the blocking filter has its main influence on the outband rejection, which is scarcely visible in the curve of Fig. 1 (linear scale).

The complete filter has a dimension of 2.1 mm in the direction of variation. It will be coupled to a CCD detector (8.4×2.1 (mm)) for the construction of a compact spectrometer dedicated to Earth observation. For imaging spectrometers, it is important to have a high spatial gradient (approximately 250 nm/mm).

The fabrication of such filters requires the use of moving masks inside the deposition system. The mask movement must be accurately controlled to achieve the desired thickness profile[5]. Additional difficulties come from the small dimension of the filter, in the direction of variation, which requires a precise fabrication of the mask itself. Moreover, the back surface filter must be perfectly aligned with the first one, having both the same spatial variation.

The coating behavior for both narrowband transmission and blocking filter was tested at cryogenic temperatures and exposure to γ-ray radiation. In both

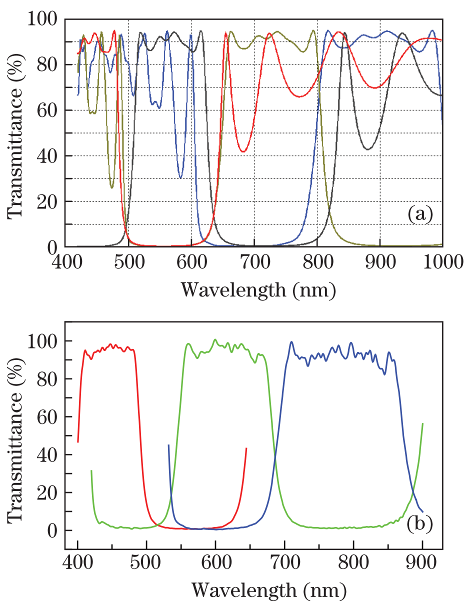

Fig. 3. (a) Calculated transmittance of the back-surface blocking filter, as the coating thickness is changed; (b) measured transmittance of the variable blocking filter.

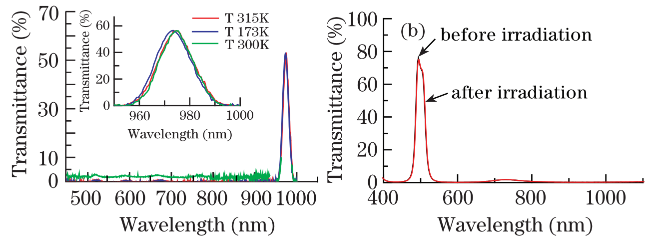

Fig. 4. (a) Transmittance of the induced transmission filter during the thermal cycling; (b) transmittance of the induced transmission filter before and after γ-ray irradiation.

cases, a uniform coating was tested; in this way, the comparison of the behavior before and after the test is easier than for variable filters. In fact, the characterization of small variable filters requires a dedicated set-up[6]. The possible modifications to its performance can be due to both the change of material properties and the different deposition conditions. The induced transmission filter contains both dielectric and metal films. The tested filters were fabricated by radio frequency magnetron sputtering.

The narrowband transmission filter behavior after eight thermal cycles in vacuum between ambient temperature and 173 K is shown in Fig. 4(a). Irradiation with γ-ray at a total dose of 200 grey (20 KRad) was also carried out[7] (Fig. 4(b)). In both tests, no significant variations were detected in the filter performance. A similar behavior was found for the all-dielectric blocking filter.

Concerning large area coatings, one of the main problem is the uniformity of the performance on the whole coated surface. The effect of non-uniform coating thickness is especially crucial for very narrowband transmission filters. In fact, the band position could be displaced with respect to the required peak wavelength. In many cases, the whole filter performance could be destroyed. For this reason, the transmission bandwidth cannot be lower than a given value, which depends on the accuracy of the fabrication system.

The filter under investigation is dedicated to the detection of the oxygen line triplet for the study of lightning phenomena. The strongest emission features in the cloud top optical spectra are produced by the neutral oxygen and neutral nitrogen lines in the near infrared spectral region. The oxygen lines are positioned between 777.15 and 777.60 nm. They must be transmitted through the filter, while the radiation out of this band should be rejected in the range of 300–1100 nm, in order to reduce the solar background contribution during daytime. Moreover, during the use of the instrument, the filter will be illuminated under converging telecentric beams with an f-number of 5.2, corresponding to incidence angles in the range between $+5.5°$ and $-5.5°$. The performance of a narrowband filter that satisfies these conditions is shown in Fig. 5(a), where the transmittance curve of a triple-cavity Fabry-Pérot filter with 65 layers of SiO_2 and TiO_2 is reported. Its maximum transmission is 90. The bandwidth is 1.5 nm-(full-width at half-maximum). As in the case of variable filters, this filter will be combined with a blocking filter (Fig. 5(b)) on the back surface of the substrate in order to obtain the required outband rejection in the 10^{-4} region in most of the spectral range.

The effect of thickness errors on the performance of

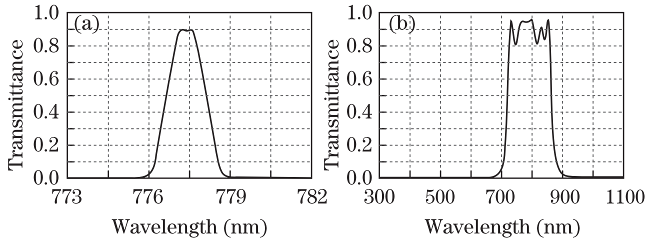

Fig. 5. (a) Transmittance of a 65-layer triple-cavity Fabry-Pérot filter, with a cone angle of ±5.5°; (b) transmittance of the 70-layer blocking filter to be combined with the triple-cavity Fabry-Pérot filter.

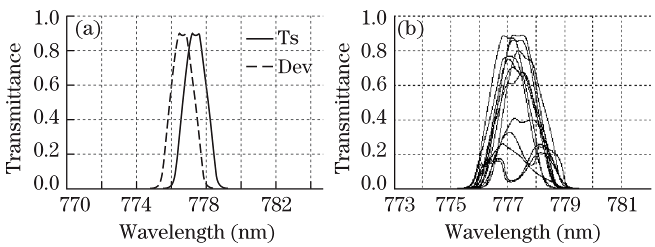

Fig. 6. (a) Effect of systematic thickness errors (Dev(–0.1%) on the transmittance Ts curve of the triple-cavity filter of Fig. 5(a); (b) effect of random errors (0.1%), in all layer thicknesses, on the transmittance curve of the triple-cavity filter of Fig. 5(a).

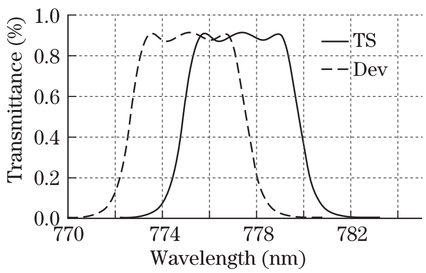

Fig. 7. Effect of systematic thickness errors (dashed curve–0.3%) on the transmittance curve of the 53-layer triple-cavity filter.

the filter in Fig. 5(a) is shown in Figs. 6(a) and (b). If a systematic thickness deviation of 0.1% is present over the coating surface, the resulting effect will be a displacement of the transmittance curve (Fig. 6(a)), whereas if a random error of 0.1% on all thicknesses is applied, the transmittance shape will be destroyed (Fig. 6(b)). This effect is mainly due to errors on the cavity layers, which is why their thicknesses should be accurately controlled.

The systematic deviation of thickness shows what may occur if the deposited coating is not uniform over the substrate surface. For large area coatings, the probability of having such an effect is quite high. The investigated optical filter should have a diameter of 150 mm, and a deviation as low as 0.1% on the whole surface is hardly achieved. A masking apparatus inside the deposition chamber is needed to improve the thickness uniformity[8]. In this case, shaped masks are added to the conventional rotation systems. However, it may be more convenient to enlarge the filter bandwidth (Fig. 7) and reduce the error sensitivity. As can be seen in this graph, the bandwidth for a 53-layer triple-cavity filter using the same materials is 5 nm, and the effect of a deviation of 0.3% on the thickness is less critical than in the previous case. In fact, the wavelengths of interest are transmitted in any case.

Such fabrication errors have much less influence on the performance of the back surface blocking filter.

For large area filters, the planarity of the substrate is also vital in order to avoid wavefront distortion. A compromise should be found between the possibility of obtaining a high planarity and a reduction of the substrate thickness required to keep a low total weight.

In conclusions, space instrumentation needs dedicated optical filters, which can have dimensions in the range of a few millimeters to several meters. The performances of two types of narrowband transmission filters have been illustrated. Different fabrication problems are encountered depending on their size. In the first case, both the small dimension and the variation of performance on the filter surface make manufacturing the device quite complicated. In the second case, the large dimension of the filter combined with the angle of incidence of the radiation requires a filter design that takes into account the limits of deposition uniformity. In both cases, dedicated apparatuses are needed for the fabrication of optical components that are not yet available on the market.

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