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VARIABLE OPTICAL FILTERS FOR EARTH-OBSERVATION IMAGING MINISPECTROMETERS

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ABSTRACT

Small-dimension, low-mass spectrometers are useful for both Earth observation and planetary missions. A very compact multi-spectral mini-spectrometer that contains no moving parts, can be constructed combining a graded-thickness filter, having a spatially variable narrow-band transmission, to a CCD array detector. The peak wavelength of the transmission filter is moving along one direction of the filter surface, such that each line of a two-dimensional array detector, equipped with this filter, will detect radiation in a different pass band. The spectrum of interest for image spectrometry of the Earth surface is very wide, 400-1000nm. This requirement along with the need of a very small dimension, makes this filter very difficult to manufacture. Preliminary results on metal-dielectric wedge filters, with a gradient of the transmission peak wavelength equal to 60nm/mm, are reported.

1. INTRODUCTION

The instrumentation for Earth observation satellites should have both small dimensions and low mass. To satisfy both requirements, the construction of mini-spectrometers was proposed [1], in which the traditional optical elements, as prisms and gratings, were substituted by graded transmission filters. There are different types of filters that can be used in spectrometers, as for example edge filters and narrow-band transmission filters [2, 3]. In the latter case the wavelength of interest can be selected, without moving parts in the spectrometer, if the filter peak wavelength is linearly displaced over its surface. Such kind of filter can be realized, taking advantage of the thin film technology, with a multilayer coating having a spatially graded thickness. This approach permits wide operating wavelength ranges but, wider is the spectrum, greater are the difficulties of filter design and fabrication. For this reason, the available narrow-band filters are typically limited to a short operating range with a ratio

between wavelength extremes lower than 2:1. The image spectrometry of the Earth surface requires a wavelength range 400-1000nm, or even more extended, then an appropriate filter is needed. Such kind of filter, with wavelength ratio 2.5:1, was designed and fabricated by the authors [4, 5], however additional work is still in progress. In Section 2 the spectrometer design will be described, whereas the filter fabrication and characterization will be illustrated in Section 3.

2. IMAGING MINISPECTROMETER DESIGN

The proposed imaging mini-spectrometer consists of a front lens and a focal plane detector equipped with the variable filter. The driven instrument requirements are typical for Earth observation from a polar sun synchronous orbit with a 700km altitude. By a dedicated radiometric model, the main characteristics of the optical objective were defined which, considering the wide spectral range, should be an "all mirror" optical system. At the end of a trade off phase, the selected configuration among some possible solutions, was a "Three Mirror Anastigmatic (TMA)" telescope, (Fig. 1) that is selected to cope with the requirements on the Field Of View (FOV). It presents some important advantages: no central obscuration, together with high optical quality on axis and on field, until an angle of ±12.45° (larger FOV).
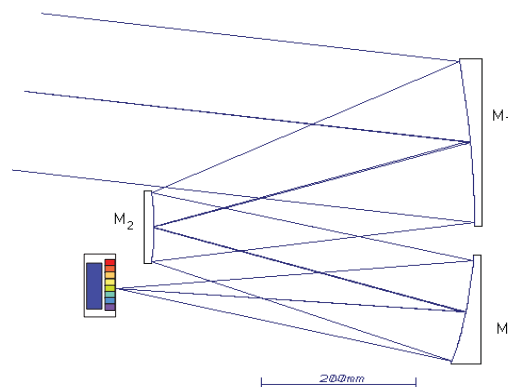

Fig. 1. Telescope configuration with three mirrors M
(CCD with variable filter on the left)

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The variable filter should be mounted as close as possible to the sensitive area of the detector in order to guarantee the requested spectral and spatial resolution. To reduce the effects of the back reflection: ghost images, stray light, cross talk, an antireflection coating deposited on the detector sensitive area is necessary. Taking into account this requirement, two detector-technology alternatives were considered, both allow the coating deposition directly on the sensitive area: back side illuminated CCD and CMOS Active Pixel Sensor. A preliminary survey shows a preference of the APS with respect to the back side CCD because this choice allows a reduction of the driven electronics complexity. In depth survey should be devoted to select sensor allowing high level of data rate acquisition needed for on-orbit acquisitions.

3. FABRICATION AND CHARACTERIZATION OF VARIABLE FILTERS

The required filter characteristics are: a linear variation of the transmission peak wavelength in the range 400-1000nm with a gradient greater than 60nm/mm and a transmission bandwidth lower than 10nm. Narrow-band transmission filters are often made using thin-film all-dielectric Fabry-Perot filters, which allow a very narrow transmission bandwidth but with the disadvantage of a very limited rejection range. For this reason, it is necessary to add blocking filters to eliminate unwanted radiation. This procedure is used when a wide operating wavelength range is required but, unless absorption filters are added, a number of dielectric filters are needed and the total number of layers becomes very high (even more than 100). Unfortunately absorption filters can not be used if the transmission peak wavelength must be moved in the spectrum of operation. An alternative solution, to enlarge the rejection range of transmission filters, is represented by the induced transmission filters that contain both metal and dielectric materials and reflect the unwanted radiation in a wide spectrum.

3.1 Filter design

The design of the variable filter for the mini-spectrometer was based on the induced transmission theory [6]. According to this theory the metal reflectivity can be eliminated at a given wavelength if a proper optical matching with surrounding media is made. In this way a narrow-band transmission filter that operates in the range 400-1000nm can be obtained with a limited number of layers, as shown in Fig. 2. The filter performance reported in this graph is obtained by a

silver layer (55nm thick) matched with air and substrate (glass) by the introduction of eight oxide layers (SiO_2, Ta_2O_5) on both sides of the metal layer. The ripple on the short-wavelength side can be reduced by an optimization of the coating design, that will cause an increase of the layer number. The result is shown in Fig. 3, where the transmittance of a 24-layer filter containing one silver layer (58nm thick) is reported. The peak transmission is about 70% and the transmission bandwidth lower than 10nm. Moreover in the same graph, the transmission peak is displaced to different wavelengths and this effect is obtained by only grading the thickness of the dielectric layers, without changing the coating structure (number and sequence of layers). The deterioration of the performance, when the peak wavelength is moved, is due to the strong dispersion of the silver refractive index. This means that the optimization of the coating design works efficiently only for the peak wavelength where this process is carried out (900nm in Fig. 3). For each peak wavelength, a proper optical matching should be calculated and a different coating design would be required. That is not possible if a variable filter must be realized; in this case only the coating thickness, and not its structure, can be varied over the substrate surface.
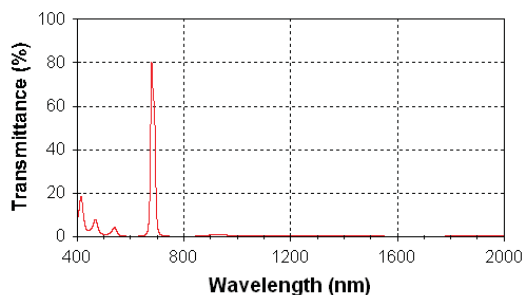

Fig. 2. Transmittance of a 17-layer induced transmission filter containing one silver layer
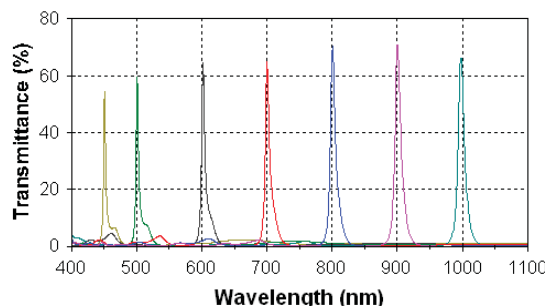

Fig. 3. Transmittance of a 24-layer induced transmission filter, which peak wavelength is moved by only grading the coating thickness

To obtain a linearly variable filter, which transmission peak is moved from 400 to 1000nm, the thickness of the coating must be wedged along the sample surface. The law of variation of each dielectric-layer thickness $t_i(x)$ depends on the desired peak-wavelength variation, along the direction x of the component surface, and can be written as:

$$n_i \; t_i(x) = q_i \, \lambda_0(x) / 4 \qquad (1)$$

where n_i is a refractive index of the i-th layer and q_i is ratio of its optical thickness, $n_i t_i$, to the reference wavelength λ_0, in terms of quarter waves (q=1 corresponds to quarter-wave thickness). The values of q_i are defined in the coating design. The refractive index n_i is not constant with wavelength but its dispersion, in the wavelength range of interest, does not influence significantly the profile of $t_i(x)$. Thus, a linear displacement of the peak wavelength along the filter surface is obtained with an almost linear variation of the thickness of each dielectric layer, as shown in Fig. 4, where the thickness variation of quarter-wave SiO_2 and Ta_2O_5 layers is reported. The peak-wavelength gradient is related to the thickness wedging. The thickness gradient, that is determined by the maximum and minimum thickness to be deposited on a given distance, depends not only on the wavelength extremes, λ_{max} and λ_{min}, but also on the refractive index dispersion of each material. In fact, owing to the dispersion, the ratio between maximum and minimum geometrical thickness of each layer will be slightly different from the ratio between maximum and minimum operating wavelengths. If λ_{max}= 1000nm and λ_{min}= 400nm, the thickness ratio will be different for each oxide layer and higher than 2.5. This value is independent from the q value, but depends only on the material.
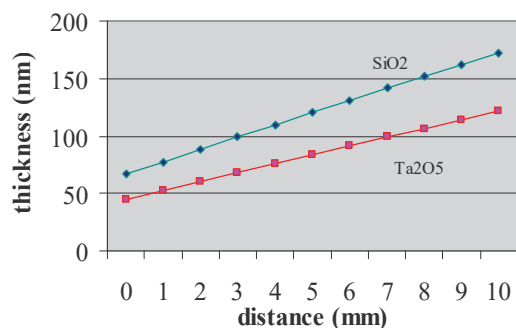

Fig. 4. Thickness gradient of two dielectric layers of the coating of Fig. 3.

The peak wavelength is coincident with the reference wavelength λ_0 for the filter design on which the optimization is carried out; but when the peak wavelength is moved, there is a small difference between these two quantities that must be taken into account in the fabrication process.

The peak-wavelength gradient that is required for the spectrometer should be greater than 60nm/mm, that means the filter should be smaller than 10mm. The limitation on the filter dimension, in the direction of variation, are only due to technological problems in the fabrication of graded thickness layers. The masking system, used to deposit wedge layers, will be described in the next paragraph.

3.2 Filter fabrication

The radiofrequency magnetron sputtering system, PE2400, was used for the filter fabrication. Three 8inch-diameter targets are installed at the top side of the vacuum chamber. Silica (SiO_2) and tantala (Ta_2O_5) targets were used as low- and high-refractive index material and silver (Ag) target was used for deposition of the metallic layer. The substrate holder is mounted on the rotary platform, which allows controlled positioning of the substrate under each of the three targets. All movements are motorized and controlled by computer. The deposition conditions were optimized for each of the used material. The deposition chamber can be evacuated using a rotary pump and a turbo-molecular pump to an ultimate pressure of $2 \cdot 10^{-4}$ Pa. Gas flow and its mixing ratio is controlled by three gas flow meters. Argon and oxygen gas mixture were used in the deposition process of tantala. The silver and silica coatings were prepared in pure argon ambient. The deposition pressure of 0.1 Pa and 0.5 Pa for oxides and silver, respectively, was regulated using a virtual regulator controlling the flow meters and throttle valve.

The deposition system is equipped by combined optical and crystal micro-balance monitoring system for precise layer thickness estimation. Spectral reflectivity is measured using an optical apparatus installed beneath the transparent substrate. The obtained spectra are periodically processed by a dedicated computer and fitted by an appropriate model in order to achieve an actual thickness and refractive index of the deposited layer. Thus, a precisely defined multilayer structure can be fabricated. The silver layer growth is monitored using crystal micro-balance monitoring system, which is more accurate than optical monitoring for such absorptive layer. Combination of dielectric layers with metal layer brings very specific problems to optical monitoring. The first dielectric layer after a metal layer becomes very insensitive for the optical monitoring; the back-side reflectivity is almost not changed by growing that layer.

Therefore, it was decided to apply an indirect optical monitoring using an optical structure, which differs from the complete structure of the optical filter. The dielectric layer growth is optically monitored on a testing zone of the same substrate. This zone is masked during the silver layer deposition. Thus the monitoring proceeds on an identical multilayer structure as the complete filter, with exception of the missing metallic layer.

Several effects were observed during the deposition experiments. First effect is associated with the well known optical shift of the optical interference features after deposition chamber venting. The humidity penetrating into the filter structure pores induces a refractive index and/or layer's thickness changes. This effect is at least partially reversible.

The second effect concerns a progressive increase of the deposition rate of each further layer. The simulation showed that this increase is accompanied by a slight decrease of refractive index. This effect is associated with the increasing porosity of the structure, which is caused by a columnar growth and a progressive increase of the grain size. The minor changes of the refractive index are detected and compensated by a fitting algorithm during the deposition process.

Table 1. Results of post-deposition analysis of the structure of a filter with transmission peak at 680 nm (the silver layer is excluded from the structure).

Layer material	Thickness (nm)	Dep. rate (Å/s)	Refractive index
Glass			
1 Ta_2O_5	108.1	1.33	2.152
2 SiO_2	91.3	2.21	1.461
3 Ta_2O_5	117.8	1.49	2.139
4 SiO_2	80.1	2.84	1.458
5 Ta_2O_5	54.3	1.68	2.133
6 SiO_2	87.1	2.97	1.449
7 Ta_2O_5	54.0	1.41	2.131
8 SiO_2	59.1	3.23	1.446
9 Ag	0.0		
10 SiO_2	74.2	2.96	1.444
11 Ta_2O_5	27.0	1.55	2.120
12 SiO_2	85.8	2.92	1.439
13 Ta_2O_5	83.7	1.64	2.118
14 SiO_2	117.2	3.00	1.440
15 Ta_2O_5	79.9	1.63	2.117
16 SiO_2	122.2	3.04	1.438
17 Ta_2O_5	78.0	1.65	2.113
18 SiO_2	120.6	3.08	1.440
19 Ta_2O_5	80.0	1.90	2.106

The mentioned observations are demonstrated in Table 1 for a 19-layer filter, where the refractive index decrease appears, going from the substrate to the air side.

The third effect is associated with a reduced deposition rate of the dielectric layer on the silver surface. This effect is probably caused by a low nucleation rate of the dielectrics on the metallic surface. Moreover the metallic film acts as a barrier layer for the columnar growth and the progressive increase of the grain size. Thus a different growth was obtained in the testing zone with respect to the area of the complete filter structure. The knowledge of this effect is very important for an accurate realization of the filter structure and it must be precisely evaluated and compensated.

The displacement of the peak wavelength along the component surface is obtained by changing all layer thickness, except for the metal layer, according to Eq. 1. To deposit the graded thickness, a proper masking apparatus must be inserted inside the deposition system. The method that was used in this work consists of a shaped mask that is positioned between the material source and the substrate. The mask is periodically moved during the deposition process so that the substrate surface under the mask, is exposed to condensing particles for a period of time proportional to the aperture of the mask itself, over each zone. The mask was prepared from a 30-μm thick stainless steel foil, which was glued on a 1 mm-thick stainless steel holder as shown in Fig. 5. The substrate is moved beneath the mask window and very near to it (<100 μm). Both, the low mask thickness and the small distance between mask and substrate, lead to minimization of the shadowing effects. The mask contains two shaped windows for the two dielectric materials and one rectangular window for the silver layer. The trapezoidal shape of the window is designed starting from the required thickness profile and appears as in Fig. 5. The larger side will correspond to the maximum required thickness, the smaller side will give the minimum required thickness. As mentioned above, for each material the mask is different. The third window shown in Fig. 5, with a rectangular shape, gives the constant thickness of the metal layer.

The optical monitoring is made at the non-variable thicker side of the mask window. The optical measurement of masked sample can be carried out after completion of certain cycle. Typically, the cycle period is set from tens of seconds to few minutes, that is a big disadvantage in respect to monitoring of uniform coatings.

The deposition process is never interrupted during the sample movement, otherwise unwanted thickness steps

would be created on the filter structure. The deposition controlling algorithm is adapted for this requirement.
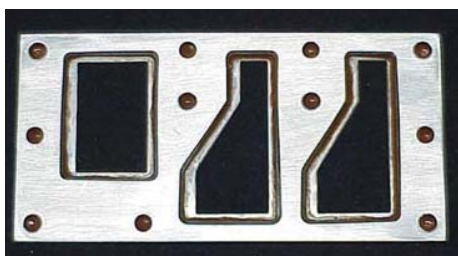

Fig.5. Photo of complete mask

A linearly variable filter, fabricated with the mask of Fig. 5, is shown in Fig. 6. The variable part and the two uniform areas of the filter can be clearly seen. The thicker uniform area, where the silver layer was excluded from the structure, was used for optical monitoring.
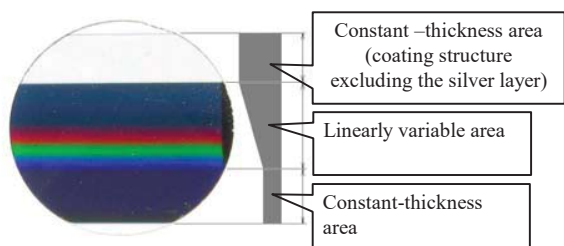

Fig.6. Metal-dielectric variable filter (the peak wavelength is moved in the vertical direction)

3.3 Filter characterization

The measurement apparatus used for the filter characterization [7] acquires the sample map 'at-once' with a CCD camera, spatial resolution being given by the pixel size. The spatial resolution of the system is 30µm, the spectral resolution is 0.1nm, in the range 400-1000nm.

A sketch of the CCD-based setup is shown in Fig. 7 and consists of three main parts. The first is the Acquisition System, which includes electronics, detector, dedicated software and PC used to acquire the signal collected by the CCD TH 7890 (512 x 512 pixels, 17µm pixel size). The second one is the Optical Ground Support Equipment Control System (OCS) consisting in its electronic, software and PC used to govern the "stimuli" optical subsystem constructed for uniform illumination with a quasi monochromatic light. The wavelength range is determined by the source choice which is currently a Quartz Tungsten Halogen lamp. The third is the Optical Test Set-up that is the optical system used to illuminate a sample and to collect the radiation passing through it. This optical subsystem works by imaging the diffuser

surface on the sample surface. Thus, this part of the optical bench realizes the "sample illumination" function. The specimen surface is then optically relayed on the CCD active surface, which collects the signal. The collecting optical system is the objective Xenoplan 1.9/35 – 0511 @ Schneider that relays the sample surface on the CCD. This lens is mounted in a Finite-Finite configuration in order to match the sample size to the CCD sizes.
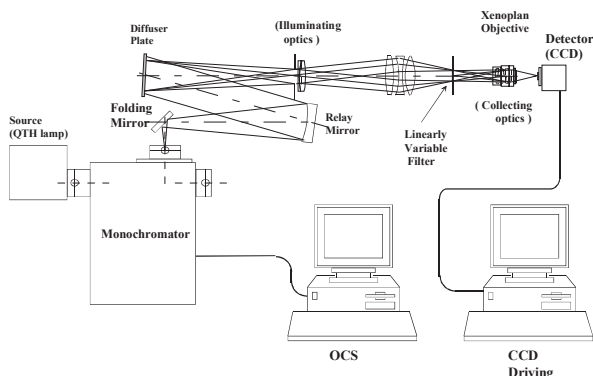

Fig. 7. Schematic representation of the CCD-based optical bench

An example of the image of the filter on the CCD detector, when illuminated at different wavelengths, is shown in Fig. 8.
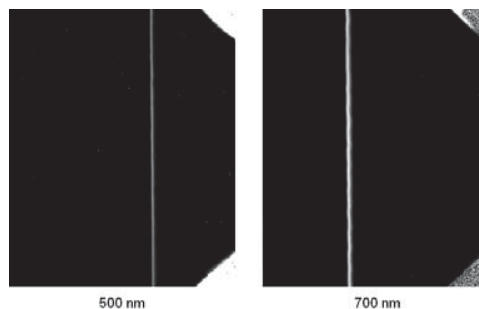

Fig. 8. Image of the filter when illuminated at 500nm and 700nm (the peak wavelength is moved in the horizontal direction)

The transmittance curve of the filter, in the whole spectrum of interest, is reported in Fig. 9 as taken at different positions over the surface of the filter itself, along the direction of the variation. Finally, in Fig. 10 the variation of the peak wavelength along the filter surface, over a 10mm distance, is shown. The linearity of the peak wavelength variation can be noticed. The resulting gradient is 60nm/mm, as required for this application, however this value can be increased by modifying the shape of the mask in the deposition system.
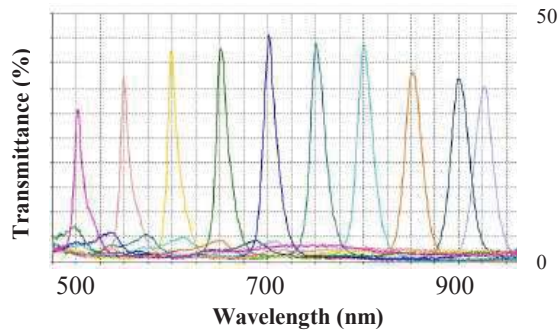
Fig. 9. Transmittance curve of the variable filter at different positions along its surface
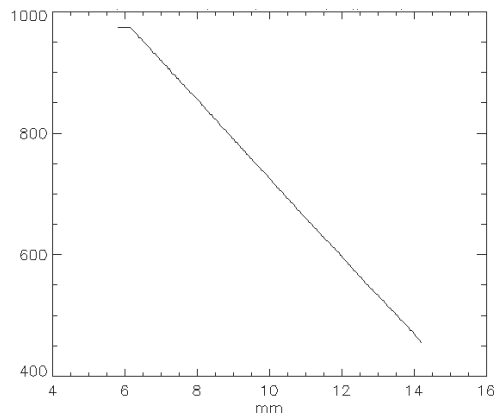

Fig. 10. Gradient of the transmission peak wavelength along the filter surface

4. CONCLUSIONS

Graded transmission filters allow the construction of small spectrometers without moving parts. The most critical points are the wide operating wavelength range and the small dimensions of the filter in the direction of variation. The first requirement was solved by the use of metal-dielectric coatings that are able to reflect the undesired radiation in a wide spectrum. The problem of small dimensions is essentially a technological issue. The masking system inside the deposition chamber allows the fabrication of wedge layers and the dimension of the coating in the direction of the variation can be reduced acting on the masking apparatus. To this end, a low number of coating layers helps in reducing fabrication errors. The deposited filters underwent a number of tests (humidity, temperature variation, gamma radiation) to verify their resistance to environmental conditions and they survived all tests. Next step will be the coupling of the filter to the CCD detector and the construction of the mini-spectrometer prototype.

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