Optical Filters for Space Instrumentation

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Optical coatings for Space

- Instrumentation
  - Spectrometers, imagers, interferometers, telescopes, ..

- Optical coatings
  - Filters, mirrors, antireflection coatings, ..
Narrow-band filters for Space

- **Two examples with different characteristics:**

1) **Spatially variable filter (for an imaging spectrometer)**
   - small dimensions (few mm)
   - high spatial gradient
   - wide spectral range (VIS-NIR)

2) **Very narrow band filter (for a lightning imager)**
   - large dimensions (> a hundred mm)
   - very narrow bandwidth (< 1 nm)
   - oblique incidence
1. Imaging Spectrometer for Earth Observation

- Polar sun-synchronous orbit at an altitude of 700 km
- Compact image spectrometer with a graded narrow-band *transmission filter* coupled to an array detector

The transmission peak wavelength is varying linearly, in a continuous spectrum (VIS-NIR), over the component surface (hyperspectral imaging)
The compact spectrometer is not limited to Earth observation, but is also useful for planetary missions.

- Replacing classical optical components (prisms, gratings) with a variable filter allows the construction of a spectrometer with reduced size and weight and with no moving parts.

Each line of a two-dimensional array detector, which is equipped with a variable narrow-band filter, will detect radiation in a different pass band.
Filter specifications (variable filters)

The variable filter shows a narrow-band transmittance which peak wavelength is displaced over its surface.

Wavelength range divided in two areas corresponding to different CCDs:

1) 440-940 nm, dimension 2.1 mm
2) 940-2500 nm, dimension 6.3 mm

Spatial gap between two adjacent areas: 0.4 mm
The variable narrow-band transmission filter is combined with the array detector by depositing a wedge coating either directly on the CCD or on a separate glass substrate.

The spatial variation is required along only one direction, the other is uniform.

This optical sensor is the core element of a compact low-mass spectrometer for hyper-spectral imaging.
Linearly Variable Filter design

- **Induced Transmission filter**: Ag - SiO$_2$ – Ta$_2$O$_5$, 21 layers
- **Back-side blocking filter**: SiO$_2$ – Ta$_2$O$_5$, 38 layers

**Operating range** 440-940 nm (first area)

The transmittance curve is displaced over the filter surface, by a variation of the coating thickness with a linear gradient

**Bandwidth**: 10-20 nm  
**Spectral gradient**: 250 nm/mm

(IT filter in the VIS-NIR: min thickness ~ 1000nm, max 2500nm)
- **All-dielectric filters**
  - limited rejection range

- **Metal-dielectric filters**
  - useful in longwave blocking
  - disadvantage of intrinsic absorption

- **Induced transmission filters:**
  - Air/ D / M / D /Substrate
    - D = dielectric stack of high and low index layers
    - M = silver
  - maximum possible peak transmission $\psi$ at $\lambda_0$ for a given thickness of the metal
Induced transmission filter

- metal layer (high reflection) matched with surrounding media (null reflection at one wavelength)

Glass/ (...HLHL) L’M L’(LHLH...) / Air

Optical constants of metals at $\lambda_0 = 550$ nm

<table>
<thead>
<tr>
<th>Metal</th>
<th>$n$</th>
<th>$k$</th>
<th>$k/n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag (Schultz)</td>
<td>0.055</td>
<td>3.32</td>
<td>60.4</td>
</tr>
<tr>
<td>Ag (Palik)</td>
<td>0.12</td>
<td>3.45</td>
<td>28.7</td>
</tr>
<tr>
<td>Al</td>
<td>0.76</td>
<td>5.32</td>
<td>7</td>
</tr>
<tr>
<td>Ni</td>
<td>1.92</td>
<td>3.61</td>
<td>1.9</td>
</tr>
<tr>
<td>Cu</td>
<td>0.72</td>
<td>2.42</td>
<td>3.4</td>
</tr>
<tr>
<td>Pd</td>
<td>1.64</td>
<td>3.84</td>
<td>2.3</td>
</tr>
</tbody>
</table>

The outband rejection improves with a higher ratio $k/n$ of the metal layer.
The peak wavelength is shifted by changing the coating thickness.
Filter design at a given peak-wavelength

- Choice of the matching stack
  Glass/(HL....)L' Ag L' (....LH)/Air
  \( H' \quad H' \)

*Input data:*
M = Ag (50 nm)  \( n_L = 1.47 \)  \( n_H = 1.96 \)  \( \lambda_0 = 550 \) nm

*Output:* Potential transmission: \( \psi = 0.817 \)

thickness \( L' = 0.1954, H' = 0.1789 \) (quarter-wave =0.25)

Calculations of the matching index depending on the number of layers

| Neff 1 | 19.68 | 11.99 |
| Neff 2 | 0.19 | 0.32 |
| Neff 3 | 11.01 | 6.71 |
| Neff 4 | 0.35 | 0.57 |
| Neff 5 | 6.16 | 3.75 |
| Neff 6 | 0.62 | 1.03 \{Glass-Air\} |
| Neff 7 | 3.45 | 2.10 |
| Neff 8 | 1.11 \{Glass-Air\} | 1.83 |
| Neff 9 | 1.93 | 1.18 |
Optimization method

- Optimization is needed to reduce bandwidth and side-lobes

basic design: Air/HL...L’AgL’...LH/Sub

The coating structure (sequence and number of layers) must be maintained at different peak-wavelengths after optimization

\[ \lambda_0 = 550 \text{ nm } \] 17 layers \[ \lambda_0 = 800 \text{ nm } \] 19 layers

\[ \lambda_0 = 550 \text{ nm } \] (same number of layers) \[ \lambda_0 = 800 \text{ nm } \]
Final filter design

**Induced transmission filter:** 1 silver layer surrounded by 20 SiO$_2$/Ta$_2$O$_5$ alternate layers

Bandwidth 10-15 nm, $T \approx 70\%$ at $\lambda_0 = 900\text{nm}$
Variable MD filter: design process

- Select the metal and its thickness
- Calculate the matching assembly (L’ LHL......)
- Introduce measured index (dispersion) of all materials
- Optimize the design for a selected peak wavelength and control the performance at other peak positions
- Calculate the spatial variation of each layer thickness for obtaining the required variation of $\lambda_0$, without changing the design (number and sequence of layers)
Peak-wavelength and thickness gradient

- Layer thickness
  
  \[ t = q \left( \frac{\lambda_0}{4n} \right) \]
  
  \[ \frac{t_{\text{max}}}{t_{\text{min}}} = \left( \frac{1000}{400} \right) \left( \frac{n_{400}}{n_{1000}} \right) \]
Masking apparatus for graded coatings

- Masking blade moved during film deposition
- Coating profile controlled by mask speed

Fixed mask to cover the adjacent filter

Uniform area for optical monitoring

Movable mask
Filter fabrication: masking apparatus

Fixed mask: alternative method not suitable for adjacent filters

Silver mask

Tantala and silica masks

Constant–thickness area

Linearly variable area

Constant–thickness area
On-line reflectance measurements

Apparatus for online reflectance measurements inside the sputtering system

- Optical fibers
- Aluminum coated prism
- Collimating optics
- Adjusting screws
Localized Transmittance measurements

- Measurements are carried out by a dedicated set-up
  - Characterization range: 400 ÷ 1000 nm
  - 2-D translation micrometric system: min step 25 μm
  - Spectral resolution: < 2 nm
  - Spatial resolution: < 20 μm

Variable filter area

3 mm

Scan track

measurements, fit
Non-linear Variable Filters

High-resolution spectrometer dedicated to planetary missions (ESA project)

Three filters operating in different wavelength ranges

Three different gradients or non-linear spatial profile

Filter dimensions: few mm

Filter at the entrance slit of the spectrometer
the beam is carried to the slit by optical fibers

Operating spectral range: 300-800nm
Non-linear variable edge filters

- Low-pass filter
  28 layers ($\text{SiO}_2 - \text{Ta}_2\text{O}_5$)
  Operating range 339-805nm

The edge wavelength is moved according to a nonlinear equation, over a distance of 4 mm

The edge slope must be also controlled @T=5% and @T=80%
Non linear variable thickness

- variable filter design (non-linear)
  28-layer low-pass filter (tantalum – silica)

Variation of edge wavelength as function of the spatial position

From this curve, the required variation of each layer thickness can be calculated

Silica thickness profile

Sample picture

useful area
2. Lightning Imager

- The Lightning Imager is an instrument of METEOSAT (MTG), for the study of lightning phenomena in the atmosphere.

- Filter must discriminate (from the background) the light generated by lightning.

**Filter requirements**
- Transmission bandwidth: 0.45 nm
- In-band Transmission: 0.8
- Out-band Transmission: $10^{-4}$
- Dimensions: 160 mm diameter
Study of lightning phenomena

*ESA Earth Observation Program:*

- Monitoring of lightning activities on Earth is an essential element in the Weather Prediction
- The strongest emission features in the cloud top optical spectra are produced by the neutral oxygen and neutral nitrogen lines. The Oxygen line triplet is located between 777.15 and 777.6 nm

Lightning Imager as part of METEOSAT THIRD GENERATION

- Transmitted bandwidth: 0.45 nm
- Operating wavelength range: 300-1500 nm
Filters for the Lightning Imager

The wavelengths of interest must be transmitted for all incidence angles in a range of +/- 5.5° or in a cone angle of +/- 5.5°.
## Filter Optical Requirements

### Lightning useful spectral range and transmittance

<table>
<thead>
<tr>
<th>Useful spectral range:</th>
<th>777.145 – 777.595 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmittance in the useful spectral range:</td>
<td>0.8</td>
</tr>
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</table>

The useful wavelength range is very narrow $\Delta\lambda=0.45$ nm.

If a high value of transmittance (> 80%) is required in this range, decreasing rapidly to a very low values ($10^{-3}$ - $10^{-4}$) out of this range, the transmission band should have an “almost” rectangular shape.

**Fabry-Perot filter (single cavity, SiO2/TiO2), varying the number of layers (green 25, red 29, black 33)**

**Multiple-cavity filter, varying the number of cavities (red 2, green 3, blue 4) and of layers (red 51, green 77, blue 104)**
Filter Optical Requirements

Angle of incidence

<table>
<thead>
<tr>
<th>Angle of incidence:</th>
<th>8 degrees collimated beam (initial req.)</th>
<th>5.5 (new req.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5.5 degrees semi-angle of convergent beam</td>
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</table>

This requirement is very critical because interference filters are very sensitive to angle variations. A narrow band filter which bandwidth is of the order of 1 nm can be completely out of specifications with an angle of incidence of only few degrees.

double-cavity filter (51 layers, TiO2/SiO2, bandwidth ≤1nm) with a variation of the incidence angle from 0 (black) to ±5.5 degrees (red)

double-cavity filter (51 layers) with a convergent beam of cone semi-angle 5.5 degrees (blue) compared to normal incidence (red)
Filter Optical Requirements

**Angle of incidence**

Theoretical formulas for small incidence angles (<20 degrees): change in position ($\delta \lambda$) and bandwidth ($\Delta \lambda$)

- **Concept A**
  \[ \theta = \pm 5.5^\circ \]
  \[
  \frac{\delta \lambda}{\lambda_0} = -\frac{\theta^2}{2\mu^*}
  \]
  \[
  \frac{\Delta \lambda}{\lambda_0} = \left[ 1 + \left(\frac{\theta^2 \lambda_0}{\mu^* \Delta \lambda_0.5}\right)^2 \right]^{1/2}
  \]

- **Concept B**
  semi-angle $\alpha = 5.5^\circ$
  \[
  \frac{\delta \lambda}{\lambda_0} = -\frac{\alpha^2}{4\mu^*}
  \]
  \[
  \frac{\Delta \lambda_0.5}{\lambda_0} = \left[ 1 + \left(\frac{\alpha^2 \lambda_0}{2\mu^* \Delta \lambda_0.5}\right)^2 \right]^{1/2}
  \]

*The higher is the value of $\mu^*$ (effective index), the lower is the performance deterioration*

Double-cavity filter (43 layers, TiO2/SiO2, bandwidth 2 nm) with a variation of the incidence angle from 0 (black) to $\pm 5.5$ degrees (red)

The same double cavity filter with a convergent beam of cone semi-angle 5.5 degrees (red), compared to normal incidence (blue)
Narrow-band filter design

- Narrow-band filter: Fabry-Perot double cavity 35 layers (SiO$_2$ - TiO$_2$ )
  bandwidth FWHM = 3 nm

- Collimated beam
- Convergent beam $\pm 5.5^\circ$

- A sun-blocking filter is needed for the required outband rejection ($<10^{-4}$)
Alternative materials (and design)

- Narrow-band Filter (51-layer double-cavity filter, HfO₂/SiO₂)

The use of a lower index material HfO₂ (as H layer) requires a higher total number of layers for obtaining the same result, and the filter is more sensitive to oblique incidence.

Calculated transmittance at normal (blue) and oblique incidence (red and green)

Experimental result

Calculated transmittance (%)

Wavelength (nm)

T₂₀ = 85.8%
Δλ = 3 nm

Transmittance (%)

Wavelength (nm)
Filter Optical Requirements

Out of band spectrum

- The whole out-of-band spectrum (300-1100 nm) is quite large and a wide-band blocking filter must be added to the narrow-band filter.

- The most inner part of the spectrum (close to the pass band) is assumed to be rejected by the narrow-band transmittance filter itself.

- This point is important to avoid more complex blocking filters.
Manufacturing challenges

Challenging requirements:
• Precise spectral positioning
• Bandwidth accuracy
• High uniformity (diameter 100 - 160 mm)

Effects on the transmission band of random errors of 0.1% and 1%, in all layer thicknesses
Masking apparatus for large area coatings

- Ion beam sputtering deposition
- Profiled mask to improve uniformity designed by software

First ion source (Sputtering)

Second ion source (Ion assistance)

Substrate

Comparison of the radial profile of a TiO$_2$ layer thickness with and without mask
Two deposition techniques are used:

- Dual Ion Beam Sputtering, DIBS
- Electron beam evaporation with ion assistance, e-IAD

A dedicated setup is needed for mapping the transmittance over the whole surface.
Measured optical performance

Narrow-band filter (35 layers)

electron beam evaporation

ion beam sputtering

The maximum transmittance is lower than the calculated value owing to manufacturing errors.
Wide spectrum characteristics

Spectral range 300 – 1100 nm
Combination of a narrow band filter with a blocking filter (70 layers)

![Graph showing transmittance vs. wavelength with blocking filter performance curves.](image)
Environmental testing

- Environmental durability
  - Mechanical resistance
  - Adhesion, abrasion, humidity....
  - Thermal cycling (cryogenic temperature)
  - Exposure to ionizing radiation: gamma rays, protons, etc.
  - Solar irradiance

Cross-sectional TEM image of a Mo/Si multilayer coating, (a) before and (b) after proton bombardment (M.G.Pelizzo et al. Opt Exp. 2011).

Silver mirrors flown on MISSE-7 showing particulate contamination and haze near its center (C.Panetta et al, OIC20013)

Impact crater on a MISSE-6 silver mirror
Many interesting experiments on material behavior are carried out directly on the International Space Station: MISSE (Materials International Space Station Experiment) [http://spaceflightsystems.grc.nasa.gov/SOPO/ICHO/IRP/MISSE/](http://spaceflightsystems.grc.nasa.gov/SOPO/ICHO/IRP/MISSE/) and this is the best way to study synergic effects, even though more expensive than experiments on the ground.