Near-Infrared Bandpass Filters for Astronomy

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Near-infrared filters operate within a wavelength range of 800 to 5000 nm and typically consist of multiple thin-film interference layers of silicon/ silicon compounds deposited on a suitable optical substrate. They can be manufactured in narrow- and wideband filters and in cut-on/-off varieties, and they have applications in both terrestrial-based IR telescopes and in satellite IR measurement payloads.

Orion Nebula as captured by VISTA in visible light. Image by ESO; J. Emerson, VISTA; and R. Gendler. Courtesy of Cambridge Astronomical Survey Unit.

Filter manufacturing techniques

Near-IR filters generally are produced using vacuum deposition techniques. The choice of the technique determines the structure of the thin films being deposited.

Traditional vacuum deposition methods involve thermal evaporation of the bulk material, with electron beam excitation being the most popular. The optical material is heated in vacuum until it sublimes or becomes molten, to produce a dispersed vapor within the vacuum process chamber. Each layer is built up progressively, as the vapor condenses uniformly across the surface of the prepared optical filter substrate.

Figure 1. *Pulsed-DC magnetron sputtering system. Images courtesy of NDC Infrared Engineering Ltd.*

An alternative method is pulsed-DC magnetron sputtering. One technique uses a single-fixed-

source sputter target of high-purity silicon and a high-power-pulsed-DC power supply[1] (Figure 1). By choosing different sputter gas combinations (argon, nitrogen or oxygen), various filter layers can be produced. Key filter parameters, indicated in Figure 2, are peak wavelength and transmission, bandwidth and blocking region.

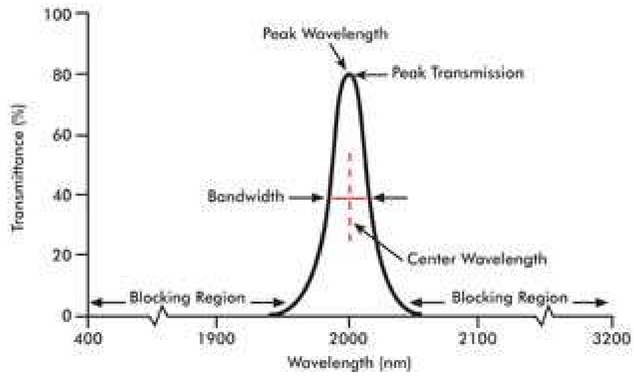

Figure 2. *Near-infrared narrowband filter characteristics.*

Bandwidth is controlled by the design of the filters and the material properties. This is achieved by optimizing the manufacturing process to deliver the same material properties repeatedly for each filter. Peak wavelength and bandwidth are determined by selecting the appropriate number, composition and thickness of filter layers deposited, and the substrate used. In this way, a wide range of filters can be manufactured with peak wavelengths ranging from 400 to 5000 nm and bandwidths from 1.0 to 14 percent full width half maximum.

Blocking filters are established by coating the back surface of the filter substrate with another multilayer of dielectric wideband filters, which typically have bandwidths upward of 14 percent.

Filters for IR telescopes

Instruments such as those on WFCAM[2] (Wide-Field Camera on UK IR Telescope on Mauna Kea in Hawaii) and VISTA[3] (Visible & Infrared Survey Telescope for **Astronomy**, European Southern Observatory in the Atacama Desert of Chile) require filters operating from 0.8 to 2.4 µm. WFCAM is composed of four Hawaii-II 2048 x 2048 x 18-µm-**pixel** array **detector**s from Rockwell Scientific, with a pixel scale of 0.4 in. (f/2.4) and a field of view per exposure of 0.21 square degrees.

Each detector is divided into quadrants, with each of those divided into eight channels of 128 x 1024 pixels. The detectors are spaced at 94 percent of the detector width. Four exposures are required to survey a contiguous area (tile) of 0.8 square degrees. WFCAM has eight filter housings, including the **broadband** set Z/Y/J/H/K, and two narrowband filters, H2 and Br-Gamma. The eighth filter housing is blanked for darks. The Y, J, H, K, H_2 1-0 S1 and Br-Gamma band filters are manufactured by NDC Infrared Engineering Ltd. using the pulsed-DC magnetron sputtering technique. The filters' specified bandpasses are shown in Table 1.[4]

	Y	J	H	K	H_2 1-0 S1 1%	Br-g 1%
50% cut-on (µm)	0.97	1.17	1.49	2.03	2.111	2.155
50% cutoff (µm)	1.07	1.33	1.78	2.37	2.132	2.177

Table 1. *Bandpasses of NDC Infrared Engineering filters for WFCAM.*

A major challenge to producing narrowband filters in this region of the spectrum using thermal evaporation techniques is loss of transmission efficiency,[1] particularly noticeable for Si/SiO filters at wavelengths in the 1200- to 1300-nm range. Typical transmission efficiencies at these wavelengths can be on the order of 60 percent, compared with 70 to 80 percent at higher wavelengths.

For high-refractive-index semiconductor film materials such as silicon and germanium, the packing density in films produced by thermal evaporation is less than the bulk or crystalline form of the material. Films deposited in this way can have a poorer definition of the absorption edge and are generally less transparent. The reasons are associated with the fact that the substrate temperature is significantly lower than that of the vapor, and there is insufficient energy in the vapor molecules to anneal the film structure into a dense solid similar to that of the bulk form of the material.

Although things can be improved somewhat by raising the temperature of the substrate, the pulsed-DC magnetron sputtering technique offers some significant advantages. It produces a vapor with much higher energy, enabling films to be deposited with well-ordered structures and near-bulk packing density, and, by choosing different sputter gases, silicon-monoxide, silicon-dioxide and silicon-nitride films also can be deposited, offering improved transmission at wavelengths down to 700 nm.

The benefits of this approach are illustrated in the case of the 1185-nm filters used on VISTA. At the heart of VISTA is a 3-ton camera containing a 16-detector array. Figure 3 shows a comparison of in-band transmission for the 1185-nm filter produced using a sputtered Si/Si_3N_4 film stack process and a similar filter produced using a conventional evaporated Si/SiO film process.

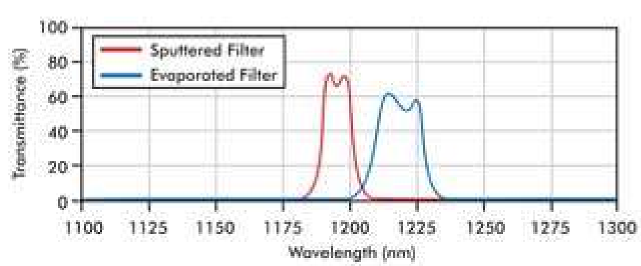

Figure 3. *Comparison of in-band transmission for sputtered versus evaporated filters of similar wavelengths.*

The sputtering process produces a filter with not only better transmission but also a narrower bandwidth. Even more challenging was the requirement by Oxford Astrophysics, a department of the University of Oxford in the UK, for matched sets of filters to operate at 975 and 985 nm on VISTA.1 The center wavelength of these filter sets falls within the spectral range most affected by silicon film optical absorption, and the specification (Table 2) requires a narrow bandwidth of approximately 1.1 percent of center wavelength.

Feature	Filter Set 1	Filter Set 2
Center Wavelength	975 ±2 nm	985 ±2 nm
Bandwidth	11 ±1 nm	11 ±1 nm
Cone Angle	f/3	f/3
Operating Temperature	100 K	100 K
Blocking Range	750 to 2750 nm	750 to 2750 nm
Blocking Efficiency	OD >3.0 below 900 nm	OD >3.0 below 900 nm
	OD >3.5 above 1100 nm	OD >3.5 above 1100 nm

Table 2. *Summary specifications by Oxford Astrophysics for 985- and 975-nm filter sets on VISTA.*

To optimize transmission at these low wavelengths, the narrowband "peak" coating was designed using a Si_3N_4/SiO_2 multilayer structure, which minimized the in-band optical losses. The blocker coating design was Si/Si_3N_4, but with some modified gas parameters for the silicon layers, which introduced a partial oxidation state. The result was excellent in-band transmission of ~80 percent for the 975- and 985-nm bands.

Another significant benefit offered by the sputtering technique is the reduced spectral shift exhibited by the sputtered filters under cryogenic conditions.

Filters for satellite payloads

Besides the application to shorter wavelength filters shown above, the pulsed-DC magnetron sputtering technique has been applied to filters for longer IR wavelengths, encompassing the upper limits of the InSb detector spectrum. It will be used on the INSAT-3D weather satellite, which is due for launch by 2011.[5]

The INSAT-3D instrument is an advanced infrared geostationary meteorological satellite being developed by the Indian Space Research Organisation Space Applications Centre for high-resolution monitoring of temperature and trace chemical species in the regions between the troposphere and stratosphere.

The instrument comprises a six-channel imaging radiometer designed to measure radiant and solar reflected energy from areas sampled on Earth, and a high-resolution infrared sounder to measure vertical temperature profiles, humidity, surface and cloud-top temperatures, and ozone distribution. Six short-wavelength infrared filters for the sounder covering the wavelength center range of 3.75 to 4.57 nm were produced using the pulsed-DC magnetron sputtering technique.[6]

The reduced spectral shift with temperature for filters produced in this way has contributed to the filters passing the environmental and spectral aging stability requirements for the mission according to standard ESA-PSS-01-702.

Meet the authors

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2. http://www.roe.ac.uk/atc/projects/wfcam

3. VISTA: http://www.eso.org/public/teles-instr/surveytelescopes/vista/camera.html

4. WFCAM instrument filters: http://www.ukidss.org/technical/technical.html

5. INSAT-3D:http://www.reading.ac.uk/infrared/research/projects/ir-isro.aspx

6. G.J. Hawkins et al (2008). High-performance infrared narrow-bandpass filters for the Indian National Satellite System meteorological instrument (INSAT-3D). Applied Optics, Vol. 47, No. 14.

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GLOSSARY

astronomy
: The scientific observation of celestial radiation that has reached the vicinity of Earth, and the interpretation of these observations to determine the characteristics of the extraterrestrial bodies and phenomena that have emitted the radiation.

broadband
: Indicating a capability to deal with a relatively wide spectral bandwidth.

detector

1. A device designed to convert the energy of incident radiation into another form for the determination of the presence of the radiation. The device may function by electrical, photographic or visual means. 2. A device that provides an electric output that is a useful measure of the radiation that is incident on the device.

excitation

1. The process by which an atom acquires energy sufficient to raise it to a quantum state higher than its ground state. 2. More specifically with respect to lasers, the process by which the material in the laser cavity is stimulated by light or other means, so that atoms are converted to a semistable state, initiating the lasing process.

germanium

A crystalline semiconductor material that transmits in the infrared.

infrared filter

A filter exhibiting transparency, absorption or reflectance characteristics specifically for spectral control of wavelengths longer than 700 µm.

optical

Pertaining to optics and the phenomena of light.

pixel

Contraction of "picture element." A small element of a scene, often the smallest resolvable area, in which an average brightness value is determined and used to represent that portion of the scene. Pixels are arranged in a rectangular array to form a complete image.

radiometer

A device used to measure the intensity of radiant energy.

telescope

An afocal optical device made up of lenses or mirrors, usually with a magnification greater than unity, that renders distant objects more distinct, by enlarging their images on the retina.