Metal-mesh optical filter technology for mid-IR, far-IR, and submillimeter

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ABSTRACT

The innovative, high transmission band-pass filter technology presented here for the mid infrared (IR), terahertz (THz) and submillimeter ranges can tolerate cryogenic temperatures (down to 4 K and below), are radiation-hard, vacuum-compatible and vibration-tolerant making them launch-capable and durable for potential space applications. In addition, Lake Shore band-pass filters (BPF) are light weight, as they employ no heavy substrates, nor have any vibronic bands due to polymer support layers. The filters are less than 2 mm thick (mostly the mounting frame) which allows insertion into tight spaces and standard filter wheels. The thin, light weight, vacuum compatible design can be incorporated into almost any detector setup. Filters are available for quick delivery in 29 standard center wavelengths (CWL) with 4 standard diameter sizes, up to 40 mm inner diameter (ID).

**Keywords:** metal-mesh, band-pass filter (BPF), frequency-selective-surfaces (FSS), cryogenic, radiation-hard, vibration-tolerant, cross-absent mesh, terahertz (THz).

1. INTRODUCTION

1.1 Introduction

Metal-mesh filters are critical for a number of astronomy instrument applications for the far infrared (IR), terahertz (THz) and submillimeter ranges. Multilayer thin film dielectric filters, used at shorter IR wavelengths, typically cannot be used in the far IR (highly cost prohibitive or difficult to manufacture) as the layer thickness must increase because the required thickness scales with increasing wavelength. In the mid to far IR spectral range, multilayer thin film dielectric filters can delaminate under the stress of cryogenic temperature cycling. Metal-mesh filters, which rely on the electromagnetic response of structured conductive surfaces, are much more robust. Metal-mesh filters are used to selectively filter infrared radiation before it reaches the detector. They can improve detection capabilities by blocking out-of-band interferences and allowing transmission of only the desired spectral regions. Lake Shore metal mesh filters can transform a cheaper detector with a broader detection profile into a high performance detector. Filtering can also improve signal-to-noise ratio (SNR) of a detector by eliminating out-of-band radiation from reaching the detector and causing spurious signal or saturation of the analog-to-digital converter.

Improvements in the detector sensitivity and format in the last few years have enabled significant development of the capabilities in the far-IR and submillimeter spectral regime. Detector arrays have improved from hundreds to thousands or millions of pixels, which has led to rapid dispersive (i.e., diffraction-grating) spectroscopy of multiple sources in multiple far IR wavebands simultaneously. In astrophysics, sensitive far IR spectroscopy from actively-cooled space telescopes can reveal the history of galaxies, heavy-element production, and black-hole growth since the very first stars. There are a number of astronomy programs such as SOFIA, SPICA/BLISS, SAFIR, and SPIRIT that will use far IR spectrometers for optimal science discovery\textsuperscript{1-2}. Other projects such as CLARREO are designed to provide a measure of the earth’s radiation budget, reveal distribution of key greenhouse gases, and probing the role of high altitude clouds could use sensitive far IR spectroscopy to improve its capabilities by orders of magnitude\textsuperscript{3}.

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1.2 Principles of operation

Several excellent journal articles and books have provided a solid foundation about frequency selective surfaces (FSS)\textsuperscript{4-9}. Due to space constraints, the authors will refer the reader to a few of these, and touch on the most relevant to this specific discussion.

There are many different build geometries suited for different filtering and spectroscopy applications. The cross-absent mesh shown in Figure 1 below is the design used by the Lake Shore BPF filters to produce a Gaussian-shaped high transmission pass-band and low transmission of out-of-band frequencies.

The Lake Shore line of band-pass filters (BPF) are primarily reflective in design, as much of the geometric area is closed (except for the absent-cross design) and mirror-like. For radiation that is adjacent to the pass band, electromagnetic waves interact with the band-pass filter material, and generate resonating electrons at the holes, producing interference effects that block out-of-band frequencies\textsuperscript{4}. The pass-band frequencies pass through the band-pass filter without generating resonating electrons to give high transmission within the center wavelength (CWL) of the BPF\textsuperscript{4}.

The majority of light impinging on the filter is reflected, reducing heating of the thin film band-pass filter.
2. INSTRUMENTATION

2.1 Instrumentation

Data with center wavelengths (CWL) from 1 to 21 µm presented in this paper were taken on a Bruker Vertex 70
FTIR with DTGS detector (mid-IR) using a Si-C glowbar IR source, KBr beamsplitter, gold coated optics at 1 cm⁻¹
resolution, background 64 scans, sample 64 scans, zero fill set to 8.

Data with CWL from 22 to 215 µm were taken on a Bruker Vertex 70 FTIR using a Mylar beamsplitter and a far-IR
DTGS detector. All other parameters are as listed above.

Data with CWL from 216 to 590 µm were taken on a Menlo Systems THz-TDS system.

3. DATA AND RESULTS

3.1 Demonstrated band-pass filters

Spectral data from Lake Shore’s BPF line of band-pass filters is shown below.

![Spectra of Lake Shore’s BPF model band-pass filters with center frequencies between 510 GHz and 30 THz.](image)

Figure 3: Spectra of Lake Shore’s BPF model band-pass filters with center frequencies between 510 GHz and 30 THz.

Figure 3 demonstrates that the band-width remains relatively constant as the center pass-band frequency
changes. Band-pass filters were chosen for the graph that gave an even distribution of frequencies from 30 THz to
510 GHz.
Figure 4: FTIR spectra of band-pass filters with CWL ranging from 10 µm to 120 µm.

Figure 5: FTIR spectra of band-pass filters with CWL ranging from 10 µm to 590 µm. Full-width half maximum (FWHM) for all peaks is between 7% and 25%.
Typical transmissions of Lake Shore BPFs are between 78% and 92%, with full-width half maximum (FWHM) ranging from 7% to 25%. Out-of-band transmission (short wavelength side) is typically below 4.6%. With two matched band-pass filters in series, out-of-band transmission (short wavelength side) is typically below 1%. Nickel support rings support the thin gold cross-absent mesh layer. Standard clear apertures of 12.5 mm, 19 mm, 25.4 mm, and 40 mm are available. Currently there are 29 standard center wavelengths (CWL) available from Lake Shore.

3.2 TeraView imaging to assess band-pass filter uniformity

![Image from a TeraView TPI 1000 imaging spectrometer of a BPF-325-025 filter using a 24 mm square grid, 0.2 mm spatial steps and 4 waveform averages at each position. The upper C-Scan section (red arrow) shows the direction of scan, corresponding to the lower B-Scan frequency uniformity plot. The band-pass frequency was found to be uniform across both directions of scan for the BPF filter.](image_url)

Spectral mapping using a TeraView TPI 1000 confirms that the band-pass filters have a uniform center wavelength pass-band across the entire filter area. A 25.4 mm aperture BPF filter is imaged above. The nickel edge support ring is visible in B-Scan (bottom right corner on plots) and C-Scan sections (top perimeter of plots).
The variations in reflected signal appear as light or dark pixels in Figure 7. Comparing the spectral content of the highlighted areas indicates that only the amplitude changes, not center wavelength (CWL). This is another indication of uniformity of the filter with respect to the center wavelength pass-band.

3.3 Repetitive temperature cycling of band-pass filters

Lake Shore BPF filters were temperature cycled in a Lake Shore probe station under vacuum, cooled with a closed-cycle refrigerator using compressed helium. The ramp rate ranged from 2.3 K to 2.5 K/min for cooling, and 3.8 K to 4.3 K/min for heating.

A BPF-050-040 (left curve in plot) was temperature cycled 100 times from room temperature (295 K) down to 55 K over the period of a week. The BPF-050-040 was tested with FTIR before and after thermal cycling with a difference in 1.2% transmission between the before and after scans, and no change in CWL. There was no visible difference in the BPF-050-040 before and after testing (Figure 8).

A BPF-075-025 (right curve in plot) was temperature cycled 112 times from room temperature (295 K) down to 55 K over the period of a week. The BPF-075-025 was tested with FTIR before and after thermal cycling with a difference in 0.61% transmission between the before and after scans, and no change in CWL (Figure 8).
3.4 Operation of band-pass filters at cryogenic temperatures

Figure 8: Repetitive thermal cycling from 295 K down to 55 K for two BPF. Before and after FTIR scans showed that CWL was unchanged, with a 1.2% T difference with BPF-050-040 (100 cycles) and 0.6% T difference with BPF-075-025 (112 cycles).

Figure 9: FTIR spectra of BPF-050-012 filter at 292 K vs. 4 K in an optical cryostat. The spectra have been normalized due to low transmission through the optical cryostat (4 silicon windows) and FTIR optics. The top spectrum has an actual maximum transmission of 3.361% at 50.1 µm.
The FTIR spectrum of the 50 µm filter at 4 K shows a 6.25% higher transmission (normalized) at cold temperatures, than at 292 K. There is also a slight shift in the band center which is 50.09 µm at 4 K versus 50.28 µm at 292 K.

3.5 Stacking 2 band-pass filters in series

Reduction of the filter center band-width can be obtained by placing two BPF in series. As long as BPF are chosen with the same wavelength center band, the performance benefits can be significant. Figure 10 shows the FTIR spectrum of two 62.8 µm BPF filters in series.

Figure 10: The FTIR transmission curve of one (top curve) and two (bottom curve) BPF with CWL of 62.8 µm. The center band transmission of the top plot is 72.2%, with 13.4% FWHM. With two filters in series, the center band transmission is reduced to 57%, and also reducing FWHM to 10.3% FWHM (bottom plot).
Figure 11 provides an increase in magnification of the baseline of the 63 µm CWL band-pass filters. Using two filters in series reduces out-of-band transmission to less than 0.3% (short wavelength side).

### 3.6 Three month vibration test of band-pass filter

A BPF-027-012 was attached to a vibration test stand speaker. A function generator operating at 440 Hz at 1.027 V RMS was the input into a speaker amplifier (at an amp setting of 3 out of 10), which drove a vibrating speaker stage at that frequency. The sample was held in place by an edge screw and washer as shown in Figure 12. The sample was continuously vibrated at this frequency for 3 months and 1 week. A FTIR scan of the BPF-027-012 was taken before and after vibration testing, and appears in Figure 13.

There is a small 1.7% transmission difference observed in the before and after FTIR spectra of the vibration tested filter. This difference could stem from a difference in sampling location on the band-pass filter or a slight difference in purging conditions or duration prior to FTIR sampling.
Figure 12: BPF-027-012 attached to a vibration rig after 3 months 1 week of vibration testing at 440 Hz. The filter is intact and taut. One edge screw with washer secures the BPF to the sample vibration stage.

Figure 13: BPF-027-012 FTIR scans before and after 3 months and 1 week of vibration testing at 440 Hz. There was 1.7% T difference in the before and after FTIR scans. The CWL was within 0.1 µm for before and after FTIR scans.
3.7 Room temperature radiation testing of band-pass filter

Two Lake Shore band-pass filters were taken to The Ohio State University’s radiation laboratory and exposed to 302.3 krad (Si) ionizing gamma radiation from Cs$^{137}$ at a dose of 2.4 krad/h at room temperature. They were re-characterized with FTIR at room temperature after the gamma radiation dose to discover if there were any differences.

Because the design of the filter is a single piece of gold foil with no substrate, no adverse optical effects from the radiation were expected from this test of this design and none were found. The all-metal construction is the reason the filter is less vulnerable to radiation in cryogenic vacuums than multilayer glass and metal oxide filters or glass and semiconductor filters.

4. CONCLUSIONS

The innovative, high transmission band-pass filter technology presented here for the mid infrared (IR), terahertz (THz) and submillimeter ranges can tolerate cryogenic temperatures (down to 4 K and below), are radiation-hard, vacuum-compatible and vibration-tolerant making them launch-capable for possible space applications. In addition, Lake Shore band-pass filters (BPF) are lightweight, as they employ no heavy substrates, nor have any vibronic bands due to polymer support layers. The filters are less than 2 mm thick (mostly the mounting frame) which allows insertion into tight spaces and standard filter wheels. The thin, lightweight, vacuum compatible design can be incorporated into almost any detector setup. Filters are available for quick delivery in 29 standard center wavelengths (CWL) with 4 standard diameter sizes, up to 40 mm inner diameter (ID).
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