Far-infrared bandpass filters from perforated metal screens

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Precision nickel printing screens are shown to be very useful as far-infrared bandpass filters. For a range of such regularly perforated sheets, transmission peaks of ~0.9 have been observed to lie at frequencies between 60 and 140 cm^{-1}. We found that this value shows little degradation by cascading several screens, but the overall filter Q value may be increased from 2.7 to a value of ~6. These screens have considerable advantages over conventional far-infrared bandpass filters in terms of strength, optical characteristics, and cost.

Key words: Far-infrared optics, metal mesh filters.

Considerable effort has gone into the development of narrow-bandpass filters for the far-infrared (FIR) spectral region. In contrast to the visible and near-infrared spectral regions, multilayer dielectric filters are not suitable for frequencies of less than 500 cm^{-1} because of problems with great layer thicknesses and material absorption.[1] Possible alternative schemes for achieving high peak transmission coupled with good out-of-band attenuation include electroformed rectangular gratings,[2] combinations of waveguide array high-pass filters with capacitive low-pass grids,[3] and regular arrays of cross-shaped[4–7] or annular apertures[8] in thin metal films. These methods have some drawbacks; for example, thin dielectric substrates may be required for filter elements, and/or photolithographic and electrodeposition processes have to be perfected. Note that the term narrow bandpass is used here to describe filters with Q values between 1 and 10, and thus high-performance Fabry–Perot interferometers constructed with fragile unsupported metal meshes[9] or high-temperature superconductor[10] mirrors are excluded.

As an alternative type of bandpass filter, we propose the use of commercial precision-printing screens.[11] Consisting of freestanding electroformed nickel sheets with a regular array of circular holes, the screens are mechanically strong and readily available in large areas. When the screens were used as filters, peak transmissions close to unity were measured with resonant frequencies between 58 and 142 cm^{-1}, depending on the mesh chosen. Furthermore, when several screens are cascaded, the resonance Q and out-of-band attenuation can be improved considerably, with little loss in peak transmission. Thus filters made from such screens may be useful, for example, in narrow-bandwidth detection experiments, in the removal of troublesome satellite FIR laser lines, or in the electromagnetic shielding of optical detector cryostats.

A series of screens with different hole diameters and spacing has been measured: In Table 1 the dimensions of the various screens are listed. The manufacturer refers to the screens by the hole pitch (number per inch). This nomenclature is also used in this Note. In general the screens are ~50 μm thick with the grating constant or pitch of the hexagonal structure g ranging from 164 to 72 μm for HiMesh 155 to HiMesh 355, respectively. The corresponding minimum hole diameters vary from 111 to 37 μm. The apertures are arranged in an hexagonally close-packed pattern, and each tapers from both ends toward the center. This taper is such that the maximum diameter is approximately twice the minimum. Scanning electron microscopy reveals that the screens have very smooth surfaces, with their granular structure visible only on a scale of <1 μm.

The transmission spectra, shown in Fig. 1, were measured in vacuum in a Fourier transform spectrometer with an $f/3$ focused unpolarized beam. The measurement resolution was 3 cm^{-1} with an experimental error of 5% of the transmission values. The spectra are similar in form with the transmission rising from a small value at low frequencies to a resonant peak of ~0.95 for HiMeshes 155, 215, and

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Table 1. Parameters of HiMesh Screens

Screen Designation	Pitch (μm)	Minimum Hole Diameter (μm)	Thickness (μm)	Open Area (%)	Resonant Frequency (cm^{-1})
HiMesh 155	164	111	70	46	58
HiMesh 215	118	77	55	42	82
HiMesh 275	92	52	55	32	107
HiMesh 355	72	37	52	27	143

275 and to a maximum of 0.85 for HiMesh 355. Here the reduced peak transmission may be related to the lower open area of the latter screen (Table 1). For all screens the peak is reached at a wave number that is approximately equal to the reciprocal of the grid constant. A small feature is observable on the high-frequency side of the resonance at a frequency of ~ 1.2 times that of the transmission maximum. The transmission then declines with increasing frequency, because of the onset of diffraction, to a value of ~ 0.30, which is maintained up to the highest frequency measured. This value is expected to remain constant at yet higher frequencies and to tend asymptotically to the fractional open area of the screens.

Such spectra have the characteristics of both waveguide filters and metal meshes. A resonant transmission that is close to unity, at a wave number of $\approx 1/g$, is a characteristic of thin meshes with thicknesses of a few micrometers. This behavior is believed to arise from the inherent capacitive and inductive properties of such structures.[12] The feature observed on the high-frequency side of the main peak was observed in previous studies of square grid structures.[2] In this case the subpeak occurs at a wave number that is $\sim \sqrt{2}$ times that of the main peak. We thus propose that this subpeak arises from a resonance from adjacent lines of apertures, which are separated in a diagonal direction by $g/\sqrt{2}$ for a square grid. In our case the feature is found at an average wave number of 1.19 ± 0.03 times that of the main peak. The separation of adjacent lines of holes in the hexagonal screen g' is related to g by $g' = g/\sqrt{3}/2$. Thus any resonance would be expected at a wave number ≈ 1.15 times that of the $1/g$ resonance, which is in reasonable agreement with the measurements.

The transmission below resonance of these relatively thick screens, decreasing rapidly toward low frequencies, more closely resembles that of a waveguide filter than that of a thin mesh. The transmission of the thin mesh declines relatively slowly,[9] reducing its usefulness as a bandpass filter. A similar low-frequency leakage has been observed with thin cross-aperture arrays.[4,7] Thus the transmission of HiMesh 215 has been further investigated at low frequencies. Here the radiation source was a pulsed CH_3F laser optically pumped by a transversely excited atmospheric CO_2 laser. The transmission of several laser lines with frequencies between 20 and 50 cm^{-1} is displayed in Fig. 2 along with the spectrometer curve. It can be seen that the transmission continues to decrease strongly toward lower frequencies, reaching $\sim 10^{-3}$ at 25 cm^{-1}. This strong attenuation suggests a further application of the screens, namely, as harmonic separation filters for nonlinear optical studies.

Conventionally, discrimination between harmonic radiation and the fundamental has been possible only with waveguide filters.[13,14] These filters are formed from an array of parallel-sided holes with conducting walls, each acting as an individual waveguide. Very high attenuation ($>10^{-6}$) of the fundamental is possible because of the cutoff of the lowest-order mode of the guides.[13] However, these filters are somewhat difficult to manufacture, and a series of screens may be a suitable replacement. It is calculated that three sheets of HiMesh 215 would have a transmission of 10^{-9} at 25 cm^{-1} and 2×10^{-7} at 37 cm^{-1} with the 75-cm^{-1} transmission remaining close to unity. The decrease in transmission does not agree well with that expected for parallel-sided circular apertures, where a sharp drop is expected at the cutoff frequency, $\nu_c = 0.586/d$, where d is the waveguide diameter.[13] For HiMesh 215 this drop implies a cutoff at ~ 80 cm^{-1}, whereas a transmission close to unity is observed at this frequency.

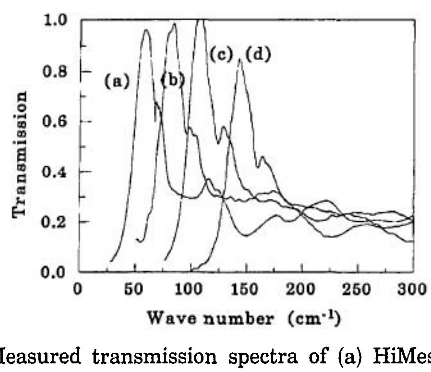

Fig. 1. Measured transmission spectra of (a) HiMesh 155, (b) HiMesh 215, (c) HiMesh 275, and (d) HiMesh 355. The Fourier transform spectrometer resolution was 3 cm^{-1} with an experimental error of 5%.

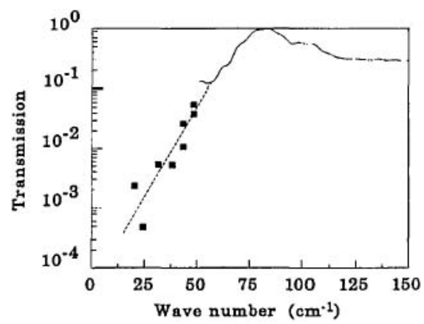

Fig. 2. Transmission spectra of HiMesh 215 measured with the Fourier transform spectrometer (solid curve) and an optically pumped CH_3F vapor laser (squares) shown on a semilogarithmic scale. The dashed line is a guide to the eye through the laser data. Note the strong decrease in transmission toward low frequencies.

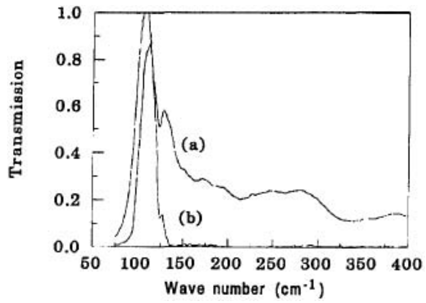

Fig. 3. Spectra (3-cm^{-1} resolution, 5% transmission) showing the transmission of (a) one and (b) four layers of HiMesh 275. Note the excellent blocking of high frequencies by the four-layer filter.

This discrepancy is understood to arise from the smoothly tapered nature of the holes, which renders the analysis above inaccurate. The tapered sides may act as individual horn antennas, enhancing the coupling of the radiation through the central apertures. An exact computational technique has been developed for uniform holes in thick conducting sheets,[15] but to calculate the transmission of these screens the propagation modes of the tapered holes must be included in any model. To date, we are aware of no attempt to do this.

To study the effect of cascading several identical screens, we placed pieces of HiMesh 275 in series, separated by ~ 0.5 mm. Figure 3 shows the measured transmission spectra. As the number of screens increases from one to four, the transmission peak is considerably sharpened, with Q rising from 2.7 to 5.7. The actual Q value of a four-screen filter may be even higher because of our relatively low spectrometer resolution. The transmission at the peak is relatively unaffected, remaining at ~ 0.85 for four screens, while that at high frequencies is severely attenuated, decreasing to within the noise level of the measurement. Note that the separations of the screens are not critical, in contrast to the exact spacings required for the best performance from a series of thin cross-aperture filters.[5] Furthermore the attenuation at frequencies above the measurement range is expected to be excellent on purely geometrical grounds.

In conclusion, we have shown that metal screen printing meshes are very useful as FIR bandpass filters. They offer significant advantages over conventional filtering techniques, including high strength, the availability of large areas, low cost, high peak transmission, and an easily controllable bandwidth (by the noncritical cascading of several screens). It is believed that the excellent optical properties arise from a combination of the nonnegligible mesh thickness and the tapered hole sides. Note that the screens measured here were standard printing items and that one can achieve improvements in filter characteristics by optimizing such dimensions as thickness, pitch, and hole diameter/taper.

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