

Designer infrared filters using stacked metal lattices

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We have designed and fabricated infrared filters for use at wavelengths ≥ 15 microns. Unlike conventional dielectric filters used at the short wavelengths, ours are made from stacked metal grids, spaced at a very small fraction of the performance wavelengths. The individual lattice layers are gold, the spacers are polyimide, and they are assembled using integrated circuit processing techniques; they resemble some metallic photonic band-gap structures. We simulate the filter performance accurately, including the coupling of the propagating, near-field electromagnetic modes, using computer aided design codes. We find no anomalous absorption. The geometrical parameters of the grids are easily altered in practice, allowing for the production of tuned filters with predictable useful transmission characteristics. Although developed for astronomical instrumentation, the filters are broadly applicable in systems across infrared and terahertz bands.

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Infrared filters, used to help define the wavelength response of infrared instruments, should have sharply defined spectral shapes with high in-band transmission (or blocking, in the case of band blocking devices) and excellent rejection outside the bands of interest. Cryogenic operation is essential in the infrared to suppress self-emission, and filters must be able to withstand cryogenic cycling without deterioration. Filters can be made, in rough analogy with optical dielectric filters, by assembling partially reflective layers in quarter-wavelength-spaced dielectric stacks. In practice, however, dielectric stacking is difficult in the infrared because of the limited range of indices of refraction in infrared transmitting materials, the difficulty of working with some of the exotic dielectric materials that are available, and the problematic stability of thick stacks of quarter-wavelength-spaced dielectrics under conditions of cryogenic cycling or long-term exposure to moisture.

A pioneering alternative design for these filters was investigated by Ulrich,¹ who used metal mesh grids made of wires or crosses. Such grids typically come in two forms, labeled according to their electromagnetic transmission line analogs: inductive meshes, which can be free standing and are typically formed from an orthogonal pattern of narrow wires, and capacitive meshes, which are the geometric inverse of inductive meshes and, as a result, are a series of metal squares which must be supported by a substrate material. Simple cross-shaped structures, dubbed “resonant crosses” because they are geometrically and electrically analogous to the superposition of inductive and capacitive grids, can also be either free standing (“inductive”) or not (“capacitive”), in nature.^{2,3} Ulrich’s designs have been developed and incorporated into submillimeter and far-infrared filters,^{4,5} which typically have layer spacings of tens of microns or more, and can be assembled manually. Metallic photonic band-gap (MPBG) structures—periodic metallic struc-

tures producing frequency regions in which electromagnetic waves cannot propagate—possess some similar mechanical and electromagnetic properties.^{6,7}

There were three challenges to the task of extending the capabilities of submillimeter mesh filters to shorter wavelengths, while improving their performance and obtaining high fabrication yields: (1) to identify ways to space the thin layers precisely without introducing excessively absorbent materials, (2) to perfect the fabrication steps, including the alignment control between layers, and (3) to develop computer models that predict the final products so that expensive failures can be avoided. By taking advantage of recent computational and integrated circuit manufacturing techniques, we have achieved reasonable successes in all of these areas and, to date, we have made filters for the 30 μm band using gold lattices photolithographically deposited onto layered polyimide stacks.

Our design for a 38 μm bandpass filter is illustrated schematically in Fig. 1 (only two of six layers are shown). The device consists of six layers, respectively, of polyimide, inductive gold crosses, polyimide, capacitive gold squares, polyimide, and inductive gold crosses. The inductive crosses are apertures with a periodicity of 22 μm and cross arm lengths of 12.8 μm , while the capacitive (filled) squares have the same periodicity, 22 μm , and sides 18.5 μm long. The cross and square lattice layers are spaced by 1.2 μm thicknesses of polyimide, resulting in a total filter thickness ≈ 4 μm . These spacings are very much smaller than the 38 μm resonant wavelength of the filter. Such small spacings have the important benefit of minimizing absorption in the spacer materials (polyimide, in this case). The spacings are smaller than sometimes used, for example, in MPBG devices.⁶

The basic analytic model of mesh filter performance, the transmission line analog, was developed by Ulrich. It has been extended with computer aided design codes^{8–11} that solve Maxwell’s equations to obtain more accurate results

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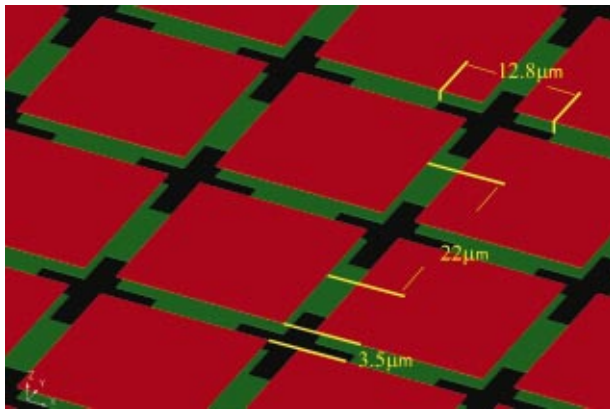


FIG. 1. (Color) Schematic picture of the $38\ \mu\text{m}$ filter structure. Two of the three metal layers are shown: The lattice of inductive gold crosses below (green) and the lattice of capacitive squares above (red); the polyimide spacers are not shown. Both crosses and squares have periodicities of $22\ \mu\text{m}$. The filter itself includes a third identical layer of inductive gold crosses positioned above the two layers shown here. Precise alignment of all the patterns ($\pm 0.1\ \mu\text{m}$) is essential.

under a much wider range of physical conditions. We have used a standard time domain electromagnetic simulation algorithm, the transmission line matrix (TLM) method,⁸ to simulate the properties of our filters. The general code we use, the MICROSTRIPES Program,⁹ has been adjusted by adding physical parameters obtained from iterative comparisons between calculations and measured prototype filters. Figure 2 shows the MICROSTRIPES calculation of the electric field at one of the metal surfaces as a linearly polarized field propagates through the filter. Figure 2 shows both the currents in the metal and the field strengths and directions on resonance (frequency of $7.78\ \text{THz}$), where the transmission peaks near 50%. Also, Fig. 2 illustrates how the spaced metal layers are

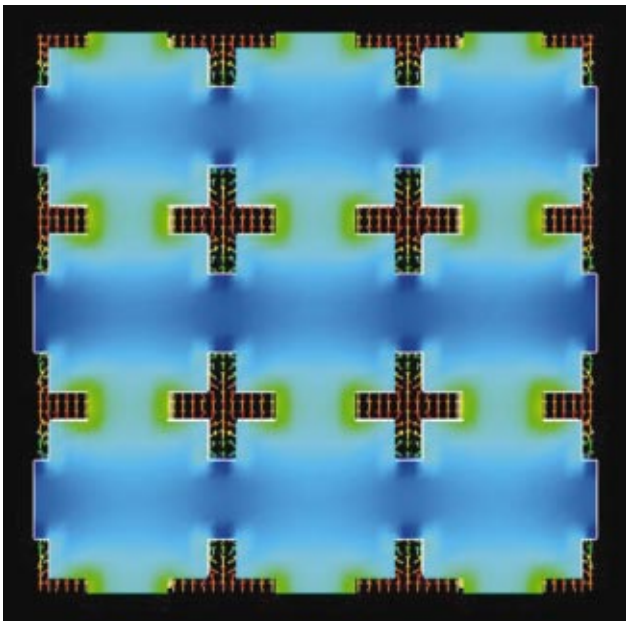


FIG. 2. (Color) The relative surface currents and electric fields on the first metal surface of the $38\ \mu\text{m}$ filter, calculated by the TLM code on resonance ($7.79\ \text{THz}$), and with polarized incident radiation. The current strengths are color coded, with the difference between the strong (light green) and weak (dark blue) currents being about 15 dB. The largest surface currents (obtained off-resonance and not shown here) are about 15 dB stronger than the strongest currents on resonance.

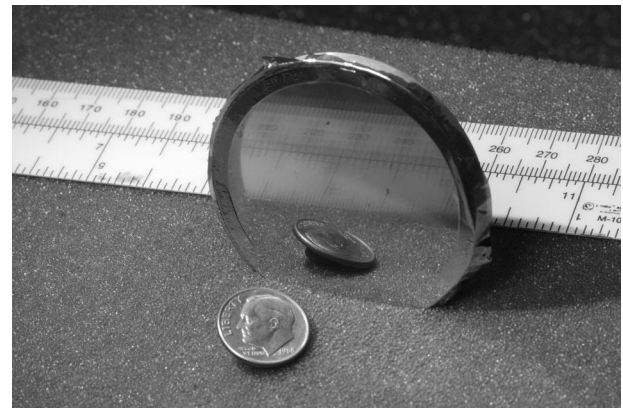


FIG. 3. Photograph of the mounted $38\ \mu\text{m}$ filter.

induced to produce strong surface currents that reflect the off-resonance radiation, while on-resonance radiation (the resonance full width half maximum $\approx 5\ \mu\text{m}$) is transmitted. As discussed next, there is good agreement between our predicted transmission profile and the measured one. This confirmation of the accuracy of the adjusted TLM code under these conditions is one of our significant conclusions. It gives us confidence that these field effects are physical, and that the simulations are reliable and accurate even when the conductive mesh layers in the design are much closer together than the resultant resonance wavelength of the device; the design method is described more completely by Sternberg.¹² (We note that Ulrich's analytic transmission line equations can be adapted for limited use, even with the subresonant-wavelength separations we use, by correcting the coefficients in the equivalent circuit expressions. Since they are sensitive parameters of the design, however, they must be recalculated for each geometry.) One drawback to the current TLM algorithm is its inability to calculate accurately for wavelengths shorter than the periodicity which, in the case of our $38\ \mu\text{m}$ filter, was $22\ \mu\text{m}$.

The filters were fabricated in the Naval Research Laboratory's Nanoelectronics Processing Facility, and all of the dimensions are better than $\pm 0.1\ \mu\text{m}$. Initially a $\langle 100 \rangle$ oriented *n*-type polished 3 in. silicon wafer was cleaned and oxidized. (The oxide layer is a sacrificial layer to aid with the removal of the filter element from the wafer at the end of the processing.) A thin layer ($\approx 1\ \mu\text{m}$) of polyimide (HD Microsystems PI-2611) was placed onto the surface by a spin coating process and then cured; control of the spin speed and cure cycle provides a way of reproducing films of a uniform thickness. Chrome ($\approx 10\ \text{nm}$, for adhesion) and gold (100 nm) films were then deposited onto the surface by metal evaporation. Optical lithography and wet chemical etching were used to define the pattern into the metal film. The sequence of polyimide coating, metal evaporation, and optical lithographic pattern definition were repeated two more times to build up a stack of three lattice elements. Optical lithography makes it possible to etch a different pattern into each metal layer, and to accurately and precisely align each layer to the previous metal layer. In principle, many more than three metal lattices can be laid down with this method. The final steps were the removal of the layered filter from the silicon wafer by immersion in a dilute HF bath, and its mounting on a metal ring. Figure 3 shows a photograph of

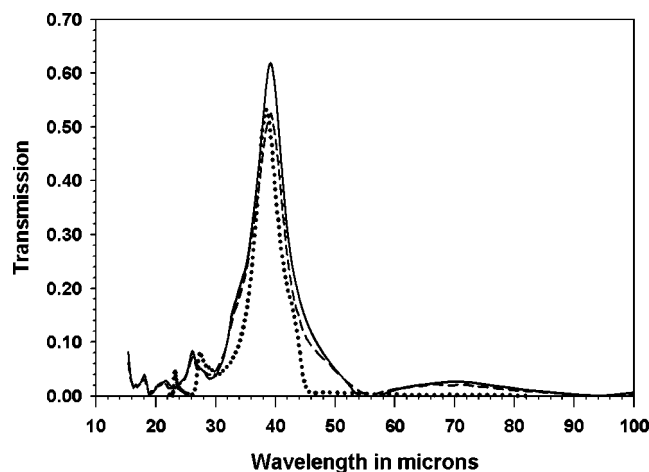


FIG. 4. Measured and modeled transmission of the 38 μm filter (solid line: as measured at 5 K; dashed line: as measured at 298 K; dotted line: the TLM simulation). The secondary peak at 27 μm is well modeled, and results from the polyimide layers. The excess transmission longward of 45 μm is not well modeled. Its origin is currently under investigation.

the mounted filter. These fabrication steps are advances over the stages we originally pioneered for the development of free-standing metal grids for use in the infrared as Fabry–Perot etalons.^{13–15}

The 38 μm filter was measured at the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center and at the Naval Research Laboratory with Bruker Fourier Transform Spectrometers whose absolute accuracy in these measurements was better than about 3%. Figure 4 shows the filter transmission, with the MICROSTRIPES-simulated transmission superimposed. The overall agreement between the measured and predicted curves is very good. For example, the peak transmission value, 52% at 298 K, is within the measurement uncertainty of the simulated value of 53%. Effects of both absorption (minor) and reflection (significant) are present in the six-layer device, accounting for the observed transmission value. The success of the modeling is due in part to our modifications to the code to account for the properties of the material (the measured index of refraction of polyimide is 1.65 near 38 μm). Several samples from this fabrication run had double transmission peaks, and/or secondary transmission maxima on the wings of the main feature; some weak residuals of these may be seen in Fig. 4. These secondary bumps may be due wrinkles introduced when mounting the filter film on rings, or to fabrication irregularities at some stage in the processing. Further investigation is underway. There is one uniform, second-order disagreement with the model. The measured filter transmission has a long-wavelength tail beyond 45 μm considerable higher than the simulation predicts, and this disagreement is currently under study.

The most significant conclusions to be drawn from this work are that the adjusted TLM simulations are reliable, and the general fabrication techniques are in hand. The combination can be used with confidence to tailor make filters with a wide range of designed properties—narrow band, cut-on or cutoff filters, beamsplitters, or other devices—without the need for expensive fabrication trials. A simple scaling of the mesh geometries and layer spacings allows the shifting of the transmission properties of the filter to longer or shorter

wavelengths. The primary current limitation is not in the fabrication steps, but rather in the absorption of the polyimide substrates, which at wavelengths below about 20 μm becomes unacceptably large for many designs. We have, therefore, begun investigating alternative processes using films with smaller absorptions.

During the development of these filters, we found instances in which small absorption features ($<1\%$) in a substrate material would be amplified into large ($\geq 30\%$) net absorption dips when resonant-grid structures were laid down on their surfaces. The effect has been reported by others as well.⁵ We find no such anomalous absorptions with our current fabrication methods. Our earlier work on free-standing metal grids¹⁵ included techniques for making three-dimensional (3D) metallic structures from similar patterns. Adding a 3D (photonic crystal-like) capability to the filter design opens further avenues of possibility. Because the adjusted TLM code now provides a relatively accurate predictor of filter performance, we can tailor the most desirable filter properties by using a variety of alternative geometrical design shapes, coupled with a more complex system of stacked layers.¹² We have already designed infrared filters with very steep cut ons, $>40\text{ dB}/\mu\text{m}$, and simple narrow bandpass filters with $\Delta\lambda/\lambda \approx 5\%$ and good out-of-band blocking, suggesting that a powerful class of mid- and far-infrared optics can be designed at low cost for the particular needs of individual instruments or measurements.

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