Nanotechnology Infrared Optics for Astronomy Missions

Grant NAG5-9363

Annual Performance Report No. 4

For the period 1 April 2003 through 31 March 2004

Principal Investigator:

Dr. Howard A. Smith

January 2004

Prepared for
National Aeronautics and Space Administration
Washington D.C.

Smithsonian Institution
Astrophysical Observatory
Cambridge, Massachusetts 02138-1596

The Smithsonian Astrophysical Observatory
is a member of the
Harvard-Smithsonian Center for Astrophysics

The NASA Technical Officer for this grant is Dr. Jay Frogel, Code SZ, NASA Headquarters,
300 E Street SW, Washington DC 20546-0001

Table of Contents

I. Program Objectives

The program "Nanotechnology Infrared Optics for Astronomy Missions" will design and develop new, nanotechnology techniques for infrared optical devices suitable for use in NASA space missions. The proposal combines expertise from the Smithsonian Astrophysical Observatory, the Naval Research Laboratory, the Goddard Space Flight Center, and the Physics Department at the Queen Mary and Westfield College in London, now relocated to the University of Cardiff, Cardiff, Wales. The method uses individually tailored metal grids and layered stacks of metal mesh grids, both inductive (free-standing) and capacitive (substrate-mounted), to produce various kinds of filters.

The program has the following goals:

1) Model FIR filter properties using electric-circuit analogs and near-field, EM diffraction calculations;

2) Prototype fabrication of meshes on various substrates, with various materials, and of various dimensions;

3) Test filter prototypes and iterate with the modeling programs;

4) Travel to related sites, including trips to Washington, D.C. (location of NRL and GSFC), London (location of QMW), Cardiff, Wales, and Rome (location of ISO PMS project headquarters);

5) Produce ancillary science, including both publication of testing on mesh performance and infrared astronomical science.

II. Progress Report

As of the preparation of this annual report (January 2004), we are pleased to report that we have achieved success in all of the primary program goals, and have successfully fabricated a 6-layer, 3-stack infrared filter that works nearly exactly according to design at 38 μm.

We have published the results in *Applied Physics Letters*. The appendix contains a copy of this paper. We have also presented our work to the SOFIA Science Team with the hope of using these filters on SOFIA instrumentation. An article on our new process appeared in "Laser Focus World" Magazine, which is also appended.

We can restate our achievements as follows:

A. Mesh Modeling

We have used the "MicroStripes" code (Flomerics, Inc.) to perform full-, near- and far-field diffraction modeling of metal mesh performance on substrates. Our "Miles Code" software, which approximates the full calculation in a quick, gui-based window, is useful as an iterative device by adjusting the input parameters (index of refraction, thickness, etc.) to provide agreement with the full calculation. However, despite the somewhat extravagant claims by the MicroStripes manufacturer, this code is also not perfect because numerous free parameters must be set. Key among these, as identified in our earlier papers and proposal documents, is the high frequency (i.e., far IR) character of the real and imaginary parts of the index of refraction of the metal mesh, the high frequency character of the real and imaginary parts of the index of refraction of the substrate, and the character of the interface between the mesh and the substrate material, and in particular the suppression (or possible enhancement) of surface effects at the interface.

B. Filter Fabrication

After numerous sample fabrication and tests, we fabricated a multi-layer preliminary sample FILTER by hand here at the Smithsonian Astrophysical Observatory X-Ray Laboratory. This sample was measured, and from that we determined that our modeling and our fabrication were on solid ground. We then proceeded to fabricate a monolithic filter, as described in the attached appendices.

C. Staff and Equipment Changes

Dr. Oren Sternberg, a postdoctoral scientist at Smithsonian Astrophysical Observatory for a brief time last year, and supported by this grant, has moved to a more permanent position with Jackie Fischer and Ken Stewart at the NRL. He is an expert on the MicroStripes modeling of these filters, on metal mesh properties, and on the filter processes in general.

III. Program Plans

This final year of the project we will attempt to patent the process (we have already begun this process), and to resolve several of the key issues outstanding -- including the anomalous tail to the long-wavelength transmission. We will also continue to work to manufacture a filter suitable for use on SOFIA or another NASA mission facility, perhaps using better substrate materials. NRL has obtained independent funding to support their development. Some modest additional travel is anticipated in conjunction with these activities. We therefore are requesting a no-cost extension of 12 months (one year) to bring these last details to resolution and closure. We do not plan any further extensions.

IV. Related Publications

"Designer Infrared Filters Using Stacked Metal Lattices," Smith, H.A., Rebbert, M., and Sternberg, O., *App. Phys. Lett.*, **82**, 3605, 2003.

"Infrared Filters Fabricated from Metal Grids Allow Easy Tailoring of the Filters' Optical Properties," Smith, H.A., *Laser Focus World*, June 2003.

"Transmittance of Thick Metal Meshes of Various Shapes and Thicknesses in the Infrared Wavelength Region," Sternberg, O., Shah, J., Moller, J., Grebel, H., Stewart, K., Fischer, J., Rebbert, M., Smith, H.A., and Fettig, R., *TDW2003: International Workshop on Thermal Detectors for Space based on Planetary, Solar and Earth Science Applications*, 2003.

"The Infrared Lines of OH: Diagnostics of Molecular Clouds Compositions in Infrared Bright Galaxies," Smith, H.A., Gonzalez-Alfonso, E., Fischer, J., Ashby, M., Dudley, C., and Spinoglio, L., in *Proceedings of the Workshop of the Neutral ISM in Starburst Galaxies,* Marstrand, Sweden, 2003.

"The Effects of Dust in Infrared Luminous Galaxies: An Integrated Modeling Approach," Satyapal, S., Dudley, C., Fischer, J., Luhman, M., Smith, H. A., *Astrophysics of Dust,* Estes Park, Colorado, May 26 - 30, Edited by Adolf N. Witt, 2003.

"Designer Infrared Filters Using Stacked Metal Lattices," Smith, H. A., Sternberg, Stewart, Fischer, Rebbert, Henry, Moller, *Frontiers of High Resolution Spectroscopy*, 25th meeting of the IAU, Joint

Discussion 20, Sydney, Australia, 2003.

"The Far Infrared Lines of OH as Molecular Cloud Diagnostics," Smith, H. A., Ashby, Fischer, Gonzales, Spinoglio, Dudley, *The Astrochemistry of External Galaxies*, 25th meeting of the IAU, Joint Discussion, Sydney, Australia, 2003.

Appendix A

Reprint: "Designer Infrared Filters Using Stacked Metal Lattices," Smith, H.A., Rebbert, M., and Sternberg, O., *App. Phys. Lett.*, **82**, 3605, 2003

APPLIED PHYSICS LETTERS VOLUME 82, NUMBER 21 26 MAY 2003

Designer infrared filters using stacked metal lattices

Howard A. Smith[a)]
Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, Massachusetts 02138

M. Rebbert and O. Sternberg
Naval Research Laboratory, 4555 Overlook Avenue, S.W., Washington, DC 20375

(Received 6 January 2003; accepted 31 March 2003)

We have designed and fabricated infrared filters for use at wavelengths $\gtrsim 15$ 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.
 [DOI: 10.1063/1.1579115]

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 structures 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

[a)]Electronic mail: hsmith@cfa.harvard.edu

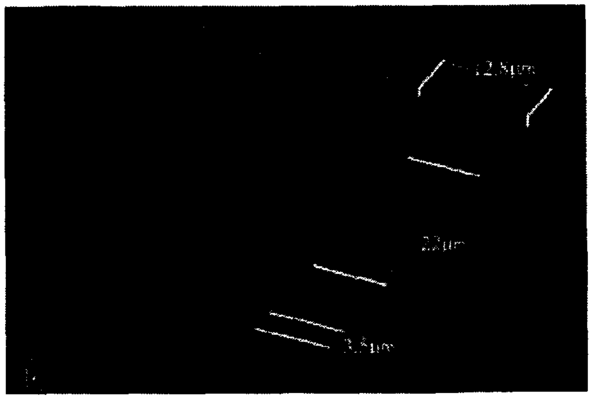


FIG. 1. (Color) Schematic picture of the 38 μm filter structure. Two of the three metal layers are shown: The lattice of inductive gold crosses below (green) and the lattice of capacitive squares above (red); the polyimide spacers are not shown. Both crosses and squares have periodicities of 22 μm. The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

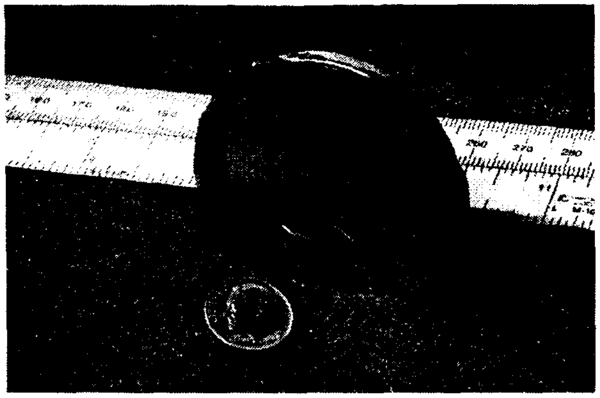


FIG. 3. Photograph of the mounted 38 μm filter.

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 THz), where the transmission peaks near 50%. Also, Fig. 2 illustrates how the spaced metal layers are induced to produce strong surface currents that reflect the off-resonance radiation, while on-resonance radiation (the resonance full width half maximum ≈ 5 μm) 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 μm filter, was 22 μm.

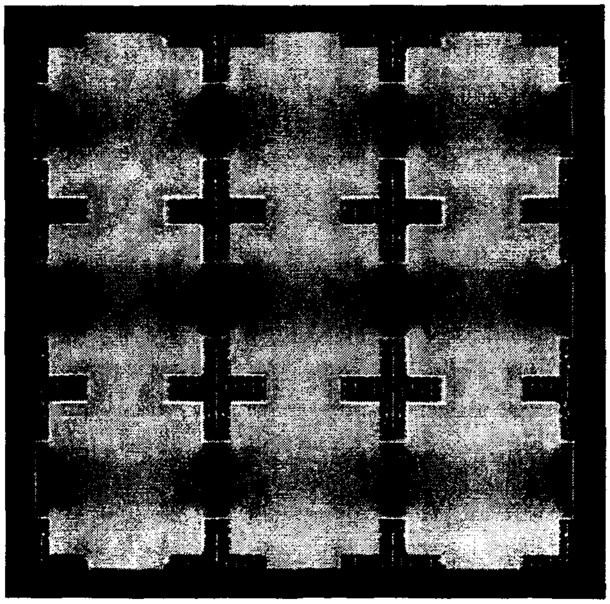


FIG. 2. (Color) The relative surface currents and electric fields on the first metal surface of the 38 μm filter, calculated by the TLM code on resonance (7.79 THz), and with polarized incident radiation. The current strengths are color coded, with the difference between the strong (light green) and 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.

The filters were fabricated in the Naval Research Laboratory's Nanoelectronics Processing Facility, and all of the dimensions are better than ± 0.1 μm. Initially a ⟨100⟩ 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 (≈ 1 μm) 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 (≈ 10 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

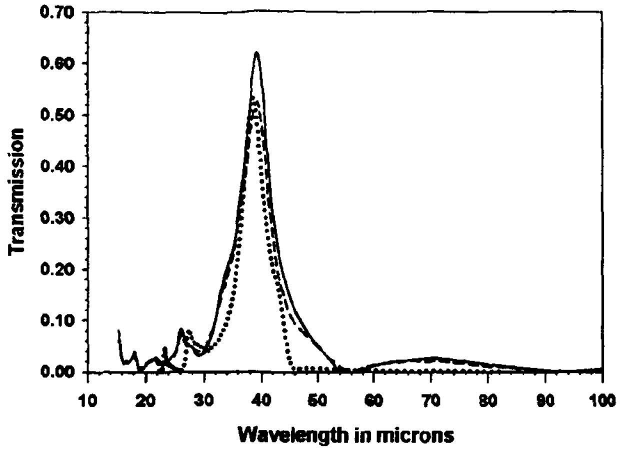


FIG. 4. Measured and modeled transmission of the 38 μm filter (solid line: as measured at 5 K; dashed line: as measured at 298 K; dotted line: the TLM simulation). The secondary peak at 27 μm is well modeled, and results from the polyimide layers. The excess transmission longward of 45 μm is not well 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 ($\geqslant 30\%$) 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 grids[15] 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 dB/μm, 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.

The authors acknowledge helpful assistance from colleagues: J. Fischer, K. Stewart, R. Bass, and B. Hicks (NRL); K. Möller (NJIT); M. Greenhouse, an early proponent of this design, H. Moseley, and R. Henry (GSFC); and J. Miles, who produced an early code (Lockheed–Martin). The first filter was hand assembled by R. Goddard (SAO); his efforts helped give us confidence for the monolithic processing. O.S. gratefully acknowledges a postdoctoral fellowship at SAO. The program was supported in part by NASA Grant No. NAG5-7394.

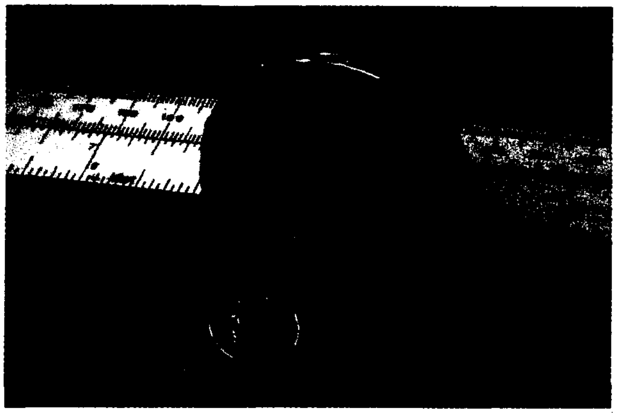
[1] R. Ulrich, Infrared Phys. 7, 37 (1967).
[2] K. Sakai and L. Genzel, in *Reviews of IR and MM Waves*, edited by K. J. Button (Plenum, New York, 1983), Vol. 1.
[3] L. Whitbourn and R. Compton, Appl. Opt. 24, 217 (1985).
[4] H. Matsuo, M. Akiba, S. Hayakawa, T. Matsumoto, H. Murakami, M. Noda, and S. Sato, Publ. Astron. Soc. Jpn. 42, 3, 459 (1990).
[5] P. G. J. Irwin, P. Ade, S. Calcutt, F. Taylor, J. Seeley, R. Hunneman, and L. Walton, Infrared Phys. 34, 549 (1993).
[6] S. Gupta, G. Tuttle, M. Sigalas, and K. Ho, Appl. Phys. Lett. 71, 2412 (1997).
[7] N. Katsarakis, E. Chatzitheodoridis, G. Kiriakidis, M. Sigalas, C. Soukoulis, W. Leung, and G. Tuttle, Appl. Phys. Lett. 74, 3263 (1999).
[8] W. J. R. Hoefer, IEEE Trans. Microwave Theory Tech. 40, 1517 (1992).
[9] MICROSTRIPES Program Version 6, Flomerics Electromagnetics Division, Nottingham, UK (2002).
[10] O. Sternberg, Ph.D. thesis, New Jersey Institute of Technology, 2002.
[11] K. D. Möller, O. Sternberg, H. Grebel, and K. P. Stewart, Appl. Opt. 41, 3919 (2002).
[12] O. Sternberg (unpublished).
[13] J. Taylor, H. A. Smith, and J. Fischer, Rev. Sci. Instrum. 59, 1094 (1988).
[14] C. J. Taylor, J. Grossman, J. Fischer, H. A. Smith, M. C. Peckerar, and M. L. Rebbert, "Method for Fabricating Thin Film Metallic Meshes for Use as Fabry-Perot Interferometer Elements, Filters, and Other Devices" (Navy Case No. 70 513, Naval Research Laboratory, Washington, DC, 1987).
[15] M. Rebbert, P. Isaacson, J. Fischer, M. A. Greenhouse, J. Grossman, M. Peckerar, and H. A. Smith, Appl. Opt. 33, 1286 (1994).

Appendix B

Reprint: "Infrared Filters Fabricated from Metal Grids Allow Easy Tailoring of the Filters' Optical Properties," Smith, H.A., *Laser Focus World*, June 2003

Designer filters rely on metal mesh

Infrared filters fabricated from metal grids allow easy tailoring of the filters' optical properties.



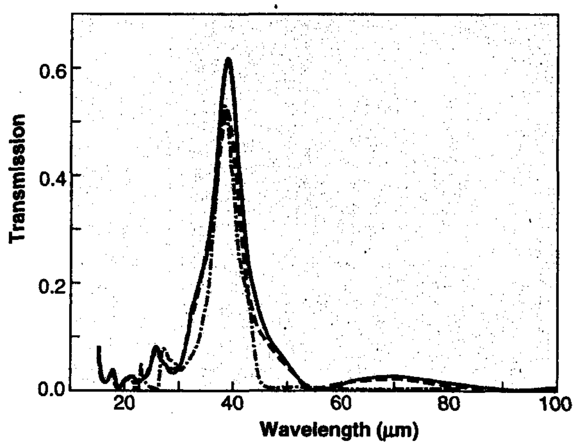
NAVAL RESEARCH LABORATORY

HOWARD A. SMITH

Infrared (IR) filters are used to help define the wavelength response of IR instruments. Like any good filters, to be effective they need sharply defined spectral shapes with high in-band transmission (or blocking in the case of band-blocking devices) and excellent rejection outside of the bands of interest. Infrared filters play one important role that is often unnecessary for optical filters: they reduce the bright background radiation that can limit the sensitivity of detectors. Hence, cryogenic operation is essential for IR filters to suppress their self-emission, and they must be able to withstand multiple cryogenic cycling without deterioration.

Infrared 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 IR. The range of indices of refraction in IR-transmitting materials is limited, many of the exotic dielectric materials that are available are hard to work with, and the thick stacks of quarter-wave-spaced dielectrics have problematic stability under conditions of cryogenic cycling or long-term exposure to moisture.

A pioneering alternative for selectively reflecting wavelengths of IR or submillimeter radiation is metal mesh grids made of wires or crosses; the principle is similar to that used for metallic grid reflectors found in microwave oven windows.[1] These grids typically come in two geometries: a pattern of narrow, orthogonal wires; and the inverse, a repeating pattern of metal squares supported by a substrate material. Other geometries are also possible, such as cross-shaped structures, dubbed "resonant crosses." The original work used the transmission properties of single grids, but today similar kinds of grids have been successfully stacked together, two or more

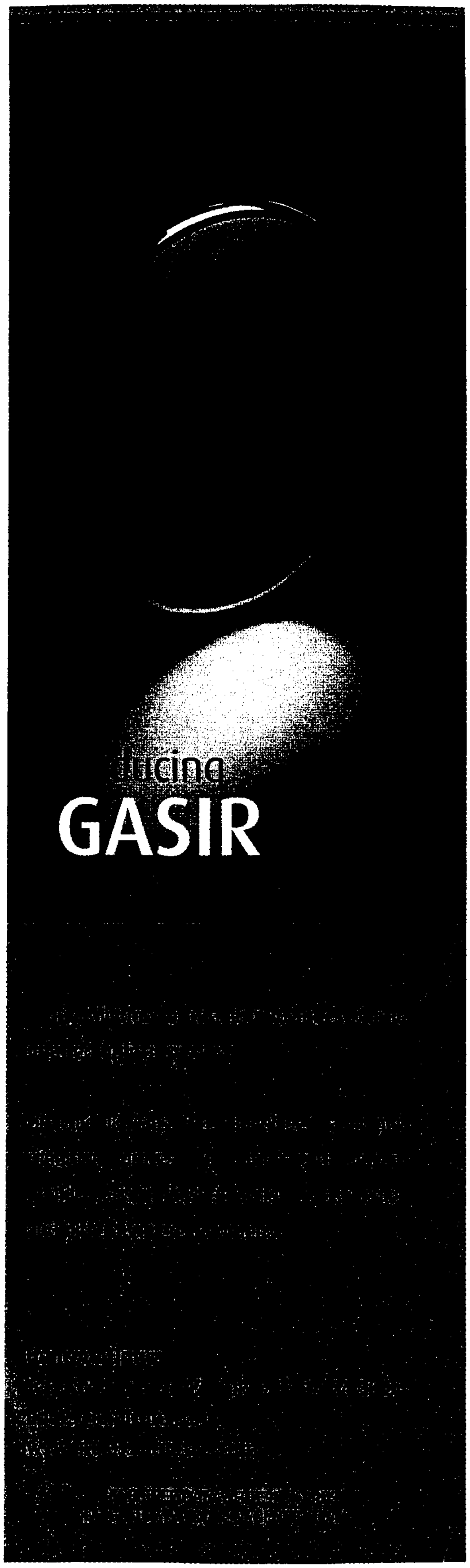


HARVARD-SMITHSONIAN CENTER FOR ASTROPHYSICS

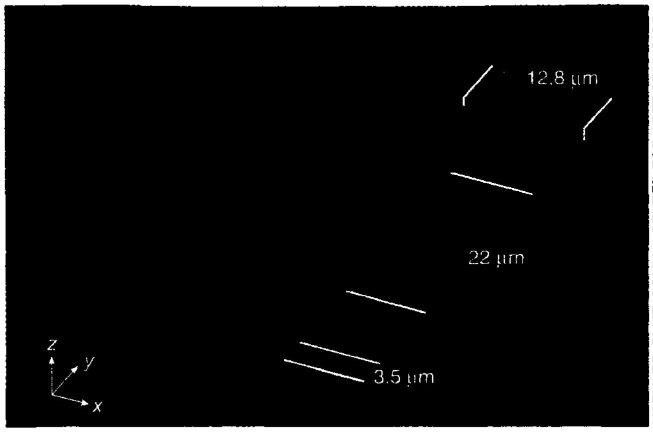
FIGURE 1. An infrared filter for use at 38 μm is fabricated from metal grids spaced by dielectric layers. The result is a film about 4 μm thick that is then stretched and mounted on a support ring (top). The measured and modeled transmission of the filter is shown at bottom. The solid blue line is data measured at 5 K, the red dashed line is data measured at 298 K, and the dash-dot green line is a computer simulation. The secondary peak at 27 μm is well modeled and results from the polyimide layers. The excess transmission on the long-wavelength side of 45 μm is not well modeled; its origin is currently under investigation.

HOWARD A. SMITH is a senior astrophysicist at the Optical and Infrared Division, Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA 02138; e-mail: hsmith@cfa.harvard.edu.

Appendix B



grids at a time, to make more-refined submillimeter and far-IR filters; they typically have layer spacings of tens of microns or more, and are assembled manually.[2,3] Metallic photonic-band-gap structures—periodic metallic structures that produce frequency regions in which electromagnetic waves cannot propagate—possess some similar mechanical and electromagnetic properties.



HARVARD-SMITHSONIAN CENTER FOR ASTROPHYSICS

FIGURE 2. Two of the three metal layers in a metal-mesh filter for use at 38 μm—the lattice of gold cross-holes below (green) and the lattice of squares pads above (red)—are visible in this depiction. The polyimide spacers are not shown. Both crosses and squares have periodicities of 22 μm. The filter includes a third, identical layer of gold cross-holes positioned above the two layers shown here. Precise alignment (±0.1 μm) of all the patterns is essential.

Extension to shorter wavelengths

Until now, no one has successfully extended these grid-layering techniques to produce useful shorter-wavelength IR filters. There were three difficult issues to overcome. First, the shorter wavelengths mean that spaces between grid layers have to be smaller while still remaining precise; a cost-effective fabrication method was needed. Next, the grids are most often spaced with a transparent layer of material, but in the IR the absorption of many common materials reduces the transmission unacceptably. Finally, the fabrication steps (including the alignment of geometrical patterns from layer to layer) are expensive; a computational method was needed that could predict the final filter properties with good accuracy.

We have made significant progress toward solving all of these problems, and have fabricated IR bandpass filters for use at around 38 μm using a stack of three gold lattice layers spaced by three thin polyimide layers (see Fig. 1). The gold lattices we used in this case have one of two geometries: crosses (holes) in a solid-gold sheet, with cross periodicity of 22 μm and cross-arm lengths of 12.8 μm; and gold squares, which have the same 22-μm periodicity and 18.5-μm-long sides (see Fig. 2). The cross- and square-lattice layers are spaced by 1.2-μm thicknesses of polyimide, resulting in a total filter thickness of about 4 μm. Note that 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).

Simulation matches measurement

We designed the filter using a standard time-domain electromagnetic-simulation algorithm, the transmission-line-matrix method, which simulated our filters' properties.[4] To adapt the method to the problem of IR filters in particular, we used the MicroStripes program and modified it by adding physical parameters that we obtained from iterative comparisons between calculations and measured prototype filters.[5] In the end, we obtained good agreement between our predicted transmission profile and the measured one. This confirmation of the accuracy of our code, under these conditions, is significant: it gives us confidence that the many predicted field effects between layers which we are modeling are reliable and accurate, even though the conductive mesh layers in the design are much closer together than the resonance wavelength of the filter. It also gives us confidence that we can tailor the most desirable filter properties by using a variety of alternative geometric design shapes, coupled with a much more complex system of stacked layers.

One of the major advantages of this method of fabricating IR filters is that a simple scaling of the mesh geometries and layer spacings can shift a filter's transmission properties to longer or shorter wavelengths. We have already designed innovative IR filters with other geometries besides crosses and squares—filters with steep cut-ons of greater than 40 dB/μm and narrow bandpass filters with $\Delta\lambda/\lambda$ of 5%, with good out-of-band blocking.

The filter fabrication was done in the Nanoelectronics Processing Facility at the Naval Research Laboratory (NRL; Washington, DC). We have been working together for more than a decade on the problem of using metal grids in IR applications and have a patent on a technique for making thick metal grids of extremely high quality for use as IR reflectors.[6,7,8] Our current work builds on these successes. The code was iterated, and the layer-fabrication processes confirmed, with tests on an initial hand-assembled filter made at the Smithsonian Astrophysical Observatory's X-Ray Laboratory. At NRL, we make the filters on a silicon wafer, but remove the film from the silicon in the final step. The process entails laying down a thin-layer polyimide layer, a layer of metal, and then using optical lithography and wet chemical-etching techniques to pattern the metal. We follow with a sequence of polyimide coating, metal evaporation, and optical lithographic pattern definition—in the case of this 38-μm filter, two more iterations were needed to build up a stack of three lattice elements.[9] All dimensions were controlled to better than ±0.1 μm, including the alignment between lattice layers.

WE BELIEVE THE COMBINATION CAN BE USED TO TAILOR-MAKE FILTERS WITH A WIDE RANGE OF DESIGNED PROPERTIES WITHOUT THE NEED FOR MANY EXPENSIVE FABRICATION TRIALS.

Tailor-made filters

The most significant results of this work are that the simulations are reliable, the general fabrication techniques are in hand, and the final filters have useful properties. As a consequence, we believe the combination can be used with confidence to tailor-make filters with a wide range of designed properties—narrowband, cut-on, or cut-off filters, beamsplitters, or other devices—without the need for many expensive fabrication trials. Currently, the primary limitation is not set by the fabrication, but rather by the modest absorption in the polyimide substrates, which precludes use for wavelengths below about 20 μm. We have, however, begun investigating alternative processes using films with smaller absorption coefficients. Today we see many possible directions this research (and filter production) might go. Several members of the team are IR astronomers, and indeed astronomy applications were a prime motivator of the development effort (which was supported in part by a NASA grant). But there are other interesting research opportunities and practical uses for this new class of IR optics; we welcome suggestions and inquiries. ❑

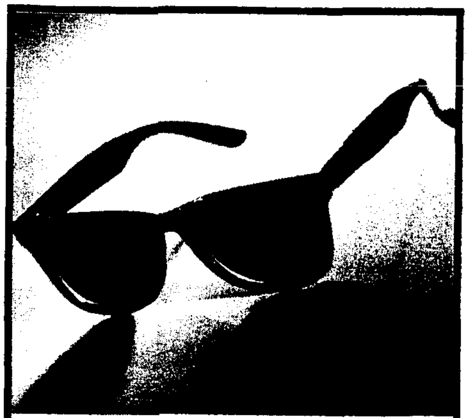
Acknowledgments

This research represents the efforts of many people: M. Rebbert of NRL's Nanoelectronics Branch; K. Stewart, O. Sternberg, J. Fischer, R. Bass, and B. Hicks of NRL's Remote Sensing Branch; K. Möller of the New Jersey Institute of Technology; and R. Henry of NASA-Goddard. The program was supported in part by NASA grant NAG5-7394; O.Sternberg gratefully acknowledges a brief postdoctoral fellowship at Smithsonian Astrophysical Observatory.

REFERENCES

1. R. Ulrich, Infrared *Physics* 7(37; 1967).
2. H. Matsuo et al., *Pub. Astron. Soc. Japan* 42, 3, 459 (1990).
3. P. G. J. Irwin et al., *Infrared Physics* 34(6), 549 (1993).
4. W. J.R. Hoefer, *IEEE Transactions Microwave Theory and Techniques* 40, 1517 (1992).
5. MicroStripes Program Version 6, Flomerics Electromagnetics Division, Nottingham, UK (2002).
6. J. Taylor et al., *Reviews Scien. Instruments* 59, 1094 (1988).
7. M. Rebbert et al., *Applied Optics* 33, 1286 (1994).
8. C. J. Taylor et al., *Method for Fabricating Thin Film Metallic Meshes for Use as Fabry-Perot Interferometer Elements, Filters, and Other Devices*, (Navy Case # 70,513, 1987), Naval Research Laboratory, Washington, DC..
9. H. A. Smith et al., *Appl. Phys. Lett.* (May 26, 2003).

Bulk reprints of all Laser Focus World *articles can be ordered from Cathleen Johnson, reprints manager, at (727) 372-4801 or FAX (727) 372-5752.*



Appendix C

NASA Grantee New Technology Summary Report (Form C-3043)

NASA GRANTEE

NEW TECHNOLOGY SUMMARY REPORT

NASA requires each research grantee, research contractor, and research subcontractor to report new technology to the NASA Technology Utilization Office. The required reports and corresponding schedules are as follows:

Title of Report	Form Number	Timetable
New Technology Disclosure	NASA 1679	The grantee discloses *each* discovery of new technology individually, at the time of its discovery.
NASA Grantee New Technology Summary Report (checkmarked "Interim")	NASA C-3043	For multi-year grants, the grantee summarizes the previous year's disclosures on an annual basis. The first Interim New Technology Summary Report is due exactly 12 months from the effective date of the grant.
NASA Grantee New Technology Summary Report (checkmarked "Final")	NASA C-3043	The grantee submits a cumulative summary of all disclosed discoveries. The Final New Technology Summary Report is submitted immediately following the grant's technical period of performance.

Grantee Name and Address: Smithsonian Astrophysical Observatory
Attn: Contracts, Grants, and Property Management Dept./MS23
60 Garden Street
Cambridge MA 02138

Report Submitted by: Howard A. Smith

Telephone Number: (617) 496 - 2198

NASA Grant Title: Nanotechnology Infrared Optics for Astronomy Missions

NASA Grant Number: NAG 5- 9363

NASA Grant Monitor: Jay Frogel

Grant Completion Date: 04 / 30 / 04

Today's Date: 01 / 20 / 04

New technology may be either patentable or non-patentable.

NASA defines a new technology item as any invention or discovery conceived or first reduced to practice during the performance of a NASA grant, contract, or subcontract; items must be disclosed as they are discovered.

Although grantees are not required to disclose non-patentable new technology, new technology items are evaluated for publication as NASA Tech Briefs. If an item is selected for publication as a NASA Tech Brief, a check payable to the grantee innovator(s) is awarded.

PLEASE COMPLETE THE REVERSE SIDE OF THIS FORM AND MAIL TO THE FOLLOWING ADDRESS:

Goddard Space Flight Center
Technology Transfer Program
Greenbelt Road - Mail Stop 504
Greenbelt, MD 20771

I. General Information

1. Type of Report: (x) Interim ( ) Final

2. Size of Business: ( ) Small ( ) Large (X) Nonprofit Organization

3. Have any nonpatentable new technology items resulted from work performed under this grant during this reporting period? ( ) yes (x) no

4. Have any patentable new technology items resulted from work performed under this grant during this reporting period? (X) yes ( ) no

5. Are new technology items (nonpatentable or patentable) being disclosed with this report? (x) yes ( ) no

II. New Technology Items

Please provide the title(s) of all new and previously disclosed new technology items conceived or first reduced to practice under this grant.

	Title	Internal Docket Number	Patent Appl. Filed	Patentable Item	Nonpatentable Item
1.	Metal mesh infrared filters		(X)	(X)	( )
2.			( )	( )	( )
3.			( )	( )	( )
4.			( )	( )	( )

III. Subcontractors

Please complete the following section listing all research subcontractors participating to date. Include each subcontractor's name, address, contact person, and telephone number.

Naval Research Laboratory
4555 Overlook Avenue S.W.
Washington D.C. 20375
Attn: Jackie Fischer
202-767-3058

IV. Certification

I certify that active and effective procedures ensuring prompt identification and timely disclosures of reportable new technology items have been followed. Furthermore, I certify that all new technology items required to be disclosed and conceived during the period identified on this form, have been disclosed to NASA.

JOHN G. HARRIS
CONTRACTING OFFICER

Name and Title of Authorized Official

John G. Harris 1/21/04

Signature and Date

Grant Monitor