ANTENNA-COUPLED BOLOMETER ARRAYS FOR ASTROPHYSICS

James J. Bock, Peter Day, Alexey Goldin, and Henry G. LeDuc
Jet Propulsion Laboratory, Pasadena, CA 91109, USA

Cynthia Hunt, Andrew Lange, Anastasios Vayonakis, and Jonas Zmuidzinas
California Institute of Technology, Pasadena, CA 91125, USA

ABSTRACT

We are developing arrays of feedhorn-coupled, silicon nitride micromesh ('spider web') bolometers for the ESA/NASA Planck Surveyor and Herschel Space Observatory for millimeter to far-infrared wavelengths. These detector systems realize high end-to-end optical efficiency, essentially fill the available focal surface, and achieve background-limited sensitivity. The Planck/HFI detectors in particular approach the fundamental sensitivity set by the photon noise from the cosmic microwave background. The silicon nitride micromesh architecture realizes low areal heat capacity. NTD Ge thermistor readouts and DC-stable electronics provide low-frequency noise stability appropriate for slow-scanned space-borne platforms. A novel Si JFET amplifier package allows us to operate large numbers of bolometers for Herschel/SPIRE with moderate power dissipation (~50 uW/JFET).

We are developing a new antenna-coupled architecture appropriate for the next-generation astrophysics applications such as CMB polarimetry and far-infrared/sub-millimeter spectral line surveys. Compared to bolometers with extended area radiation absorbers, antenna-coupled bolometers offer active volumes that are orders of magnitude smaller, promising further gains in sensitivity and speed of response. We are developing a focal plane architecture for CMB polarimetry consisting of a distributed array of slot antennae coupled to a micro-strip transmission line network with integral filters, and transition-edge superconducting (TES) bolometers. This architecture eliminates the massive feedhorns and filters that must be cooled to sub-Kelvin temperatures in current focal planes. Because antenna-coupling allows us to manipulate the electric field, we can develop novel architectures such as multi-color imagers and 2-D dispersive spectrometers for spectral line surveys.

INTRODUCTION

The decade of the spectrum from 100 GHz to 1 THz contains the bulk of the energy in the Cosmic Microwave Background (CMB), much of the Cosmic Infrared Background (CIB), believed to represent the integrated emission from ultra-luminous infrared galaxies at high redshifts, and virtually all of the observable emission from cool (T<15K) clouds in our own galaxy. It is in this range of wavelengths that significant advances in space astrophysics will best be realized: making definitive maps of the temperature and polarization anisotropy of the CMB, understanding the spectrum, spatial distribution and origins of the CIB, and unveiling the epoch in which the first stars and galaxies in the universe formed.

The sensitivity of current bolometers allows for background-limited performance for photometry at millimeter- to far-infrared wavelengths. Instruments with a moderate number of background-limited bolometers are intended for the next generation of millimeter- and sub-millimeter space-borne observatories (Planck and Herschel).

Advances in detector technology are likely to remain vital for cosmology in the post-Planck/Herschel epoch. For example, careful study of CMB degree-scale polarized structure can be used to detect primordial gravitational waves [1]. However, the sensitivity needed for these observations exceeds that

Contact information for James J. Bock: Email: jjb@astro.caltech.edu, phone (818) 354-0715

attainable with the Planck satellite, and requires a significant increase in focal plane format. We are developing antenna-coupled bolometers for large-format millimeter-wave focal plane arrays.

MICROMESH BOLOMETERS FOR PLANCK/HFI

We are fabricating single-element bolometers made from a micromachined, free-standing silicon nitride membrane (see Fig. 1). This structure is ideal for detection of millimeter-wave radiation as it minimizes the large absorber volume. The membrane consists of an inner absorber region metalized with a thin Ti/Au layer providing optimal coupling to electro-magnetic radiation, and radial support legs providing mechanical support and thermal isolation. The thermal rise of the absorber from radiation is detected by a semi-conducting Neutron Transmutation Doped (NTD) Ge thermistor attached to the absorber via In bump bonds and readout with lithographed electrical leads. The thermal conductance of the device is tailored by adjusting the thickness of the leads metalization.

***Table 1**. Properties of Micromech Bolometers*

T [K]	G [pW/K]	G(sup) [pW/K]	C [pW/K]	1/f ν_c [Hz]	NEP [1e-17 W/√Hz]	NEP √τ [1e-18 J]
0.1	4	0.06	0.2	< 0.03	0.2	0.5
0.3	10	2	0.7	< 0.015	1.3	2

Notes: 1. G, C, 1/f knee frequency, NEP, and NEP √τ refer to minimum achieved values to date.
2. G(sup) is estimated minimum G allowed by silicon nitride support beams.

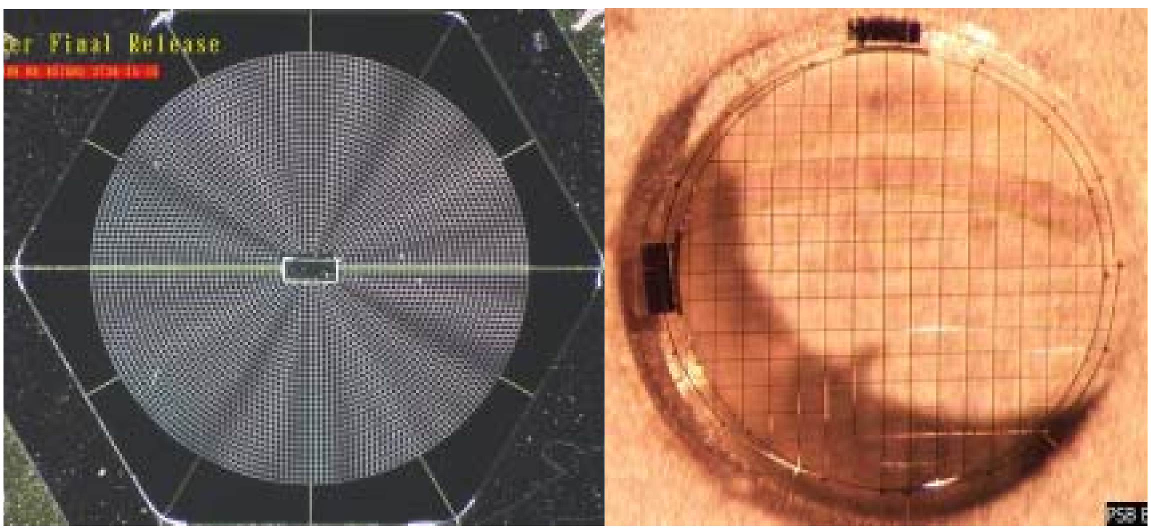


***Figure 1:** Silicon nitride micromesh bolometers for Planck/HFI. (Left) Dual-polarization 857 GHz bolometer with a 2.7 mm diameter absorber (the inner region patterned as grid) suspended by 12 radial support legs. The NTD Ge thermistor, located in the middle of the absorber, is readout by two lithographed electrical leads at the left and right. (Right)Polarization-selective pair of bolometers mounted in corregated waveguide. Each bolometer is sensitive to linear polarization, and the difference signal between the detectors produces a Stokes Q or U parameter per feed.*

The best device parameters achieved to date with In bump-bonded NTD Ge thermistors are described in Table 1. These bolometers have been applied to millimeter-wave cosmology from balloon-borne (BOOMERANG, MAXIMA, ARCHEOPS) and ground-based (ACBAR, SUZIE) experiments. NTD Ge thermistors offer extreme 1/f stability often desirable in slow-scanned observations. The achieved NEP is sufficient for background-limited, single-mode broad-band photometry set by the astrophysical foreground. The minimum achievable NEP, determined by the thermal conductance of the silicon nitride support beams, allows for sensitivities approaching 1e-19 W/√Hz at 100 mK. Although such ultra-sensitive devices are not practical for photometry, they can be applied to space-borne sub-millimeter spectroscopy. For example, high sensitivity bolometers coupled to a dispersive spectrometer and a cooled telescope promise orders of magnitude improvement in space-borne line survey capabilities. Unlike heterodyne receivers, direct detectors can achieve background-limited sensitivity even under these extremely low background conditions.

We are developing polarization-selective bolometers for measuring cosmic microwave background polarization anisotropy. Two detectors, each sensitive to linear polarization, are housed in corrugated waveguide at the end of a scalar feedhorn (see Fig. 1). A single Stokes parameter (Q or U) may be obtained from the difference in signal between the bolometers. The bolometers are located a distance $\lambda/4$ from the back of the waveguide for maximal optical coupling, and are separated by a small distance to minimize cross-polarization. This compact arrangement results in well-matched beams, since both detectors observe through the same feedhorn optics, maximizing the rejection of common-mode optical signals. The close proximity of the bolometers also helps reject common-mode environmental signals from the instrument (temperature drifts, microphonics, etc).

Simulation of the cavity, feed, and waveguide with HFSS indicates that the optical efficiency of the feedhorn and detector system alone may be high (> 95 %) with low-cross polarization (< 1 %). To date, we have achieved a maximum end-to-end optical efficiency, including millimeter-wave filters and an additional back-to-back feedhorn, of 40 % with a minimum cross-polarization of ~3 % (W.C. Jones, private communication). Polarization-selective bolometers are planned for QUEST and Planck/HFI [2].

BOLOMETER ARRAYS FOR HERSCHEL/SPIRE

Further improvement in background-limited photometers can only be realized by implementing arrays of detectors. We are developing bolometer planar arrays of micromesh bolometers coupled to conical feedhorns, similar to arrays developed for SCUBA and MAMBO, for ground-based (BOLOCAM), balloon-borne (BLAST), and space-borne (Herschel/SPIRE) cameras. Feedhorn coupling maximizes the sensitivity per bolometer. In the case of background-limited detectors, a feedhorn-coupled array approaches the theoretical mapping speed achievable with Nyquist-sampled bare arrays that use 16 times more pixels and require multiplexing [3]. Feedhorn coupling controls the spatial response of the detector, and allows for high end-to-end optical efficiency.

Table 2. *Parameters of Micromesh Bolometer Array*

Quantity	@ Q = 0 pW	@ Q = 2.4 pW	Units
Yield	0.9	-	
R_0	180 ± 44	-	Ω
Δ	42 ± 0.8	-	K
G_0 (300 mK)	55 ± 8	-	pW/K
β	1.85 ± 0.16	-	
τ	-	11.3 ± 2.4	ms
C (390 mK)	-	1.3 ± 0.3	pJ/K
S_e	5.0 ± 0.3	3.6 ± 0.3	10^8 V/W
V_n (calc)	11.7 ± 0.6	21.0 ± 1.2	nV/√Hz
V_n (meas)	14.1 ± 1.0	21.2 ± 1.2	nV/√Hz
NEP	2.9 ± 0.3	5.8 ± 0.2	1e-17W/√Hz
NEP_{tot} / NEP_{photon}	-	1.21 ± 0.03	

Notes:
1. Standard deviations over the array quoted for all parameters.
2. S_e, V_n, and NEP determined at 22 mV bias (near peak responsivity).
3. V_n, NEP include 3.5 nV/√Hz amplifier noise.

We have developed a bolometer array [4] (see Fig. 2), designed for operation at λ = 350 μm, that demonstrates a dark NEP = 2.9 x 10^{-17} W/√Hz and mean heat capacity of 1.3 pJ/K at 390 mK. The measured noise performance is in good agreement with the calculated contributions from photon, phonon and Johnson noise, with photon noise dominant under the design background conditions. Excess noise is negligible for audio frequencies as low as 30 mHz. The optical efficiency of the feedhorn and bolometer combination (η = 0.45 – 0.65) is somewhat lower than anticipated, but has since been improved (η ~ 0.75, Jason Glenn, private communication).

The SPIRE focal plane array is packaged in a compact format (see Fig. 2), designed to withstand launch conditions but provide minimal thermal conducted power to the 3He refrigerator (~10 uW for 5 bolometer arrays). The detectors are readout with Si JFET amplifiers attached to the 10 K vapor-cooled optical bench. The JFETs are thermally isolated on silicon nitride membranes that reduce the power dissipation per JFET to 50 μW. The bolometers are AC-biased and demodulated for low-frequency noise stability required for making drift-scanned maps.

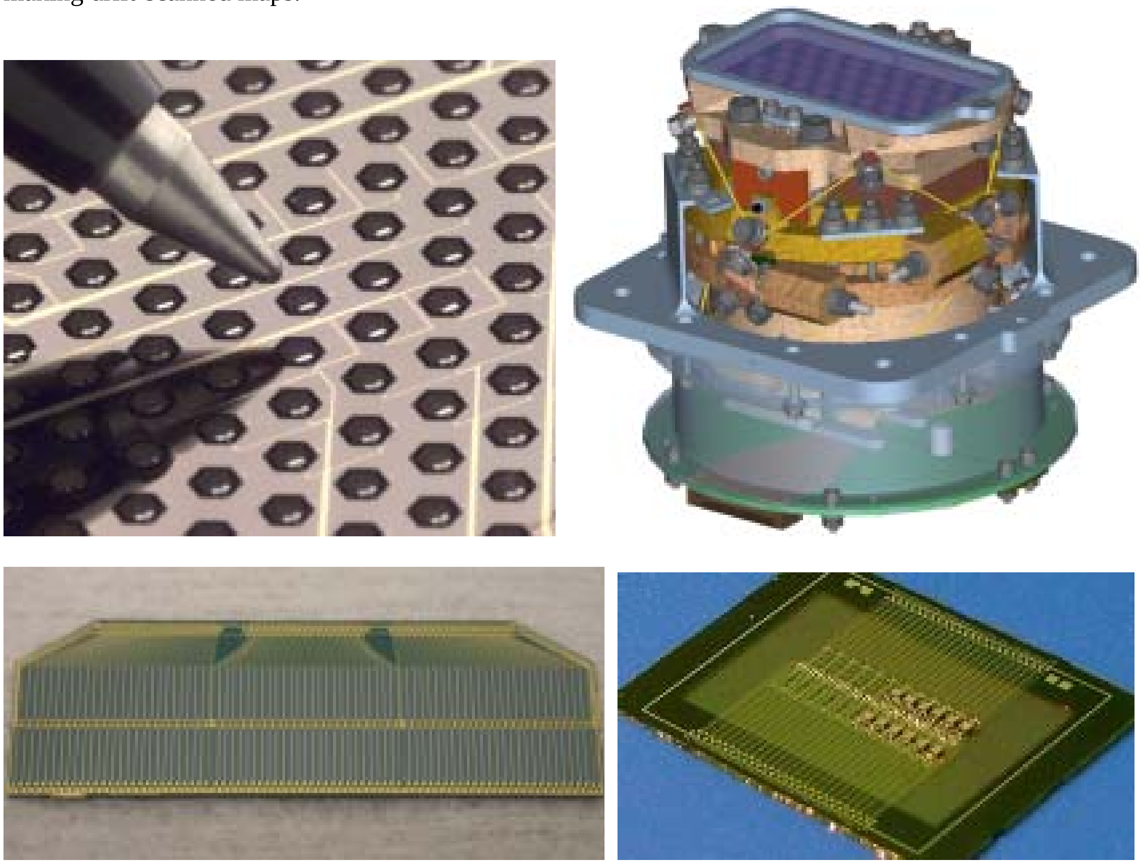
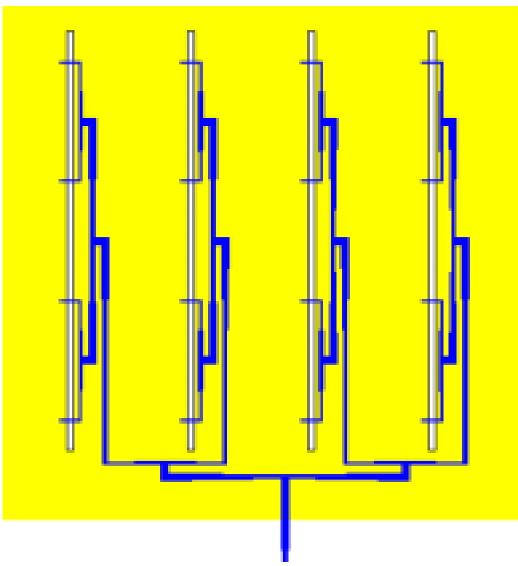


Figure 2: *(Upper left) Array of silicon nitride micromesh bolometers developed for the SPIRE instrument on Herschel. The bolometer array is designed to be operated at λ = 350 μm coupled to an array of conical feedhorns. (Upper right) The bolometer array is mounted behind feedhorns and thermally isolated in Kelvar-suspended mechanical assembly. (Lower left) Assembly of 90 matched lithographed load resistor pairs. (Lower right) JFET amplifiers thermally isolated on a membrane of silicon nitride.*

ANTENNA-COUPLED BOLOMETER ARRAYS

Because the bolometers intended for Planck/HFI now closely approach the background-limited sensitivity at millimeter-wavelengths available in space, further advances in the sensitivity of millimeter-wave focal planes must come from increases in array format. At millimeter-wavelengths, large format bolometer arrays also require a new focal plane architecture. In practical applications, millimeter-wave bolometers need beam-collimating optics to control their illumination, or a significant sensitivity penalty will arise due to thermal emission from the instrument, even if the instrument is cooled to 2 K [3]. Cryogenic re-imaging optical systems can be used to define the illumination pattern, but must be cooled to sub-K temperatures for bare absorbing pixels. While feedhorns provide collimation in current instruments, they can only used with modest numbers of pixels as they create a significant mass penalty at 0.1 – 0.3 K, preventing practical implementation of large-format focal plane arrays. In the case of Planck, the HFI focal plane fills much of the available useful field at ν > 100 GHz and approaches the maximum practical mass at 100 mK for a space application. A significant improvement in sensitivity over Planck will be needed to map the polarization of cosmic microwave background anisotropy, yet clearly feedhorns cannot be scaled up to 10^3 to 10^4 pixels for space applications.

We propose a new architecture for millimeter-wave focal plane arrays of bolometers coupled to antennae and filters via low-loss superconducting Nb microstrip. Microstrip-coupling provides several important advantages over coupling via a distributed absorber. Antennas may be coupled to a bolometer by means of superconducting microstrip terminated in a resistor. Unlike a distributed absorber, which requires an active area at least as large as λ^2 in order to couple efficiently, the microstrip termination resistor may be as small as lithographic techniques permit. The termination resistor does not couple easily to stray radiation. Future space-borne applications in which a cooled aperture and/or narrow spectral bandwidth will reduce the background loads to fWs, and stray radiation from 2 K alone (~1 pW/mm^2) makes use of bolometers with radiation absorbers intractable.



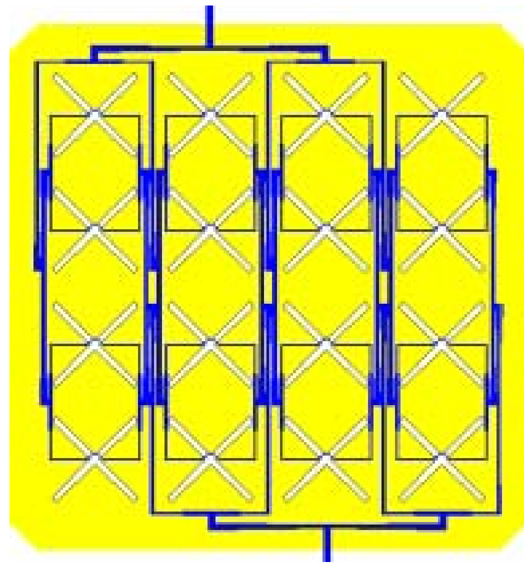


Figure 3: *Two possible pixel geometries for antenna-coupled focal planes. (Left) Continuous slot-lines are tapped off and coherently summed in microstrip. The summing produces a useful antenna-pattern without lens coupling. The bandwidth of this arrangement is large, and multiple spectral bands can be obtained by diplexing the final microstrip line. (Right) A dual-polarization antenna sums both linear polarizations onto two striplines at the top and bottom.*

Our focal plane architectures consist of a distributed network of slot antennae [5] (see Fig. 3). The distributed antennae provide beam collimation and low-cross polarization in a single broad spectral band, and eliminate hyper-spherical lens coupling. Each antenna is summed with a binary tree onto a common transmission line. A dual-polarization geometry (see Fig. 3b) uses discontinuous dual-polarization slots to receive both polarizations simultaneously. Although the slot discontinuity limits spectral range to a single, broad photometric band, but both polarizations are obtained without a polarized beam splitter.

A multi-color, single-polarization geometry can be made with continuous slots (see Fig. 3a) to operate in several broad photometric bands simultaneously. The microstrip are summed in phase with adiabatic tapers onto a single transmission line in a binary tree. Because the microstrip are added in phase, and the slots are continuous, the intrinsic bandwidth of the antenna is large. The common transmission line can then be split with a diplexer to allow simultaneous imaging in several broad photometric bands. This arrangement has a significantly higher detector density, which helps realize large array formats.

We are developing single-pixel stripline-coupled bolometer using a normal metal resistor to terminate the stripline, and a separate trilayer TES with Nb leads for readout (see Fig. 4). This simple device, ideal for testing, realizes the sensitivity required for background-limited operation at 300 mK [6]. Further improvement in detector sensitivity, possible due to the small active areas allowed by stripline coupling, could later be realized by any of a number of microstrip-coupled detectors (e.g. SQPC, HEB, kinetic inductance, e-phonon decoupled TES, etc).

The key to the successful implementation of microstrip-coupled bolometers is the ability to transport signals across macroscopic distances via superconducting microstrip transmission line. Loss measurements on niobium superconducting films with an SiO dielectric layer [7] show that Nb microstrip has sufficiently low loss for the focal plane architectures in Fig. 3. Indeed low transmission loss allows more complex focal plane structures, such as a 2-D spectrometer [8] to be realized in microstrip.

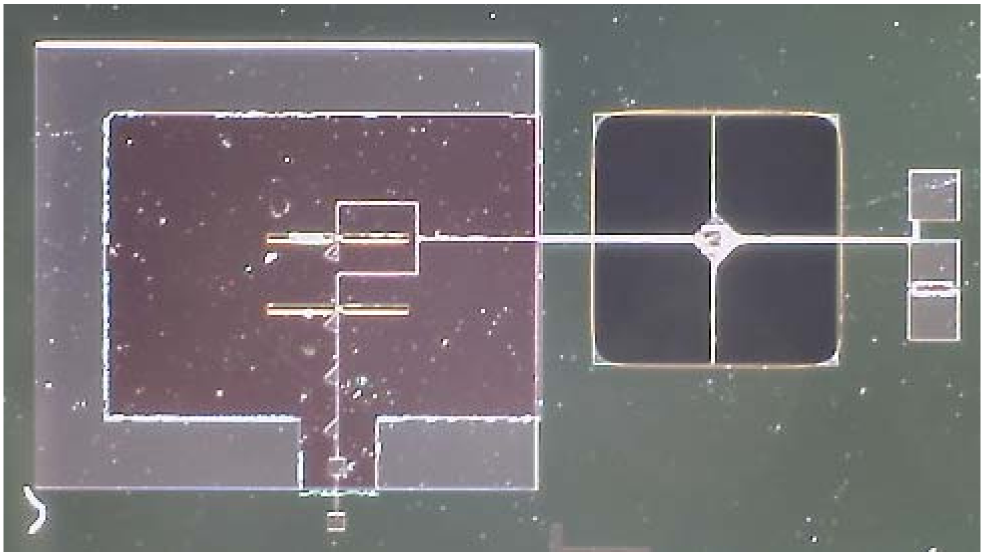


Figure 4: *Single-element antenna-coupled TES bolometer, currently under development, consists of a dual slot antenna (at left) coupled to superconducting Nb microstrip. The microstrip passes over a suspended beam of silicon nitride to a termination resistor located on the thermally isolated diamond-shaped region. An Al/Ti/Au transition-edge superconductor, located near the termination resistor, is readout via superconducting Nb leads to contact pads located on the right-hand side.*

CONCLUSIONS

Silicon nitride micromesh bolometers demonstrate sensitivities required for background-limited imaging of the csomic microwave background in ongoing instrumentation efforts from balloon-borne and ground-based receivers. Arrays of micromesh bolometers are planned in the next generation of millimeter- and sub-millimeter space-borne observatories. Further improvements require large-format detector arrays with integral filtering and beam direction. Microstrip-coupled focal plane structures greatly reduce the size, mass, cooling requirements, risk, and cost of mm- and sub-mm focal planes for future space-borne astrophysics.

ACKNOWLEDGEMENTS

The authors would like to acknowledge support from NASA grant NAG5-10317 and from the JPL DRDF.

REFERENCES

1. Lange, A.E., Proc. Far-IR, Sub-mm & mm Detector Technology Workshop, Monterey, CA, 2002, in press.
2. Piat, M. *et al*., Proc. Far-IR, Sub-mm & mm Detector Technology Workshop, Monterey, CA, 2002, in press.
3. Griffin, M.G., Bock, J.J., and Gear, W., 2002, *Applied Optics*, submitted.
4. Turner, A. D. *et al*., 2001 "Si_3N_4 Micromesh Bolometer Array for Sub-millimeter Astrophysics," *Applied Optics*, 40,4921.
5. Goldin, A. *et al*., Proc. Far-IR, Sub-mm & mm Detector Technology Workshop, Monterey, CA, 2002, in press.
6. Hunt, C. *et al*., Proc. Far-IR, Sub-mm & mm Detector Technology Workshop, Monterey, CA, 2002, in press.
7. Vayonakis, A. *et al*., Proc. Far-IR, Sub-mm & mm Detector Technology Workshop, Monterey, CA, 2002, in press.
8. Bradford, C.M. *et al*., Proc. Far-IR, Sub-mm & mm Detector Technology Workshop, Monterey, CA, 2002, in press.