Frequency Selective Bolometers

M. S. Kowitt
NASA/Goddard Space Flight Center, Code 685.0, Greenbelt, MD 20771

D. J. Fixsen
Applied Research Corporation, NASA/GSFC Code 685.3, Greenbelt, MD 20771

A. Goldin
Department of Astronomy and Astrophysics, University of Chicago, Chicago, IL 60637

S. S. Meyer
Enrico Fermi Institute, Department of Astronomy and Astrophysics, Department of Physics, University of Chicago, Chicago, IL 60637
Danish Space Research Institute, Juliane Maries Vej 30, Copenhagen, DENMARK

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We propose a new concept for radiometry in the millimeter, sub-millimeter, and far-infrared spectral regions, the Frequency Selective Bolometer (FSB). This new system uses a bolometer as a coupled element of a tuned quasi-optical interference filter, in which the absorption, transmission, and reflection characteristics of the filter depend on frequency in a controlled manner. Several FSBs can be cascaded within a straight light-pipe to produce a high-efficiency, compact, multi-band radiometer. A prototype design is presented, together with its anticipated performance based on a one-dimensional transmission-line model. Instruments based on FSB technology should have several advantages over current multi-band bolometric radiometers, including: smaller and more compact cryogenic optics, reduced demands on cryostat size and weight; high coupling efficiency; minimum constraints on the geometry in the focal plane. An FSB system can be configured as a multi-band, close packed focal-plane array, permitting efficient use of the throughput of a telescope.

Key words: Bolometer, resonance filter, frequency-selective bolometer, resonant mesh, cryogenic

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1. Introduction

Measurements of the Cosmic Microwave Background Radiation (CMBR) and other diffuse broad-band millimeter, sub-millimeter and far-infrared sources are well served by cryogenic bolometric technology[1–3]. At frequencies above 30 GHz and below the band-gap of photo-conductive detectors, bolometers achieve the highest sensitivity to low-background broadband emission of any type of detector. Traditionally, multi-mode bolometric radiometers have used spectral filters to define the band of sensitivity and a broadband absorber, sometimes matched with a tuned backshort[4]. The spectral filters include absorptive and scattering filters, single-layer metal mesh elements, and multi-layer interference filters used in transmission or reflection. The filter optics, which must be kept at very low temperatures, are large compared to the detectors themselves. The design and size of the cryostat are driven by the filter system rather than the detectors.

The need for multiple spectral channels is well established. Quantitative measurements at these frequencies require several channels because often several fore- and backgrounds are mixed with the desired signal. High-fidelity spectral separation is usually possible with a sufficient number of properly placed channels. Measurements consistent with a hypothesized source spectrum are often the strongest evidence that a detection is understood.

Several schemes for making multi-frequency bolometric measurements exist. Light-pipe dichroic systems permit simultaneous observations in all bands but have large, complicated optics. In multi-pixel systems, these optics restrict the focal-plane geometry. Other systems have single-band bolometer elements placed at different points in the focal plane. This results in an array where the elements in a given band are not in a close-packed array which places restrictions on the observing sequence. An alternative solution is to place an entire close-packed array of bolometers behind a single large dichroic filter. This design is usually limited to only a few spectral channels. Filter-wheel bolometric systems require that each band be observed sequentially leading to low efficiency, and for ground-based systems, to errors in derived colors due to temporal variations in the atmosphere.

We present a new radiometer design that overcomes many of these drawbacks. By incorporating a bolometer element into a quasi-optical interference filter, we are able to design a device with tailored frequency dependent absorption, reflection, and transmission — a Frequency Selective Bolometer (FSB). The chief advantage of this scheme is that it permits the possibility of cascading multiple FSBs within a straight light-pipe to produce a complete multi-channel radiometer in a compact cylinder. Arrays of such cylinders, with greater freedom in the geometry of the focal plane, will be possible. Because of the small size of the FSB radiometer, the cryogenic system can be simplified.

In this article, we outline the design of a prototype FSB radiometer. Section 2 gives the overall design of the assembly. In Section 3, we describe the optical model used to predict the FSB performance, along with its results. Section 4 describes the design of an 8-band radiometer built with FSBs. We then show in Section 5 the expected sensitivity of this FSB radiometer for measuring the Cosmic Microwave Background Radiation (CMBR) anisotropy, and compare this to other existing experiments.

2. The Construction of an FSB Prototype

The design, shown in Fig. 1, consists of a system with an étendu of 0.15 cm^{-1} sr defined by the size of the aperture. Radiation enters from the left through an input cone, which in this case is matched to an f/2.8 telescope. The beam is then re-expanded to fill the 1 cm light-pipe. The solid angle of the radiation in the pipe is 0.2 sr or a 14° half angle. Eight FSB elements are cascaded within the light-pipe, producing an 8-band radiometer with spectral bands from 5 to 22 cm^{-1}.

Fig. 1 goes here

Each FSB element consists of a resonant bolometer followed by several capacitive mesh filters. All components are prepared on silicon wafers, back-etched to approximately 10 μm thickness and then reactive ion etched to leave only a thin silicon grid. Identically shaped, periodic metal features are deposited onto the bolometer and filter planes to form a capacitive-type resonant mesh. Silicon microlithography is used to produce the metal features, assuring the sharp feature edges necessary for good filter performance. For the bolometer plane, the thickness of the conductor, and thus the resistance, is set to achieve optimal absorption. The subsequent meshes have several skin depths of metal deposited to make them nearly a pure reactance. The power absorbed by the bolometer element is measured using a thermistor implanted near the center of the grid. On the bolometer element, ~80% of the thermal gradient is taken up by the four support legs, leaving the grid nearly isothermal. By thinning and etching the silicon, the effective dielectric constant of the substrate is greatly reduced, improving the impedance match to free-space.

We have developed the micromachining techniques necessary for this process, constructed prototype silicon filters[5], and measured their performance using a Fourier transform spectrometer. This first measurement confirmed the effectiveness of micromachining in reducing the effective dielectric constant.

A square frame of the parent silicon wafer is left to allow mounting (see Fig. 2). The frames are cemented together with silicon spacers between them to form the resonant structure. This is cemented to an Invar mount. Invar is critical for matching the thermal contraction of the silicon during cool-down — other mounting materials typically cause the bolometers to break upon cooling. Electrical contacts for the thermistor are made through doped conduction paths in the grid, and then wire-bonded from the silicon frame to thin copper wires. The wires from each FSB in the cascade are threaded through holes near the outer diameter of the Invar mounts, and brought out the back end of the FSB radiometer for coupling to low-thermal conduction manganin wires to bring the signals to the first stage amplifiers. Shown in Fig. 2 is the geometry of a single mesh and the mounting hardware. In the complete FSB a total of 4 such meshes are cemented together.

Fig. 2 goes here

A multi-FSB cascade is made with selected thicknesses of high-frequency absorber placed between the FSB elements. These block radiation which would otherwise be absorbed at harmonics of the FSB design frequency. The FSB elements are arranged so that the highest frequency absorbers come first (on the left in Fig. 1) as described in Section 3.

3. Optical Model

Each FSB element is designed using a one-dimensional transmission line model[6–9] together with a numerical calculation of the frequency dependent admittance of each mesh. In this framework, the light-pipe is treated as a simple transmission line, and each mesh is modeled with a complex scattering matrix. Interplane gaps are described as wavelength-dependent phase shifts. A cascade matrix formalism can then be applied to obtain the frequency-dependent transmission, reflection, and absorption of the FSB. Usually, filter meshes are made to have high conductivity, so the grid impedance is mostly reactive; in this work, however, we include a bolometer with a resonant mesh that has a finite resistance as well as reactance.

The simplest capacitive meshes consist of a square array of square metal patches; for these geometries, Ulrich has demonstrated good agreement between the mesh performance and the transmission-line model based on an analytic form for the grid impedance derived solely from geometrical factors[7]. Better mesh performance can be obtained using more complicated, cross-shaped patches[10] — this is geometry that we use in our design. The model works well over nearly the entire non-diffractive region $g \lesssim \lambda = 1/\nu$, where g is the grid constant (or spatial frequency) of the mesh, λ the wavelength, and ν the wavenumber or frequency (in cm^{-1}). At higher frequencies, diffractive effects cause the transmission line model to break down, but we rely on the steep spectral cutoff of the high-frequency absorber and the up-stream FSBs to attenuate frequencies above the diffractive limit.

For each mesh, we calculate the complex transmission and reflection amplitudes of bolometer element and filter meshes using an FFT-based numerical method[11,12]. This method agrees well with measurements for a variety of periodic geometries, including the simple crosses we use here[12]. The method permits calculations of the current distribution on periodically spaced arbitrary shaped patches, with infinite or finite conductivity, induced by incident radiation. Once the current distribution is obtained, one may calculate the amplitude of the transmitted and reflected electric field:

$$E_s = -\frac{k}{4\pi\nu\epsilon_0} J_0 \tag{1}$$

where J_0 is the average current over one grid cell. This follows from eq. 3 in Cwik *et al.*[12]. Transmission and reflection coefficients are then just

$$T = 1 + \frac{E_s}{E_i} \tag{2}$$

$$R = \frac{E_s}{E_i} \tag{3}$$

respectively, where E_i is incident field.

The metal shapes are supported on a web of etched silicon. It is important to minimize the geometrical cross-section of the silicon for two reasons. First, because it has a very high dielectric constant (about 3.5), very thin legs maintain high coupling efficiency by reducing reflections from the dielectric interface. Second, for the bolometer element, a small silicon area reduces the cross-section to cosmic ray hits. The power spikes from these events are a major source of noise for high-altitude balloon- and space-borne bolometric radiometers. For our design we use simple crosses with length $l = \frac{5}{8}g$ and width $w = \frac{1}{64}g$, where g is the grid constant. Our calculations show that such filters have resonant frequency $\nu_0 = 0.745/g$. For this geometry, the peak absorption of bolometer occurs with a surface resistance of $R_0 = 2.5\Omega/\Box$.

The FSB is a stack of 4 such meshes, a single mesh with finite resistance followed by three low-loss meshes. We have been able to create a satisfactory FSB model using identical capacitive geometries for all four planes, thus simplifying the design.

The first plane, the bolometer, would have $R/R_0 = 1.0$ for peak ideal efficiency of 100%, while the 3 mesh planes all have $R/R_0 \lesssim 5 \times 10^{-2}$, a value easily achievable with several skin depths of chrome-gold at low temperature. Reducing the bolometer resistance to $R/R_0 = 0.5$ slightly reduces the peak efficiency (to 90%), but decreases the out-of-band absorption two-fold. Increasing the bolometer resistance to $R/R_0 = 2.0$ also results in a slight decrease in peak efficiency, but nearly doubles the out-of-band absorption. We can understand this trend in terms of the intrinsic resonance of the bolometer mesh, which is damped by the ohmic losses in the conductor. As the mesh becomes more resistive, the resonance becomes broader. Good performance should be achievable with $0.5 < R/R_0 < 1.0$ for the bolometer resistance; thus, fine-tuning of this parameter is not required. For our nominal FSB element, we take $R/R_0 = 0.75$.

The bolometer is located $\lambda/4$ upstream of the first of three passive conductive meshes. These also have $\lambda/4$ gaps between them. The three conductive mesh planes form a resonant quarter-wave backstop behind the bolometer (which itself only resonantly absorbs in-band).

It is the use of a patterned absorber on the bolometer element which permits the transmission of the FSB to be controlled. In particular, the bolometer with a capacitive, patterned, resistive mesh is a poor absorber at frequencies below resonance making possible the cascaded multiband radiometer. The modeled performance of a single FSB element is shown in Fig. 3.

Fig. 3 goes here

4. Multiband Radiometer

We illustrate the cascaded FSB radiometer with an 8-band FSB design appropriate for a CMBR anisotropy experiment, although the method is not limited to the sub-millimeter wavelength band. To avoid problems arising from radiation in the diffractive regime, the elements are arranged in order of decreasing frequency, with the highest frequency band first. Thus, upstream elements and high-frequency absorber material between each FSB removes radiation near higher-order response of the FSBs. We use Fluorogold (a Teflon and glass composite) for the absorber. At 4K, it has an absorption coefficient $\alpha = 3.5 \times 10^{-3}\nu^{3.6}$ cm^{-1}, and a refractive index of 1.68[13]. The Fluorogold thickness between each FSB is set so that the total Fluorogold absorption contributes 20% attenuation at the band center. At the third harmonic, the absorber provides 50dB attenuaution due to its steep, frequency dependent absorption coefficient. Black polyethylene[14], 3 mm thick, is included preceding the first FSB to absorb radiation at frequencies above 100 cm^{-1}, where Fluorogold has a transmission window[15,16].

The individual FSB elements are separated by many coherence lengths because of the finite solid angle of the radiation in the light-pipe. We model interactions between FSB filters by considering only the power transmitted and the attenuation by the Fluorogold. That is, we neglect interference effects between the FSB elements. Fig. 4 shows the result of this modeling, giving the 8 absolute passband efficiencies of the radiometer. This model includes all losses except the reflections from the Fluorogold surfaces. We will prepare a graded index transition on the Fluorogold absorbers with several layers of perforated polyethylene.

Fig. 4 goes here

The absolute optical efficiency of the FSB system is significantly higher than traditional dichroic multi-channel bolometer designs. To illustrate, we compare our model results to the analysis of the radiometer used in the FIRS and MSAM experiments[15]. The FIRS system had a modeled peak filter efficiency of 0.51, 0.30, 0.07, and 0.12 at 6, 9, 16, and 22 cm^{-1} as determined by the product of the measured individual filter responses. The actual response of the individual capacitive grid filters matched the predictions of the one-dimensional models within 20%. In the FIRS optics, a number of other losses in the system result from the rather complex dichroic optics. The 90 degree bends needed for the dichroic filters (with transmission of about 0.6, 0.7, 0.8, 0.9 respectively in the four channels), and the inefficient coupling of the detector element (approximately 50% in each channel) result in peak efficiencies of 0.15, 0.10, 0.03, 0.05 in the four channels. The FSB system optical efficiency shown in Fig. 4 is substantially higher than the FIRS/MSAM system.

5. FSBs for Measuring CMBR Anisotropy

The prototype FSB system of Section 4 is analyzed for observations of CMBR anisotropy from a balloon-borne platform or spacecraft in the presence of galactic foreground emission. We do this by coupling the optical model of Section 3 with a calculation of the uncertainty of the CMBR temperature given a model detector sensitivity and a set of galactic foreground sources[17].

The separation of primordial signal from the foreground is done on the basis of the different spectra of the sources. Fig. 5 shows the CMBR anisotropy signal for a fluctuation of $\Delta T/T$ of 10^{-5} along with reasonable high galactic latitude values of galactic bremsstrahlung, synchrotron, and dust emission.

Fig. 5 goes here

To determine the CMBR anisotropy sensitivity, a least-squares analysis is used to evaluate a series of alternative sky models. The channel placement shown in Fig. 5 is optimized for these foreground models and use measured or projected instrument sensitivity. Constraints on the FSB band selections are: (a) no more than 8 spectral channels, (b) no band below ~ 5 cm^{-1} (to limit diffraction), and (c) no band at 18.5 or 25 cm^{-1} (to avoid extremely strong H_2O atmospheric emission lines). Detector noise is modeled using a radiation-loaded detector model at 0.3K in addition to photon noise[18].

Sky models include the CMBR anisotropy spectrum, one parameter (amplitude only) or two parameter (amplitude and spectral index) dust emission, bremsstrahlung, and synchrotron radiation[19,20]. The model predicts the uncertainty in CMBR temperature variations which includes the uncertainties due to the errors in the measurements of foreground emission. Table 1 shows the result of this calculation and for a single pixel FSB system and for other combinations of experiments chosen because we know their properties well. Note that the results in the first row of Table 1 are the raw sensitivities to a CMBR fluctuation if foregrounds can be ignored. For the FSB system, this corresponds to requiring less than two seconds of integration to match the total sensitivity of one of today's CMBR anisotropy experiments. This gain comes both from the high coupling efficiency and the utilization of the whole band from 5 to 20 cm^{-1} .

Table 1 goes here

6. Summary

We present an innovative design for a new type of radiometer: the Frequency Selective Bolometer. Bolometers, placed into a filter structure, become a coupled element in a resonant circuit. This design permits the cascading of several spectral channels resulting in a single small unit which is easily configured in a focal-plane array without the usual restrictions inherent in bolometer/filter systems. The total cryogenic volume and mass of a multi-spectral, multi-pixel radiometer will be greatly reduced facilitating larger arrays or reduced requirements on the cryogenic system. Modeling of the FSB systems also indicates that the overall optical efficiency will be improved over existing bolometric radiometer designs. Construction and testing of a prototype is in progress.

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Fig. 1. Schematic of a Frequency Selective Bolometer (FSB) Radiometer with eight frequency bands. The radiation enters the feed horn on the left. After passing through the étendu (0.15 cm^2 sr) defining aperture, the beam is expanded and passes through the FSB elements. Because each element absorbs only in a narrow range of frequencies, they can be cascaded. To avoid frequencies in the diffracive region of a given filter, the elements are arranged from highest to lowest frequency. Between FSBs, a high frequency absorber such as Fluorogold of the appropriate thickness reduces radiation above the design frequency.

Fig. 2. Schematic drawing of a single silicon mesh and the Invar mount. The filter is shown above the mount for clarity. The mesh itself is made of 10μm thickness silicon and width of 10μm. The silicon is metalized in a cross-shaped pattern. The frame at the outside edge of the mesh attaches to the mount. A complete FSB will consist of 4 such meshes. The back three, $\lambda/4$ apart, absorb no energy because of the high conductivity of their metalization. The first mesh, spaced $\lambda/4$ in front of the others is metalized with a the same pattern but whose surface resistance maximally absorbs at resonance. This first element has the bolometer thermistor on it. The spacing of the elements is controlled by silicon spacers and are cemented together by their frames.

Fig. 3. Performance of a single FSB element. The curves show a model of the transmission, reflection, and absorption of the FSB versus frequency for a device tuned to $\nu_0 = 10\ \mathrm{cm}^{-1}$. High efficiency is possible for both absorption and transmission.

Fig. 4. The modeled absolute response function for an eight-band FSB system. Incomplete absorption by the bolometer elements, losses in the metal meshes, reflected power, and absorption due to the Fluorogold are all included in the model. The high efficiency of the model is realized because losses typical of dichroic light-pipe radiometers, arising from diffraction from corners in the light pipe and from extra optical elements, are absent. The overlay curves show the shape of the CMBR and Galactic dust spectra.

Fig. 5. Differential spectra of foreground sources for typical Cosmic Microwave Background Radiation (CMBR) anisotropy experiments. The solid curve shows the spectrum for CMBR anisotropy at $\delta T/T = 10^{-5}$, corresponding to the level being detected by current experiments. The dashed, dot, and dot-dash curves are Galactic dust emission, bremsstrahlung, and synchrotron radiation at high Galactic latitude[17]. Also shown are the frequencies and bandwidth for FIRS/MSAM I, *COBE*/DMR, MSAM II instruments, and the proposed FSB radiometer.

Table 1. A comparison of the modeled sensitivities of several experiments to the CMBR in the presence various sources of foreground emission with known spectrum but unknown amplitude. The figures are the RMS sensitivity per sky pixel in a given the integration time. For existing experiments, the figures are derived from achieved levels of sensitivity. For a single pixel FSB radiometer the RMS sensitivity is given for 20 seconds of integration. The first row of figures is the sensitivity of the experiment if no foreground removal is needed.

Model[d]	MSAM[a]	FSB[b]	Mapping Experiments[c]		
			FIRS[e]	*COBE*[f]	*combined*
	(μK RMS)	(μK RMS)	(μK RMS)	(μK RMS)	(μK RMS)
CMBR	21	5.6	100	80	62
CMBR+Dust$_1$	22	5.6	120	82	67
CMBR+Dust$_2$	35	7.8	210	180	82
CMBR+Dust$_1$+Brem	240	38	1500	140	95
CMBR+Dust$_2$+Brem	240.[g]	38	2600.[g]	360	130
CMBR+Dust$_1$+Brem+Sync	300.[g]	39	4300.[g]	360	170

[a] Sensitivity per single difference, integrated for 10^3 seconds. Based on 20-minute integrated noise measured during June 1992 flight[21].

[b] Sensitivity, single difference, integrated for 20 seconds. Based on Fig. 4, the bolometer model of Mather[18] and a 0.3K cryostat.

[c] Sensitivity per $2\overset{\circ}{.}5$ pixel.

[d] Components are CMBR anisotropy, one- or two-parameter dust, bremsstrahlung, and synchrotron emission.

[e] Based on noise measured during October 1988 flight.

[f] Based on the DMR first-year map sensitivity. FIRAS sensitivity determines dust removal.

[g] No extra spectral degrees of freedom—simple solution only.