Quasi-Optical Filters

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Abstract: We describe the current state-of-art of quasi-optical filters made from metal meshes photolithographed on thin, near-lossless plastic substrates. An important benchmark in the application of such filters to an orbital CMB mission is the High Frequency Instrument (HFI) on *Planck*. The metal-mesh filters employed on *Planck* provide high in-band transmission and excellent blocking at frequencies above the passband. A future orbital mission dedicated to CMB polarimetry (CMBpol) will likely have additional requirements. (i) Back-to-back feedhorns and small (~ 1cm) filters cooled to 4K thermally shield the sub-Kelvin stage of the HFI, at the cost of slightly increased detector loading. Some of the optical designs currently envisioned for CMBpol would require significantly larger (~ 30 cm) thermal blocking filters. (ii) Optical designs that include no feedhorns will require metal-mesh filters that block below the passband, unless such blocking is provided by microstrip filters in the focal plane. (iii) Some optical designs may place more stringent requirements than have been measured for the HFI filters on scattering, diffraction and cross-polarization. Sub-orbital CMB polarization experiments are currently driving the development of the metal-mesh filter technologies that will be necessary for CMBpol. Especially important among these are balloon-borne experiments that achieve the low backgrounds and high instantaneous detector sensitivities typical of an orbital mission, and thus require filtering solutions that provide low instrument emission as well as high in-band transmission and out-of-band blocking.

1. Introduction

Metal mesh filters have proven to be the best choice for band selection in FIR/submillimetre wave instrumentation[1]. Their convenience is embodied in the observation that the optical transmission properties of metal meshes can be accurately modelled by considering each mesh as a lumped circuit element in a free space transmission line. Importantly, the lumped element impedance for metallic patterns is only dependent on the geometric properties of the metallic pattern. This analogue between the geometrical parameters and the optical response is key as it allows the required optical properties to be predetermined before manufacture.

This filter technology has found ready application in both suborbital and space borne instruments such as *BOOMERanG, MAXIMA, Archeops, Acbar, QUaD, BICEP, and Planck*. All of these use horn-fed bolometric detectors with the filters placed in filter caps on the horn entrance. In *Planck*, in order to overcome small sidelobe features associated with the front mounted filters, a three-horn architecture was used comprising a back-to-back horn pair, which creates a beamwaist where the filters are placed, followed by a final horn to condense the radiation onto the detector. The performance of a *Planck*-like filter stack, shown in Fig 1, below, is an important benchmark in the current state of CMB filter technology.

2. Current State-of-the-Art

A *Planck*-like instrument designed for CMB polarisation studies requires good in-band transmission of the filter stack (> 80%) and excellent rejection of near and far band power. The rejection needs to be at a level whereby all source types within the telescope beam do not contribute an out of band power at the detector which is greater than, say, 10% of the rms noise power of the receiver itself. For a typical sub-millimeter photometer such a calculation produces a requirement that the out of band rejection of the band defining filter stack should be graded in the following scheme:

Near band $< 10^{-3}$ Mid IR band $< 10^{-6}$ Optical/NIR band $<10^{-9}$

In *Planck* and other instruments this specification has been met by the usage of ~ five multilayer mesh filters in series as shown below. To ensure no harmonic leaks the edges are staggered to cut-off at successively higher frequencies.

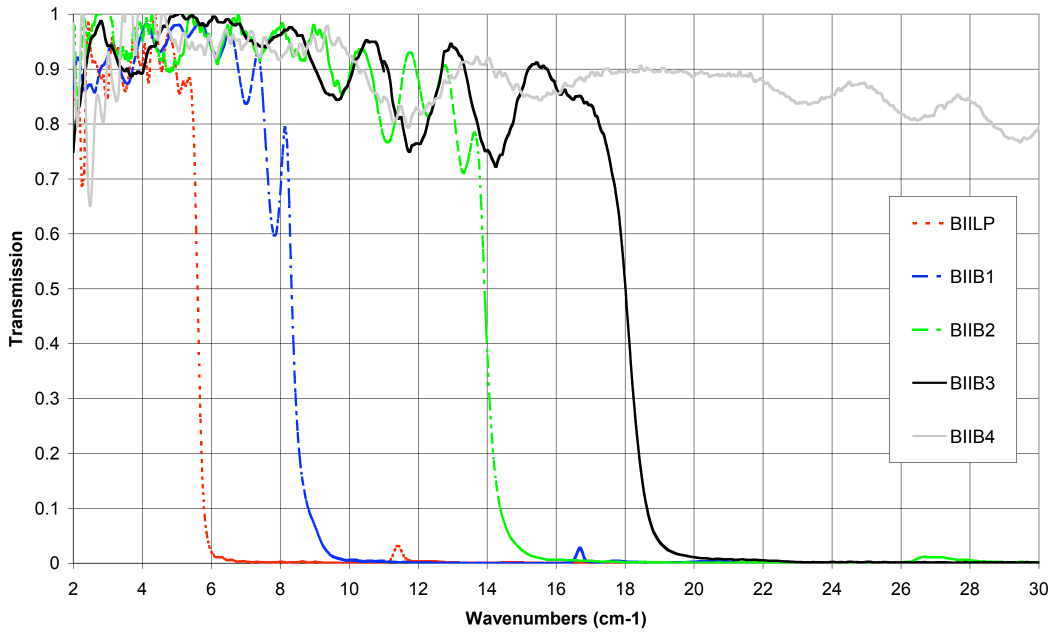

Figure 1: Spectral transmission of the individual components of a 143GHz filter stack.

For horn-fed focal planes, the first filter of the stack provided the high frequency band-edge definition and the waveguide, used to feed the sky signal to the detector, provided the low frequency band-edge. Importantly the complete stack then requires a series of four additional low-pass edge filters to meet with the extremely low leakage requirement on the high frequency side.

Fig. 2 shows the overall filter leakage determined by measuring each component over the full spectral range and multiplying the data together to get the stack transmission. It is immediately apparent from this plot that metal mesh filters alone can meet the demanding blocking requirements for a B-mode CMB experiment. The implementation of the filters, however, may be significantly different, as discussed in the next section. Thus, significant development may remain to meet requirements of clear aperture, in-band emissivity, and out of band reflectivity.

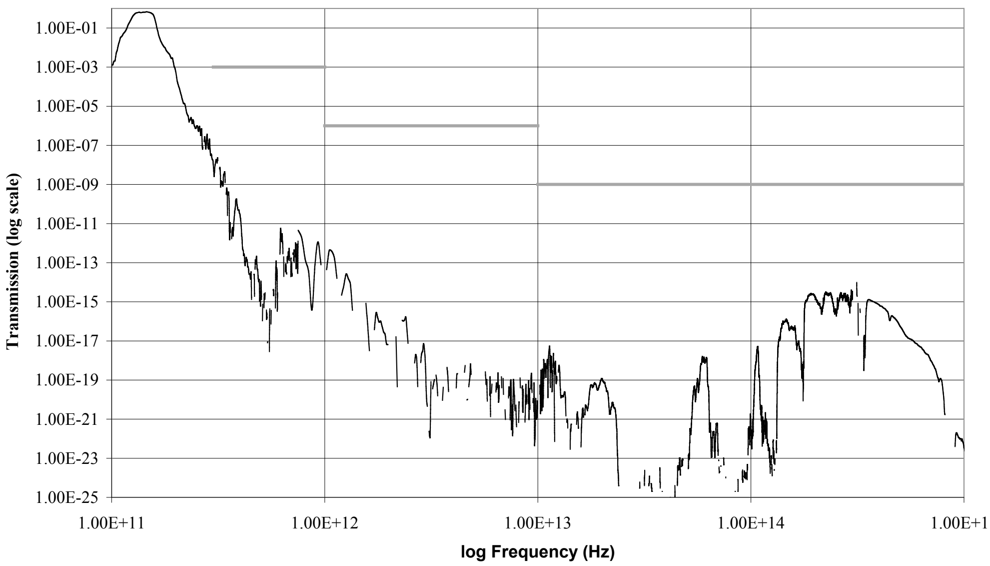

Figure 2: Total spectral transmission of a typical Planck like 143GHz filter stack with the waveguide low-pass defining edge. The thicker horizontal lines indicate the *Planck* science requirement on the level of blocking.

3. Requirements for CMBpol

The optical layout of the Planck HFI, shown in Fig. 3, was driven in part by the desire to eliminate placing requirements on maximum scattering or diffraction of the beam by metal-mesh filters. All of the filters were placed behind the beam-forming optics. This had the additional benefit of minimizing the required clear aperture of each filter to no more than several wavelengths.

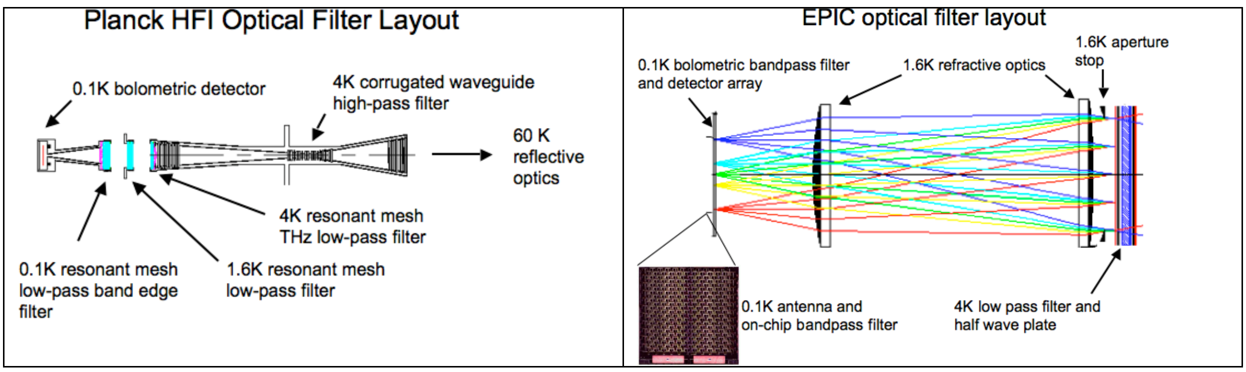

Figure 3: Comparison of the layout of the metal mesh filters in the Planck HFI (left) with those in the EPIC concept for CMBpol (right). All of the HFI filters are placed behind a 4K back-to-back feedhorn that defines the single spatial mode that couples to the telescope and provides a sharp cut-off at the lower edge of the passband. Requirements on scattering or diffraction in the filters are thus sharply relaxed, and both the physical size of and the heat load on the filters is minimized. In contrast,

the EPIC concept requires much larger filters that intercept orders of magnitude more out-of-band thermal radiation and are placed near the entrance aperture of the optics

It is possible that a CMBpol mission could have an optical layout similar to Planck, but there are at least two reasons to believe that the optical layout of CMBpol will be different in ways that will require further development and demonstration of performance in sub-orbital CMB polarization experiments: (i) it is almost certain that CMBpol will require polarization modulation, and it is advantageous to place such modulation, in the form of a waveplate, as far forward in the optics as possible. (ii) there is a sensitivity advantage of ~ 2x to be gained from eliminating the in-band optical loading from the 4K back-to-back feeds and filters.

4. Current Developments

The development of a new generation of large planar detector arrays for astronomy has already generated the need for greater optical throughput to increase the sky coverage for survey instruments (for example *BLAST*[3], *QUaD*[2], *Clover*[4], *SCUBA-2*[5], *Olimpo*[6], *EBEX*[7]). To accommodate the large beam throughputs required, metal mesh filters with diameters of 300 mm have been manufactured by the Cardiff Astronomical Instrumentation Group and they are currently working on extending their facilities to build components up to 450mm diameter. It is clear that this capability will also drive possible instrument designs for this proposed B-mode CMB instrument. Open format arrays also need either a band defining or a combination of low and high-pass filters to define the photometric band. Appropriate high-pass metal mesh filters are used on *Planck* to define the two highest frequency bands.

In most instruments, the use of several filter elements is a bonus because it enables us to distribute the placement of the individual low-pass edges on the various cold stage shield apertures within the photometric system and thus limit the thermal power reaching the colder stages. This is important since the heat lift available at sub-Kelvin stages is very limited. The CMBpol photometric instrument would certainly benefit from using these concepts even if the actual band definition is effected through stripline filters. There are useful advantages of using these large format filters for open format focal planes:

- All detectors can be filtered by one component and thus should have near identical pass-bands.
- The removal of the 4K horn as used in instruments like Planck also removes an in-band 4K photon noise contribution so sensitivity can closely approach the limit of the CMB photon-noise.

A problem associated with these large filters is self-emission giving rise to an additional photon noise component at the detectors. For small aperture horn fed photometers the filters can be thermally anchored conducting most power from the filter substrate to the cryogen bath. However, as the aperture diameters are increased the relatively poor thermal conductivity of the polypropylene substrate limits the amount of absorbed power that can be conducted away. To exacerbate this problem the absorption coefficient of polypropylene increase with frequency so that NIR heating of the relatively thick (~2mm each) low-pass edges creates a significant thermal re-emission some of which is in-band. To counter this Cardiff developed the thermal filters[8] which comprise very fine metal mesh patterns on very thin substrates (~3μm). These filters are deployed, as shown below, in front of the main low-pass filters to reflect back the majority of the NIR flux. The main filters will then naturally come into thermodynamic equilibrium with the cool radiant environment within the instrument.

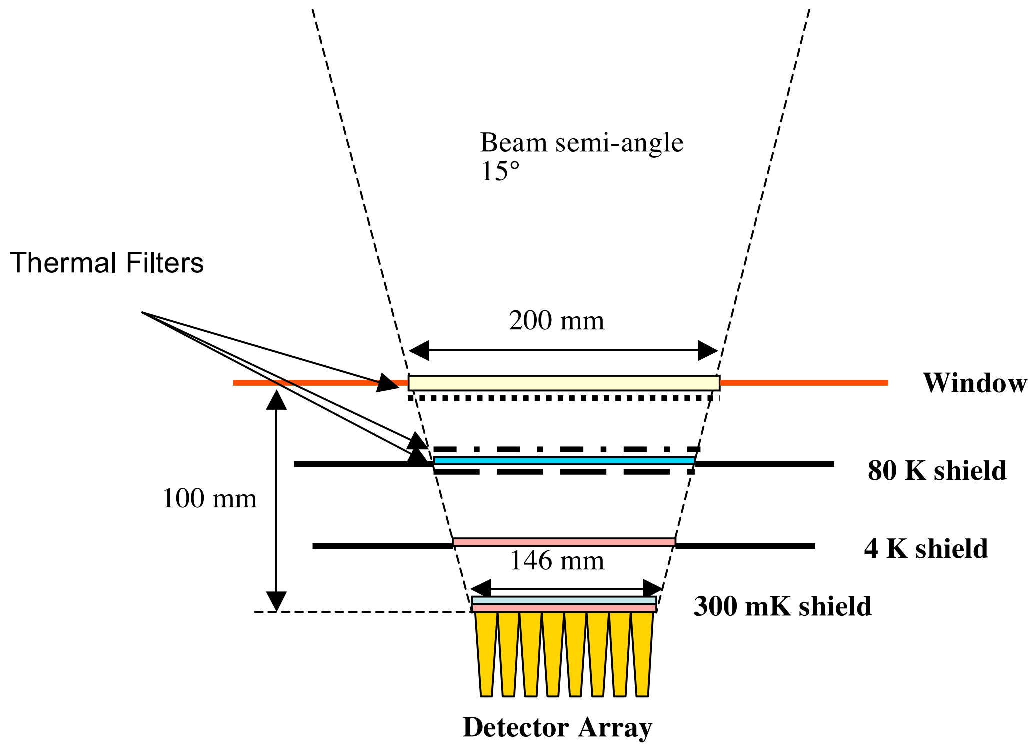

Figure 4: Deployment of thermal filters in QUAD.

These additional filters have proven effective in removing excess photon noise as well as thermally deloading the cryogenic systems. The final design of an appropriate CMBPol instrument will define the need for these filters. The important point here is that they exist and can be used to block thermal heating of a cryogenic focal plane from the thermal infrared. Such filters may prove necessary to guard against Moon transits or near vicinity spacecraft components.

Finally, question may arise about cross-polar response – here we mean explicitly the conversion of a small fraction of a 100% polarised input into the orthogonal vector. Cardiff have quantified this using a polarising FTS and have shown that the cross-polar response of a typical metal mesh filter is less than 30dB (see Fig. 5). A cross-polar requirement budget needs to be set for each component once the instrument design is determined.

In summary, we believe that metal mesh filters can be used to define the photometric bands and to de-load the cryogenic systems. They can be easily cut to shape and placed strategically at apertures to limit stray light. They can also be used in addition to strip-line filtering to provide the necessary extended rejection to optical and NIR wavelengths. Importantly they are space proven components with heritage from ISO-LWS, various Mars missions, Cassini-CIRS instrument and now Planck and Herschel instruments.

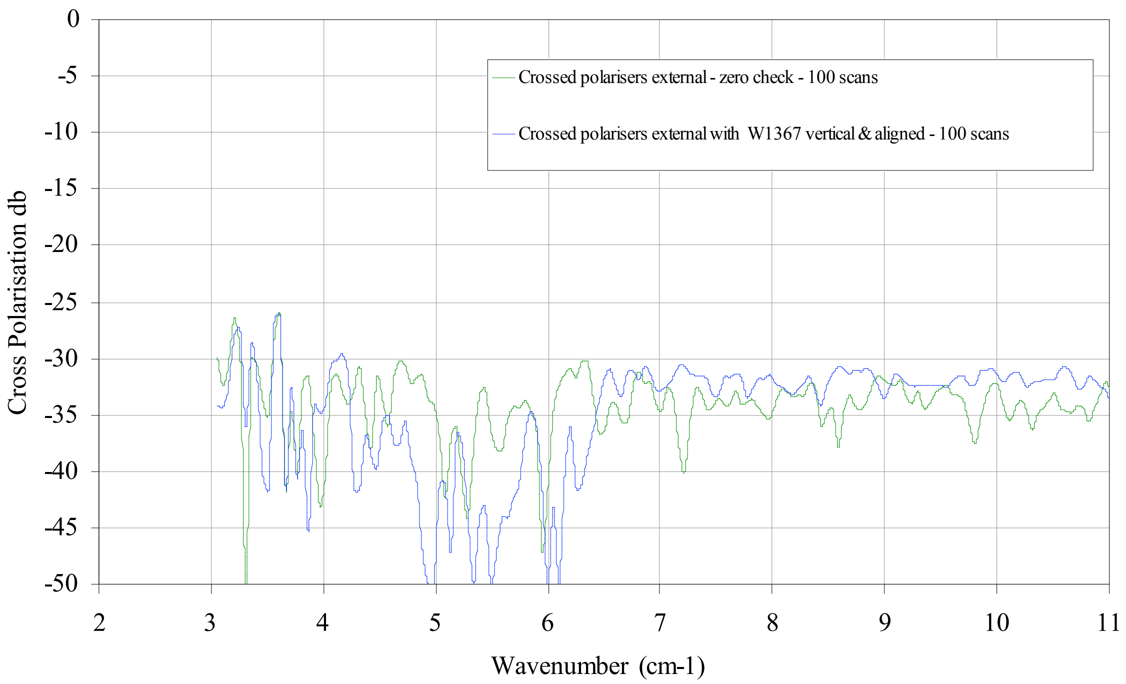

Figure 5: Recent measurements at Cardiff setting ~ 30 dB upper limits to the cross-polarization of a metal mesh filter.

5. Half-Wave Plate

A critical part of any polarimetric instrument is a polarisation modulation scheme. There are many methods available but the most used technique is to use a HWP that can be made by stacking together several birefringent plates oriented in different directions following the Pancharatnam recipes. For high throughput efficiency layers of anti-reflection coatings are used on both sides of the stack to match the device to the free space and minimise reflection losses. The absorption losses vary in the range 0.2-0.5% depending on the operational frequency. Cross-polarisations of the order of -30 dB are easily achievable in wide bands using 3 plates but better achromatic performance can be reached using 5 or 7 plates. A good understanding of the expected performance of these crystalline HWPs has been documented[9,10].

An alternative solution for an achromatic HWP is to use metal mesh components. By stacking alternate layers of inductive and capacitive grid patterns phase delays between orthogonal polarised components of 180 degrees can be achieved. Such artificial birefringent materials (termed meta-materials) have useful properties in that they are not size limited (Quartz only available 120mm diameter and sapphire available upto 260mm diameter) and have low absorption across the submillimetre bands. The only slight negative is that these components are still under development so should attract a higher risk factor.

References

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