A 700 GHz single chip balanced SIS mixer

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***Abstract*— We present the design and simulated performance of a single chip balanced SIS mixer for the 600-720 GHz band. The mixer is based on back-to-back finline transitions, fed by a pair of Pickett-Potter horn-reflector (PPHR) antennas. As all of the signal combination is carried out on the chip in microstrip planar circuits, the split mixer block is very simple to manufacture. The simulation results predict that the performance of the balanced mixer will be significantly better than previous single-ended finline SIS mixers in this band, and that the mixer with have much lower LO power requirements than single-ended SIS mixers. We also show how the performance of the 700 GHz quadrature hybrid used can be measured by using the balanced mixer in the direct detection mode as a bolometric interferometer.**

I. Balanced SIS mixers

BALANCED mixers combine two identical single-ended mixers with a 3 dB, $90°$ or $180°$ hybrid junction in the RF signal path and a 3 dB, $180°$hybrid in the IF signal path (fig. 1). Balanced mixers offer a number of advantages over single-ended mixers[1]:

- A LO coupler or diplexer is not required in the signal path to the mixer
- The required LO power is substantially reduced over a single-ended mixer with weak LO coupling
- Sideband noise from the LO is rejected

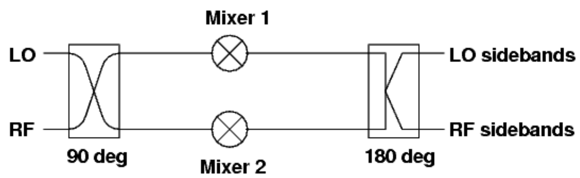

Fig. 1. Circuit diagram of a general balanced mixer using a $90°$ RF hybrid.

A number of balanced SIS receivers have been reported. In particular the CalTech Submillimeter Observatory is currently upgrading all of it's SIS receivers below the 660 GHz band to balanced SIS receivers[2], and a number of groups are investigating balanced and image separation mixers for use on ALMA[3].

Most previously reported balanced SIS receivers have implemented the RF hybrid as a waveguide branchline circuit, and used two separate SIS mixer chips. This has limited the availability of balanced SIS receivers at high frequencies due to the difficulty in machining waveguide hybrids at these frequencies. In an effort to avoid the problem of machining complicated waveguide circuits, Kerr *et al*[4], [5] have built and tested single chip balanced and image separation SIS mixers operating in the 200-300 GHz band.

The degree of LO sideband rejection in a balanced mixer depends on the accurate matching of the amplitude and phase through the two arms of the circuit. The total amplitude and phase imbalances are given by

$$\Delta A = \Delta A_{RF} + \Delta G + \Delta A_{IF} \quad (1)$$

$$\Delta \theta = 2\Delta \theta_{RF} + \Delta \theta_{IF} \quad (2)$$

where RF and IF refer to the two hybrid couplers and ΔG is the difference in the gains of the two SIS mixing elements. From (1) it can be seen that amplitude imbalance in the hybrids can be at least partially cancelled by controlling the relative gain of the two mixing elements by biasing at different points on the I-V curve. No such cancellation can be achieved in the phase imbalance. Fig. 2 shows contours of LO sideband rejection as a function of the amplitude and phase imbalances in a balanced mixer.

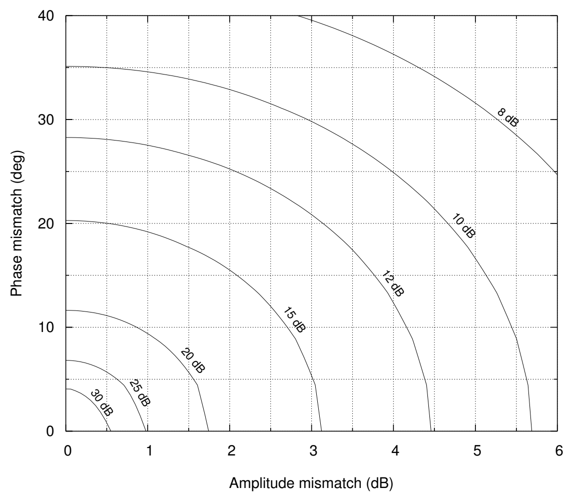

Fig. 2. Contours of LO sideband rejection as a function of amplitude and phase imbalance (after Kerr *et al*[4].).

II. The single chip finline balanced mixer

Our single chip balanced mixer is based on the back-to-back finline layout previously used by Campbell *et al*[6] as the basis for a 350 GHz bolometric interferometer. A single split mixer block is used, incorporating Pickett-Potter horn-reflector (PPHR) antennae[7] coupled to either end of a $160 \times 320\,\mu\mathrm{m}$ waveguide. The mixer chip incorporating the finline transitions, RF circuit and SIS mixers is mounted in slots in the side of the waveguides. An external IF hybrid is mounted on the Dewar cold plate along with the cryogenic IF amplifiers.

A. Mixer block

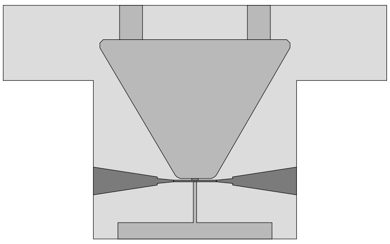

Fig. 3. One half of the mixer split block. The IF board pocket is in mid-grey and the back-to-back horns, waveguide and chip slot in dark-grey.

The mixer block (fig. 3) is machined in two halves from aluminium, and includes the PPHR, waveguide, chip mounting slots and a pocket for the IF connection board. After machining the two halves of the block are sputtered with niobium to reduce losses below the niobium gap frequency of ~ 680 GHz.

The Pickett-Potter horn-reflector antennae are identical to those used on our previous single-ended 700 GHz finline SIS mixers[7], and give a low sidelobe, 10° beam across a 15% bandwidth. The reflectors are mounted on the outside of the mixer block after the block is assembled, along with the IF SMA connectors and the superconducting electromagnet used to suppress the Josephson current in the SIS junctions.

B. Mixer chip

Working towards the centre of the chip, the mixer chip (fig. 4) is made up of finline waveguide-to-microstrip transitions at either end, bond pads to connect the bias and IF circuits, two parallel junction SIS mixers, DC/IF blocking capacitors (to prevent leakage of the IF signal from one mixer to the other, and to allow independent biasing of the mixers) and the quadrature RF hybrid at the center of the chip. Ground connections are made by bonding the pad at the top of the chip to the mixer block.

The mixer chip is being fabricated at KOSMA on a $220\,\mu\mathrm{m}$ thick quartz substrate in 6 layers (fig. 5). A $\mathrm{Nb}-\mathrm{AlO_x}-\mathrm{Nb}$ trilayer is deposited first to form the ground-plane, lower finlines and SIS junctions. The junctions are defined and the lower $200\,\mu\mathrm{m}$ thick SiO insulation layer deposited, followed by a second $225\,\mu\mathrm{m}$ SiO insulation layer. A $400\,\mu\mathrm{m}$ Nb layer forms the bond pads, mixer tuning circuits and top contacts to the SIS junctions. The ends of the microstrip input to the mixer

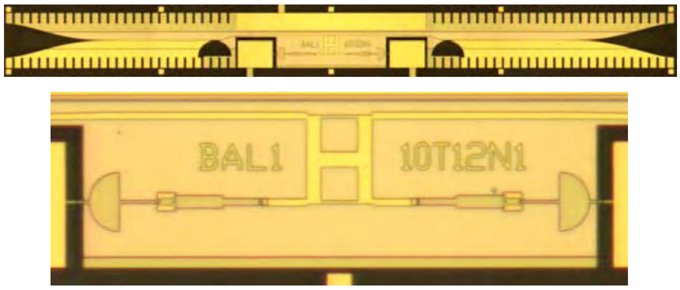

Fig. 4. *Top,* completed balanced finline mixer chip; *Bottom,* Enlarged image of circuits at the centre of the chip

tuning circuits are anodised to form $5 \times 7\,\mu\mathrm{m}$ parallel plate capacitors with a $30\,\mathrm{nm}$ thick $\mathrm{Nb_2O_5}$ dielectric. Finally the RF hybrid, top capacitor electrodes and top finlines are deposited as a $400\,\mu\mathrm{m}$ thick Nb layer, topped by a gold passivation layer. Prior to mounting in the mixer block, the mixer chip is lapped to $60\,\mu\mathrm{m}$ thickness and points are diced onto the end of the finlines.

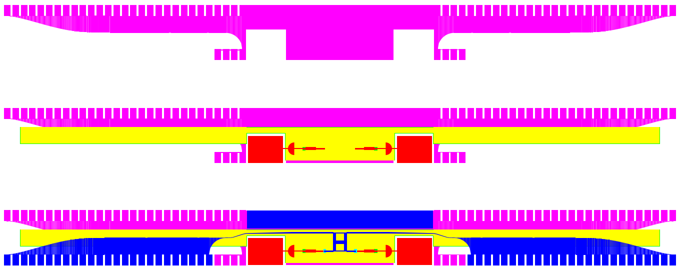

Fig. 5. Layers deposited during mixer chip fabrication. *Top*, ground-plane trilayer; *Middle*, ground-plane, insulation and junction definition layers and first wiring layer; *Bottom*, completed chip.

C. Planar circuit components

The quadrature RF hybrid is a 2-stage microstrip branchline design[1] (fig. 6) optimised in ADS and Sonnet Inc.'s *em* to provide good phase and amplitude balance across a 550-750 GHz band. The Sonnet simulations in fig. 7 include the effects of the frequency dependence of the surface impedance of Niobium across the superconducting gap, including above gap losses. Due to our choice of dielectric and wiring layer thickness, the highest impedance microstrip lines that can be reliably fabricated by UV photo-lithographic techniques are $2-3\mu\mathrm{m}$ wide, with characteristic impedances of $27-20\,\Omega$. In order to give good performance, the 2-stage branchline hybrid designs requires that the highest impedance lines have characteristic impedances approximately twice the characteristic impedance of the input lines. We therefore switched from the $20\,\Omega$ impedance input used in our previous finline mixers to a $10\,\Omega$ input impedance. The $20\,\Omega$, $3\,\mu\mathrm{m}$ wide output microstrip line from the finline design is tapered over several wavelengths to $10\,\Omega$, $7\,\mu\mathrm{m}$ wide microstrip. In this way, the use of finline tapers in transforming the waveguide mode to microstrip modes allows an essentially free choice of microstrip impedance with little impact on performance, except for an increase losses above the gap frequency due to the extra length of transmission line used to implement the taper.

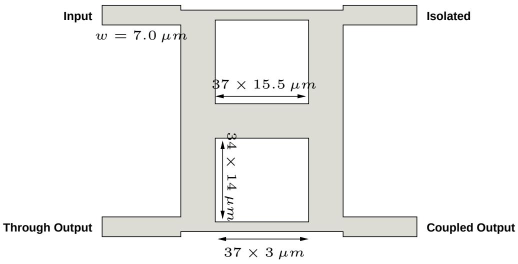

Fig. 6. Final RF quadrature hybrid design.

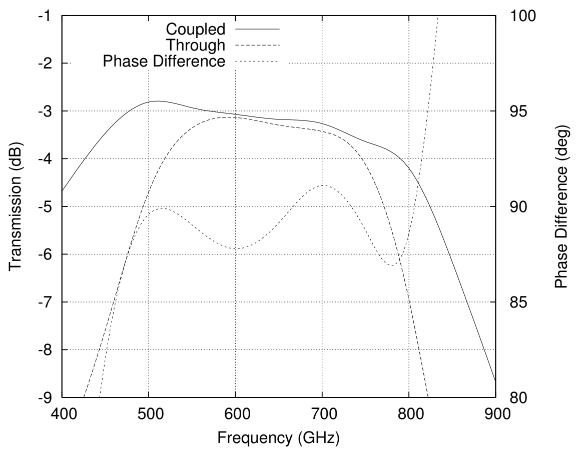

Fig. 7. Simulated transmission and phase balance of the RF hybrid.

The change from $20\,\Omega$ input to $10\,\Omega$ input has an additional advantage, in that it allows the use of larger SIS junctions in the parallel junction tuning circuit (fig. 8), improving the tolerance of the tuning response to slight inaccuracies in the area of the junctions. The impedance change also effectively increases the IF system input impedance relative to the junction impedance, which in turn increases the conversion gain of mixers. The parallel junction tuning circuit was chosen for its broadband tuning characteristics, thus reducing the risk of badly matched tuning responses for the two mixers on the mixer chip. The tuner design was extensively simulated as a single-ended mixer in SuperMix[8] using measured I-V characteristics from previous finline mixers produced at KOSMA with similar critical current densities to those required for this mixer.

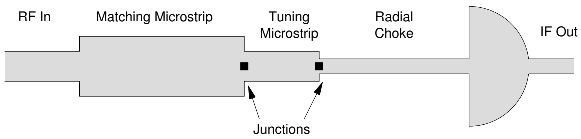

Fig. 8. Parallel junction tuning circuit.

Although balanced mixers can be operated by using a simple microstrip tee to combine the IF signals, this discards the LO sideband signal. Therefore we have decided to use a $180°$hybrid to combine the IF signals so that the down converted LO sideband signal is available for diagnostic purposes. This method also allows us to bias the mixers with identical or opposite voltages and still recover both IF signals, which may be helpful in removing the effects of trapped flux.

The IF hybrid is based on a broadband 2-stage rat-race design (fig. 9) reported by Knoechel and Mayer[9]. The design was adapted using ADS and Sonnet *em* to give good amplitude and phase matching across the 4.2-5.8 GHz bandwidth of our IF systems. The IF hybrid was fabricated on the same RT/Duroid 6010LM material used for the IF connection boards on this and previous finline mixers, and tested at room temperature on a VNA. The measured amplitude and phase balance is shown in fig. 10.

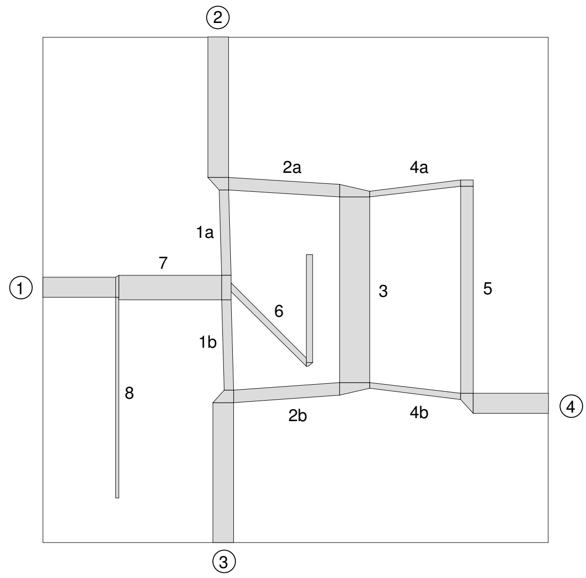

Fig. 9. IF hybrid, based on the Knoechel and Mayer design[9].

D. Optics

The layout of the back-to-back PPHR in the mixer block gives two output beams pointing in the same direction, separated by $23\,\mathrm{mm}$. To produce enough separation between the two beams, so that the LO coupling optics do not impinge on the RF signal beam, the reflector on one of the PPHR antennae is reversed and two flat mirrors added inside the cryostat to bring the LO beam to a separate window. The beam from the Gunn-doubler-tripler source is focused onto the PPHR antenna using a parabolic mirror outside the cryostat. The RF beam is coupled directly from the cryostat to the hot/cold load. The layout to be used for mixer tests is shown in fig. 11.

III. Mixer Performance

The mixer chips are currently being fabricated at KOSMA. Once these chips are completed, testing of the balanced receiver will begin by measuring the mixer performance of the receiver without the IF hybrid in place. Although the noise performance in this configuration will be poor, due to the 3 dB

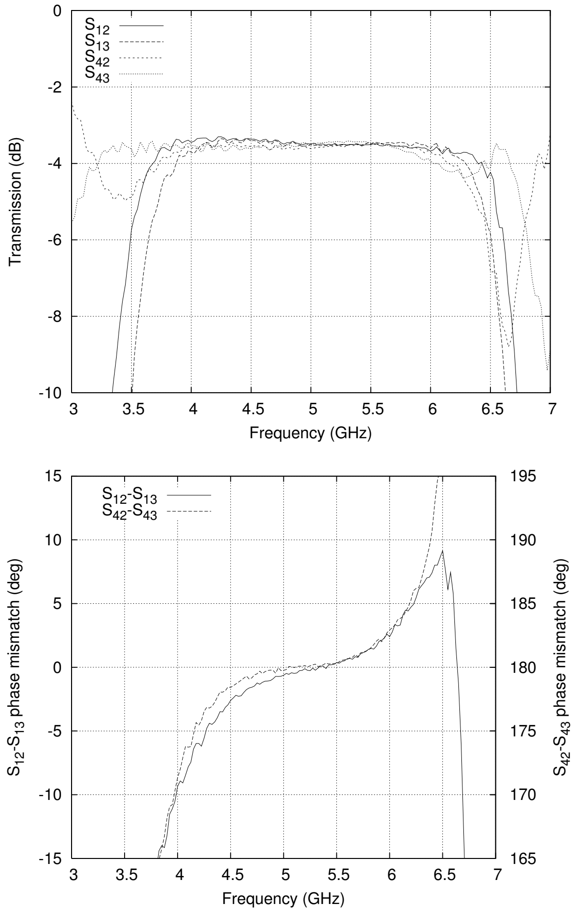

Fig. 10. Performance of the IF hybrid as measured at room temperature.

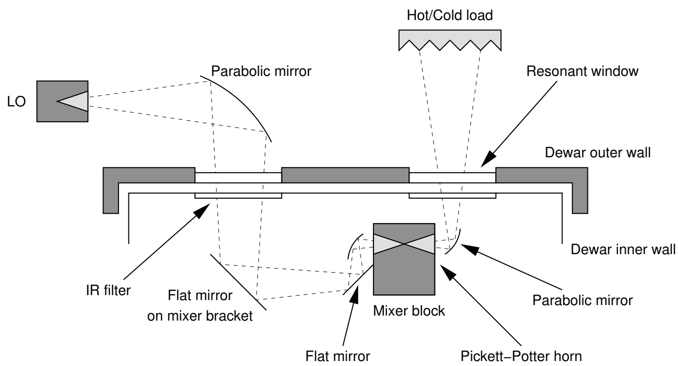

Fig. 11. Optical layout of the test receiver.

coupling to the 300 K LO sidebands, the conversion gain and LO distribution between the two mixers can be evaluated, providing a measure of the amplitude matching in the RF hybrid and between the conversion gains of the two component mixers. Adding the IF hybrid back into system will allow the performance of the full balanced receiver to be measured.

SuperMix based software has been used with Sonnet results for the two hybrids and I-V curves from previous finline mixers to predict the performance of the balanced receiver. These simulations include all components of the receiver from the output of the finline transitions to the inputs of the two IF amplifiers. The predicted mixer conversion gain, LO sideband rejection and DSB noise temperature is shown as a function of LO frequency in fig. 12. The effect of varying the bias voltage of one of the mixing elements on the conversion gains between the input sidebands and output signals is shown in fig. 13. Fig. 14 shows that the balanced performance should be maintained across the full IF bandwidth.

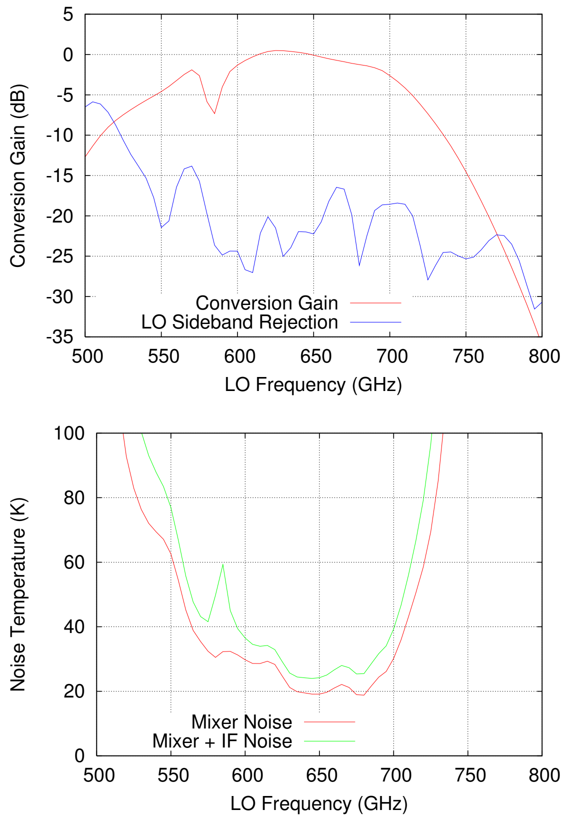

Fig. 12. Simulated performance of the balanced mixer as a function of LO frequency. LO power, bias voltage and IF frequency are fixed at a value that gives maximum conversion gain in the centre of the tuning.

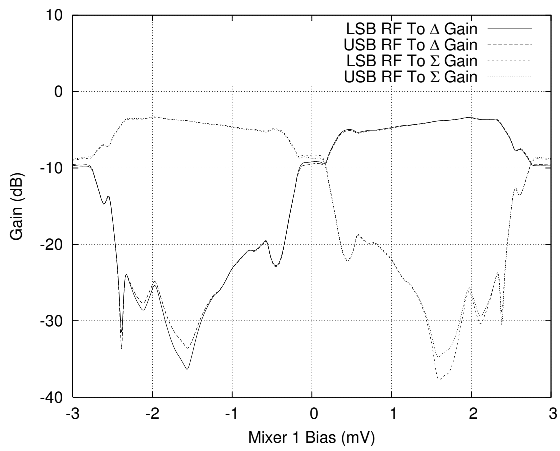

Fig. 13. Simulated conversion gain of the balanced mixer as a function of the bias voltage on one mixing element. By reversing the bias voltage on one mixing element the IF outputs are interchanged.

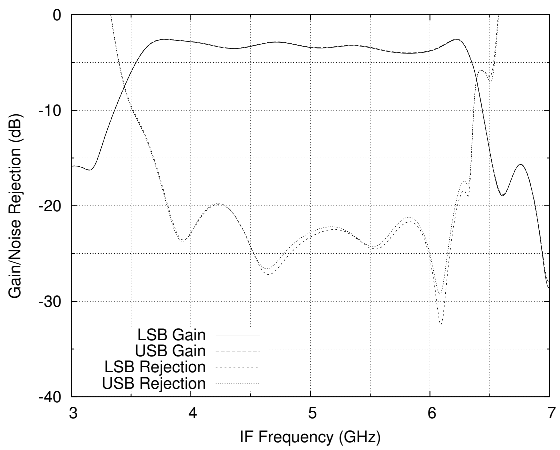

Fig. 14. Simulated noise performance of the balanced mixer across the IF frequency band.

SuperMix simulations of previous finline mixers have predicted conversion gains comparable with measured results, but have consistently predicted receiver noise temperatures 2-3 times lower than the best measured results. If this again proves to be true for the balanced mixer, then we can reasonably hope to achiever receiver noise temperatures around 100 K with near unity conversion gain.

IV. Operation as a bolometric interferometer

The back-to-back finline layout has previously been used as the basis for bolometric interferometers at 350 GHz[6] and 150 GHz[10], using SIS and TES detectors respectively. The balanced mixer chip can also be operated as a bolometric interferometer by using each of the SIS mixing elements in the direct detection mode and the optical layout shown in fig. 15, although the mixer tuning circuits are not optimised for ultimate direct detection sensitivity.

The balanced mixer chip has one crucial advantage over the previously reported back-to-back interferometers, in that it uses a 3-dB quadrature hybrid coupler rather than a 15-20 dB parallel line coupler or a 180° hybrid coupler. In conjunction with the DC blocking capacitors, this allows simultaneous detection of both the sine and cosine fringes with no attenuation of either signal path.

By operating the balanced mixer as a bolometric interferometer with a coherent point source in the far-field, we can directly measure the amplitude and phase balance of the RF quadrature hybrid. Amplitude imbalances in the hybrid will reduce the visibility of the fringes, and phase imbalances will both reduce the visibility of the fringes and shift the sine and cosine fringe patterns relative to each other. Any difference in responsivities of the SIS detectors will also contribute to the amplitude imbalance, but it should be possible to separate this contribution out by biasing the detectors at different voltages.

Simulated fringes are shown in fig. 16 for two frequencies, firstly where the amplitude and phase are well matched, and secondly where they are poorly matched. These simulations were carried out in SuperMix, using a measured beam pattern

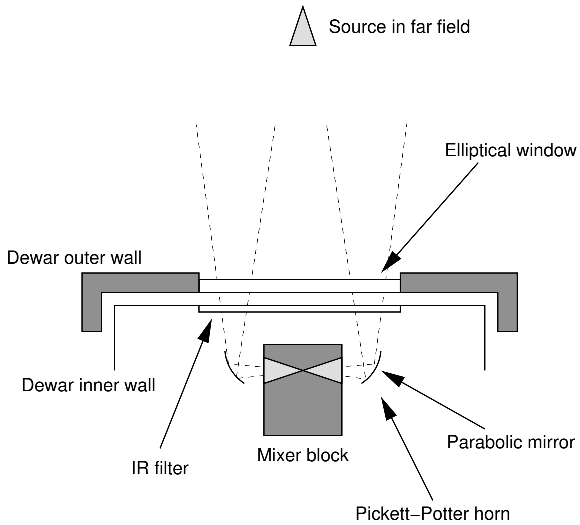

Fig. 15. Optical layout for testing the balanced mixer chip as a bolometric interferometer.

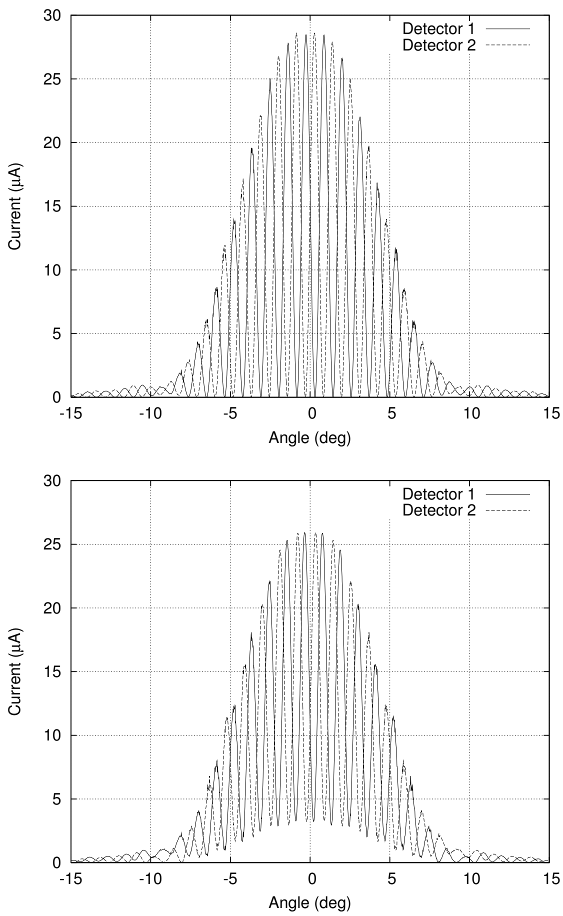

Fig. 16. Predicted fringes for the interferometer experiment when the amplitude and phase through the RF hybrid are well matched (660 GHz, top) and imbalanced (670 GHz, bottom).

of a Pickett-Potter horn-reflector antenna and the Sonnet *em* results for the RF quadrature hybrid.

V. Concluding remarks

We have presented the design of a single chip balanced mixer for the 600-720 GHz band. By basing the design on the back-to-back finline layout we have been able to use a simple, easy to machine mixer block in conjunction with high performance PPHR antennae and standard mixer chip fabrication techniques. Simulations of the performance of the balanced mixer lead us to expect very good performance, with near unity conversion gain and a reduction in noise temperature of about a factor of two over our previous finline SIS mixers in this frequency band, as well as a reduction in required LO power of at least 12 dB.

The successful operation of this balanced mixer design would enable us to consider a number of further developments. By using higher energy gap materials for some or all of the microstrip circuitry, a future mixer could be operated well above the gap frequency of niobium. The successful use of complex microstrip circuitry in a mixer will allow us to design more advanced compound mixers, such as sideband-separating or even balanced sideband-separating mixers. The back-to-back finline layout also lends itself naturally to use with photonic LO sources, particularly given the reduced LO power requirements of the balanced mixer design.

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