Broadband Finline Ortho-Mode Transducer for the 750-1150 GHz Band

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Abstract—We present the design and fabrication of a novel full waveguide band ortho-mode transducer (OMT) for operation from 750-1150 GHz, and scalable to frequencies as high as 5 THz. At submillimeter and THz frequencies, quasioptical techniques are generally used to implement dual polarization receiver systems. OMTs offer significantly increased simplicity, eliminating polarization diplexing optics. Since both linear polarizations use the same feedhorn and optics, alignment issues between polarizations are also eliminated. Advances in micromachining technology, semiconductor processing techniques and electromagnetic simulation now allow the design and fabrication of OMTs at frequencies where quasioptical approaches were the only viable option. While most OMTs used for radio astronomy are derivatives of the Bøifot design, the proposed design uses a finline circuit to separate orthogonal linear polarizations. Unlike Bøifot type designs, the Robinson OMT is fully planar, allowing easy fabrication as a single split block waveguide structure with all ports in one plane. The finline circuit is also planar, and can be fabricated using photolithographic techniques on a thin dielectric substrate. This design uses micromachining technology to fabricate the waveguide split-block by laser etching a silicon substrate that is later metallized. At lower frequencies, direct micromilling can be used to fabricate the split block directly. The finline chips are fabricated on a thin (1 μm) SOI substrate with thick (5 μm) gold finline metallization, and gold beam leads for chip grounding. This chip construction technique compatible with both direct and laser machined waveguide blocks. Both the waveguide and the finline structures can be scaled to frequencies as high as 5 THz using these fabrication techniques. Feedhorns are integrated with the structure at all three ports to allow testing with a Fourier transform spectrometer and ^{4}He bolometer system. This technique can measure the throughput, cross-polarization and isolation of the OMT through comparison with a back to back feedhorn. Later, this OMT design could be a part of a fully integrated dual polarization mixer block, with the input horn, OMT and both mixers fabricated in a single flangeless split block. Integrated dual polarization mixers of this type can dramatically decrease the complexity of dual polarization imaging arrays as well as traditional single beam receiver systems at submillimeter and THz frequencies.

Index Terms—Radio Astronomy, Ortho-mode Transducer, Micromachining

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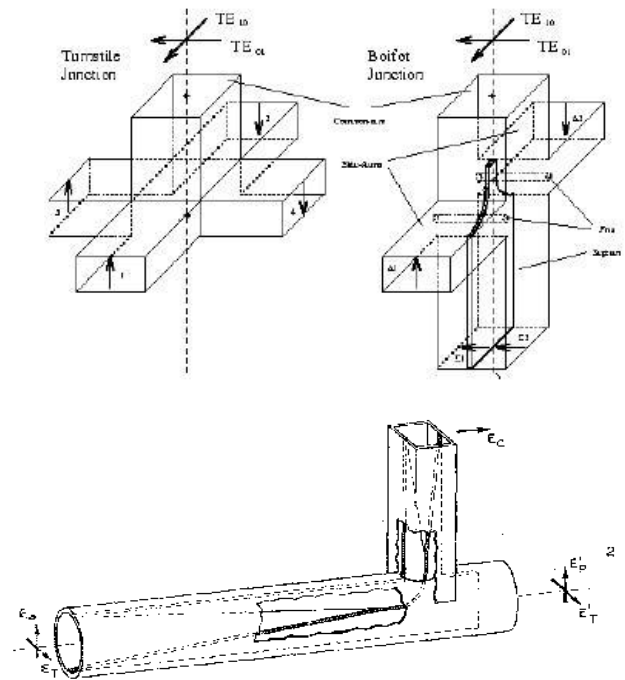
Fig. 1: The Bøifot OMT [1], [2] (top) and Robinson finline OMT [1] (bottom) designs.

I. INTRODUCTION

The design of symmetric ortho-mode transducers at mm-wave frequencies has been discussed extensively by Wollack [1], [2]. This design, referred to as the Bøifot OMT, is based on the 5 port turnstyle junction [3], folded into a more compact shape (Figure 1). Recently, Narayanan and Erickson [4], [5], have developed a Bøifot type design replacing the capacitive pins used in previous designs with a capacitive step. This and other refinements make the design far easier to fabricate and make it suitable for scaling to frequencies as high as 1 THz. These waveguide designs offer very low loss, good crosspolarization performance and excellent isolation, but are fundamentally three dimensional. Another design exists, using finline to extract one polarization from the square or round input guide. This design was originally proposed by Robinson [6] and was recently pursued by Chattopadhyay and Carlstrom, Skinner and James and this group [7],[8],[9] (Figure 1). This design is planar, and could be easily fabricated at THz frequencies using micromachining techniques for the waveguide, and

photolithographic techniques on a silicon substrate for the finline. This structure does suffer from somewhat higher loss than the Bøifot design due to ohmic losses in the fin. For operation at frequencies below the bandgap of NbTiN (1.4 THz), the fin could be fabricated from this superconducting material if the losses in a normal metal fin prove to be too high. With a fin of zero resistivity (PEC) the losses in the device are significantly reduced.

In the past, the ability to fabricate waveguide structures at high frequency was limited by available machining technology. Electroforming techniques allow construction of high frequency waveguide components, but this technique is extremely costly and time consuming. Today, classical CNC micromachining equipment is available commercially, and micromachining techniques have been pioneered by the JPL Sub-mm Wave Advanced Technology group and the University of Massachusetts [10]. In addition, the Steward Observatory Radio Astronomy Lab has developed a laser micromachining system that uses a He-Ar laser to machine structures in silicon. This technique is a non-contact process, with no debris field. The silicon vaporized by the laser is reacted with chlorine gas in the milling chamber producing silicon tetrachloride gas. Additionally, silicon melted at the etching site re-grows epitaxially as it cools, producing high surface quality [11]. The current system has the potential for fabricating waveguide structures at frequencies beyond 5 THz. A Veeco optical profiling system is used to measure structure depth and surface roughness to accuracies better than 100 nm. In addition to their laser micromachining and metrology capabilities, SORAL is equipped with a Coherent/DEOS far infrared laser system. This THz source is complimented by a Fourier Transform Spectrometer (FTS) system and an Infrared Laboratories ^{4}He bolometer.

II. OMT Design

Two design features have prevented scaling successful Bøifot type OMT designs to higher frequencies: the septum and the capacitive pins used to compensate the septum. As shown in Figure 1, the septum is a thin metallic plate that acts like a splitting junction for one polarization of the input guide, directing that mode into the two side arms. The presence of the septum requires capacitive compensation for broadband performance in the side arms. In the newest NRAO design for use in ALMA, these pins are realized as thin gold wire run through holes in the guide walls. At high frequencies, these pins are nearly impossible to fabricate. The design by Narayanan and Erickson has eliminated these pins in favor of capacitive steps in the waveguide walls. The capacitive steps could be too small to reliably etch at frequencies above 1 THz.
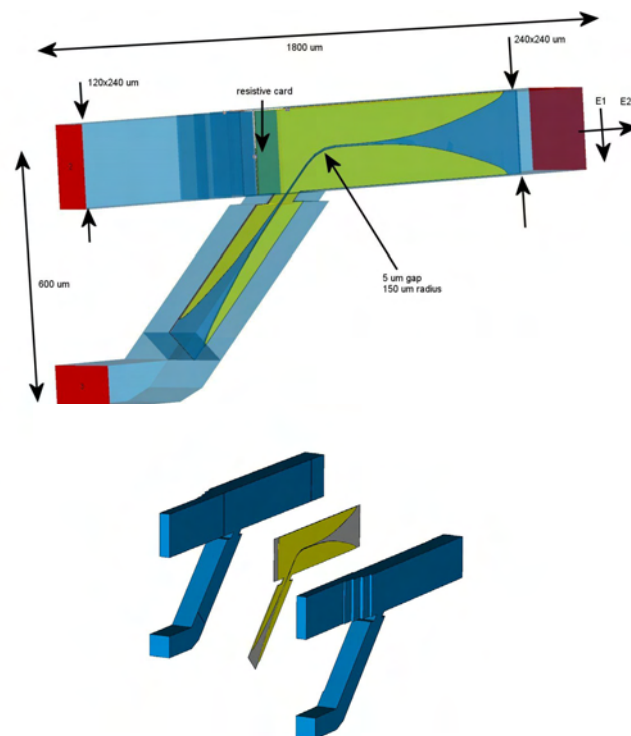

Fig. 2: CST Microwave Studio model of the Robinson OMT design for THz applications. The design consists of a laser machined silicon split-block structure, with a gold on SOI finline chip grounded via beam leads.

An OMT design proposed by Robinson in 1956 (Figure 1) has the potential to be the superior approach for THz applications. We have chosen to optimize this design for terahertz applications, and fabrication with silicon processing technology. This device is planar, unlike the Bøifot type designs. A single split block structure contains all the necessary waveguide components, and will allow integration of horns and mixers. In the Chattopadhyay and Carlstrom scale model design, the fins were realized as two separate metallic plates, held at the proper separation with alignment pins. Scaling their design to 1 THz, the fin gap is ~5 μm. Since construction of freestanding fins would be exceptionally difficult, the finline structure for our design is fabricated on a thin silicon membrane with photolithographically defined gold fins. A thick substrate requires a transition from waveguide to dielectric loaded waveguide, then a transition from dielectric loaded waveguide to finline [12]. Since silicon has a very high dielectric constant (ε_r~11.66), even relatively thin membranes can require a vacuum to dielectric loaded waveguide transition. Simulations with CST microwave studio show that a 1 μm thick substrate requires no transition at 1 THz, producing S11 less than -25 dB from 800-1200 GHz. The match degrades as the substrate thickness is increased.
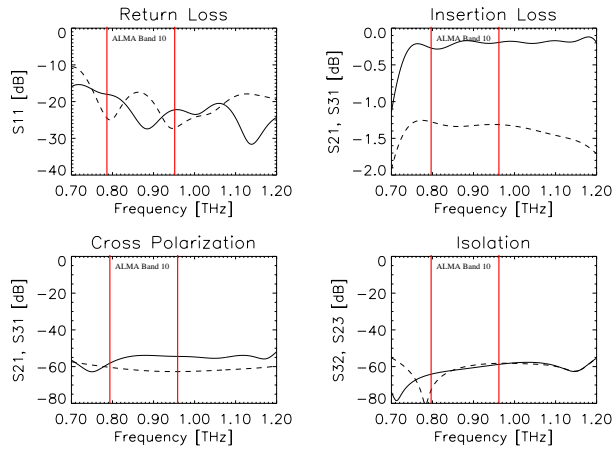
Fig. 3: OMT simulation results. Frequency range is 700-1200 GHz for all plots. Return loss, insertion loss, crosspolarization and isolation are shown for horizontal (solid) and vertical (dotted) polarizations. These CST Microwave Studio simulations include conductor, dielectric and surface roughness losses, assuming 30% increase in the conductivity of gold for operation at 4K.

When the thickness exceeds ~5 μm, a transition becomes needed. The finline tapers are of a simple exponential form $a_0 e^{z/l}$, where a_0 is half the b dimension of the waveguide, and l is the taper length. The taper length was chosen to be 550 μm, as the best compromise between matching and loss. The 5 μm fin gap at 1 THz should allow scaling of this design to ~5 THz. In addition, the use of silicon as a substrate material allows easy realization of the resistive card at the end of the finline. A palladium-gold film with a surface resistivity of 12.5 Ω/□ was deposited on the thin silicon substrate to realize the resistive card.

The Robinson OMT design has been simulated using CST microwave studio, including conductor losses for both the waveguide and the fin, dielectric losses for the silicon substrate and losses due to waveguide roughness. We assume that the conductivity of gold is increased by 30% at 4K, and assume 25 nm RMS surface roughness in the waveguide (typical of Si micromachined waveguide after an isotropic polishing etch). The design consists of two waveguide to finline transitions connected via a 45 degree, 1/2 wave radius finline bend. Chattopadhyay and Carlstrom found that a 45 degree finline bend minimized mode conversion, improving crosspolarization performance. The through-arm transitions from square to full height rectangular waveguide via a three section matching transformer, while the full height rectangular side arm uses a mitered 45 degree bend to bring both output guides to the same plane. The test structure has been fabricated with the mitered bend reversed to make the two arms perpendicular to facilitate the addition of output horns. A 40% height waveguide iris is used at the junction between the side and main arms to minimize the effect of the side arm on the horizontal polarization, while not disturbing the finline guide mode. The waveguide structure is fabricated as a split-block, with the finline chip sandwiched between the block halves (See Figure 2). As shown in Figure 3, the device offers good performance from 750-1150 GHz, fully including ALMA band 10 (787-950 GHz). The input match is approximately -20 dB across the band for both

polarizations. Insertion loss for the horizontal (through) polarization is ~0.5 dB, while the loss for the vertical (side) polarization is ~1.3 dB. Crosspolarization performance of the design is good, with crosspolarization levels of less than -50 dB. Because the current density in the fin near the narrow gap is relatively high, conductor losses in the fin increase the loss in the side arm. These losses could be eliminated by fabricating the fin using NbTiN rather than gold. Losses would be dramatically reduced. This is a straightforward application of NbTiN, since exceptional film quality is not vital as in SIS junction fabrication. For the prototype, we plan to fabricate and test only gold fins. If the measured losses prove to be too high, a design with superconducting fins can be developed in the future, with losses of less than 0.5 dB (Figure 4).
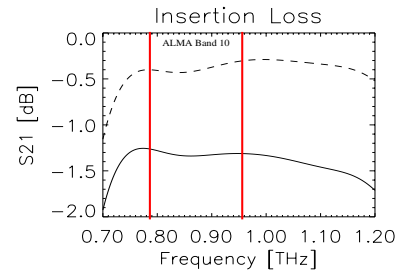

Fig. 4: Comparison of insertion loss for the side arm of the Robinson OMT with NbTiN superconducting fins (dotted) and gold fins (solid).

The design will also allow easier integration of mixer chips for future development as an integrated dual polarization mixer. Since both output ports are in the same plane and very close to one another (600 μm), two mixing devices and their associated waveguide probes and tuning structures can be fabricated on a single chip for integration with the OMT/feedhorn assembly. The small separation between ports, with all output ports in the same plane and axially aligned with the input port allow this design to be used in large, two dimensional focal plane array applications. An example of a compatible mixer design is shown in Figure 5. This design was developed to be compatible with both HEB and SIS devices, and is scalable to frequencies as high as 5 THz. The mixer is entirely fabricated from laser machined and photolithographically processed silicon [13].
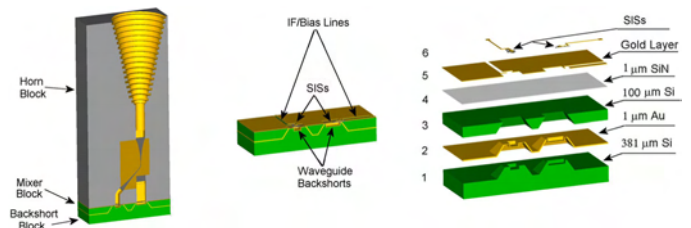

Fig. 5: A laser micromachined, SiN membrane mixer mount (Designs for beamlead/SOI devices also exist). This device, consisting of 4 blocks, has 33% bandwidth at 1 THz, and is made entirely of micromachined and photolithographically processed silicon.

III. OMT FABRICATION

We are fabricating the OMT waveguide circuit using a standard split-block approach and laser micromachining technology. The finline chip has been fabricated using photolithography on a 1 μm thick SOI substrate (Figure 6).

Beamleads are used to ground the device to the block. Beamleads are thin, freestanding metallic tabs fabricated on a substrate that is later etched away [14]. They are thick enough to act as handles for manipulating the structure, and offer very good RF grounding performance. During assembly, a beam lead device is placed in a split-block waveguide structure, suspended by the beam leads. When the split-block is assembled, the gold beam leads are crushed between the block halves providing grounding. Beam lead devices are used extensively in the multipliers used in the Hershel HIFI LO system, as well as in many modern SIS and HEB detector designs. The SOI (Silicon-On-Insulator) technique allows silicon membranes thinner than 1 μm to be produced. The thin membrane is attached to a carrier wafer. After fabrication of the structure, the back side carrier wafer is released from the thin membrane. Silicon membranes are fairly flexible, and are much easier to handle than quartz wafers of the same thickness. The finline chip is a straightforward fabrication task compared to a SIS junction; only a single gold metallization layer needs to be deposited on the substrate. The finline has been defined using standard photolithographic processes on the SOI wafer, using thick photoresist techniques. A 1:1 aspect ratio of finline gap width to metallization thickness realizable with these techniques. SEM and interferometric microscope imaging show that the finline chips fabricated conform to all design dimensions to better than 5% (Figures 6,7).

Because there is no out of plane guide, milling the waveguide split block for the Robinson OMT is relatively straightforward. There are no small, tuned structures (i.e. capacitive steps) in the design, relaxing fabrication tolerances. In addition, the entire device can be made from a single split block, including input and output horns. The design of the waveguide block, including the side arm iris, is compatible with fabrication using the SORAL laser micromachining system. Prototype devices will be fabricated with a feedhorn at each port for quasi optical testing with a FTS and a ⁴He bolometer. Alignment crosses are machined into the silicon away from the waveguide structure during the milling process to facilitate alignment. After laser machining, the waveguide split block halves are gold plated with an e-beam evaporator (the alignment crosses are masked off during plating). The planar beamlead structure is dropped (by hand) into a pocket milled into the bottom of the split-block. The precision milled pocked registers the chip (Figure 8). No electrical contacts need be made, since the beam leads will contact when the split block is closed. Alignment of the top split block with the bottom is achieved with an infrared semiconductor alignment tool or flip-chip bonder. This tool holds both the top and bottom halves of the chip in air chucks on precision motion stages. An IR microscope looks through the (transparent) silicon at the location of the alignment crosses to allow registration of the top and bottom of the structure. The air chucks then clamp the halves together. The Van der Waals forces between the gold metallization layers bond the split block together. The silicon block is then glued into a copper fixture for use. This design is also well suited for fabrication via direct micromilling in a metal block, for frequencies as high as 1.5 THz. Only small modifications to the design are necessary to compensate for finite sized tools.
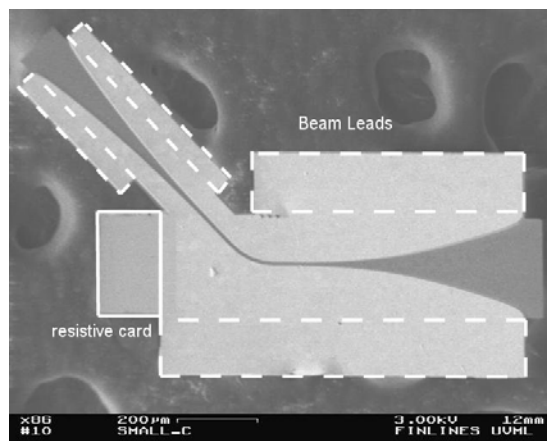

Fig. 6: SEM image of a finline chip fabricated at the University of Virginia. The finline gap is 5 μm, with a 1 μm thick SOI substrate and 5 μm thick gold metallization. The resistive card is realized as a palladium gold film, with a surface resistivity of 12.5 Ω/□.
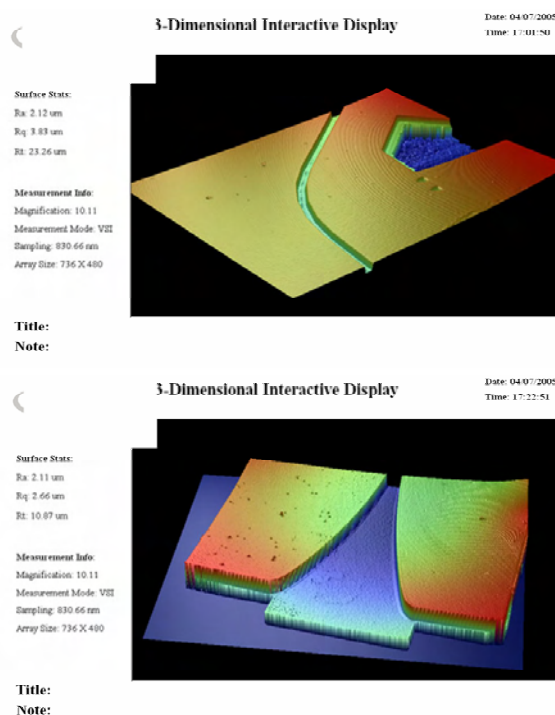

Fig.7: Veeco interferometric microscope images of a SOI finline chip. Metallization thickness is controlled to better than 100nm (the vertical resolution of the microscope). The width of the fin gap is within 5% of the design value.

IV. OMT TESTING

For testing, horns will be laser machined at both the input and output ports, integrated with the OMT. In addition, a back to back feedhorn structure will be fabricated to allow measurement of the loss of the feedhorn structures. The FTS in the SORAL lab has a broadband FIR source. Combined with a IR Laboratories ⁴He bolometer system, measurements can be made throughout the sub-mm and FIR. The system has been measured to respond from below 200 GHz to several THz, with peak sensitivity at ~ 1 THz (Figure 9). We can measure insertion loss, crosspolarization and

isolation of the OMT structure through comparison with the back-to-back feedhorn structure. With some additional optics, it is also possible to measure return loss from the device as well. Measurement with a FTS does not provide the same accuracy expected from a scalar network analyzer at lower frequencies, but should be able to verify the performance of the device. A block diagram of the proposed test set is shown in Figure 10. If the dynamic range of this test set proves to be too small to measure the crosspolarization and isolation signals, the FIR laser can be used in place of the FTS to measure these properties at discrete frequencies.
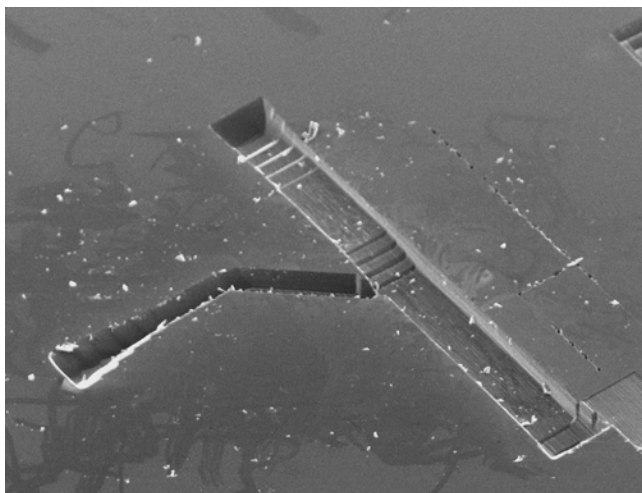

Fig. 8: SEM image of a laser micromachined prototype mixer block. Final blocks will have three integrated, corrugated feedhorns, and will be gold plated before assembly.

V.   CONCLUSION

We have designed and have began fabrication of a 40% bandwidth orthomode transducer capable of operation from 750-1150 GHz. This design is scalable to frequencies as high as 5 THz. Recent advances in micromachining and electromagnetic simulation allow the realization of such a structure. A laser micromachining system at the University of Arizona will allow low cost and high precision waveguide structures to be milled directly in silicon. A finline OMT design first proposed by Robinson in 1956 is planar and relatively easy to fabricate. Simulations of an OMT based on this design demonstrate good performance from 750-1150 GHz. This design uses laser machined silicon waveguide components with a photolithographically defined finline circuit on a thin SOI substrate with beamlead grounding. Waveguide structures fabricated at SORAL will be combined with planar structures fabricated at the University of Virginia, and assembled at either UVa or SORAL. Testing will be done using a Fourier transform spectrometer and ^{4}He bolometer system, allowing measurements of throughput, isolation and crosspolarization. Eventually, the OMT could become part of a dual polarization mixer, with the feedhorn, OMT and mixers integrated into a single, flangeless block.
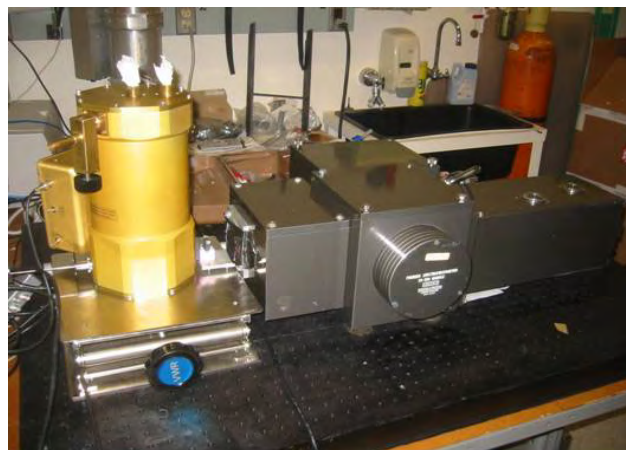

Fig 9: The University of Arizona 4He FTS system. This system has been verified to work from 200 GHz to 2 THz, and provides peak sensitivity at ~1 THz.
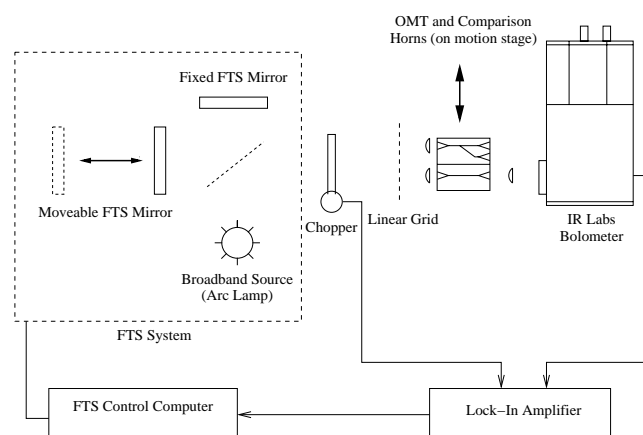

Fig 10: A block diagram of the OMT measurement system. This test set can measure throughput, crosspolarization and isolation of the OMT by comparison to a back-to-back feedhorn structure.

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