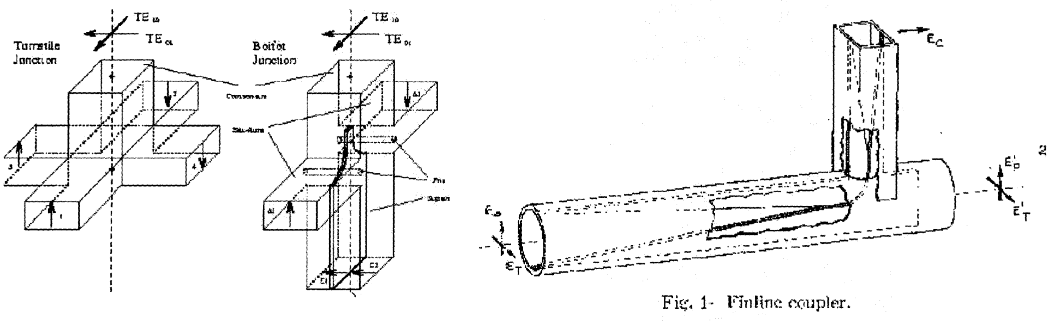
A Broadband Finline Ortho-Mode Transducer for TeraHertz Applications

Christopher Groppi[1], Christian Drouet d'Aubigny[2], Christopher Walker[2] & Arthur Lichtenberger[3]
[1] National Radio Astronomy Observatory, 949 N. Cherry Ave., Tucson, AZ 85721
[2] University of Arizona, 933 N. Cherry Ave., Tucson, AZ 85721
[3] University of Virginia, 351 McCormick Rd., Charlottesville, VA 22904
email: cgroppi@nrao.edu

Abstract

At low frequencies, the preferred method for implementing a dual polarization, low-noise receiver for radio astronomy applications is the Ortho Mode Transducer, or OMT. This waveguide junction allows compact, low loss coupling of two detectors, each sensitive to a single linear polarization, to the (usually) randomly polarized signal. While these devices are the de-facto standard for receiver systems below 100 GHz, most systems built for the sub-mm and THz frequency range use quasi-optical polarization diplexers like the linear wire grid, or are single polarization systems. We plan to fabricate and test an OMT capable of operation at 1 THz and beyond. Recent advances in both electromagnetic simulation and micro-fabrication techniques allow construction of far more ambitious waveguide structures at high frequencies. Successful Bøifot type designs have been scaled to frequencies above 100 GHz, but these devices will be difficult to realize at frequencies significantly over 1 THz. A design using finline waveguide could prove to be far simpler to fabricate at THz frequencies. The proposed design is a finline OMT operating from 750 GHz to 1150 GHz. This design could be fabricated using laser micromachining techniques at frequencies above 1 THz, or with classical CNC micromilling techniques below 1 THz. The finline is a photolithograpically defined thick gold fin, fabricated on a thin Silicon-On-Insulator (SOI) substrate, with beamlead grounding. Losses are ~1 dB or less from 750-1150 GHz, with -20 dB input match. Crosspolarization is at the -50 dB level. Testing will be done optically using a Fourier transform spectrometer and a ^{4}He bolometer system. The prototype OMT will be equipped with horns at all three ports to facilitate testing, with the eventual goal of integrating both mixers and the input horn with the OMT in a single block.



Wollack et al. 2002 *Robinson 1956*

Figure 1: The Bøifot OMT (left) and Robinson finline OMT (right) designs.

Introduction

The design of symmetric ortho-mode transducers at mm-wave frequencies has been discussed extensively by Wollack (2002, 2003). This design, referred to as the Bøifot OMT, is based on the 5 port turnstyle junction (Meyer and Goldberg, 1955), folded into a more compact shape (Figure 1). Recently, Narayanan and Erickson (2002, 2003), 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 (1956) and was recently pursued by Chattopadhyay and Carlstrom (1999) (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.

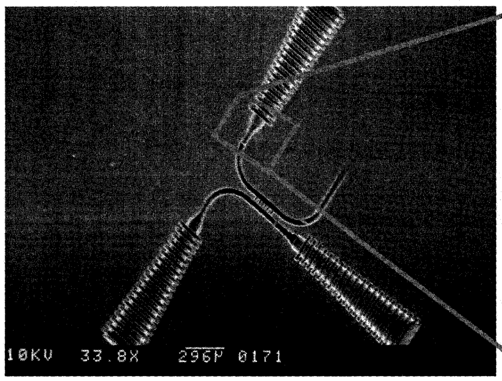


Figure 2a: Laser micromachined 1.5 THz coherent beam combiner with corrugated feedhorns

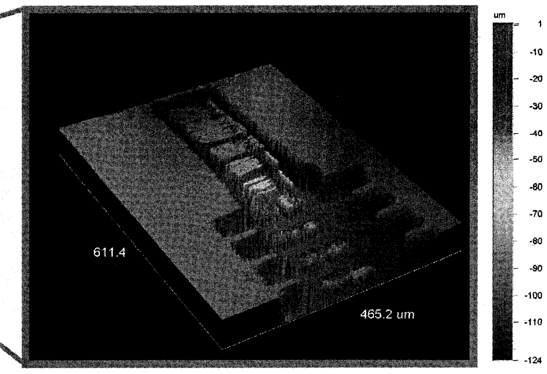


Figure 2b: 3-D image of quarter-wave transformer and horn throat made with the Veeco optical profiling system.

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 (Narayanan et al. 1999). 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 (Drouet d'Aubigny et al. 2003). The current system has the potential for fabricating waveguide structures at frequencies beyond 5 THz. Figure 2 shows example structures made via this process at the University of Arizona. 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.

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. A thin septum disrupts the orthogonal polarization very little, allowing it to pass by the septum to a square to rectangular waveguide transition. 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. Fabrication of the septum poses little problem if made from silicon using photolithographic techniques, but fabrication of the capacitive steps in the waveguide walls, and the out of plane output waveguide pose significant challenges at THz frequencies. The capacitive steps could be too small to reliably etch at frequencies above 1 THz. Laser etching is limited in the depth of structures it can fabricate with straight walls, since the beam of the laser has a finite *f* number. This makes etching the out of plane guide a difficult task. Also, this design requires that the feedhorn or mixer assembly for the out of plane port be made as a separate block.

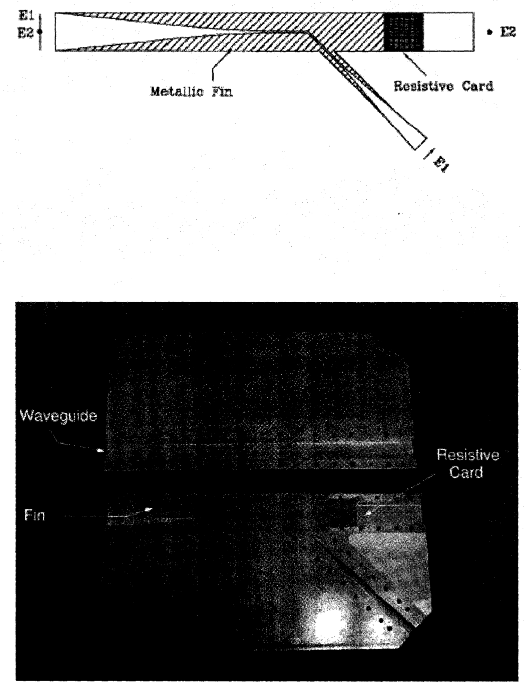


Fig. 2. A picture of the *X*-band finline OMT.

Figure 4: The Chattopadhyay and Carlstrom finline OMT design (1999). Above is a schematic diagram, below is the X-band scale model realization.

An OMT design proposed by Robinson in 1956 (Figure 1) has the potential to be the superior approach for THz applications. This design has been investigated at lower frequencies by Skinner and James (1991), and was also considered for mm-wave applications by Chattopadhyay and Carlstrom (1999), who tested a scale-model device at X-band (Figure 4). 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 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 the proposed design will be fabricated using photolithographic techniques on a thin dielectric substrate. A thick substrate requires a transition from waveguide to dielectric loaded waveguide, then a transition from dielectric loaded waveguide to finline (Uhde et al. 1990). 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. When the thickness exceeds ~5 μm, a transition becomes needed. The 5 μm fin gap and 5 μm thickness limit on the substrate at 1 THz should allow scaling of this design to ~5 THz. In addition, the use of silicon as a substrate material will allow easy realization of the resistive card at the end of the finline noted in Figure 4. Current simulations show that a lossy card may not be necessary to suppress unwanted modes in the square waveguide, in which case the card could be a simple silicon tab. If a lossy card proves to be necessary, a resistive film can be deposited on the silicon substrate.

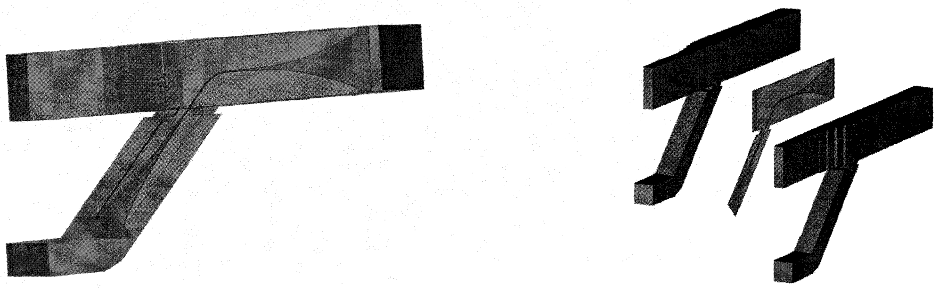


Figure 5: CST Microwave Studio model of the Robinson OMT design for THz applications. The design consists of a laser machined silicon split-block structure, with a gold on SOI finline chip grounded via beam leads.

The Robinson OMT design has been fully 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% to simulate operation 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. 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 will be fabricated using a split-block, with the finline chip sandwiched between the block halves (See Figure 5). As shown in Figure 6, 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. The bandgap energy of this superconductor is ~1.4 THz, so the material would behave like a PEC in the frequency band of interest. Losses would be dramatically reduced, at the cost of increased difficulty in 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 7).

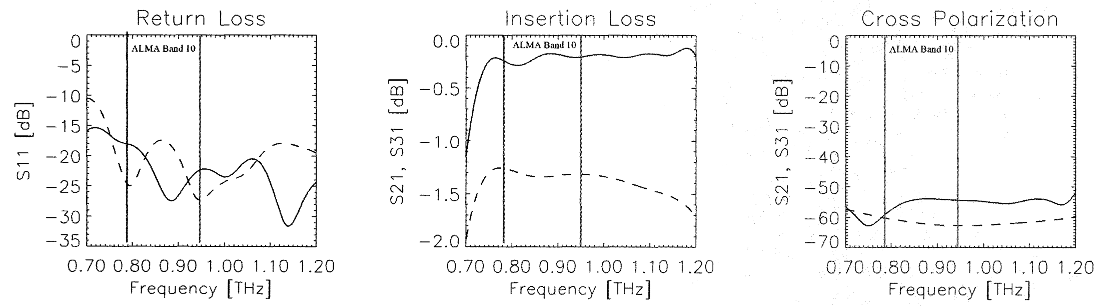


Figure 6: OMT simulation results. Frequency range is 700-1200 GHz for all plots. Return loss, insertion loss and crosspolarization are shown for horizontal (solid) and vertical (dotted) polarizations. These CST Microwave Studio simulations include conductor, dielectric and surface roughness losses, assuming operation at 4K.

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 7. 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 (Walker et al. 2003).

OMT Fabrication

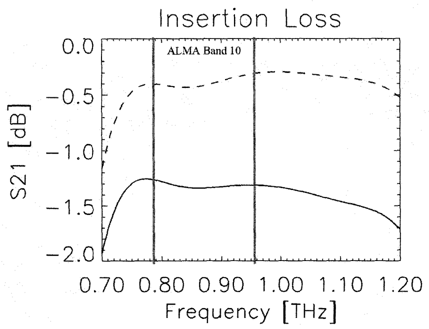


Figure 7: Comparison of insertion loss for the side arm of the Robinson OMT with NbTiN superconducting fins (dotted) and gold fins (solid).

We plan to fabricate the OMT waveguide circuit using a standard split-block approach and laser micromachining technology. The finline chip will be fabricated using photolithography on a 1 μm thick SOI substrate. Beamleads will be used to ground the device to the block. Beamleads are thin, freestanding metallic tabs fabricated on a substrate that is later etched away. 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. SOI (Silicon-On-Insulator) wafers allow 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. Prototype devices will be fabricated with a feedhorn at each port for quasi optical testing with a FTS and a ^{4}He bolometer. Eventually, the OMT could become part of an integrated dual polarization mixer, with the input feedhorn, OMT and both mixers integrated into a single, flangeless block (see Figure 8).

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. Alignment crosses are machined into the silicon away from the waveguide structure during the milling process to facilitate assembly with a flip-chip bonding tool. 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 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 will be 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. In addition, the design is not sensitive to the metallization layer thickness; variations of over 1 μm can be tolerated with almost no qualitative impact on the device performance. 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. 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.

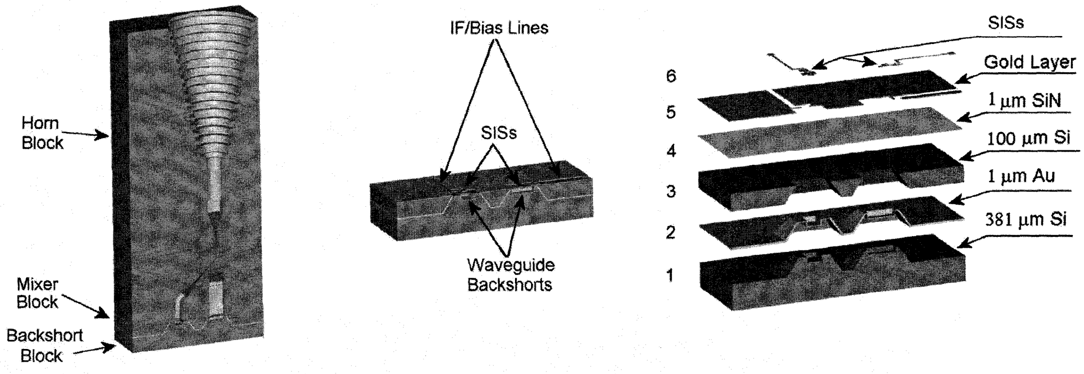


Figure 8: A laser micromachined, SiN membrane mixer mount (Designs for beamlead/SOI devices also exist). This device, consisting of 4 blocks, has 33% bandwidth at 1 THz, and is made entirely of micromachined and photolithographically processed silicon.

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 ^{4}He bolometer system, measurements can be made throughout the sub-mm and FIR. 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 9. 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.

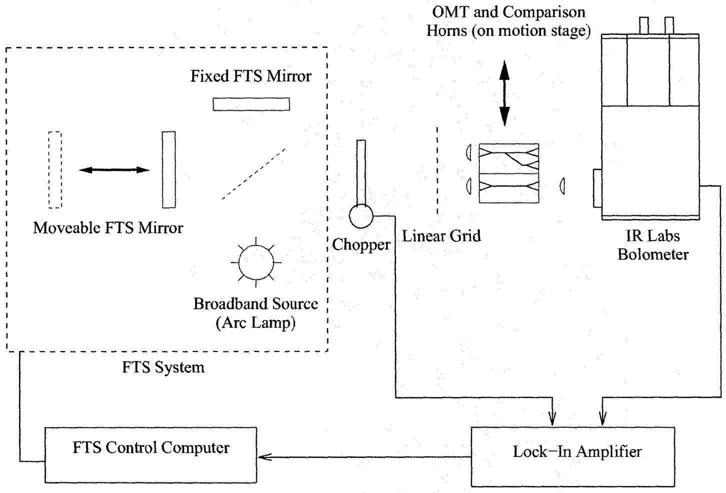


Figure 9: A block diagram of the measurement system proposed for the THz OMT. This test set can measure throughput, isolation and crosspolarization of the OMT by comparison to a back-to-back feedhorn structure.

Conclusion

We have designed and plan to fabricate and test 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 SORAL and 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.

References

Chattopadhyay, G. & Carlstrom, J.E., *Finline Ortho-Mode Transducer for Millimeter Waves*, IEEE Microwave and Guided Wave Let., vol. 9, no. 9, pp. 339, 1999.

Drouet d'Aubigny, C.Y., Walker, C.K., Golish, D., Swain, M.R., Dumont, P.J, & Lawson, P.R., *Laser Micro-machining of Waveguide Devices for Sub-mm and Far IR Interferometry and Detector Arrays*, Proc. SPIE., vol. 4852, pp. 568, 2003.

Meyer, M.A. & Goldberg, H.B., *Applications of the Turnstyle Junction*, IRE Trans. MTT, vol. 3, no.6, pp. 40, 1955.

Narayanan, G. & Erickson, N., *Full-Waveguide Band Orthomode Transducer for the 3mm and 1mm Bands*, 14th International Symposium on Space Terahertz Technology, In Press, 2003.

Narayanan, G., & Erickson, N.R., *A Novel Full Waveguide Band Orthomode Transducer*, 13th International Symposium on Space Terahertz Technology, Harvard University, 2002.

Narayanan, G, Erickson, N.R., & Grosslein, R.M., *Low Cost Direct Machining of Terahertz Waveguide Structures*, 10th International Symposium on Space Terahertz Technology, pp. 518, 1999.

Robinson, S.D., *Recent Advances in Finline Circuits*, IRE Trans. MTT, vol. MTT-4, pp. 263, 1956.

Skinner, S.J, & James, G.L., *Wide-Band Orthomode Transducers*, IEEE MTT, vol. 39, no. 2, pp. 294, 1991.

Walker, C.K., Groppi, C.E., Drouet d'Aubigny, C.Y., Kulesa, C., Hedden, A.S., Prober, D.E., Siddiqi, I., Kooi, J.W., Chen, G, & Lichtenberger, A.W., *Integrated Heterodyne Array Receivers for Submillimeter Astronomy*, Proc. SPIE, vol. 4855, pp. 349, 2003.

Wollack, E.J., & Grammer, W., *Symmetric Waveguide Orthomode Junctions*, 14th International Symposium on Space Terahertz Technology, In Press, 2003.

Wollack, E.J., Grammer, W. & Kingsley, J., *The Bøifot Orthomode Junction*, Alma Memo #425, 2002.