Tests of a planar L-band orthomode transducer in circular waveguide

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Abstract

This note describes tests made in March 2000 of a planar L-band orthomode transducer. The transducer consists of 4 probes symmetrically arranged in a circular waveguide and two wideband baluns, made from back-to-back slotline-to-microstrip transitions.

We designed this device to model the performance of a millimeter wave transducer where probes and baluns are microfabricated with SiON thin-film dielectric deposited on a quartz substrate. In the L-band model, probes and baluns are printed on 0.010″ thick Duroid 6006, mounted on a 0.25″ thick piece fiberglass and placed flush against the waveguide. Each pair of opposite probes is coupled through a balun to a 50 ohm microstrip output.

Measurements show that, from 1.2 – 1.9 GHz, the orthomode transducer has an output return loss less than –18 dB and crosspolarization less than –35 dB. It should be possible to scale this design to cover the 80-115 GHz or 210-270 GHz bands.

Introduction

Conventional dual polarization receivers for millimeter wavelengths use wire grids to separate the orthogonal linear polarizations, coupling them to independent feed horns. This scheme is awkward to implement with the straight-through design of the current BIMA receivers (Lugten 1995; Plambeck 2000). Converting BIMA to dual polarization would be made easier if the two polarizations could be split in a waveguide orthomode transducer that followed a single feed horn.

Although a number of designs exist for waveguide orthomode transducers (e.g., Wollack 1996; Chattopadhyay and Carlstrom 2001), machining them is difficult for 3mm wavelengths and nearly impossible for 1mm wavelengths. A much simpler approach might be to arrange 4 planar probes symmetrically in a square or round waveguide (Figure 1). Electric fields generated by opposite probes driven 180 degrees out of phase should couple to the TE11 waveguide mode. By symmetry, orthogonal pairs of probes should be uncoupled. Bock (1999) reported a preliminary test of this design.

Bock made measurements with freestanding metal probes and a packaged 180 degree hybrid. These elements would be difficult to mass produce at millimeter wavelengths. The goal of the work described here is to determine if the probes and hybrids can be printed onto a dielectric substrate that can be inserted across the waveguide. MMIC amplifiers or SIS mixers could then be wirebonded to the 50 ohm microstrip outputs of this circuit.

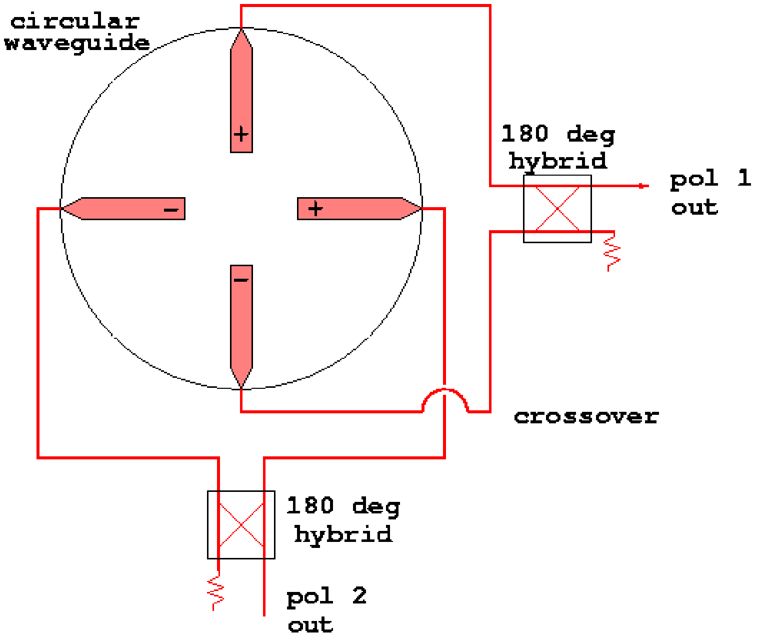

Figure 1. Basic design of the orthomode transducer.

Our approach presents two technical challenges: (1) to design a low-loss planar hybrid or balun which will cover a full waveguide bandwidth; (2) to insert a dielectric substrate across the waveguide without launching unwanted surface modes or exciting parasitic resonances.

Silcon oxynitride as a microstrip dielectric

First we consider the problem of fabricating a planar balun. It is difficult to build microstrip components at millimeter wavelengths because the *width* of the microstrip lines becomes a substantial fraction of a wavelength on even the thinnest commercially available substrates. For example, on 0.005″ thick Duroid 5880, a 50 ohm line has a width of 0.014″, while a quarter wavelength at 230 GHz is just 0.009″.

One alternative is to use coplanar waveguide (CPW). Since the impedance of CPW depends on the ratio of the central conductor width to the groundplane separation, the central conductor can be made arbitrarily narrow, at least in principle. Since CPW is uniplanar, the substrate thickness can remain fixed. Finally, since the characteristic wavelength is somewhat longer than for microstrip, resonant circuit elements are larger. CPW has some drawbacks, however. Since it is physically equivalent to a pair of coupled slotlines, both odd and (unwanted) even modes can propagate. To short out the even mode, one couples the two ground planes with regularly spaced capacitive bridges (e.g., Kerr et al. 1998), which require additional fabrication steps.

Another approach – the one we prefer – is to manufacture the microstrip components on an extremely thin dielectric, which may be deposited as part of the fabrication process. Tokumitsu et al. (1990) demonstrated that miniature microstrip transmission lines could be fabricated on clad dielectric films, made by alternately depositing 3 micron layers of silicon oxynitride (SiON, $\varepsilon_r \sim 5.0$) and polyimide ($\varepsilon_r \sim 3.3$) on metallized GaAs. These layered dielectric films had an extremely uniform thickness and remarkably low surface tension. Common dielectric films like SiO and SiO_2, deposited by evaporation or sputtering, develop high surface tension if they are more than a few thousand Angstroms thick, causing them to peel or crack as they cool. (Indeed, the main challenge in scaling the BIMA SIS mixer design from 230 GHz to 100 GHz was making stable 1 micron thick films of SiO.) It is feasible to make a thicker film of SiON because it is deposited by low temperature chemical vapor deposition (CVD). Thus, we envision sputtering a ground plane on a quartz substrate; depositing a dielectric film of SiON on the ground plane by CVD; then fabricating microstrips on top of the SiON.

Table 1 lists the dimensions of stripline and slotline components fabricated on thin films of SiON. Even at 345 GHz, the linewidths are of order 1.5 microns, which should be straightforward to fabricate with photolithography. To simulate the SiON layer in the L-band scale model we used 0.010″ thick Duroid 6006, which has a dielectric constant similar to SiON.

Table 1

	1.5 GHz model	100 GHz	230 GHz	345 GHz
SiON layer thickness (ε = 5.0)	0.010″ Duroid 6006 (ε=6.15)	5.0 μm	2.2 μm	1.5 μm
50 ohm stripline width	0.016″	6.7 μm	2.9 μm	1.9 μm
50 ohm slotline width	0.012″	5.0 μm	2.2 μm	1.5 μm
waveguide diameter	6.0″	3099 μm	1270 μm	900 μm
probes (l × w)	1.75 × 0.50″	723 × 173 μm	314 × 75 μm	210 × 50μm

Slotline balun

The 180 degree power combiner, or balun, used in the model is shown in Figure 2. It is adapted from a 180 degree pulse inverter designed by Hede (see Gupta et al. 1979, pp. 250-253) and from a coupled slotline magic T described by Aikawa and Ogawa (1980). The two inputs are coupled to a slotline with oppositely directed microstrip stubs. By symmetry, only signals that are out of phase at the inputs couple to the output microstrip. The bandwidth is limited only by the microstrip to slotline transitions.

We tested the L-band balun using an 8720A network analyzer. Figure 3 shows the test results, overlaid on the predictions by Zeland Software IE3D; an rms substrate roughness of 3 μm was assumed in calculating the transmission loss. Over the 1.2-1.9 GHz design band, the amplitude imbalance is less than 1 dB and the phase balance error is less than 4 degrees.

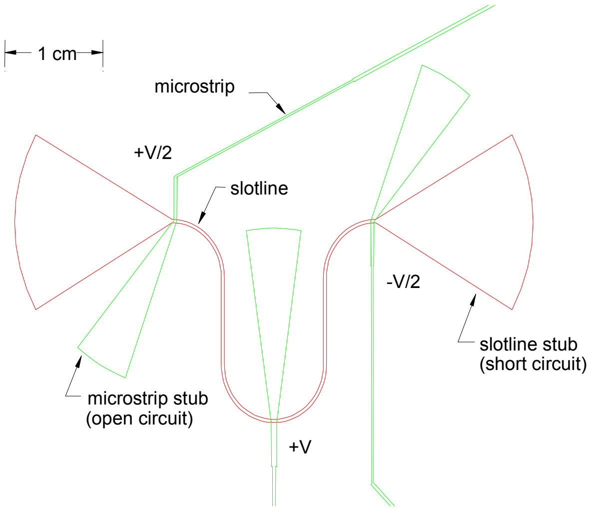

Figure 2. Balun used to combine the voltages from two probes with a 180 degree phase shift. The red outline is an opening in the ground plane. Green lines are microstrips. The slotline and microstrip stubs have radii of $\lambda/4$.

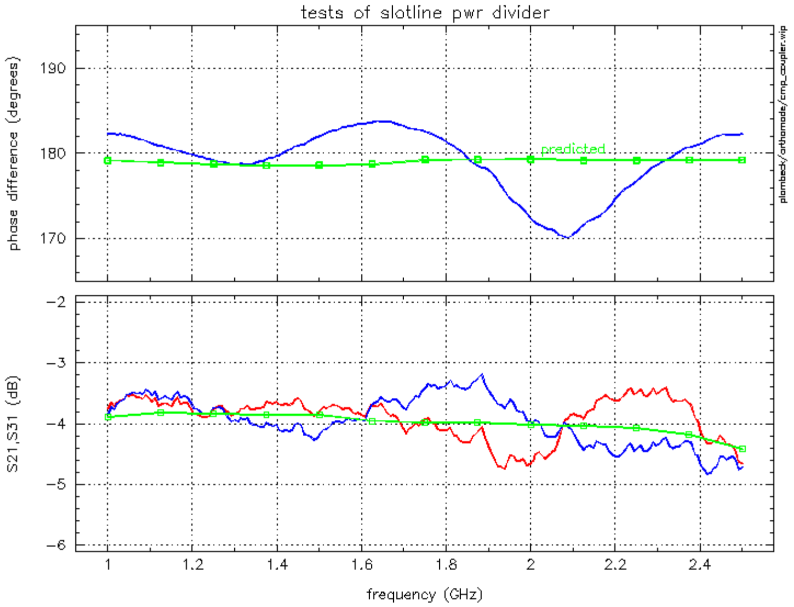

Figure 3. Measurements of the phase difference (top) and coupling (bottom) of the slotline balun. Green curves are the predictions of Zeland Software IE3D.

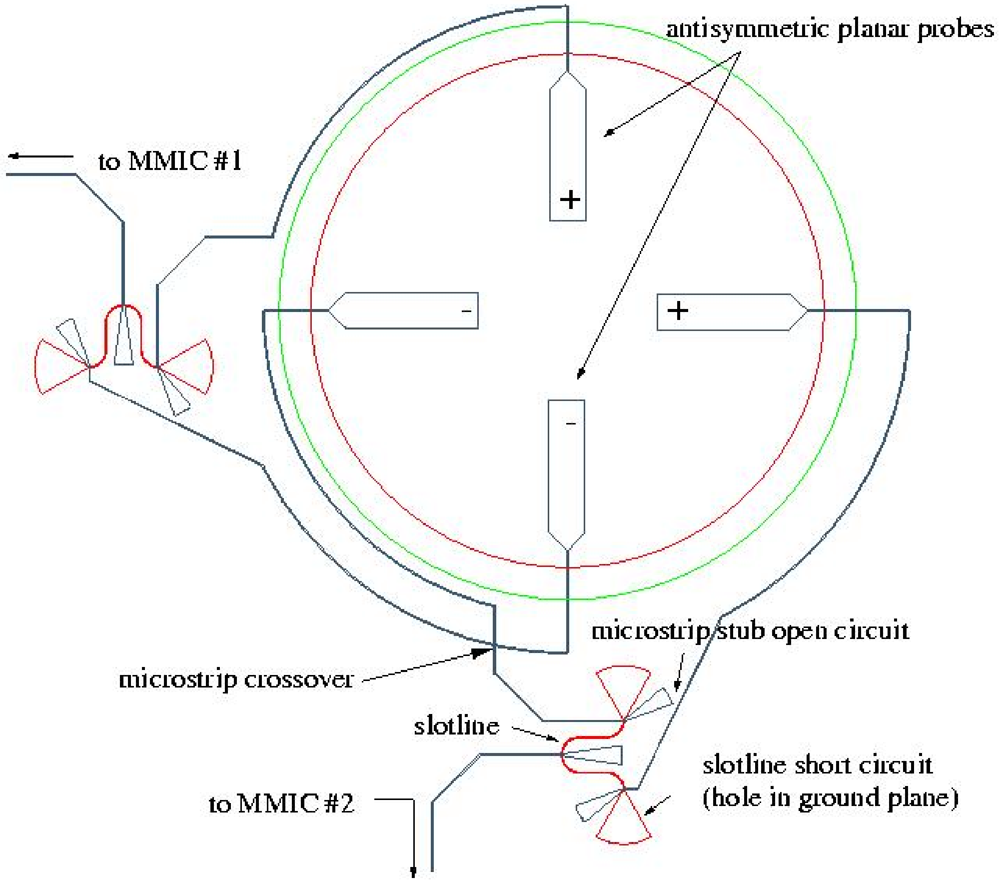

Figure 4 The complete planar orthomode transducer. Blue lines represent microstrip transmission lines and stubs. Red lines represents slotlines, slotline stubs, and a hole in the ground plane for the waveguide cross section. In an actual receiver based on this design, MMIC amplifiers could be wirebonded to the outputs of the power combiners. At the crossover, a short wirebond or microfabricated bridge joins the ends of the interrupted microstrip.

Transducer tests

Figure 4 shows the complete orthomode transducer, consisting of 4 probes and 2 baluns, again fabricated on 0.010″ thick Duroid 6006. This thin circuit board was taped onto an 0.25″ thick sheet of fiberglass, which crudely simulates a quartz substrate. SMA connectors were clamped to the fiberglass sheet and soldered to the two 50 ohm microstrip outputs. The four waveguide probes were pieces of copper tape pasted onto the circuit board and soldered to the microstrip lines. A short length of wirewrap wire was soldered onto the board as a microstrip crossover.

Measurements were made using an 8720A network analyzer and the 6″ diameter circular waveguide which Bock (1999) used to test the freestanding probes. The microstrip lines on the PC board faced the waveguide backshort; small slots, 0.125″ wide × 0.05″ high, were milled into the section of circular guide which contacted the circuit board to avoid shorting out the microstrips. Four dowel pins were used to align the backshort assembly, circuit board, and fiberglass sheet with the waveguide.

To measure return loss and polarization isolation, we directed radiation from the orthomode transducer toward a waveguide load (Figure 5, top). Port 1 of the network analyzer was connected to one set of probes, port 2 to the other; |S11| is the return loss and |S21| is the crosspolarization. To measure transmission, we connected port 1 of the network analyzer to the packaged hybrid and freestanding probes previously used by Bock, and radiated toward the orthomode transducer (Figure 5, bottom), which was connected to port 2 of the network analyzer. |S21| is the transmission. Figures 6 and 7 are photos of the test setup.

For the transmission measurements, losses in the packaged 180 degree hybrid, SMA cables, and a connectorized 180 degree power combiner (the balun tested previously) were calibrated out. Therefore, the measured signal attenuation was due to the combined insertion loss of the source probes, circular waveguide, receiver probes, and the extra length of 50 ohm microstrip used in the orthomode transducer. We did not measure cross polarization by radiating from the freestanding probes to the planar transducer because slight misalignments of the two sets of probes were likely and would lead to spurious results.

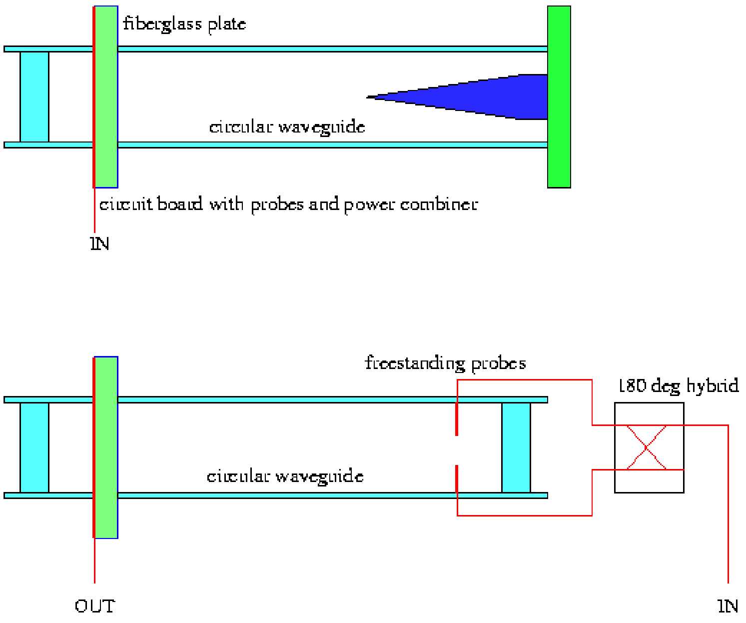

Figure 5. Test setups for measuring return loss and cross polarization (above) and transmission (below). In this L-band model, the thin 6006 substrate simulates an SiON film at millimeter wavelengths; the fiberglass plate simulates a quartz substrate. The termination in the top figure is a conical absorber.

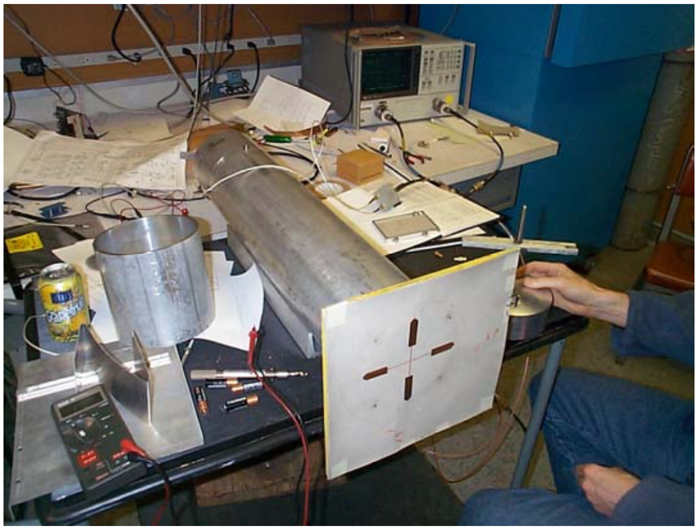

Figure 6. Photo of the transmission test setup with backshort removed to show the two sets of planar probes on 0.010″ thick Duroid 6006. The sheet of Duroid is taped to an 0.25″ thick sheet of fiberglass (yellow). On the opposite end, the circular waveguide is terminated by the freestanding probes and a backshort.

Figure 7. Transmission test setup with the backshort installed.

The measured return loss and crosspolarization of the orthomode transducer are shown in Figure 8. Over the design band of 1.2 – 1.9 GHz, the return loss is –18 dB to –25 dB. The coupling to the orthogonal set of probes is -35 to -40 dB, comparable to that measured by Bock with freestanding probes. It appears that the microstrip crossover, necessary to place two pairs of probes on a single planar substrate, induces negligible cross-polarization coupling.

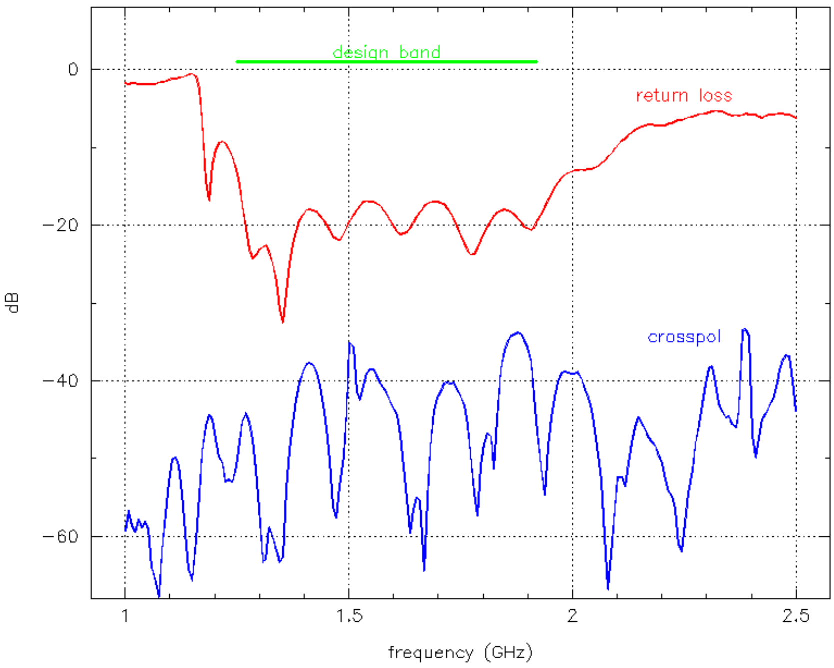

Figure 8. Return loss and cross polarization measurements.

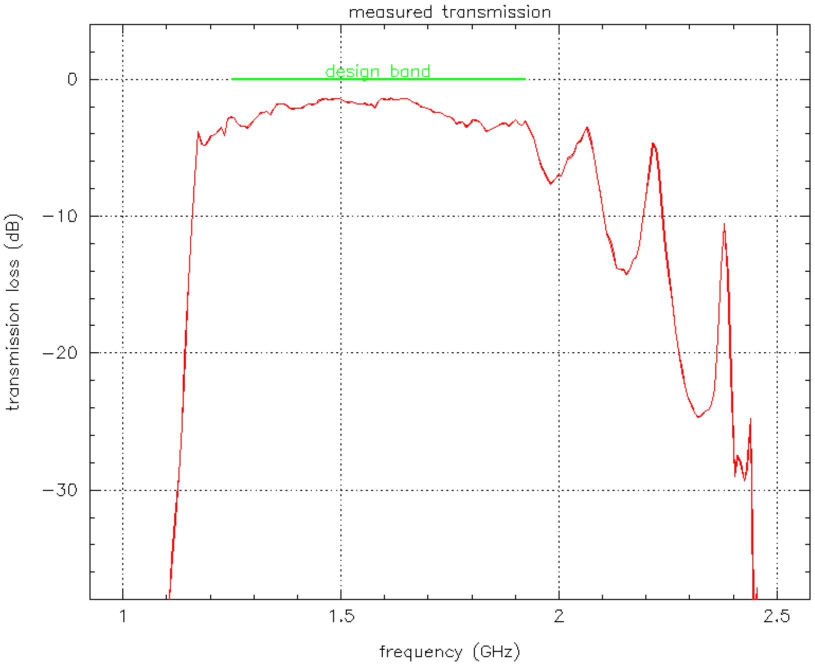

Figure 9 – Transmission measurements.

The origin of the 2 to 3 dB transmission loss is reasonably well understood. The 6″ lengths of 50 ohm microstrip line attached to the probes contribute ~ 1 dB of loss; 30 – 40 % of this arises from dielectric surface roughness, and the remainder is mostly ohmic loss in the metal traces. SiON film sputtered on optically polished quartz should be at least two orders of magnitude smoother than Duroid, and cryogenically cooled traces should exhibit much lower ohmic loss. Scattering of the TE_{11} mode into surface modes on the fiberglass substrate can account for the remaining transmission loss. FDTD simulations predict 0.8 to 1.5 dB attenuation from this effect. This loss could be reduced dramatically by machining a radial choke into the waveguide flange next to the substrate. We omitted this choke in our L-band model because of the difficulty of mechanically modifying the meter-long section of 6″ diameter aluminum pipe used for the input waveguide.

Future Development

Measurements of a L-band scale model confirm that a planar orthomode transducer is a promising device for further development. It provides an excellent input match and good crosspolarization isolation and appears to be manufacturable for frequencies up to 345 GHz. The next step is to build a scale model for the 26 - 40 GHz band, which can be thoroughly tested with our 8722 network analyzer.

We are considering several design modifications:

1. Putting a waveguide flange with a radial choke groove flush with the microstrip substrate to reduce loss.

2. Replacing the slotline balun with an all-microstrip hybrid. While the slotline balun provides exceptionally wide bandwidth, it is more difficult to fabricate because the microstrip and slotline layers must be aligned accurately.

3. Dispensing with the SiON layer altogether and using inverted microstrip. Inverted microstrip is made by depositing leads on a mechanically rigid substrate (e.g., quartz or alumina), then suspending the wiring layer ~0.001″ above a polished metal ground plane. To insure uniform spacing, a film of PTFE or Mylar might be sandwiched between the substrate and ground plane.

4. Terminating the 50 ohm microstrip lines with waveguide probes. The original plan was to wirebond MMIC amplifiers directly to the microstrip outputs, but waveguide outputs could be connected directly to existing SIS mixer blocks.

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