Orthomode Transducer with Waveguide Ports and Balanced Coaxial Probes

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Abstract—**We describe measurements and simulations of a K-band orthomode transducer (OMT) consisting of orthogonal balanced coaxial probes in a circular waveguide linked by coaxial transmission lines to balanced coaxial probes in orthogonal WR42 waveguides. Over most of the frequency range 18 – 26 GHz, the reflection coefficient is < –12 dB and the cross-polarization coupling is <-30 dB. The insertion loss is ~0.4 dB at room temperature.**

To operate at 200-270 GHz, this OMT must be scaled so that the phase imbalance of the matched coaxial transmission lines is less than 15^0, equivalent to a line length difference of less than 0.0015-in, to mitigate periodical resonances. Probes must be located with 0.001-in accuracy. We predict an insertion loss of 0.25 dB at 4K.

Index Terms— **Radio astronomy, Coaxial transmission lines, Polarimetry, Waveguide transitions.**

In a radio astronomical receiver, an orthomode transducer can link a single scalar feedhorn to two independent detectors, where each detector couples signal from one of two mutually orthogonal polarizations [1]. Recent examples of compact orthomode transducers demonstrated to work well at millimeter wavelengths [2] are based on the BØifot orthomode junction [3], which includes a tapered septum in a square waveguide to direct $TE_{0,1}$ and $TE_{1,0}$ modes into separate rectangular waveguides. We explore the possibility that polarization separation at these frequencies can be done with balanced orthogonal coaxial probes in a circular waveguide, instead. Teflon coated wire with ~0.012-in diameter can be placed in narrow channels machined in metal to make low-loss coaxial transmission lines linking coaxial waveguide probes. In this paper we describe measurements and simulations of a K-band scale model orthomode transducer with coaxial probes to measure electromagnetic performance in relation to fabrication tolerances. The results are extrapolated to millimeter wavelengths.

I. Design

Fig. 1 shows an internal view of our orthomode transducer design. Incoming radiation of arbitrary polarization couples into a circular waveguide of diameter 0.455-in. Orthogonal, balanced probes made of Teflon-covered wire enter the circular waveguide wall through four square apertures of width 0.120-in. The wire has a circular cross section with an insulator diameter of 0.117-in and a central conductor diameter of 0.036-in. The four probes lie in a plane displaced 0.13-in (~1/4 λ_g) in front of a fixed circular waveguide backshort. The wire itself was made from Belden RG-402/U type coaxial cable by etching away the outer conductor with nitric acid. Balanced probes for the WR42 waveguide-to-coax transitions, made from the same Belden wire, are 0.068-in long – with a 0.034-in gap between probes – and lie in a plane 0.107-in in front of a fixed backshort cavity.

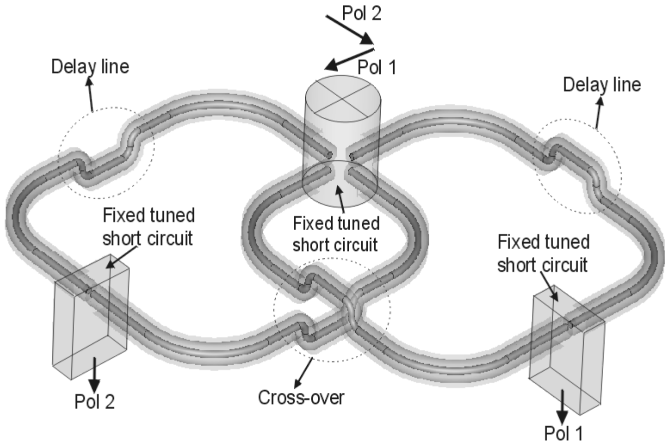

Fig. 1 Internal view of the orthomode transducer showing the input circular waveguide to four-probe coaxial line transition, the cross-over, the delay lines, and the two WR42 waveguide to dual-probe coaxial line transitions at the output.

Transmission lines with 50 Ω impedance are formed by capturing the stripped Belden cable in a symmetrically split channel with 0.120-in x 0.120-in square cross section. Matched transmission lines link coaxial probes formed by wire extensions into waveguide.

The split view of the orthomode transducer (Fig. 2) shows the circular and rectangular waveguides, the coaxial transmission line channels, the delay lines, and the cross-over region. The coaxial lines without their external conductors are seen in the block to the right. The transmission lines are confined largely to a single plane. However, at one position the lines must cross over. Delay lines are used to compensate for the added electrical length due to vertical deflection at the crossover.

The electromagnetic software Microwave Studio from CST, based on the finite integration technique was used to optimize the coax-to-waveguide transitions and simulate the performance of the entire structure, shown in Fig. 1.

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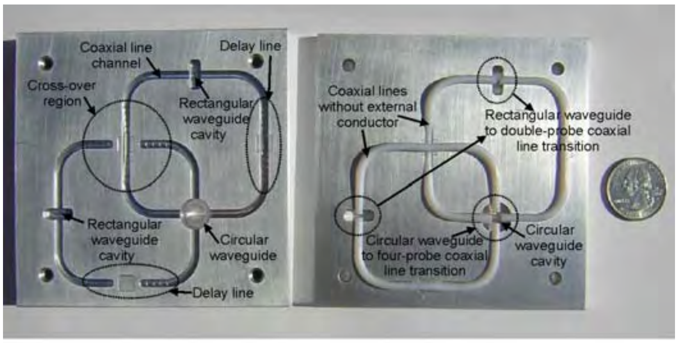

Fig. 2 Internal view of the two aluminum blocks of the orthomode transducer shows the circular and rectangular waveguides, the coaxial line channels, the delay lines, and the cross-over region. The coaxial lines are installed on the block shown on the right.

We assumed a dielectric constant ε_r of 2.05 for the FEP Teflon wire insulation, a conductivity of 6.1 x 10^7 S/m for the silver coated wire core, and a conductivity of 3.5 x 10^7 S/m .

II. K-BAND MEASUREMENTS, FABRICATION ERRORS, AND MODE CONVERSION

If two coaxial transmission lines which link two anti-symmetric probe pairs differ in length, they will transform the probe impedances Z_p differently. This will cause reflections at the waveguide-coaxial probe transitions. These reflections can trap RF energy in 1-d modes on the coaxial transmission lines with guide wavelengths λ_g = 2L/m, where L is the length of the line and m is the mode index. If the two arms of the polarization channel are of slightly different length, sharp resonances appear. When the length of the coaxial lines in the orthomode transducer is 3.42-in, then modes with indices 15 - 22 will occur in K-band.

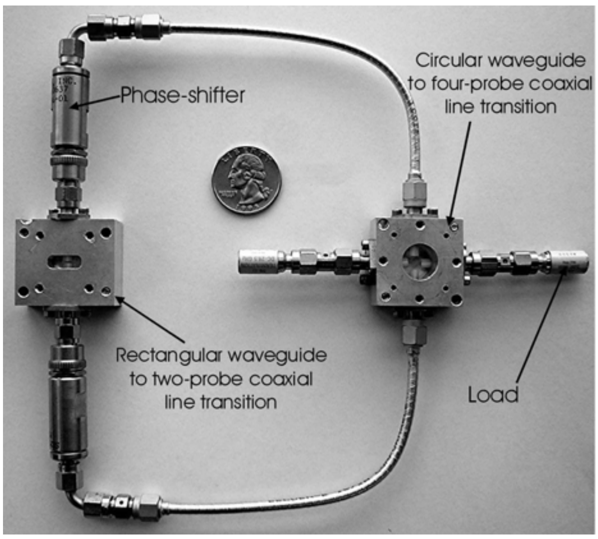

Fig. 3 Orthomode transducer assembled from separable components. Shown are waveguide-coaxial probe transitions, SMA semiflex cables, and Semtech, Inc coaxial phase-shifters. The circuit was used to study resonances due to trapped modes in coaxial transmission lines due to phase imbalance.

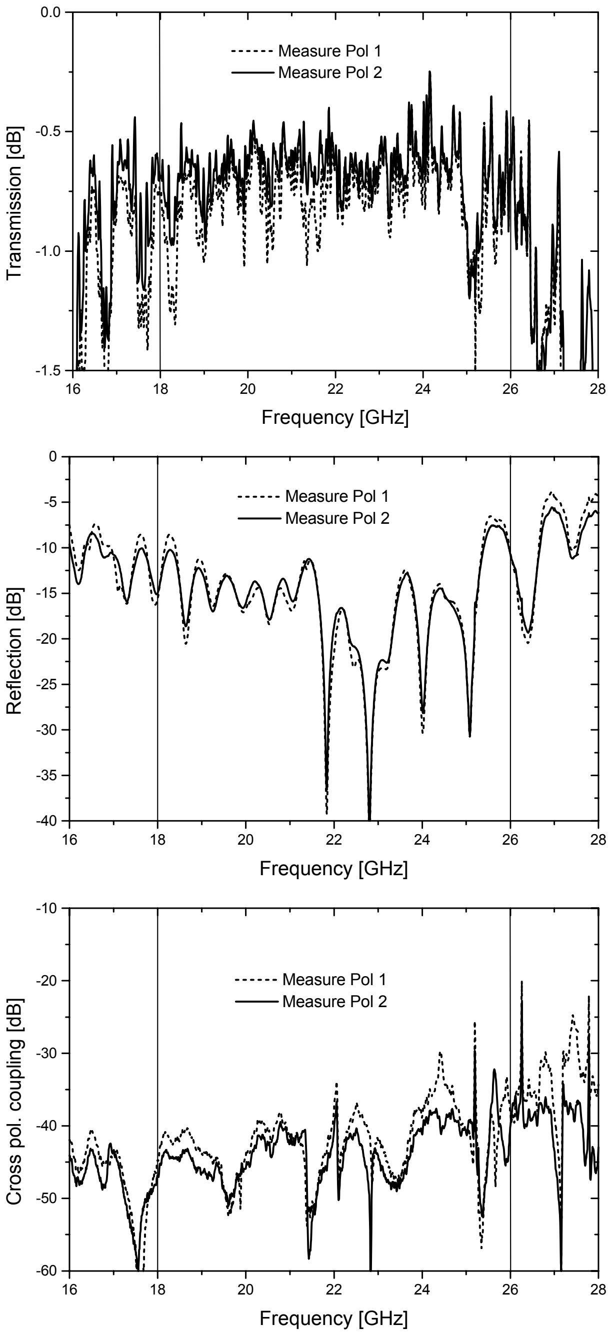

Fig. 4 Measured transmission, reflection, and cross polarization coupling of the separable orthomode transducer for polarization channels Pol. 1 (dashed line) and Pol. 2 (solid line). Measured insertion loss is ~0.65 dB across most of K-band. Reflection amplitude varies between –13 dB at K-band edges and –26 dB at band center. Cross polarization coupling is –30 dB to -40 dB.

To study the origin of the modes, we constructed an orthomode transducer, shown in Fig.3, from separable components. Measurements of the separable orthomode transducer are shown in Fig. 4. The performance of the orthomode transducers shown in Figs. 2 & 3 is comparable, with the exception that the insertion loss of the separable orthomode transducer is somewhat greater (-0.65 dB) than that of the integrated one (-0.4 dB). Both devices have a return loss less than –12 dB and a cross polarization coupling of less than –30 dB over most of the band.

The orthomode transducer functions as a 180^0 power divider (the circular waveguide-coaxial probe transition) in series with a 180^0 power combiner (the coaxial probe-WR 42 transition) linked by equal lengths of transmission line. Any difference in coaxial cable lengths Δ will unbalance the phase of the two lines by $k\,\Delta$, where k is the wave-number of the signal, resulting in a reduced transmission of 10 log ½ (1+ cos k Δ) dB for the recombined signal.

In Fig. 5 the results of deliberately unbalancing the coaxial transmission line arms of Pol. 1 are shown. The phase shifters were used to effectively increase one of the line lengths 0.020-in (~20^0 at 22 GHz) relative to the other. This produces eleven ~1 dB insertion loss resonances spaced at ~0.8 GHz intervals (mode indices m = 23, 24, …, 33) and reduces the average transmission by –0.13 dB. Simulation and measurement both show an insertion loss of ~-0.65 dB. Also, simulation and measurement show nearly identical insertion loss resonances.

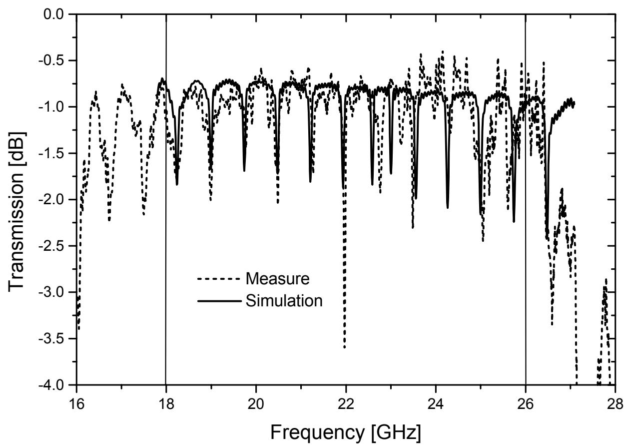

Fig.5 The transmission characteristic for a single polarization channel of the separable orthomode transducer for the case where the coaxial transmission lines have been deliberately unbalanced by 0.020-in, resulting in a 20^0 phase difference at 22 GHz. Prominent resonances arise at ~0.8 GHz intervals. The CST Microwave Studio simulations of the equivalent integrated orthomode transducer circuit predict results remarkably similar to measurement.

In Fig. 6 we present at high resolution (Δf ~ 2 MHz) a typical transmission resonance profile as a function of phase imbalance between the coaxial arms of a single polarization channel. From top to bottom the transmission profiles correspond to phase imbalances which vary from 0^0 to 50^0, where the curves are plotted at 5^0 intervals. As expected, the curves shift to lower frequencies with increasing phase (or line length) imbalance; the profiles get deeper and wider, indicating a rising level of mode conversion [4].

In addition to the unbalanced coaxial line we mention the effect of fabrication errors on the probes. As stated in Section II (a) anything that breaks the four-fold symmetry of the four-probes to circular waveguide coupling structure has the potential to excite higher order modes. However, in K-band only the TM_{01} and the TE_{21} modes can be coupled. Due to the

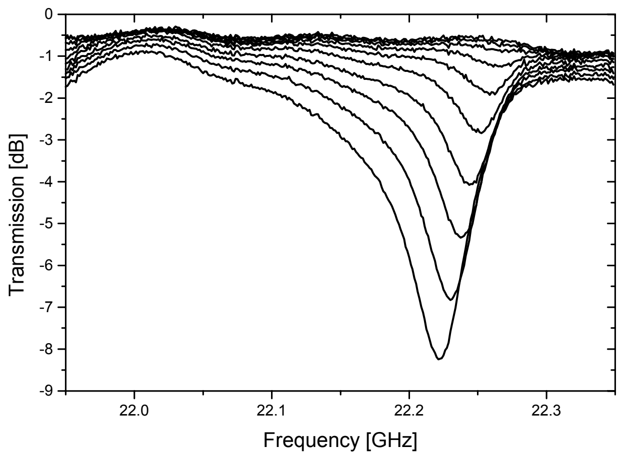

Fig. 6 A typical transmission resonance profile measured as a function of phase imbalance between the coaxial arms of a polarization channel. From top to bottom, the phase imbalance varies from 0^0 to 50^0, with curves plotted at 5^0 intervals.

anti-symmetric phasing of the probes, the TM_{01} mode can couple only very weakly to the fundamental TE_{11} mode, even for substantial probe fabrication errors. Moreover, the TE_{21} mode if excited affects only a very narrow section of the pass-band at 25.195 GHz. More importantly is how probe asymmetries interact with the 1-d coaxial modes. When the probes in either waveguide transition have incorrect lengths or positions they will become reflective discontinuities, trapping energy in coaxial transmission line modes. We tested a number of cases using CST Microwave Studio simulations: for example, probes deflected off-axis (causing azimuthal offsets) by 0.005–0.010-in or probes made unequal (shifting the gap between probes off-center) by 0.005–0.010-in. We find that, provided the coaxial transmission lines are equal length, probe defects have a minor effect on insertion loss. Unequal length diametrically opposite probes will excite a series of coaxial transmission line modes but the amplitude of the resonances will be ~0.1 dB; they barely excite the TE_{21} mode. Probes with azimuthal deflections are much more effective at coupling energy to the TE_{21} mode, but as mentioned before this represents limited insertion loss in the band.

III. Scaling Coaxial Orthomode Transducer to Millimeter Wavelengths

The insertion loss of the coaxial transmission lines in the orthomode transducer scaled for operation at λ = 1 mm must be of an acceptably low level for the device to be useful for astronomical measurements. This can be estimated by combining theory and measurement. When we immersed in liquid nitrogen a straight 3.42-in section of coaxial transmission line identical in length and cross section to those shown in Fig.2, the insertion loss declined from a room temperature value of 0.35 dB to 0.20 dB at 77 K.

An approximation for the losses can be estimated using simple formulas by assuming that both the inner and outer conductors have circular cross sections of radii R_i and R_o, where we set $R_o \sim w/2$, the half-width of the square channel.

The attenuation of the coaxial line α_T equals the sum of the conductor loss α_c and dielectric loss α_d given by (expressed in dB/m):

$$\alpha_c = 8.686\,[(\nu\,\mu_I/\pi\sigma_i)^{1/2}\,1/R_i + (\nu\,\mu_o/\pi\sigma_o)^{1/2}\,1/R_o]/4\,Z_0 \quad (1)$$
$$\alpha_d = 8.686\,\pi\,\nu\,(\varepsilon_r)^{1/2}\tan(\delta)/c \quad (2)$$

Here, $\sigma_{i,o}$ indicates the DC electrical conductivity of the metals, $\mu_{i,o}$ the magnetic permeability of the conductors, Z_0 the characteristic impedance of the line, *c* the speed of light in vacuum, tan (δ) the loss tangent of the dielectric, and ν is the frequency in Hz.

Using room temperature values of σ_i = 6.3 10^7 S/m for silver, σ_o = 3.5 10^7 S/m for aluminum, and tan(δ) = 4 10^{-4} for Teflon, we calculate a loss at 22 GHz of α_T = 2.7 dB/m, where α_c = 1.6 dB/m and α_d = 1.15 dB/m. This gives a total insertion loss of 0.25 dB for a 3.42-in length of 0.120-in diameter coaxial line. If we assume that the conductor losses α_c scale as $T^{0.5}$, then α_c(77K) is approximately 0.4 dB/m [2]. The larger contribution to α_T at cryogenic temperature comes from the temperature independent α_d, and α_T(77K)~1.5 dB/m. The total predicted loss at 77 K for the 3.42-in coaxial line is 0.16 dB. The predicted relative reduction in α_T (~40 %) due to cooling is consistent with the reduction in loss measured when the coaxial line fixture is immersed in liquid nitrogen.

The losses at λ = 1 mm for the coaxial cable can be estimated by rescaling by ~10 the dimensions of the lines used in K-band but now assuming a gold outer conductor, where σ_o = 4.26 10^7 S/m at room temperature. The room temperature losses at 230 GHz estimated by the model for a section of Rubadue wire in a channel are α_T = 19.2 dB/m, where α_c = 7.2 dB/m and α_d = 12.0 dB/m. For a 0.34-in long section of coaxial line, this gives a total loss of 0.17 dB. Ohmic losses will be reduced by a factor of 3 to 4 upon cooling gold to cryogenic temperature, according to Wollack [2], which reduces α_c(4K) to 2.1 dB/m. This results in a total loss of α_T(4K) ~ 14.1 dB/m or an insertion loss of 0.13 dB for our 0.34-in long coaxial lines.

For satisfactory performance, we conclude from scaling the K-band results that wire length and placement in a 230 GHz orthomode transducer must be correct to within approximately 0.001-in.

Connecting to the rectangular and circular waveguide ports requires adequate separation between the ports to allow the attachment of three waveguide flanges. A slight modification of the orthomode transducer geometry makes this simple, as shown in Fig. 7. The circular and rectangular waveguide ports emerge from orthogonal sides of the orthomode transducer, instead of opposite faces, as shown in Fig. 2. Note that the rectangular waveguides are split along the E-plane. Another consequence of this modification is that the coaxial lines can be made much shorter. This reduces the insertion loss of the orthomode transducer and the number of coaxial line modes which can be supported as a result of line length errors.

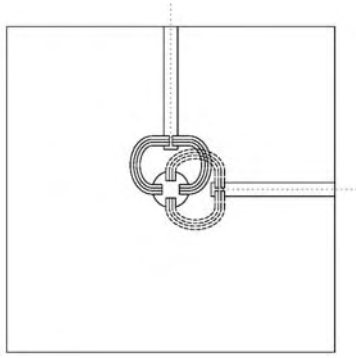

Fig. 7 Proposed geometry of a coaxial orthomode transducer which operates at millimeter wave frequencies. The circular and rectangular waveguides immerge from orthogonal sides of the orthomode transducer, instead of the same side, as shown in Figs. 1 & 2.

The dimensions of the waveguide flanges set the minimum external dimensions of the orthomode transducer. If a standard UG-387M/U flange with 0.75-in external diameter is used, the rectangular waveguide sections have lengths on order of half this value. We estimate that the room temperature loss associated with the attenuation of the single TE_{10} mode in a ~0.35-in long section of gold-plated WR3.7 is 0.45–0.66 dB/in, using Formula 1.66 in Harvey [5] substituting half of the dc gold conductivity. This corresponds to an insertion loss of 0.16–0.23 dB for a ~0.35-in section of rectangular waveguide, that reduces to 0.05–0.07 dB upon cooling the waveguide to 4 K. We estimate that the attenuation of the TE_{11} mode in the circular waveguide, which must be approximately the same length as the rectangular waveguides, is nearly the same (see Formula 1.79 [5]). Hence, for either polarization channel, the combined loss of the input circular waveguide, the coaxial lines, and the output rectangular waveguide is 0.23 – 0.27 dB. In comparison, Wollack [6] measures an insertion loss of ~0.4 dB for a Bøifot-style orthomode transducer fabricated for operation at λ = 1 mm. The noise temperature increase due to 0.25 dB insertion loss at 4 K in front of a SIS receiver with 30 K noise temperature is only 2 K.

References

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