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A FULL WAVEGUIDE BAND ORTHOMODE JUNCTION

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1. Introduction

Receiver systems for radio astronomy require high-performance polarization-discrimination components. In this report, the fabrication and performance of a wideband linear polarization diplexer for 18 to 26.5 GHz are described. The orthomode transducer (OMT) design outlined here employs the concepts laid out by Bøifot (1991).

For dual polarization operation, it is desirable for the cross-polarization induced by the OMT to be less than the level resulting from the quarter-wave plate, the feed, and scattering from the telescope. In the envisioned application. the OMT will be operated at cryogenic temperatures, thus, ohmic loss in the transducer is not a great limitation. In order to facilitate interpretation of spectral line data, it is desirable that the bandpass be smooth (*i.e.*, free of transmission resonances resulting from trapped higher order modes). We adopt the following specification in implementing this design:

- Return Loss: $> 20\,\mathrm{dB}$
- Insertion Loss: $< 0.2\,\mathrm{dB}$
- Isolation: $> 40\,\mathrm{dB}$
- Fractional Bandwidth: > 0.4

In addition, the response of the feed, thermal transition/vacuum window, 45° mode splitter, phase shifter, and isolators (if present) should have a symmetric response for both polarizations and not adversely affect the feed assembly bandwidth.

For a survey of narrow band OMT designs of historical interest, see Ragan (1948) and Harvey (1963). The comments of Smullin and Montgomery (1948) on microwave diplexers are also highly recommended. Skinner and James (1991) outline general considerations for OMTs which arise in context of radio astronomy. Also. see the work by Uher, *et al.* (1993) for a review of OMT designs used in communication systems. Orthomode transducers are also commonly referred to as polarization diplexers, dual-mode transducers, orthomode tees, and orthomode junctions (OMJ) in the literature.

2. Broadband Waveguide Junctions

It is useful to briefly consider the challenges presented in achieving a "good" match in waveguide. When the response of a junction is insensitive to frequency, the junction is said to be broadband. It can be demonstrated that the necessary and sufficient condition for this behavior is that the electromagnetic energy is the same for all accessible eigen-solutions (see *e.g.*, Montgomery, *et al.*, 1948). This level of degeneracy is rarely present in waveguide structures with a finite number of accessible modes.

In practice, a more realizable condition than frequency independence is a slowly varying frequency response, which is achievable in an adiabatic structure. [1] If the coupling to higher order modes along the direction of propagation is slight, energy transport through the guide occurs with little reflection over a wide frequency band. Such structures are adiabatic in the following sense: a one-to-one mapping between the mode set at the input and output of the transition is produced by gradually deforming the cross-section geometry or guide curvature. To achieve a broadband response with this technique, the number of accessible modes associated with the direction of propagation must be large (*i.e.*, the continuum limit). As a result, such designs are typically large compared to a wavelength.

Compensation can also be based upon the principle that a reflection due to a discontinuity can be corrected by a reflection of the same frequency dependence but of opposite sign excited in a common reference plane (De Ronde. 1966). By keeping these lumped discontinuities relatively close together and as few as possible, broadband designs can be realized. However, the required compensating elements can become geometrically complex and difficult to manufacture. The applicability of double-tuned broadbanding techniques is somewhat limited due to the effects of guide dispersion.

The junction symmetry [2] is also of considerable importance for orthomode transducer design. The bandwidth of the isolation and match are essentially determined by the excitation of

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[1] Note added in proof: An "adiabatic" invariant is any physical quantity which remains constant under a slow variation of the system's parameters or boundary conditions. One example which provides a powerful tool in the investigation of such perturbations is the action $I \equiv \int\int dp_i\, dq_i$, where p_i and q_i are the i^{th} component of the generalized canonical momentum and coordinates (*e.g.*, momentum or wavenumber and position, energy or frequency and time, phase and number. spatial-wavelength and position, *etc.*). Physically, the action corresponds to the total accessible phase space volume. The boundary conditions must be continously differentiable and slowly varying on the scale of the characteristic wavelength for adiabatic propagation. In waveguide structures, the generalized coordinates are wavenumber and position, and the relevant field parameter is the reflection coefficient (Bolinder, 1950).

Twists, bends, and transitions which have smooth and long geometric profiles provide common realizations of adiabatic structures from waveguide practice. One should contrast this situation with the "sudden" approximation which is used in describing abrupt changes in system parameters. For example, a step in guide height exhibits a lumped capacitive behavior since the boundary conditions for the electric field change over a length scale small compared to the guide wavelength (see, *e.g.*, Slater, 1942).

[2] A junction is symmetric if the fields are invariant under a rotation by 180° about a symmetry axis. A junction is asymmetric if the field distribution differs by a factor of minus one upon carrying out this operation. A mode has even parity if the field distribution is parallel with the image produced by mirroring the field about the symmetry plane (*e.g.*, a magnetic wall or an E-field maxima at the symmetry plane).

higher order modes. Since both polarizations must propagate in the common-arm, the higher order mode's cutoff frequencies can be lower than the upper-band-edge. Most of the modes in the structure are evanescent and thus do not propagate: however. if excited. the resulting reactance must be compensated. The remaining modes are typically controlled by careful definition of the junction symmetry (Bøifot, 1991).

For discontinuities which are symmetrical with respect to both the guide's horizontal and vertical illumination planes, the dominate mode can only excite a sum of the following terms:

$$\sum_{m=1}^{\infty}\sum_{n=0}^{\infty} \mathrm{TE}_{(2m-1)2n} \quad \text{and} \quad \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} \mathrm{TM}_{(2m-1)2n}.$$

Similarly, if symmetry with respect to the horizontal axis is present. only

$$\sum_{m=1}^{\infty}\sum_{n=0}^{\infty} \mathrm{TE}_{m(2n)} \quad \text{and} \quad \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} \mathrm{TM}_{m(2n)}$$

modes are excited; while for a junction with vertical symmetry, only

$$\sum_{m=1}^{\infty}\sum_{n=0}^{\infty} \mathrm{TE}_{(2m-1)n} \quad \text{and} \quad \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} \mathrm{TM}_{(2m-1)n}$$

will be present. In the single mode limit, application of these concepts reduces to maintaining the modal symmetry and a constant impedance at the junction.

From the standpoint of maximal junction symmetry, the modified turnstile design with four-fold symmetry by Gehin and Tourneur (1986) is preferred. However. we choose the two-fold symmetric junction introduced by Bøifot (1990) as the starting point for the K-band orthomode considered here. The principle strength of this junction is that it can be manufactured as a split-block with conventional numerically-controlled machining techniques.

3. The Bøifot Junction

The Bøifot junction (1990) can be thought of as a turnstile junction where two of the ports have been folded parallel to the common-port (see Figure 1). See Figure 2 for the OMT split-block layout. The two ports that form the main-arm are separated by a thin septum. combined, and transformed to standard height waveguide. For the other polarization, this septum forms a pair of back-to-back "mitred" bends which feed the symmetric side-arm ports. The pin number, diameter, and location are a compromise between tuning the septum reactance produced in the side-arm ports and allowing a low impedance return path for the main-arm currents. From the perspective of the main-arm, it is useful to think of the pins as a pair of short-circuited waveguide-stubs used to tune out the discontinuity due to side-arm

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A mode has odd parity if the field is anti-parallel with its mirror image (*e.g.*, an electric wall or an E-field null at the symmetry plane). If the integrand of the overlap integral at the junction has odd parity, the coupling is zero and the mode is not excited. See Dicke's discussion on Maxwell's equations and symmetry (Montgomery, *et al.*, 1948, section 12.8).

junctions. The signal coupled to the side-arms is transformed down to half-height guide with a cosine taper and recombined. The side-arms can be thought of as a "thick septum" from which the main-arm is carved.

This configuration allows the use of relatively compact and wideband E-plane bends and power combiners. At each junction in the structure, to lowest order, the impedance is constant (voltage-power basis). The main and side-arm junctions are two-fold symmetric about the horizontal and vertical guide planes, thus, $TE^{\square}_{11}$ and $TM^{\square}_{11}$ excitation is avoided. However, the side-arm junction has lower symmetry (a higher level of modal excitation) than the main-arm due to the location of the septum and pins. This reduction in symmetry manifests itself as an increase in junction reactance and results in a significant complication in achieving a broadband match for this illumination. The isolation is determined by the junction symmetry, modal conversion, and the length of septum. In addition, alignment of the common-arm flange is also critical. A breakdown of the transducer return loss is given in Table 1. A brief description of the details of the main and side-arm transitions follows:

The Main-Arm Transition: When a signal illuminates the main-arm junction, the pins act as symmetric short-circuit waveguide-stubs which tune out the discontinuity due to the side-arm ports. With two pins, the return loss is minimized when the pins are centered in aperture formed by the side-arm wall. With one pin, the optimal position is when the outer diameter of the pin is flush to the side-arm aperture (*i.e.*, the pins are in the common-arm). The septum tip forms an adiabatic impedance transformer from 1:1 guide to $1 - dt_{\rm sep}/a_o : 1$ guide. This is followed by a four-step, 2.471:1 Tchebyshev impedance transformer with a normalized fractional bandwidth of $w_q = 0.839$, and synchronous frequency of $f_o/f_c = 1.565$ (Matthaei, *et al.*, 1964). This transformer is followed by an E-plane double-stepped mitre-bend which is used to avoid the side-arm guides. Since a mitre-bend is compensated in the De Ronde sense, the dimensions are somewhat critical. For millimeter applications, an adiabatic bend should be considered as an alternative for the main-arm mitre.

The Side-Arm Transitions: For side-arm illumination, the septum appears as two back-to-back mitres which act as a series power divider. Notice, the main-arm appears as a dispersive reflective termination. The pin/septum geometry provides a double-tuned match which is sensitive to small perturbations in the geometry. The length and width of the septum tips are varied to produce the resonance at the upper/lower band edges. A variant on Kane's (1955) tuning procedure for E-plane forked hybrid-tee junctions was adopted to define the final geometry. (See Bøifot (1990) for a schematic of the side-arm test junction.) Further optimization is possible if desired. The side-arm bends and impedance transformers are a compromise between ohmic and return loss. In addition, they must be the same electrical path length for the side-arm signals to correctly recombine. [3] The side-arm power combiner septum is compensated for minimal reflection.

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[3]Consider the limit where one arm experiences a phase shift of π with respect to the other—the signals cancel at the output power combiner. Due to the length of the side-arms, a phase error manifests itself as a constructive/destructive interference or "beating" between the signals at the side-arm output. This will also occur if the upper and lower split-blocks are not precisely aligned in the side-arm septum region.

4. Fabrication and Test

An OMT to mate with WR42 waveguide [4] was designed and fabricated. The split-block was milled out of 353 leaded brass. The septum was made out of beryllium copper spring stock $\delta t_{\rm sep}/a_o \simeq 0.024$ thick. Two pairs of equally spaced pins, flush with the main-arm wall, having an outer diameter of $2d_{\rm pin}/a_o \simeq 0.095$, were employed. These beryllium copper pins were sinuously ground by Meyer Gage Co., S. Windsor, CT. All components were gold-plated. The pins were lightly pressed into the lower split-block section. The upper split-block receives the pins with a slip-fit and requires mechanical stabilization in order to eliminate variations in port-to-port isolation with pin contact. This stabilization was realized with 60/40 lead-tin solder (Kester 1544 flux, heat to 210 C) or H-20E silver epoxy (100 C cure). The mass of the finished piece was approximately 0.47 kg.

Tests of the prototype and two production orthomode transducers reveal essentially identical electrical response. (See Figure 3 for an example of the measured performance.) Extending the lower band edge can be achieved with a slight increase in tuning complexity and overall transducer volume. In scaling this design to lower frequencies, the total heat capacity and mass can be reduced by increasing the relief and changing the block material to aluminum. In light of the tight mechanical tolerances required in scaling this device above $\sim$ 150 GHz, the finline approach articulated by Robinson (1956) should be considered as a possible alternative.

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[4] The dimensions of WR42 guide are $a_o : b_o = 0.4200'' : 0.1700'' \simeq 2.471 : 1$, where a_o is the broadwall and b_o is the height. This guide is typically used in K-band (18 to 26.5 GHz). The square common-arm guide dimensions are $a_o : b_o = 0.4200'' : 0.4200''$.

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TABLE 1
RETURN LOSS BY OMT DISCONTINUITY

Junction Discontinuity	Return Loss [dB]	Notes:
Pins/Septum	~ 23	(simulated, HFSS)
Main-Arm Mode Combiner Septum	38	uncompensated
Main-Arm Transformer	40	$N = 4$, $w_q = 0.839$
Main-Arm Mitre-Bend	35	compact single mitre
Main-Arm Finite Tool Size	42	$d_{\rm tool}/b_o \approx 0.3$
Side-Arm Adiabatic Bend	48	Gaussian curvature
Side-Arm Adiabatic Taper/Bend	35	cosine blend (Bolinder, 1950)
Side-Arm Mode Combiner Septum	53	compensated

Unless indicted otherwise, the estimates are based upon the expressions given in Marcuvitz (1951) and Alison (1987). The entries reflect the order of magnitude of the return loss for the major discontinuities in the structure.

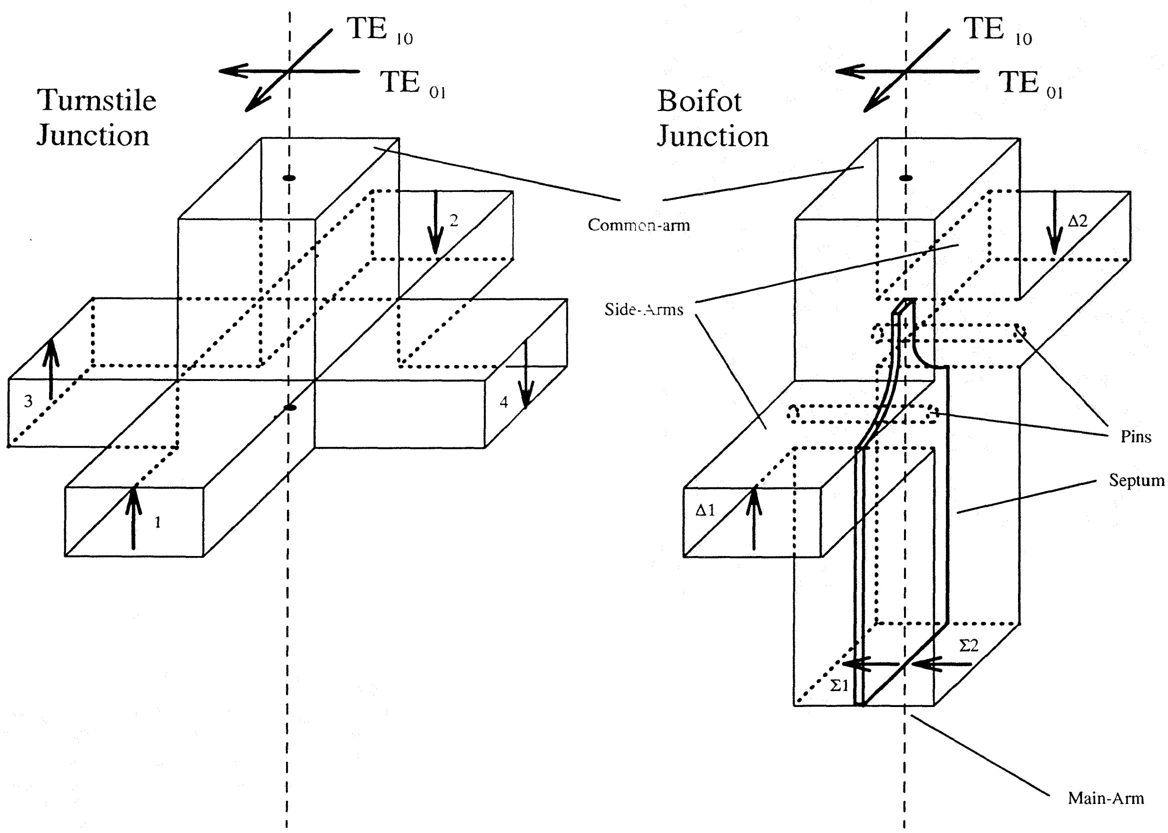

Figure 1. Turnstile and Bøifot Junctions

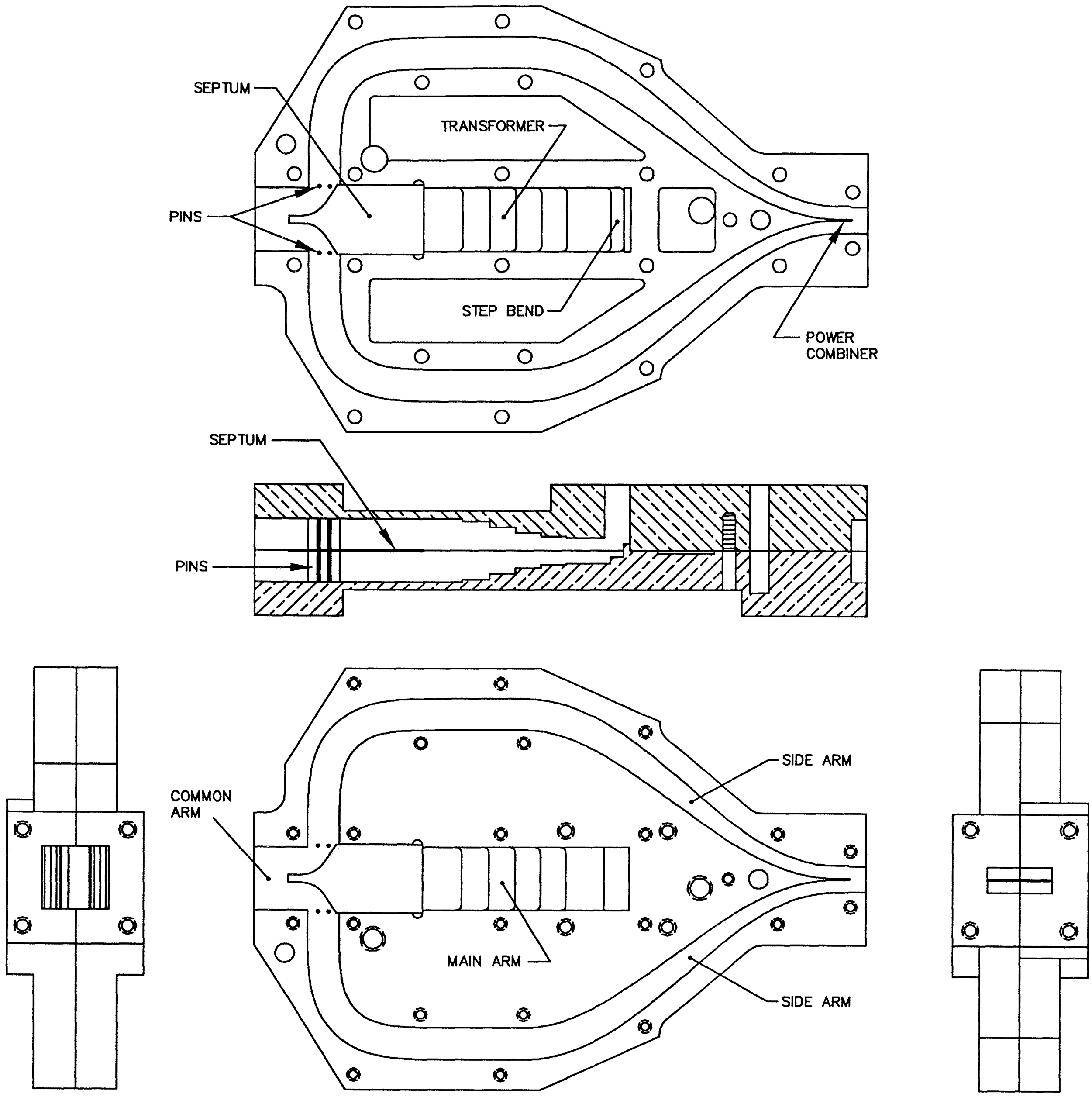

Figure 2. K-Band Orthomode Junction Split-Block

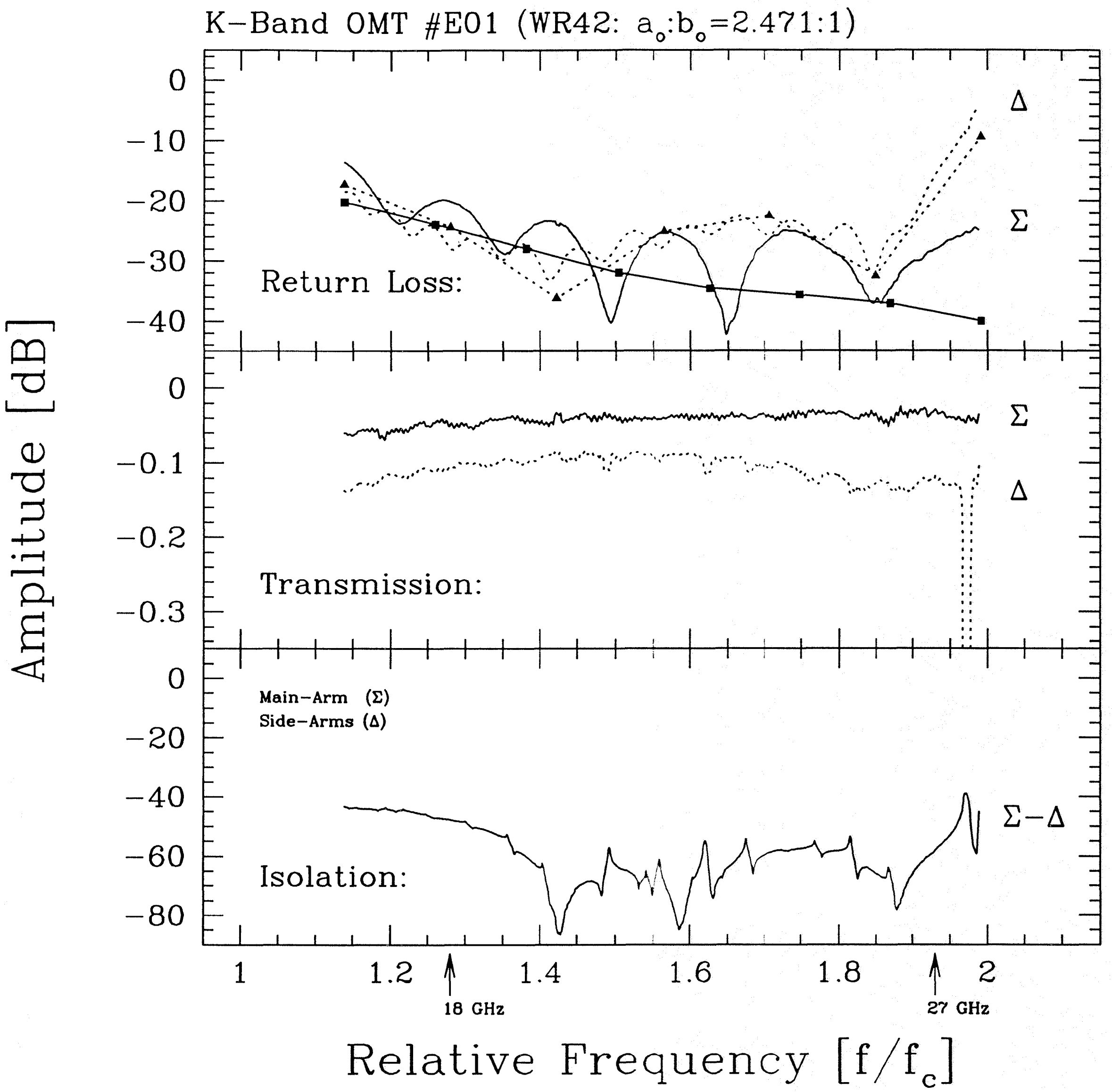

Figure 3. Measured K-Band Orthomode Transducer Performance. The main arm response is indicated by a solid line and labeled "Σ." The side-arm is indicated by a dashed line and labeled "Δ." The results of a finite element analysis of the junction (the bends and transformers are not included) are indicated by squares and triangles for the main and side-arms, respectively. The measured transmission loss and isolation are consistent with the component geometry, the material properties, and the tolerances held during fabrication. The theoretical ohmic loss in the main and side-arms are respectively −0.07 dB and −0.2 dB for a gold electro-plated surface (Marcuvitz, 1951; $\alpha_c \simeq 1.9$).