Wide-Band Orthomode Transducers

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***Abstract* —A summary of the results of a mainly experimental investigation into the development of wide-band orthomode transducers (OMT's) is presented. We show that satisfactory performance for many applications is possible over bandwidths in excess of 2:1. The wide-band return loss and cross-polarization behavior is given where the OMT used is measured in conjunction with a wide-band corrugated horn. Two types of OMT are considered: one based on a finline technique and the other on a quad-ridged waveguide geometry. Overall, the latter design gives superior performance.**

I. Introduction

THERE is an ever-increasing need for antenna systems to operate over large bandwidths in almost all applications, from radio astronomy to defense. To increase further the capacity and versatility of the antenna system, dual-polarization operation is often required or, in some cases, mandatory. With the development of high-performance (corrugated) feed horns [1], [2] capable of dual polarization performance over bandwidth ratios up to 2.4:1, there is a need to develop an orthomode transducer (OMT) of similar bandwidth performance to match the capabilities of the horn. In this paper we report the outcome of an extensive, largely experimental investigation into some possible means of developing a wide-band OMT capable of separating two orthogonal, linearly polarized signals over the bandwidth range of the available horns [1], [2]. Our particular application was to use the OMT within the feed system of the Australia Telescope, which is a new synthesis instrument designed to receive dual linear polarization over a wide range of frequencies of interest to radio astronomers [3].

The various OMT designs commonly used operate with acceptable performance over a limited bandwidth, typically between 10% and 20%. For operation over much wider bandwidths it was deemed necessary to convert from the usual circular or, in some cases, rectangular waveguide at the input to the OMT (i.e., where it connects directly to the feed horn in the case of linear polarization)[1] to a waveguide that is inherently wide-band. In this context a wide-band waveguide is one whose geometry provides a large separation between the cutoff frequency of the fundamental mode and the cutoff frequency of the first high-order mode that can be excited. Common examples include the double-ridged and the quad-ridged waveguide. For the present work, we investigated three possible OMT options, namely, the finline technique described in Robertson [4], a quad-ridged design similar to that found in quad-ridged horns [5], and a commercially available wide-band OMT, the Adams Russell WRD650 OMT [6]. The first two OMT types are described in detail below.

II. Performance Criteria

The degree of bandwidth achievable in any given system is dependent on the performance criteria that are acceptable. There are four main criteria applicable to all designs.

i) *Return Loss*: A number of commercially available quad-ridged horns claim to operate over bandwidth ratios in excess of 3:1. However, this is achieved at the expense of (in part) a return-loss performance which can be as low as 10 dB (sometimes even less) over part of the band. Such a return-loss performance is unacceptable in many instances, especially so in application to radio astronomy, where it is essential for losses to be kept to a minimum. A return loss of no less than 15 dB is more usual, with close to 20 dB over most of the operating band desirable. This more stringent performance criterion inevitably reduces the bandwidth capability.

ii) *Isolation*: The isolation between the output ports of the OMT is of importance and a figure of at least 30 dB is considered essential where dual polarization is required.

iii) *Cross-Polarization*: An important consideration often overlooked in the design of wide-band waveguide components is the excitation of unwanted high-order modes. These are inevitably excited to some degree at the higher frequencies. One of the serious manifestations of unwanted modes is the additional levels of cross-polarization radiated by the horn antenna used in conjunction with the OMT. Thus, another performance criterion in the OMT design is the increase in the cross-polar field that can be tolerated over that of the inherent level from the horn alone.

iv) *Insertion Loss*: The insertion loss of the OMT must be kept to a minimum, with some applications, such as radio astronomy, demanding a figure considerably below 0.5 dB for frequencies in the lower GHz region.

Other criteria, such as ease of manufacture and power handling capabilities, will also be of importance under certain circumstances.

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[1]For the feed horn to operate in the circular polarization mode, it would be necessary to provide a wide-band polarizer between the OMT and the horn.

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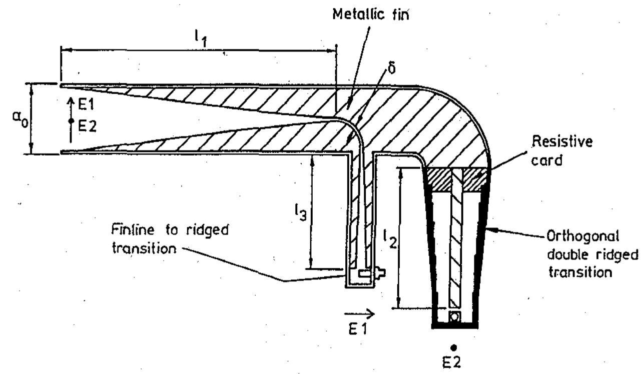


Fig. 1. Cross-sectional view of the finline OMT.

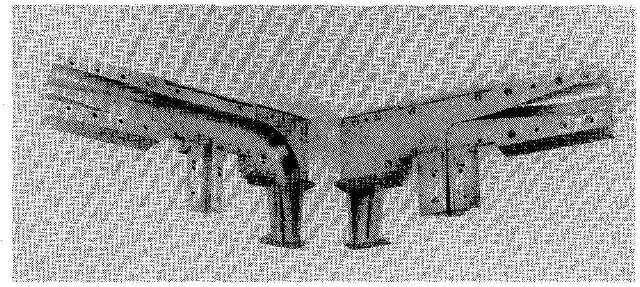


Fig. 2. Exploded view of the prototype finline OMT.

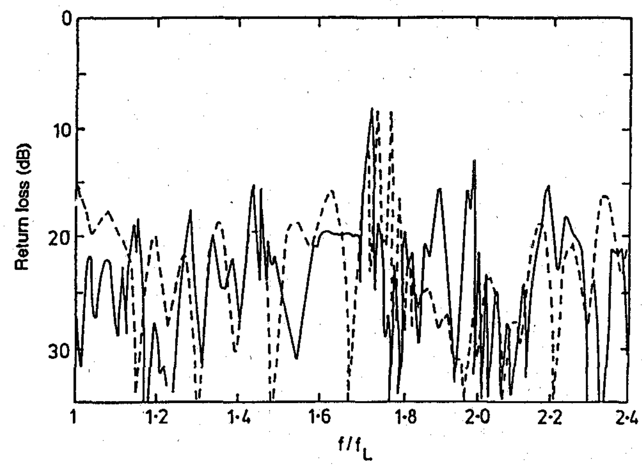


Fig. 3. Measured return loss of the finline OMT connected to a wide-band corrugated horn ($f_L = 7.5$ GHz):——— $E1$ polarization; ---- $E2$ polarization.

III. FINLINE OMT

The basic concept of the finline OMT was developed many years ago by Robertson [4]. In essence, a pair of diametrically opposite tapered metallic fins are fitted inside the waveguide to transform gradually the dominant propagating waveguide mode (polarized parallel to the fins), into a finline mode whose energy is essentially confined to the small gap between the fins in the center of the waveguide. This energy can then be removed from the waveguide by simply curving the fins around a 90° bend and out through a small hole in the side of the waveguide. It is then possible to launch this energy into any other waveguide as desired. A mode polarized orthogonal to the fins continues to travel along the waveguide virtually unperturbed, provided that the fins are sufficiently thin.

Our implementation of this technique for a wide-band OMT is illustrated in Fig. 1. Two orthogonal polarizations, $E1$ and $E2$, are assumed to be excited in square waveguide of width α_0. Polarization $E1$ is gradually transformed over a length l_1 to a finline mode within the small gap, δ. This mode is then taken through a 90° bend and out through a hole in the waveguide wall to permit removal of $E1$ from the waveguide. A further transition from the finline to conventional wide-band double-ridged waveguide over a length l_3 enables the signal to be extracted from the waveguide system by a conventional wide-band coaxial-to-double-ridged waveguide adapter. The orthogonal polarization $E2$ is in turn transformed into double-ridged waveguide (to permit wide-band operation) via a square-to-double-ridged waveguide transition over a length l_2, as shown in Fig. 1. The resistive card is necessary, as in [4], to suppress the excitation of unwanted modes at the termination of the fin. The only purpose of the 90° bend in the square waveguide is to permit the coaxial outputs containing $E1$ and $E2$ to be located physically close together.

For acceptable performance it is necessary to ensure that the various transition lengths, l_1, l_2, and l_3, are of sufficient size and that both the fin width, Δ (not shown in Fig. 1), and the gap between the fins, δ, are sufficiently small. The transition from square to double-ridged waveguide was designed using standard quarter-wave transformer theory over seven steps. The profiles of the tapered fins and finline to ridged transition were not found to be especially sensitive to the curve chosen provided the changes were smoothly varying. Nevertheless, our preference was, eventually, for a sine-squared-type profile as described in [1][2].

For our purposes the OMT is connected directly to a wide-band corrugated horn having a circular waveguide input. The necessary transition from circular to square waveguide is most conveniently performed within the length l_1, of the OMT. Provided this transition is gradual, there is no measurable effect on the performance of the OMT. Fig. 2 is an exploded view of the prototype OMT clearly illustrating the various components[3].

If λ_L is the wavelength corresponding to the lowest operating frequency, then to achieve an acceptable return loss over a bandwidth ratio of up to 2.4:1 it was found (referring to Fig. 1) that we require $\alpha_0/\lambda_L \approx 0.6$ (this value is for the square waveguide input; to have a circular waveguide input with the same diameter as the corrugated horn, we need a diameter α_1, such that $\alpha_1/\lambda_L = 0.75$), $\delta/\alpha_0 \approx 0.01$, $\Delta/\lambda_L \approx 0.02$, $l_1/\lambda_L \geqslant 4$, and $l_2/\lambda_L = l_3/\lambda_L \geqslant 1.3$. An OMT designed to these values has a measured return loss for the two polarizations, $E1$ and $E2$, shown in Fig. 3[4]. Except for a small region within the center of the band where the first high-order mode is in the vicinity of cutoff, the return loss is

[2]The expression Si (χ) in [1] is equivalent to $\sin\chi/\chi$ and is not to be confused with the sine integral function.

[3]The fins screwed into place as shown in Fig. 2 are for the illustration only.

[4]Most of this measured return loss is due to the OMT. The horn alone has a return loss well above 30 dB over most of this band, while the waveguide to coaxial adapter used was generally above 25 dB.

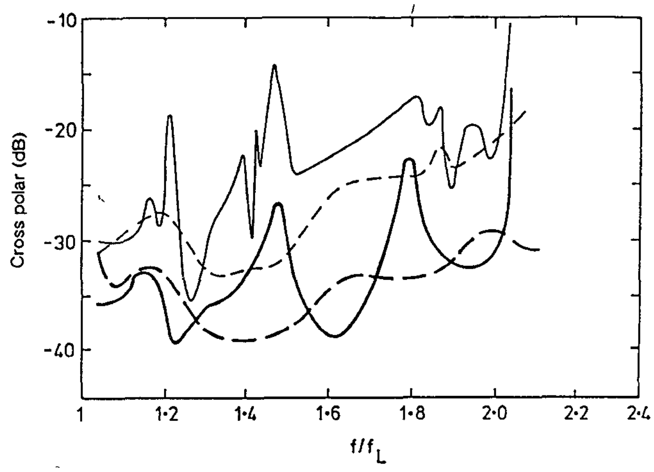


Fig. 4. Measured cross-polar levels of the finline OMT/corrugated horn combination (f_L = 7.5 GHz):

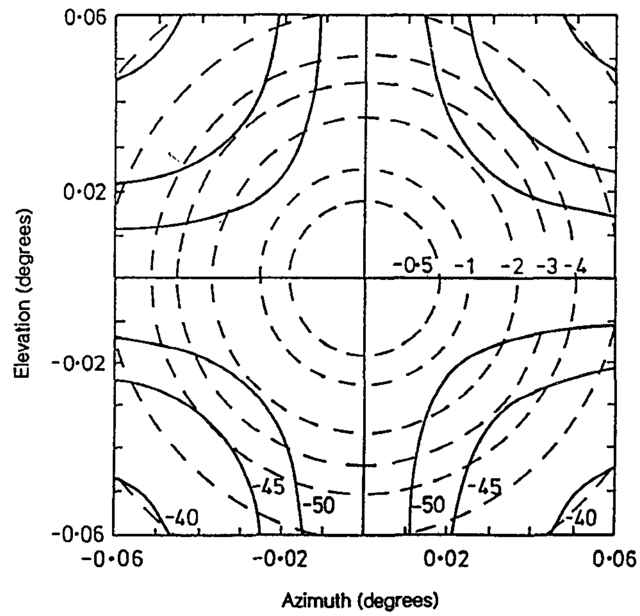
———— $E1$ } max. cross-polar levels
- - - - - $E2$

━━━━ $E1$ } on-axis cross-polar levels.
▬ ▬ ▬ $E2$

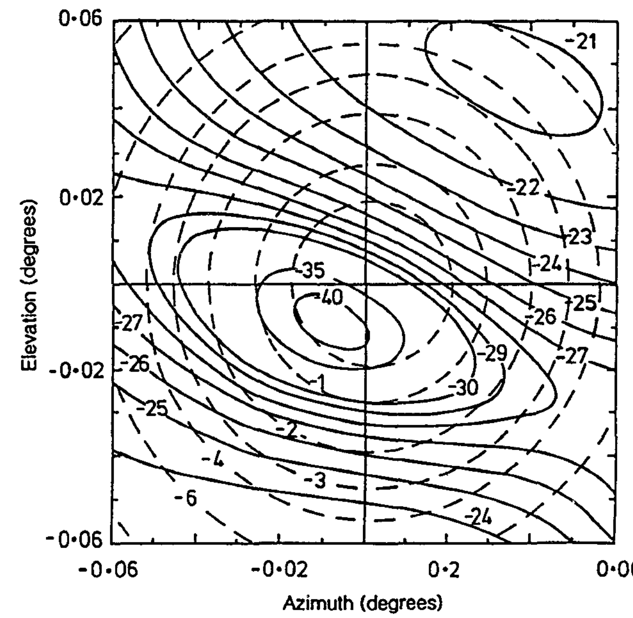
seen to be generally within the required 15 dB level. For frequencies above $2.4 f_L$, the return loss (not shown in the figure) was not readily measured by our experimental setup, but some limited tests indicated a rapid deterioration in return-loss performance at higher frequencies. This is not surprising since the commercial ridged-waveguide-to-coaxial adapters are out of band here. Further, frequencies above $2.4 f_L$ are of little interest in the current application since the corrugated horn used in conjunction with the OMT is also out of band at these frequencies. The measured isolation between the two ports of the finline OMT was in excess of 30 dB over the band.

For dual-polarization applications the cross-polarization radiated by the feed horn is of paramount interest. With the finline OMT connected to a compact wide-band corrugated feed (as described in [1]) the increase in cross-polarization at the higher frequencies, as a consequence of unwanted modes being generated in the OMT, was considerable, particularly for polarization $E1$. In this latter case it was clear that the 90° bend of the fin gap in the waveguide was responsible for most of the increased cross-polarization. For example, as soon as the TM_{11} mode can propagate in the waveguide there is a substantial increase in the cross-polar field. Both the maximum and the on-axis cross-polar level for each polarization are plotted in Fig. 4, and the results clearly illustrate the above comments.

When the maximum cross-polar level exceeds -20 dB, the use of the OMT/horn combination as a feed for a reflector antenna operating with dual polarization ceases to be a viable option. In the case of the finline OMT, this is exacerbated by the strongly asymmetric patterns that often accompany high levels of cross-polarization. As an example, using the measured radiation pattern of the combined OMT/horn as a feed for the dual-reflector antenna in [3], the copolar and cross-polar fields in the vicinity of the main beam were calculated. Two examples are shown in Fig. 5. A "best case" result is shown in Fig. 5(a), where the OMT/horn system is operating at a low frequency where no propagating high-order modes are generated within the OMT. By comparison, Fig. 5(b) represents a "worst case," where the OMT is operating near the top end of the band. In this case it generates high-order modes (especially for polarization $E1$), to such an extent as to increase substantially cross-polarization levels and also produce a slight beam squint. (To make comparison of the radiation patterns easier, both plots in Fig. 5 have been scaled to the same frequency.) In some applications these cross-polar levels will be unacceptably high.



(a)



(b)

Fig. 5. Calculated copolar (dashed line) and cross-polar (solid line) fields in the vicinity of the main beam of a dual reflector antenna fed by finline OMT/wide-band corrugated horn combination. Values on the curves show the level is dB relative to the on-axis copolar value. (a) Low-frequency example where high-order modes are not be excited in the OMT. (b) High-frequency example showing the effects of high-order modes excited within the OMT.

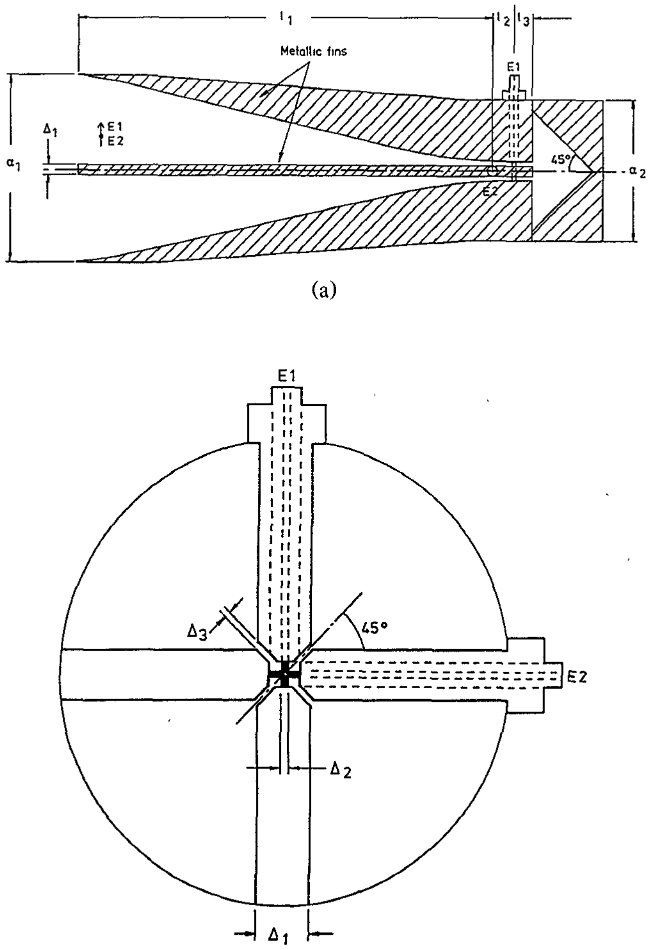


Fig. 6. The quad-ridged OMT: (a) cross-sectional view; (b) end view with shorting cap removed.

In an attempt to reduce the level of unwanted high-order mode generation within the finline OMT, we modified the design to maintain symmetry. In particular, the electric field trapped between the fins in the center of the guide was split equally into two identical paths with the separate signals emerging through side ports on opposite sides of the OMT to be recombined later. Although several techniques were tried, no significant improvement in cross-polar performance resulted.

Some initial concern was expressed as to the likelihood of relatively high return loss when the field was confined to the small gap between the fins. We undertook some insertion loss tests; we used a waveguide with finline sections where the small gap was continued over a length at least equal to or greater than that required by the OMT design in Fig. 1. These tests showed that the insertion loss at X-band for such a section of finned guide was well below 0.1 dB.

IV. Quad-Ridged OMT

An OMT designed around a quad-ridged waveguide has been studied previously [7]. This particular OMT was to be used on a radio telescope operated by the National Radio Astronomy Observatory (NRAO), Greenbank, West Virginia. We had the opportunity to measure an OMT based on

TABLE I
Parameters for Quad-Ridged OMT

$\alpha_1/\lambda_L \approx 0.75$
$\alpha_2/\lambda_L = 0.44$
$l_1/\lambda_L > 4.0$
$l_2/\lambda_L = 0.015$
$l_3/\lambda_L = 0.04$
$\Delta_1/\lambda_L = 0.05$
$\Delta_2/\lambda_L = 0.01$
$\Delta_3/\lambda_L = 0.005$

this initial study [8]. The results were not particularly encouraging with a usable bandwidth ratio obtained of only 1.7:1. The overall length of the quad-ridged OMT design in [7] [8] was kept within $2\lambda_L$ and this relatively short length appears to be a major factor in restricting operating bandwidth.

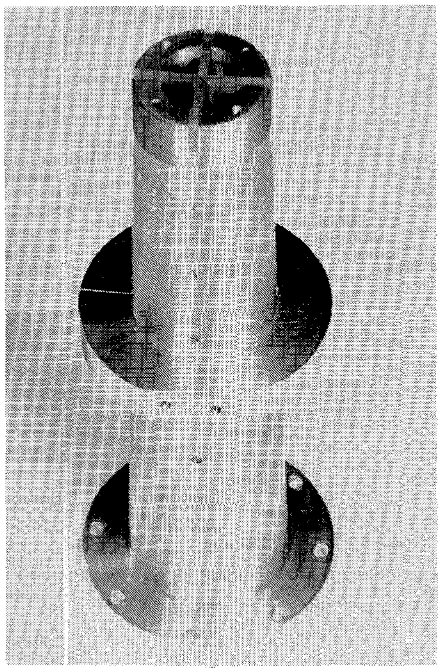
The quad-ridged design is similar to the finline in that tapered fins, or ridges, are used inside the waveguide. However, in this case two orthogonal pairs of ridges concentrate the field into a small gap in the center of the guide. Fig. 6 illustrates the essentials of the OMT. As for the finline OMT, the quad-ridged OMT is designed to connect directly to the wide-band horn, and it retains the circular cross section throughout.

The main purpose of the quad-ridged OMT is to transform the orthogonally polarized fields in the circular waveguide to a quad-ridged waveguide. Provided this latter waveguide is symmetrically excited, its bandwidth (with respect to the separation between the fundamental mode and the next higher order mode discussed earlier) is considerably greater than those for the circular waveguide. The energy is extracted from the waveguide via coaxial lines passing through the center of the ridges. This allows two orthogonal probes to extend across the small gap between the ridges, as shown in Fig. 6(b).

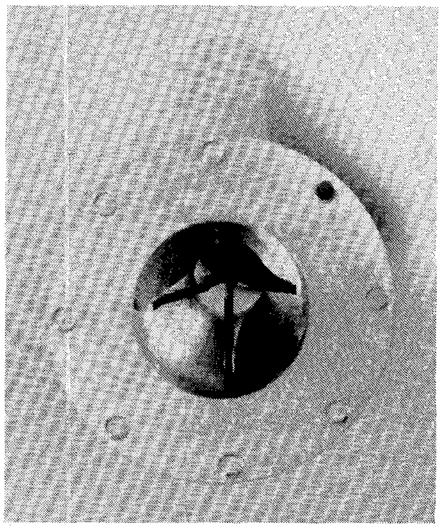
The two main design problems in the quad-ridged OMT are (a) providing a sufficiently smooth transition from the circular to the quad-ridged waveguide and (b) effective matching of the probes over the wide bandwidth required. Based on the experience in developing the finline OMT above and that of [7], [8], we carried out an extensive experimental program. To summarize our results the values of the parameters shown in Fig. 6 which gave the best results are listed in Table I. Initially we used a sine-squared-type taper (as for the finline OMT) for both the ridges inside the waveguide and the outside radius of the waveguide. The short circuit following the termination of the ridges is shown in Fig. 6(a) to be in the shape of a 45° semi-angle cone. This was found to give slightly better performance than a flat back plate. Its final position is best found by experiment.

Fig. 7 shows this OMT developed to operate over both C and X bands. Fig. 8 shows the measured return loss for the OMT (attached as before) to a compact horn. It can be seen that the return loss is generally well above the 15 dB level over a 2.2:1 bandwidth ratio. Outside of this band the return loss rapidly falls to low levels.

Fig. 9 shows the maximum measured cross-polar side-lobe level for the two polarizations together with some results for the maximum cross-polar field arising from the feed alone. The quad-ridged OMT does introduce a general deterioration in the cross-polar performance across the band but this is not as severe as for the finline OMT shown in Fig. 4. Cross-polar levels are maintained at or below the -20 dB



(a)



(b)

Fig. 7. Photograph of a prototype quad-ridged OMT designed for C/X-band operation: (a) general view with the shorting cap removed; (b) view looking into the OMT.

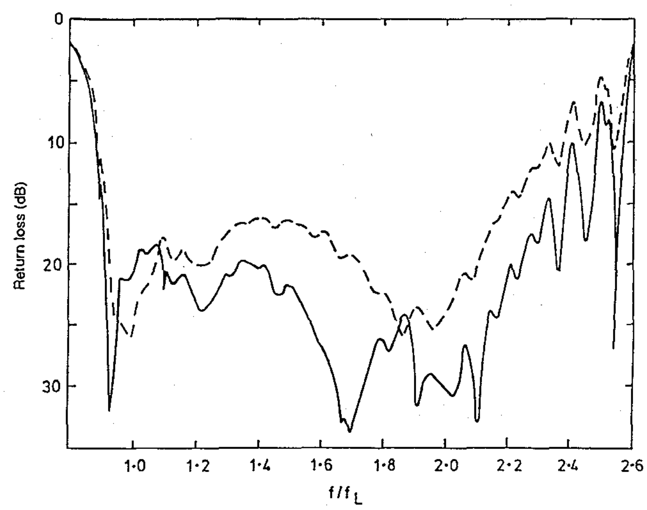


Fig. 8. Measured return loss of the quad-ridged OMT connected to a wide-band corrugated horn ($f_L = 4.4$ GHz): ——— $E1$ polarization; ---- $E2$ polarization.

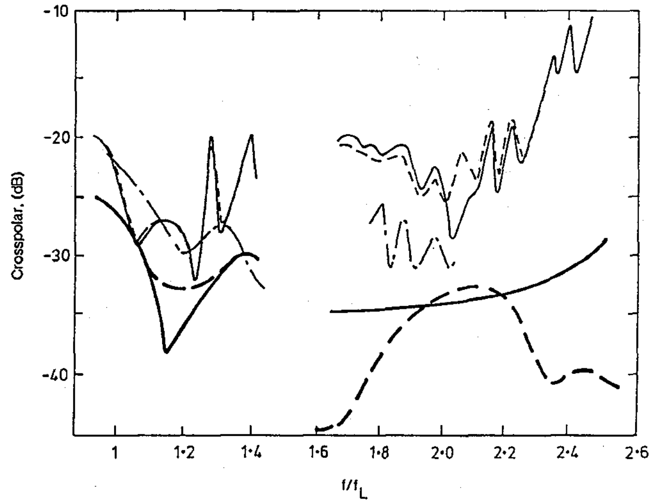


Fig. 9. Measured cross-polar levels of the quad-ridged OMT/corrugated horn combination ($f_L = 4.4$ GHz):

——— $E1$ }
----- $E2$ } maximum cross-polar levels
—·— Horn alone }

——— $E1$ }
----- $E2$ } on-axis cross-polar levels.

level over the same bandwidth ratio of 2.2:1. Also note that there is little to distinguish between the maximum cross-polar performance of the two polarizations. This is in contrast to the finline OMT (Fig. 4). The on-axis cross-polar level with the quad-ridged OMT does vary somewhat between polarizations but is below −30 dB over most of the 2.2:1 bandwidth. Using the measured radiation patterns of the quad-ridged OMT/horn combination at the upper end of the operating band, the copolar and cross-polar fields in the vicinity of the main beam of a dual reflector antenna were computed and are shown in Fig. 10. Compared with the equivalent "worst case" results of the finline/OMT combination shown in Fig. 5(b), the results in Fig. 10 demonstrate the improved cross-polar performance of the quad-ridged OMT, with the levels being sufficiently low as to be suitable for many applications beyond the present one.

As mentioned above, the profiles and lengths of the ridges in the quad-ridged OMT were initially based on the finline OMT developed previously. To obtain some assessment of the effect of length, a quad-ridged OMT with ridges half the length of those used for the results given in Figs. 8–10 (but with the same profile) was constructed and tested. The measured results showed marked deterioration in both return loss and cross-polar performance, making it unsuitable for wide-band application. The ridge profiles in [7] were designed on the basis of maintaining a constant cutoff frequency through the OMT. In waveguide transition design this is a desirable approach for reducing the effects of

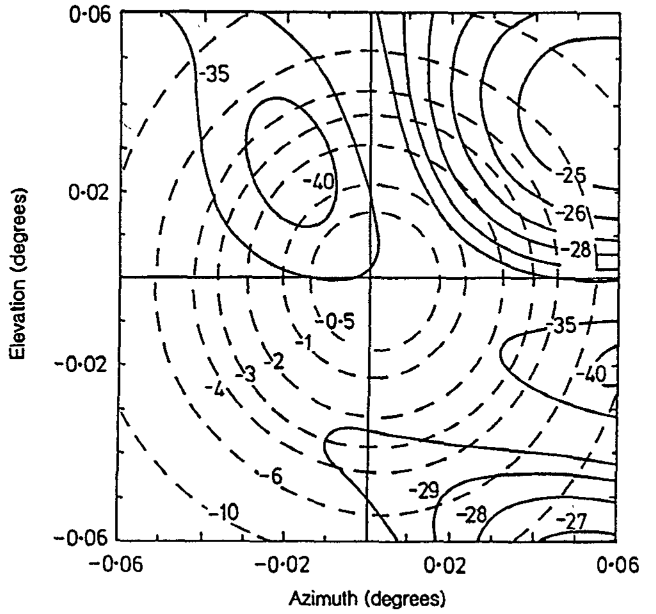


Fig. 10. Calculated copolar and cross-polar fields in the vicinity of the main beam of a dual reflector antenna fed by a quad-ridged OMT/wide-band corrugated horn combination operating at a high frequency to show the effects of high-order mode excitation within the OMT.

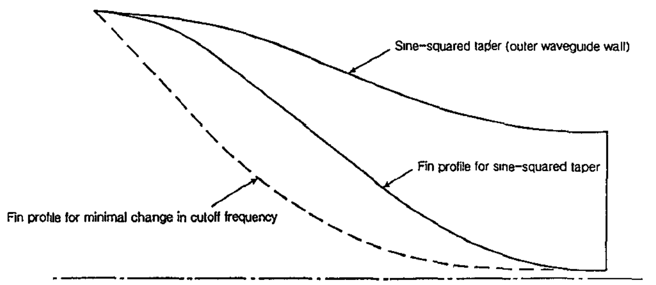


Fig. 11. Comparison of ridge profiles used in the quad-ridged OMT design.

changing cross section. However, in any given design it may not always be convenient to maintain the waveguide dimensions for constant cutoff. As an alternative, and for comparison with previous results, we designed ridge profiles to give the least change in cutoff frequency. This design used a computer program to analyze waveguides of arbitrary cross section [9]. The two profiles are compared in Fig. 11 with Fig. 12 showing the measured return loss using the new ridges. The return-loss level is maintained above 15 dB over at least a 2:1 bandwidth ratio (this was limited in this instance by our measurement range). Qualitatively, this performance is similar to that given in Fig. 8, although a generally "flatter" response is noted in Fig. 12, owing, probably, not so much to the shape of the ridges but to the coaxial connector to the OMT.

The prototype quad-ridged OMT was developed for C- and X-band operation where it was unavoidable, in practice, to have the radius of the 50 Ω coaxial line of the connector different from the 50 Ω coaxial line through the ridge. While in principle a smooth transition is possible between these two coaxial lines with the same impedance but having differing radii, practical implementation was difficult in this case

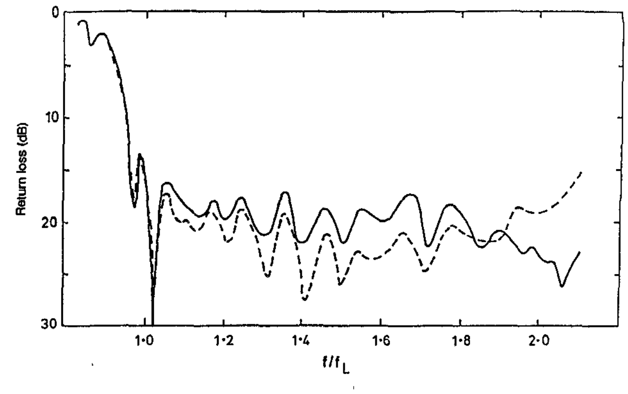


Fig. 12. Measured return loss of the quad-ridged OMT where the profiles are designed for minimal change in cutoff frequency ($f_L = 1.25$ GHz): ——— $E1$ polarization; ---- $E2$ polarization.

given the small physical size of the coaxial lines. Hence, an abrupt junction was tolerated and the characteristic shape on the return-loss curves in Fig. 8 is not inconsistent with a small mismatch at the junction of the coaxial connector to the coaxial line through the ridge. This problem does not arise at lower frequencies, as the results in Fig. 12 show. In this case the OMT was developed for L- and S-band operation, where with the physically large waveguide components it was possible to avoid an abrupt junction at the connector–ridge interface.

The measured cross-polar performances of the C/X- and L/S-band OMT's was very similar. Further, when we compared our near-constant cutoff frequency ridge design to the similar but shorter ridge design given in [8] over the same frequency band, it was possible to draw close parallels to the length comparison made above. It is our conclusion, therefore, that for adequate performance the length of the OMT is more important than the particular design of the ridge profiles, provided the latter are smoothly varying and the variation in cutoff frequency is not too large. Finally, measurements undertaken on an L/S-band OMT (where $f_L =$ 1.25 GHz) cooled to a temperature of 70 K gave a noise temperature reading of 3 K. This corresponds to an insertion loss of < 0.2 dB at room temperature.

V. Adams Russell WRD650 OMT

The only commercially available wide-band OMT that we are aware of is the Adams Russell WRD650. This is an ingenious design which has a performance similar to that for the quad-ridged OMT. However, it has a somewhat complicated geometry, making it relatively difficult to manufacture, as well as a relatively high insertion loss. Further, it was not readily available in the frequency bands we required. Nevertheless, this OMT is capable of handling considerably higher power than the other two designs and in such instances would find wide application.

VI. Conclusion

The results of an experimental investigation have shown that a wide-band OMT can be designed to operate over a 2.2:1 bandwidth ratio with a return loss better than 15 dB and a maximum cross-polar level (when used in conjunction with a high-performance wide-band corrugated horn) of -20 dB or less. As an application, performance results are given for an OMT/corrugated horn combination operating as a feed for a dual-reflector antenna.

Acknowledgment

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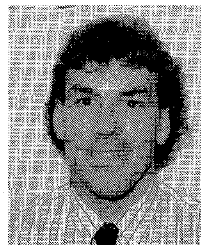

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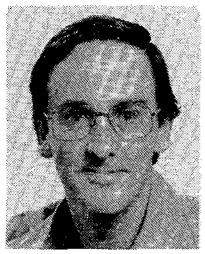

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