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Directional Couplers for Detecting the TE_{11} and TE_{12} Circular Waveguide Modes

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This article describes the theoretical and experimental results for a pair of mode-selective directional couplers designed to detect the TE_{11} *and* TE_{12} *modes in a multimode circular waveguide. A brief description of the design of the couplers is presented, followed by a comparison of their measured and calculated parameters. The couplers were used to measure the characteristics of a circular waveguide mode converter. The results of these measurements are described.*

I. Introduction

This article is the last in a series describing the transmission-line components required for a proposed high-power (400-kW) millimeter-wave (34.5-GHz) transmitter. The high-power and high-frequency requirements pose many problems that are unique to this transmitter (Ref. 1). In order to transmit power from the amplifier to the antenna focus without breakdown, an oversized multimode circular waveguide must be used. Directional couplers that are sensitive to individual modes are required for monitoring transmitter output power, and for testing the waveguide components and the proposed gyroklystron amplifier. This article describes theoretical and experimental results for two such couplers, one for detecting the TE_{11} circular waveguide mode, and the other for detecting the TE_{12} mode.

II. Mode-Selective Coupler Design

The theory used to design the mode-selective directional couplers is basically the loose coupling theory described by Miller (Ref. 2). The main circular waveguide is coupled to a rectangular waveguide through a series of coupling holes as depicted in Fig. 1. For *TE* couplers, the coupling is designed to be through the longitudinal magnetic field (H_z) in the circular and rectangular waveguides; therefore, the rectangular guide is attached to the circular guide through its small (b) dimension as shown in Fig. 1. This configuration eliminates any coupling of *TM* power from the main waveguide.

Coupling to a particular *TE* mode in the circular guide is maximized by adjusting the rectangular waveguide's wide (a) dimension so that the phase velocity of its dominant mode matches that of the circular waveguide mode of interest. The coupling waveguide is then tapered down to a standard size for connection of a detector. High directivity is assured by spacing the holes at one quarter of a guide wavelength. Since the coupler is mode-selective, it must by definition reject power present in other circular waveguide modes traveling in the forward and reverse directions. This rejection is usually specified in dB and is called the selectivity. Selectivity for specified modes can be optimized by using a large number of

coupling holes and tapering the coupling profile with distance (i.e., changing hole size). These effects can be simulated quite easily with a simple computer program that adds up the contributions from each hole in the coupling array to obtain the total coupling for each circular waveguide mode at each frequency of interest. Finite wall thickness and the effects of various coupling profiles can be included in the model with little complication.

III. Final Design Parameters

TE_{11} and TE_{12} couplers were designed for a circular waveguide with a diameter of 1.75 in. operating at a center frequency of 34.5 GHz. Design goals included a directivity of at least 40 dB and a selectivity of at least 30 dB for each of the forward and reverse traveling spurious TE_{1n} modes over a 1% bandwidth.

The TE_{11} coupler requires a highly oversized coupling guide with a wide dimension of 1.493 in. in order to match the phase velocities of the TE_{11} circular mode and the TE_{10} rectangular mode. Since for the frequencies of interest and these dimensions the TE_{30} mode is allowed to propagate in the coupling guide (and it is strongly coupled to the TE_{12} mode in the circular guide), great care must be taken in tapering the coupling guide down to standard WR28 size. A highly nonlinear taper was used to avoid coupling large amounts of this TE_{30} power into the TE_{10} mode during the transition. A first prototype of the coupler used a linear taper and showed poor selectivity for the TE_{12} mode due to these effects. In both couplers, the small dimension of the coupling guide was chosen to be the standard WR28 dimension of 0.14 in. The number of holes required to meet the selectivity requirements was determined to be 154 through computer simulation, and a linearly tapered coupling profile was also found to be necessary in order to meet the specifications. Hole spacing was 0.087 in. and wall thickness was 0.020 in. The actual coupling value can be set by scaling the hole diameters, and a coupling value of about 70 dB was obtained using a maximum hole diameter of 0.060 in. A photograph of the fabricated TE_{11} coupler is shown in Fig. 2.

The design of the TE_{12} coupler is similar, requiring a coupling guide width dimension of 0.516 in. and 144 coupling holes with a spacing of 0.092 in. Once again, a linearly profiled coupling profile was used. A maximum hole diameter of 0.050 in. gave a coupling value near 55 dB at the design frequency of 34.5 GHz. The predicted coupling and selectivities for the forward traveling spurious modes are displayed for this coupler versus frequency in Fig. 3. Selectivities for the reverse traveling modes are predicted to be greater than 60 dB and are not plotted.

IV. Coupler Results

Measurements were performed to determine the coupling, directivity, and selectivity values for the two couplers using an HP 8510 automatic network analyzer and additional components required to extend the instrument to the 26.5- to 40-GHz range. The measurement of the TE_{11} coupling is compared to the theoretical results in Fig. 4. A WR28-to-circular waveguide transition and taper up to the 1.75-in. circular waveguide size were used to launch a pure TE_{11} mode into the 1.75-in. circular waveguide in order to make the measurement. The loss through these components was calculated and removed from the measured data. The difference between the theory and measurement is within the error specification for the HP 8510 network analyzer for these large values of attenuation. A measurement of the reverse coupling was also attempted, but no reverse coupling was detectable down to the noise floor of the HP 8510, which is about -100 dB. From this, we conclude that the directivity is greater than 30 dB.

A similar measurement was made for the TE_{12} coupler. In this case, a TE_{11} to TE_{12} mode converter was included in the experimental setup. This device, which was described in a previous report (Ref. 3), is capable of generating a highly pure TE_{12} mode over a limited bandwidth around 34.5 GHz. The measured coupling value of 53.49 dB at 34.5 GHz for the TE_{12} coupler may be compared to the calculated value of 55.50 dB. The agreement here is seen to be somewhat worse than that for the TE_{11} coupler, but still satisfactory considering the possible measurement errors and approximations made in the theoretical calculations.

The measured reverse coupling at 34.5 GHz once again approached the limits of the HP 8510, reaching 99.4 dB. This translates to a directivity near 46 dB at the center frequency. Further measurements involving the mode converter and the two couplers are described later in this article.

An effort was also made to determine the selectivities for the couplers. Since with the available mode converter and tapers it was possible to produce only relatively pure TE_{11} and TE_{12} modes, the TE_{11} coupler's rejection of the TE_{12} mode and the TE_{12} coupler's rejection of the TE_{11} mode were measured. A known composition of TE_{11} and TE_{12} modes was injected into each of the couplers. The phase between the two modes entering the couplers was then changed by adding straight sections of guide before the couplers. As the length is changed by at least one beat wavelength, all relative phases between the two modes can be observed. The interference caused by the unwanted mode can then be seen as a ripple in the coupled power. The technique is very similar to the sliding short method of determining coupler directivity. By placing a limit on the observed ripple, and by know-

ing the mode composition in the waveguide, one can calculate the desired selectivity. Measurements at the center frequency of 34.5 GHz revealed that the selectivity of the TE_{11} coupler for the TE_{12} mode was slightly better than 20 dB, while the TE_{12} coupler rejected the TE_{11} mode by more than 30 dB, and thus met the selectivity goal. Although the selectivity of the TE_{11} coupler with respect to the TE_{12} mode was lower than expected, this should not pose a serious problem in the expected applications of the coupler. This is the case because the coupler will be used to detect the TE_{11} mode, where only small amounts of spurious power are expected to be present, whereas the TE_{12} coupler will be used to detect small amounts of TE_{12} power in the presence of large TE_{11} signal levels.

V. Mode Converter Measurements

This section of experimental results discusses measurements of the frequency response and mode content versus distance for the TE_{11} to TE_{12} mode converter. These measurements were also made using the far-field pattern measurement method described previously (Ref. 3). Once mode-selective couplers have been built and characterized, the above measurements can be made more easily and directly. The directional coupler method is also better suited to high-power measurement than the far-field pattern method.

The frequency response of the TE_{11} to TE_{12} mode converter is depicted in Fig. 5. For these measurements, a pure TE_{11} mode enters the mode converter, and the relative power in the TE_{11} and TE_{12} modes exiting the device is measured using the mode-selective couplers. Theoretical and measured results are given for both modes. Near the center frequency of the converter, nearly all of the input power is converted into the TE_{12} mode. Therefore, the power coupled out by the TE_{12} coupler peaks, while the TE_{11}-coupled power dips. Good agreement is found for all frequencies for the TE_{12} power. Good agreement is also found for the TE_{11} power at all frequencies except for those near maximum TE_{12} output and minimum TE_{11} output. Here, only a 20-dB drop in TE_{11} power is seen, even though a much larger drop is predicted. This is to be expected due to the finite selectivity of the TE_{11} coupler with respect to the TE_{12} mode. The TE_{11} coupler only rejects the TE_{12} mode by 20 dB, so when the TE_{12} power exceeds the TE_{11} power by more than 20 dB, the TE_{11} coupler's output power is primarily due to TE_{12} leakage. These results are then consistent with the previous measurements, which showed 20-dB selectivity for the TE_{11} coupler.

Next, the mode content as a function of distance along the mode converter at a frequency of 34.5 GHz was measured using the couplers. This is possible since the mode converter, which is a ripple-walled circular waveguide, was manufactured in several sections. The complete device contained 7 ripples, and was made up of two sections with 2 ripples each, and one section with 3 ripples. By using different combinations of these sections, the mode content after 0, 2, 3, 4, 5, and 7 ripples may be determined. The theoretical mode content may be calculated for any position in the device, however, and is plotted in Fig. 6. The mode content after 0, 2, 3, 4, 5 and 7 ripples as measured by the couplers is also plotted for comparison. For reference purposes, each ripple is 1.364-in. long. Once again, excellent agreement is found for almost all of the data points. There is some disagreement for the 0- and 7-ripple cases due to the finite selectivities of the couplers. For the 0-ripple case, essentially no TE_{12} power is present, but the TE_{12} coupler does produce some output power due to its finite selectivity for the TE_{11} mode. Note that the measured power is over 30 dB below the TE_{11} power. This is consistent with a selectivity value of greater than 30 dB for the TE_{12} coupler with respect to the TE_{11} mode, as was quoted earlier. For the 7-ripple case, the finite selectivity of the TE_{11} coupler comes into play, and gives an artificially high value for the measured TE_{11} power.

VI. Conclusions

A brief description of the method used to design mode-selective couplers has been presented, along with parameters for a TE_{11} and a TE_{12} coupler that have been fabricated and tested. Good agreement between predicted and actual performance has been obtained. These couplers were then used to determine the characteristics of other multimode devices, once again with good agreement between theory and experiment. These latter experiments also demonstrated the limitations that these couplers have due to the finite rejection of other modes. Couplers may be designed to detect other *TE* modes by a change in coupling guide and hole dimensions, while couplers for the *TM* modes would require coupling through the broad wall of the rectangular waveguide instead of the narrow wall.

Acknowledgments

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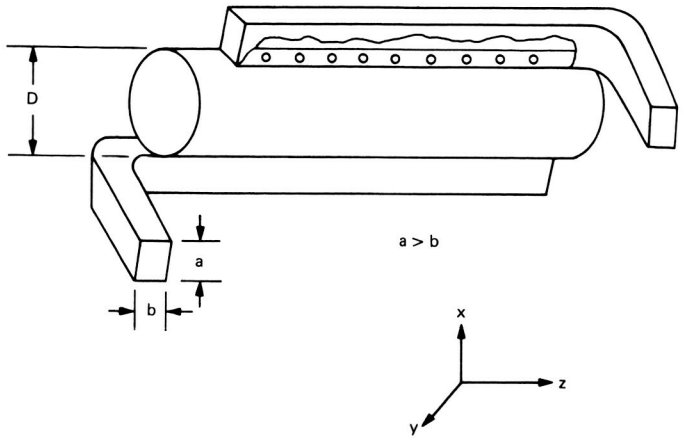

Fig. 1. Mode-selective coupler configuration

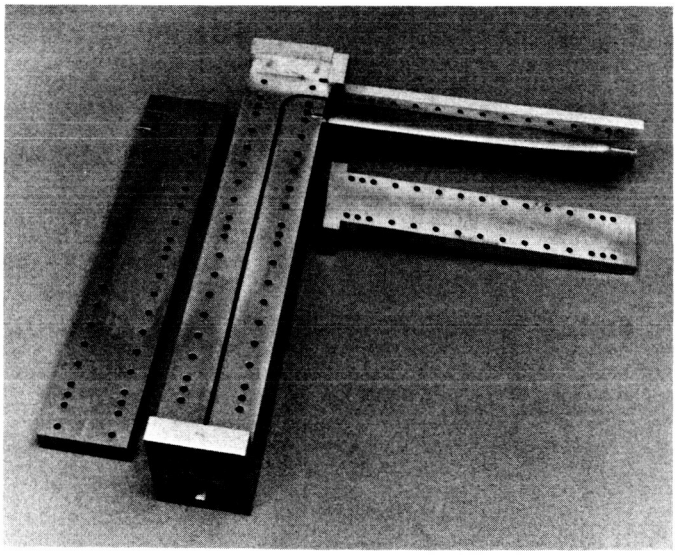

Fig. 2. Fabricated TE_{11} coupler

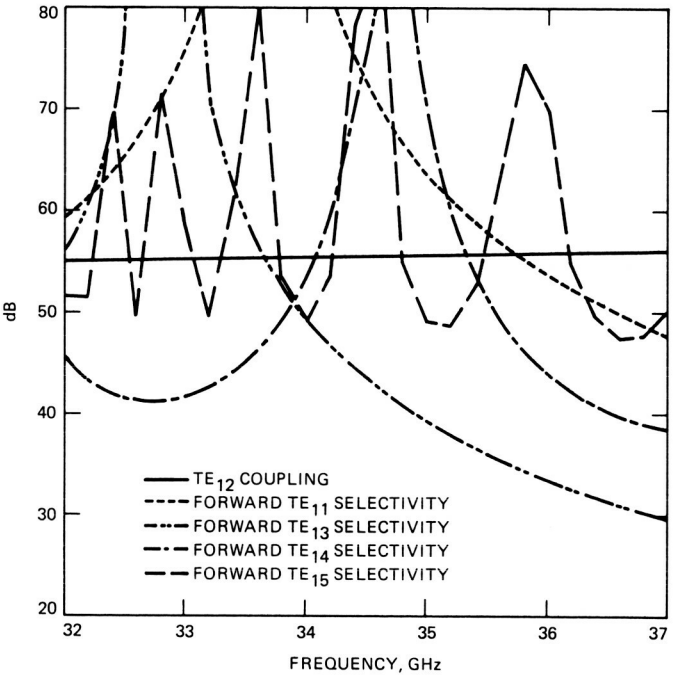

Fig. 3. Predicted coupling and selectivities for TE_{12} coupler

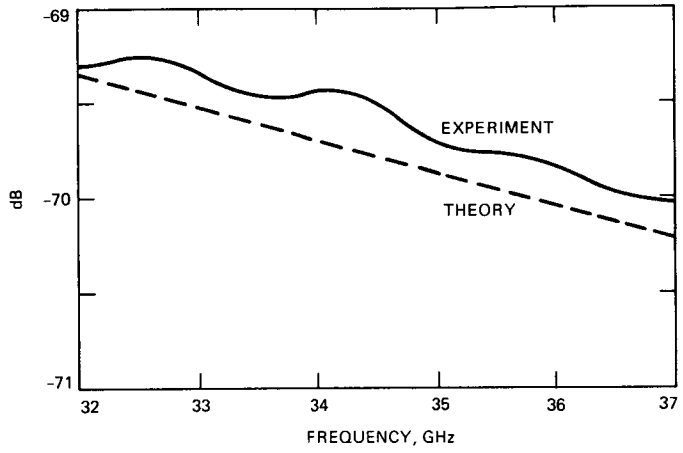

Fig. 4. The TE_{11} coupling measurement vs theoretical results

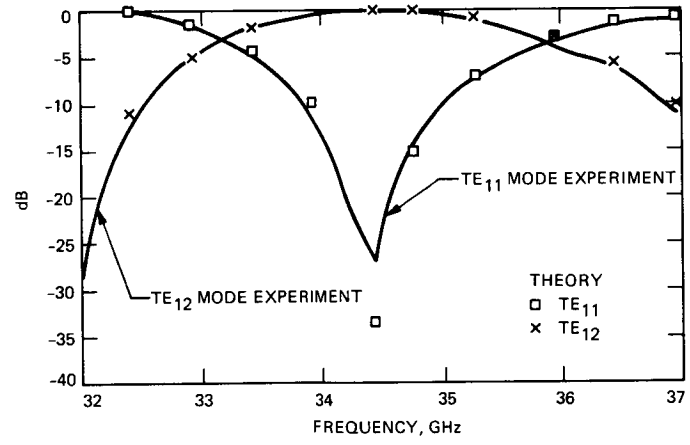

Fig. 5. The TE_{11} to TE_{12} mode converter frequency response

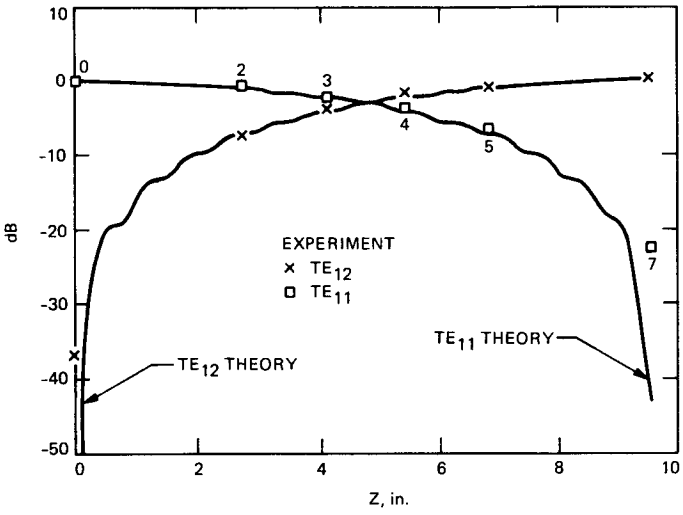

Fig. 6. Mode converter mode content vs distance