FLOWER-PETAL MODE CONVERTER FOR NLC*

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Abstract

It is important to minimize power loss in the waveguide system connecting klystron, pulse-compressor, and accelerator in an X-Band NLC. However, existing designs of klystron output cavity circuits and accelerator input couplers utilize rectangular waveguide which has relatively high transmission loss. It is therefore necessary to convert to and from the low-loss mode in circular waveguide at each end of the system. A description is given of development work on high-power, high-vacuum 'flower-petal' transducers, which convert the TE_{10} mode in rectangular guide to the TE_{01} mode in circular guide. A three-port modification of the flower petal device, which can be used as either a power combiner at the klystron or a power divider at the accelerator is also described.

I. INTRODUCTION

Various types of transducers have been developed for converting the TE_{10} mode in rectangular waveguide to the low-loss TE_{10} mode in circular waveguide. Many employ adiabatic tapering from the cross-section of one wavguide to the other, as exemplified by the design originally proposed by Marié [1]. These designs require elaborate machining or electroforming, and the finished transducers are quite long, which leads to significant insertion loss, and possibly trapped weak resonances due to mismatches. They are most suited to communications systems, where broad bandwidth is required.

The rf systems used to drive linear accelerators can be relatively narrow-band. In these applications the so-called 'flower-petal' transducer [2] can be used. It is compact and, as will be seen, can be designed to have low loss and high mode purity. The essential features of the transducer are shown in Figure 1. The input rectangular waveguide is bifurcated through matched transformer steps into two rectangular guides having the same cross-section as the input guide. The two guides are coupled to a circular waveguide by an arrangement of four slots (the flower-petal) in their side walls. After the coupling slots, the two rectangular guides are terminated in short circuits. Although the transducer is required to couple into 1.75-inch circular guide, the diameter of the section of guide coupled directly to the slots is 1.6 inches. The reason for this is to guarantee that the TE_{41} mode generated by the slots is sufficiently evanescent over the intended bandwidth. A non-linear taper is provided to match this section to the required 1.75-inch circular guide.

In recent years, 3-D computer modeling has proved to be both feasible and practical for the design and analysis of complex microwave structures. In the case of the flower-petal transducer, the 3-D electromagnetic codes HFSS and MAFIA have been used successfully to simulate its behavior.

Low-power measurements have been made to optimize the bifurcation transformer and the dimensions of the flower-petal slots, and to quantify the power in unwanted modes generated in the circular waveguide.

Several models of the finished transducer have been made for high-power and high-vacuum operation. Two have been tested back-to-back in an X-Band resonant ring up to a power level of 150 MW.

II. PRINCIPLE OF OPERATION

We present here symmetry-based arguments which provide some insight into why the design works as well as it does. Referring to Figure 1, it can be seen that the symmetry (both in terms of the structure and the excitation) is such that it is sufficient to consider only the positive y side of the x–z plane and modes consistent with a metal boundary condition being imposed there. This implies that, at most, five of the ten propagating modes in the circular guide can be excited. These are TE_{01}, TE_{11}, TM_{11}, TE_{21} and TE_{31}. The TE_{01} and TE_{21} modes satisfy a symmetry relation with respect to radial planes at 45° to the axes, corresponding to a metal boundary for the TE_{01} and a magnetic boundary for the TE_{21}. If an individual petal slot is approximated to the form of a thick elliptical iris, then by using formulas appropriate to that geometry, it is found that the ratio of the induced magnetic dipole moments associated with the two symmetries is approximately 0.012 in the sense which discriminates against the TE_{21} mode. Since the ratio of the powers in the two modes is the square of this quantity, there is a strong discrimination against driving the TE_{21} mode, which improves with increasing iris thickness.
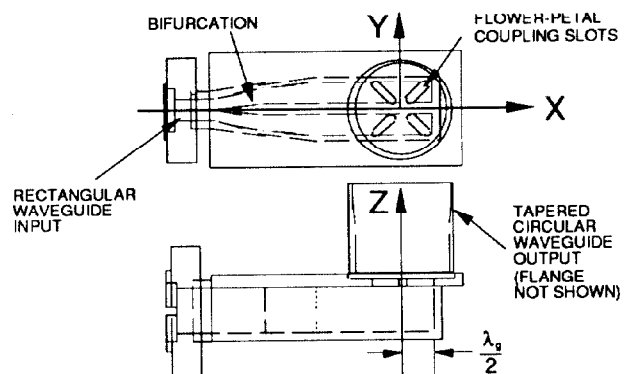

Figure 1. Schematic diagram of the mode transducer.

It is a good approximation to assume that the shorting plane in the rectangular section is one half a guide wavelength from the origin, and that this has the effect of requiring the fields in the circular guide to satisfy a metal boundary condition on the y–z plane. To the extent that this is the case, the TE_{11}, TM_{11} and TE_{31} modes are not excited. The failure of
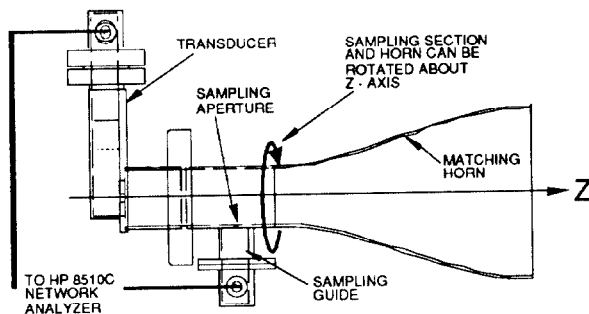
Figure 2. Schematic diagram of mode analyzer.

this condition to hold exactly is likely to manifest itself as an inequality in the excitation of the slots nearest the shorts, as compared to the other pair, with perhaps also a small departure from the precise phase equality which the assumed symmetry would imply. A similar situation has been considered in connection with the four-spoke mode transducer [3], and the formulas derived there are likely to hold approximately here. Let d represent the fractional amplitude deficiency of the more weakly excited pair, and ϕ the phase difference. Then, according to [3], the fractional power lost to non-TE_{01} modes is

$$[d^2 + 4(1 - d).(\sin\phi/2)^2] / [4(1 - d + 0.5d^2)] ,$$

from which one can estimate the deviations which will produce significant power loss to unwanted modes. The details of the slot design, apart from discrimination against the TE_{21} mode, determine what fraction of the incident power will be reflected. The slot width which minimized the reflection was determined experimentally and, as is described later, a tuning post was added to obtain the best match.

III. EXPERIMENTAL DEVELOPMENT

Numerical modeling of the flower-petal transducer has been described in [4]. Here we discuss the experimental development. The all-important measurements of mode purity in the circular guide were made with a rotating H_z probe coupled to a network analyzer and a computer, as shown schematically in Figure 2. The circular waveguide output of the transducer is coupled to another circular guide section of the same diameter which is free to rotate about the common z-axis. This rotating section is connected in turn to a nonlinearly tapered horn which acts as a well-matched load for many modes. A small circular-hole in the wall of the rotating section couples to a rectangular waveguide with its large dimension parallel to the axis of the circular guide. The coupling is small enough to avoid significant perturbation of the fields in the circular guide, and large enough to provide signals within the dynamic range of the network analyzer. About -45 dB is optimum. Mode conversion due to the hole is negligible for most modes. The H_z is sampled at sixteen equi-spaced points around the periphery. At each point the phase and magnitude of the complex transmission coefficient as a function of frequency over a selected band, between the input of the transducer and the output of the sampling guide, is dumped from the network analyzer via a GPIB link onto a PC disk.
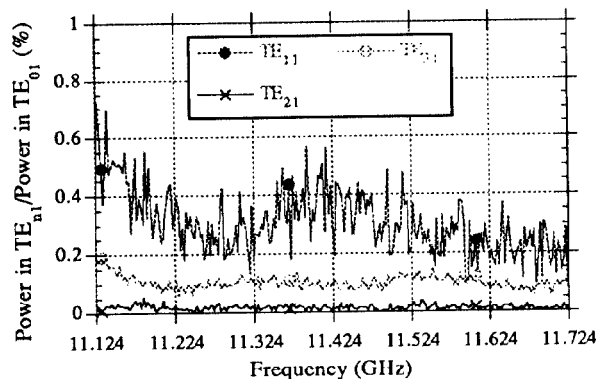

Figure 3. Mode analyzer measurements of fractional power in unwanted TE mode propagating in 1.5-inch circular guide
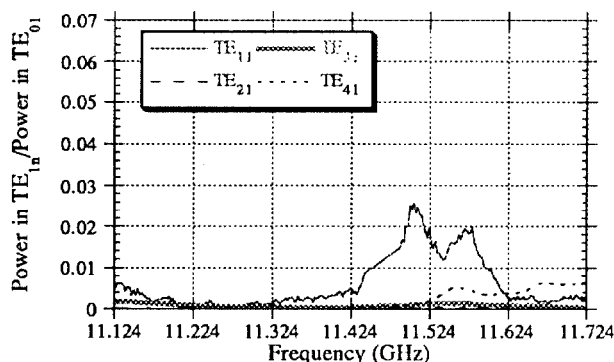

Figure 4. TE mode contamination with taper.

From these data, azimuthal space harmonics of H_z can be calculated and, in turn, the power contained in a TE mode which has m azimuthal repeats can be deduced [4]. The mode analyzer is insensitive to TM modes. Figure 3 shows the results obtained with the mode analyzer in 1.5-inch guide, while Figure 4 shows the results after the taper to 1.75 inches. The rise in TE_{11} power above 11.424 GHz is probably spurious. The mode analyzer cannot distinguish between TE_{11} and TE_{12}, and a comparison of Figures 3 and 4 suggests that the striking difference is associated with the passage of TE_{12} through cutoff. If one assumes that the excess excitation is TE_{12}, the actual power loss associated with it is reduced by a factor $\lambda_{g11}/\lambda_{g12}$.

As mentioned earlier, it is necessary to add an inductive post in the input rectangular waveguide, close to the beginning of the bifurcation section, in order to obtain a well-matched input. The resultant input VSWR is shown in Figure 5.

In order to measure the conversion efficiency from the rectangular guide to the desired circular guide mode, two flower-petal transducers were joined at the circular flanges and S-parameter measurements were made between the rectangular waveguide flanges. After correcting for flange losses at the rectangular junctions, the observed transmission loss was 1.0±0.7%, and the reflection loss was 0.25%. Variations in these measurements as the transducers were rotated with respect to each other at the circular flange junction were below
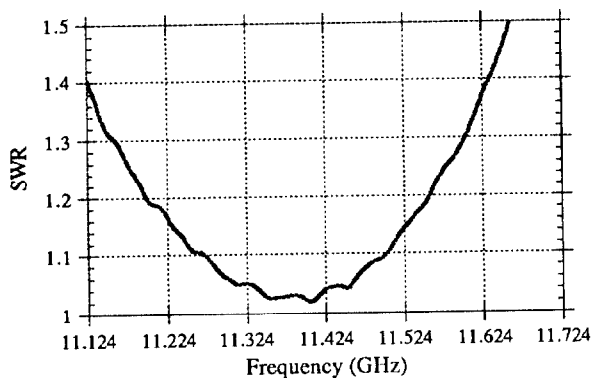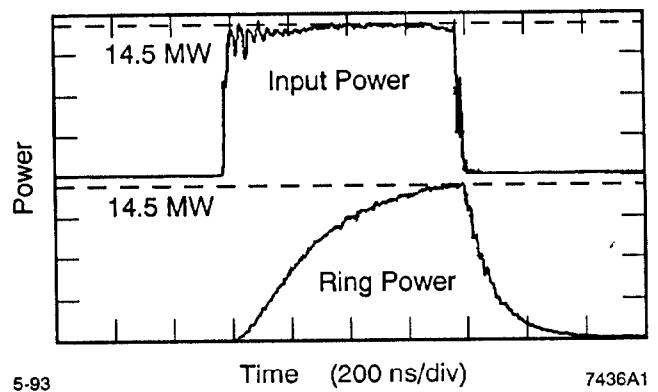
Figure 5. Transducer input VSWR

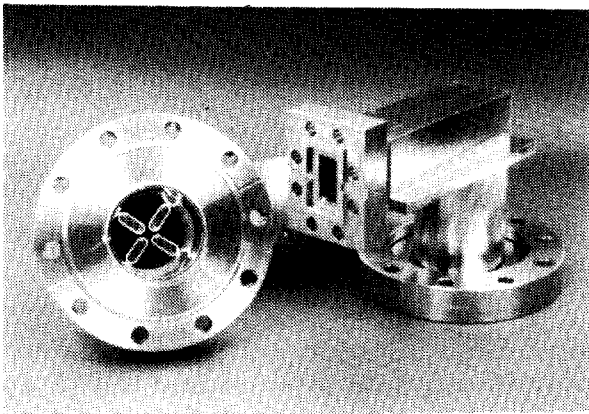Figure 7. High power performance of transducer.

Figure 6. Completed flower-petal transducer

Figure 8. Transducer/combiner/divider.

the level of measurement sensitivity, thus providing additional evidence that conversion to azimuthally varying modes is small, and our only evidence that conversion to the TM_{11} mode is small. We take these results to indicate that the loss attributable to a single transducer is less than 0.7%.

IV. HIGH POWER TESTING

A completed flower-petal transducer, suitable for high-power operation under high-vacuum is shown in Figure 6. Two of these units have been operated back-to-back in an X-Band resonant ring up to 150 MW, with a pulse width of 800 ns. The pulse waveforms for the klystron and the resonant ring are shown in Figure 7. The power level reached was limited by the klystron and its window, and not by the transducers usder test.

V. TRANSDUCER/COMBINER/DIVIDER

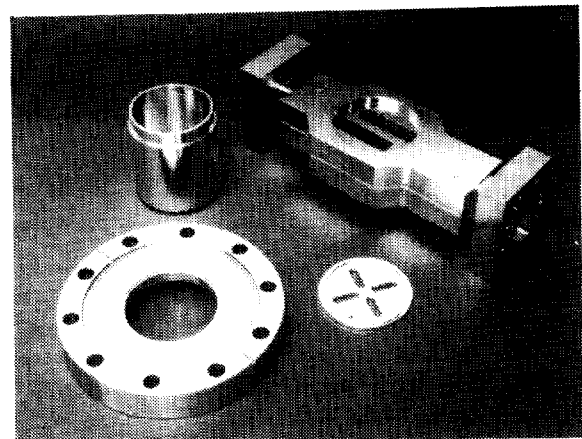A three-port version of the transducer, in which the flower-petal couples to two rectangular waveguides which are not joined by a bifurcation section, but are taken to two separate ports symmetrically placed on each side of the flower-petal has been built, and is shown in Figure 8. It is expected that this device will be used in the NLC Test Accelerator, both as a power combiner and as a power divider. Preliminary tests will begin shortly.

VI. REFERENCES

[1] S. S. Saad et al., "Analysis and design of a circular TE_{01} mode transducer," *Microwaves, Optics and Acoustics*, Vol. 1, No. 2, January 1977.

[2] Formerly manufactured for several high- frequency bands by Alpha Industries Inc. This device was brought to our attention by George Spalek.

[3] N. Kroll and K. Ko, "The Four-Spoke Mode Transducer/ Power Combiner," in preparation.

[4] S.Tantawi, K. Ko and N. Kroll, "Numerical Design and Analysis of a Compact TE_{10} to TE_{01} Mode Transducer," Computational Accelerator Physics Conf., Pleasanton, CA, February 1993.