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NUMERICAL DESIGN AND ANALYSIS OF A COMPACT TE_{10} to TE_{01} MODE TRANSDUCER*

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ABSTRACT

A high-power low-loss mode transducer design has been proposed to adapt the output of the X-Band klystron, WR90 rectangular waveguide, to the input of the pulse compression system, SLED II, which utilizes overmoded circular waveguides operating in the low-loss TE_{01} mode. This device is much more compact than the conventional Marie' type mode converters. The device splits the incoming klystron output into two separate rectangular guides that are then fed into a circular guide through a four-slot arrangement. We will use both MAFIA and HFSS to calculate the transmission properties of the three-dimensional structure. We will also determine the extent of mode contamination and compare the numerical results with experiments.

1. INTRODUCTION

Various types of transducers have been developed for converting the rectangular TE10 mode into the low-loss circular TE_{01} mode. Most of these transducers are based on a design proposed by Marie'[1]. In general, they consist of three sections with adiabatic tapering from one cross-section to the other. The first is a transition from TE_{10} rectangular to TE_{20} rectangular, the second from TE_{20} to a cross-shaped guide, and the third is from that shape to a TE_{01} circular guide. Because the transitions need to be smooth, the transducer length is usually long, leading to unnecessary losses. The excessive length also leads to undesirable closely spaced weak resonances which result from mismatches at the transitions.

The Marie' type mode transducers just described are mostly suited to applications in communication systems where broad bandwidth is required. For accelerator systems, such as the Next Linear Collider Test Accelerator (NLCTA), the bandwidth requirement is much less. The RF components utilized for the NLCTA pulse compression (SLED II) are desired to be compact and low-loss. Based on these requirements, a more compact design with adequate bandwidth was proposed [2] and a sketch of it is shown in Fig. 1. It consists of a bifurcation which splits an incoming rectangular guide into two identical guides. The latter are side-coupled to a circular guide through a four-slot (flower-petal) arrangement in the common wall before terminating in a short at the ends. Such a device is intrinsically three-dimensional and the flower-petal geometry is not amenable to theoretical analysis. As a result, the design approach has primarily been experimental.

In recent years, however, 3-D computer modelling has shown to be both feasible and practical for the design and analysis of devices of complex geometries. In the present paper, we will report our experience with the 3-D electromagnetics codes, HFSS and MAFIA, in simulating the new transducer mentioned above. The motivations behind the numerical effort are to gain insight into the operation of the device, to confirm experimental observations and to assess the accuracies of HFSS and MAFIA in modelling this type of RF components. The paper is organized as follows. In Section 2 we explain the underlying principle for the design while in Section 3 we describe the experimental procedure used to evaluate the device. The numerical models are discussed in section 4 and the comparison between the measurements and simulation results is presented in Section 5. We conclude with a summary on the usefulness of the numerical effort in section 6.

2. PRINCIPLE OF OPERATION

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Fig 1. shows a schematic diagram of the mode transducer. The basic operation of the device can be understood by the following considerations. First, the structure has a reflective symmetry about the Y-Z plane which bisects it. Because the incoming mode in the WR90 guide is TE_{10}, this symmetry plane can be taken to be an electric boundary. This has the consequence that in the circular section TM_{0n} modes are not excited and only one of the two polarizations of the azimuthally varying modes can be excited. Now if one ignores the coupling slots and terminates the WR90 guides at the half-wavelength point from the X-Z plane, then about that plane, there is an additional reflective symmetry for the fields in the region where the WR90 and the circular guides overlap, also equivalent to an electric boundary. To the exent that neglect of the perturbation is vaild, modes with odd azimuthal variation are not excited in the circular section. In the limit in which the slots are narrow and radial with respect to the circular section, the magnetic fields in the slots are radial and provide a drive in the circular waveguide with azimuthal symmetry of the form 4n. If the circular guide radius is such that it cuts off modes with m=4 and above, then TE_{01} is the only propagation mode excited as desired.

A mode transducer operating as above in such a way that the coupling slots are a small perturbation would have excellent mode purity but very poor power conversion. That is to say, most of the power would be reflected. An essential feature of the device is to transfer all the incident power to the circular guide in the TE_{01} mode. While it would be possible to accomplish this objective by means of a strongly resonant matching section, such a solution is unsatisfactory because it would be excessively narrow band and lead to excessive field strengths in the matching section. The alternative is to open up the slots to increase the coupling. The limiting conditions are then significantly compromised, which may be expected to lead to some mode impurity. The design program was directed towards minimizing this effect while at the same time optimizing the power transfer. This was accomplished by the shaping and sizing of the coupling slots and slightly adjusting the distance of the shorting plane. The final dimensions shown in Fig. 1 are arrived at after much empirical experimentation [3].

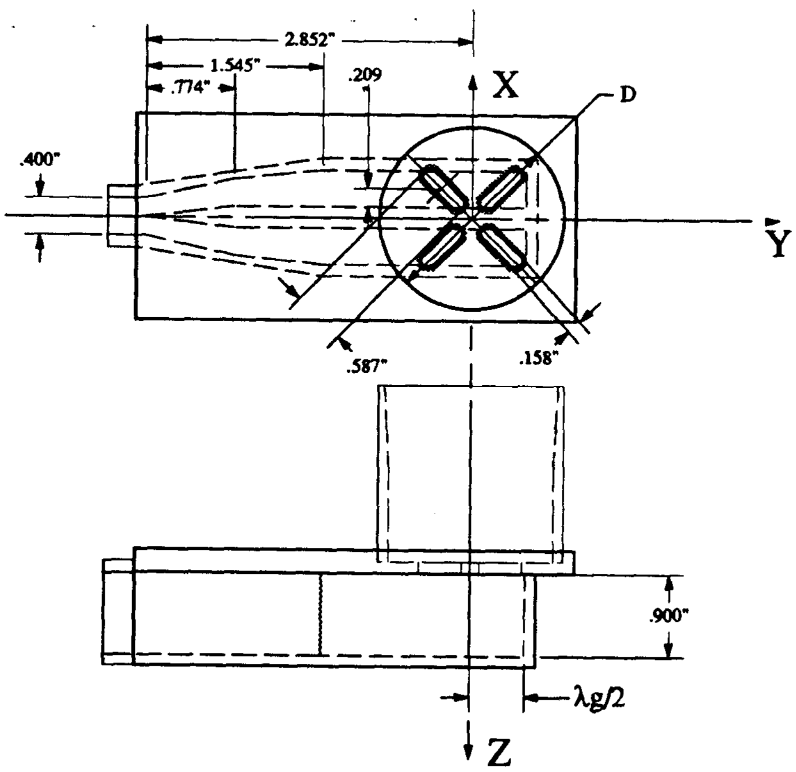

Fig. 1 TE_{10} to TE_{01} Mode Transducer.

3. EXPERIMENTAL PROCEDURES

Fig. 2 shows the experimental setup used for measuring the transducer properties. The transducer circular port is terminated with a slowly tapered horn. The horn acts as a matched load for the transducer. This method of matching the transducer proved to be considerably better than matching it with a tapered lossy cone. The inner surface of the horn has a special curve to reduce as much as possible mode conversion. A sample of H_z (the magnetic field in the Z direction in the circular guide) at the wall is measured through a small circular hole that opens to a rectangular waveguide with its large dimension parallel to the axis of the circular guide. The hole size is chosen such that the coupling between the TE_{01} mode in the circular guide and the TE_{10} in the rectangular guide is small enough so that it does not perturb the fields in the circular guide and at the same time it is large enough to accommodate the dynamic range of the network analyzer and it's test sets (HP 8510C). A reasonable number for that is -45 dB. The wall thickness between the rectangular sampling guide and the circular guide is .03 inches, the smallest size possible for machining the hole without distorting the inner wall of the circular guide. The hole size for the previously mentioned coupling was calculated using a modified Bethe formula [4] to get a approximately 0.1 inch diameter hole. Mode conversion due to this hole for all modes can also be calculated as shown in [5] and is negligible for most modes.

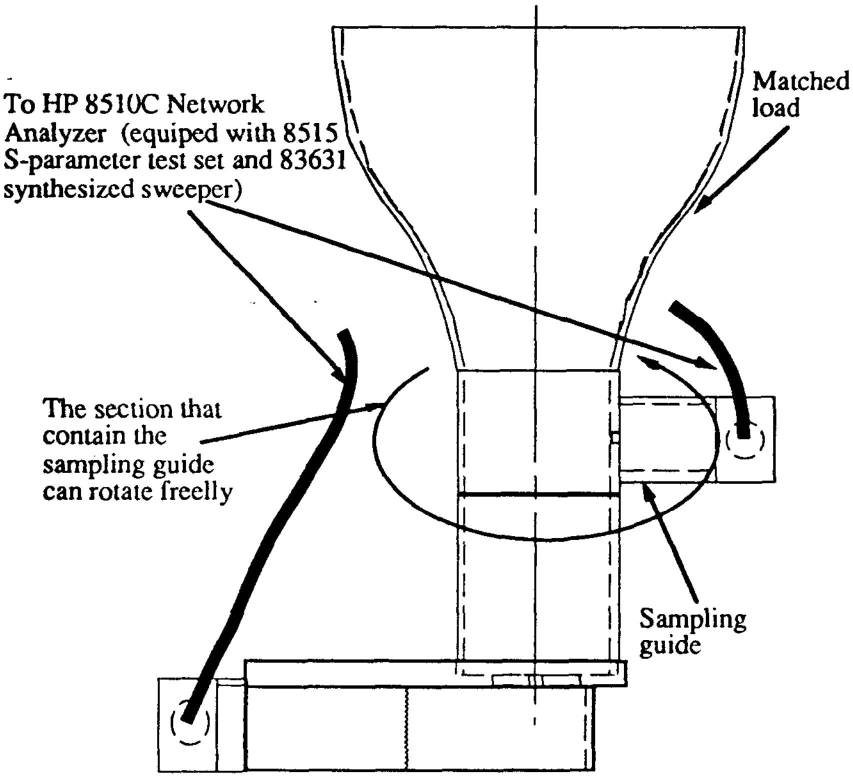

Fig. 2 Experimental Setup for Measuring the Transducer Properties.

The section that contains the sampling rectangular guide is free to rotate around the axis of the circular guide. H_z is sampled at 16 different points around the circular guide. At each point the transmission coefficient, as a function of frequency, between the input of the transducer and the output of the sampling guide is dumped on a disk through GPIB link between the network analyzer and a PC. Both phase and magnitude of the *complex* transmission coefficient (Ti ; 0 i 15) is stored at each point i. The azimuthal harmonics (Hzn -7 n 7) of Hz can be calculated from

$$H_z^n = \sum_{i=0}^{15} T_i \, e^{-j\frac{i n \pi}{8}}$$

Eq. (1) represents a circularly polarized component of the total field H_z. The power contained in a mode that has azimuthal variation m can be calculated from

$$\frac{Power\ \ in\ \ TE_{n1}}{Power\ \ in\ \ TE_{01}} = \left(\frac{x_0'}{x_n'}\right)^2 \left(1-\left(\frac{n}{x_n'}\right)^2\right) \frac{\sqrt{1-\left(\frac{f_c^n}{f}\right)^2}}{\sqrt{1-\left(\frac{f_c^0}{f}\right)^2}} \frac{\left|H_z^{+n}\right|^2+\left|H_z^{-n}\right|^2}{\left|H_z^0\right|^2} \ ;$$

where x_m is the first zero of the derivative of Bessel function of first kind and mth order, f_c^m is the cutoff frequency of TE_{m1} mode, and f is the operating frequency.

This method of measurements is suitable only for TE modes. In the case of TM modes there is no H_z. If we change the polarization of the sampling guide to sample the azimuthal magnetic field there will be no reference to compare with since TE_{01} has no azimuthal magnetic field also. However, the presence of TM modes has no effect on the measurements. The method also breaks down for the TE_{m1} if the circular guide diameter is large enough to allow TE_{m2} to propagate.

4. NUMERICAL MODELS

Both HFSS and MAFIA are 3D electromagnetic codes capable of calculating S parameters of many port devices. There are several differences between the two codes. HFSS is a finite-element code which evaluates in the frequency domain while MAFIA is based on a finite-difference scheme and solves in the time domain. Fig. 3 shows half the transducer geometry we constructed with MAFIA. It includes both the bifurcation and the flower-petal cut along the Y-Z symmetry plane that we referred to in Section 1. In practice, we simulate the two parts separately. Figs. 4a and 4b show the HFSS model for the bifurcation and the flower-petal respectively. We point out that the coupling slots as modeled by both codes have sharp edges whereas all the edges are rounded in the actual design. This approximation is mainly for numerical expediency and it turns out to have an non-negligible effect on the results.

With either codes, we calculate the input characteristics for each part separately. From the individual scattering matrices we can construct the input characteristics for the total device as follows:

$$S_{11}^t = S_{11}^b + \frac{S_{11}^s\left(S_{12}^b\right)^2}{1-S_{22}^b S_{11}^s}$$

The superscript t stands for the transducer as a whole, b for the bifurcation, and s for the slot section respectively. In Eq. (3), all the matrix elements are complex quantities in which the relative phases have been retained.

Fig. 3 MAFIA Model for One Half of the Mode Transducer.

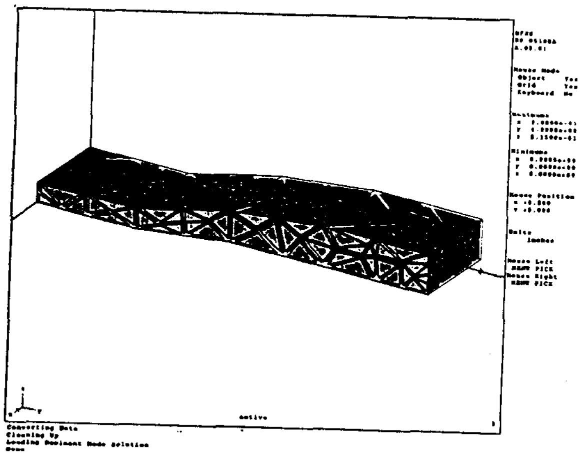

Fig. 4a HFSS Model for One Half of the Bifurcation.

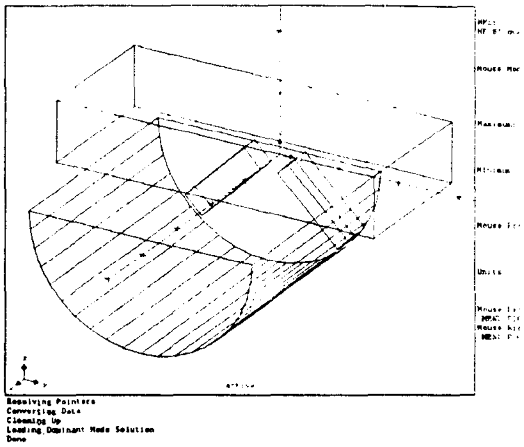

Fig. 4b HFSS Model for One Half of the Flower-petal.

5. COMPARISON BETWEEN SIMULATIONS AND EXPERIMENTS

The operating frequency of the NLCTA is 11.424 GHz (X-Band). The input characteristics of the bifurcation around this frequency as calculated with HFSS and MAFIA are shown in Fig. 5. Both simulations indicate that the section is well-matched. They also agree reasonably well with each other.

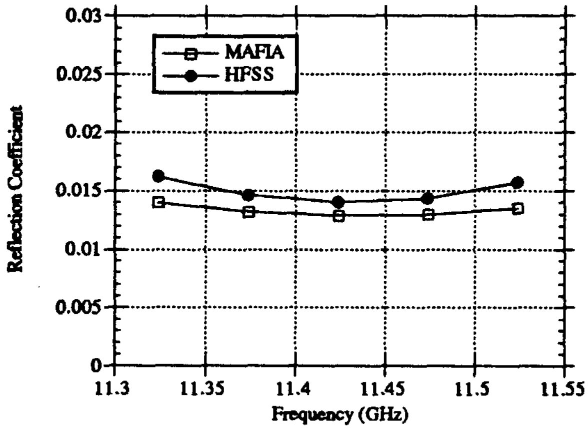

Fig. 5 Input Characteristics of the Bifurcation from HFSS and MAFIA.

In SLED II, the diameter of the circular waveguide chosen to manipulate the power in the TE_{01} mode is 1.75" and the TE_{41} mode will propagate in this guide size. Fig. 6a shows the input characteristics of the total device at this diameter as found from HFSS and from measurements. The agreement is very good.

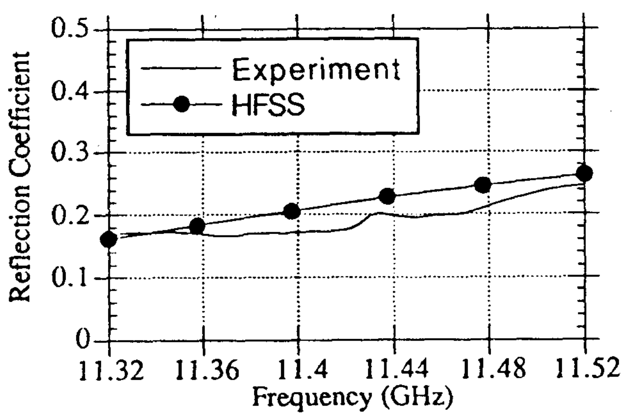

Fig. 6a Input Characteristics of the Transducer from HFSS and Experiment (1.75").

The agreement is less satisfactory when one considers the mode contamination by the TE_{41} mode. As Fig. 6b indicates, measurements show a peak around the cutoff frequency of the TE_{41}. This is not observed in the HFSS results possibly due to the large frequency spacings we have taken in the simulations.

To reduce the TE_{41} contamination, one may start the circular guide with a smaller diameter, 1.5" and then slowly taper up to 1.75" after a distance over which the unwanted modes have decayed sufficiently. For this diameter guide, the reflection coefficient and mode contamination

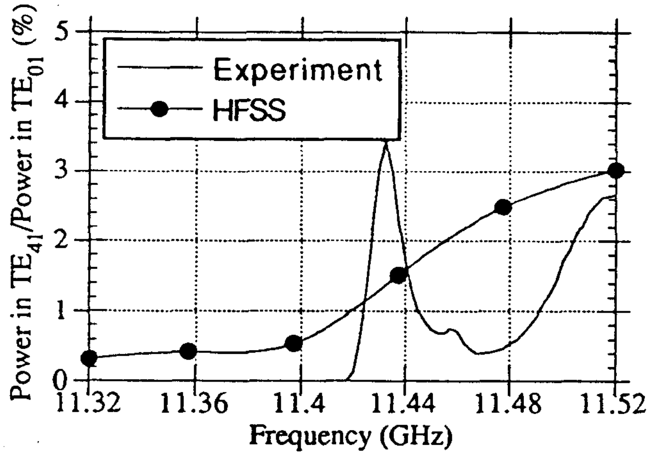

Fig. 6b Mode Impurity in the Transducer from HFSS and Experiment (1.75").

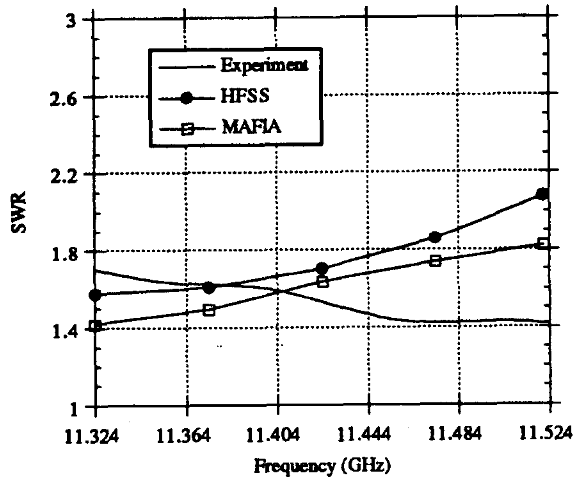

Fig. 7a Input Characteristics of the Transducer from HFSS, MAFIA and Experiment (1.50").

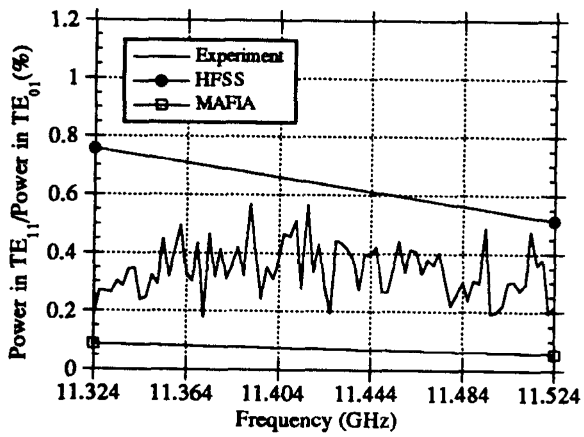

Fig. 7b Mode Impurity in the Transducer from HFSS, MAFIA and Experiment (1.50").

are shown respectively in Figs. 7a and 7b. Again the two codes agree with each other but not as well with the measurements. Regarding mode contamination, both HFSS and MAFIA find that the impurities are mainly due to the odd modes, namely TE_{11} and TM_{11}. Fig. 7b shows how the TE_{11} mode contamination compares between simulations and experiments. We attribute a probable cause for the observed differences to the inaccurate description of the flower-petal by either the HFSS or the MAFIA meshes.

It is worth mentioning that the device can easily be matched with a post in the rectangular guide. The result of such operation is shown in Fig. 8. The SWR is ¡ 1.05 at 11.424 GHz, and the bandwidth is wide enough for the NLCTA applications.

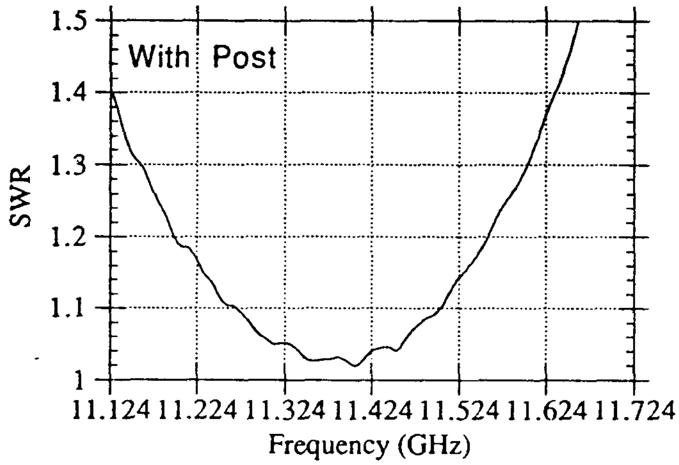

Fig. 8 Input Characteristics of the Transducer from Experiment with an Inductive Post (1.50").

6. CONCLUSION

We tested both experimentally and numerically a compact type of mode transducers. Both simulations and experiments agreed qualitatively. Both showed a very small amount of mode contamination mainly in odd modes. Exact agreement was not possible because of the sensitivity of the device to small variations in geometry, which are difficult to model precisely in the simulations.

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