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Overmoded Waveguide Components for High-Power RF

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Abstract. High-power applications of rf often require the use of overmoded waveguide to reduce the probability of rf breakdown by lowering surface fields, as well as to reduce the attenuation due to ohmic losses in transporting the power from the point of generation to the point of use. This is particularly true in the development of warm linear collider designs, such as NLC, JLC, and CLIC, especially the former two which involve extensive rf pulse compression / power distribution systems. Transitioning to and from overmoded waveguide and manipulating rf in such systems requires specialized components in whose design care must be taken to avoid parasitic mode loss and excessive field enhancement. Although fixed frequency operation means modest bandwidth requirements, power levels up to several hundred megawatts must be accommodated, and efficiency is important. Consequently, physicists working at laboratories engaged in the above efforts have produced a number of novel waveguide components in the past several years. These include tapers, mode converters, bends, directional couplers, power splitter/combiners, switches, phase shifters, etc. Often the circular TE_{01} mode is used for its lack of surface electric field and low attenuation. A class of components using planar geometries for over-height rectangular waveguide has been developed at the Stanford Linear Accelerator Center. The current paper describes a few additional passive high-power components that have not been presented elsewhere — a height taper, a compact mode converter, a four-way power splitter, fractional directional couplers and tap-offs. These were designed at X-band as part of the NLC R&D, but may find wider application.

INTRODUCTION

As part of the R&D effort toward the design of the Next Linear Collider, SLAC has been developing a number of non-standard rf waveguide components [1-5]. In order to handle X-band power levels ranging from 75 MW to 600 MW, these must generally be oversized, and thus overmoded. In all rf manipulations, therefore, parasitic mode coupling losses must be avoided. To minimize the potential for rf breakdown [6], we have tried to maintain surface electric fields below 45 MV/m and surface magnetic fields below 200 kA/m. For our fixed-operating-frequency rf systems, bandwidths on the order of 100 MHz at 11.424 GHz are sufficient. One class of components developed exploits planar symmetry in overheight rectangular waveguide to limit the modes which can be coupled to TE_{n0} modes. Other components use azimuthal symmetry in circular waveguide to limit the modes which can be coupled to the TE_{0n} modes employed in our delay and transmission lines. This paper describes some components not described elsewhere which, although they are not all used in our high-

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power systems, were developed as part of this program and may be of interest. Brief explanations of their function and design are given.

SOME SPECIFIC COMPONENTS

Compact Height Taper

Even in systems where oversized waveguide is required, rf power generally originates in and/or must finally be fed into standard waveguide. In NLC R&D this means WR90 at the klystron outputs and at the accelerator structure inputs. Many components in our system designs use overmoded rectangular waveguide. While tapering in width can present a relatively simple matching exercise, particularly if the cut-off of TE_{30} is not passed, tapering in height is more complicated. Here the planar symmetry which we exploit in many of our components is necessarily violated. In addition to TE modes, creation of a z-component of the electric field in a height taper can introduce parasitic TM modes. In particular, as the height of a 0.900” wide waveguide passes 1.26”, TE_{12} and TM_{12} coupling must be avoided. A compact triple step taper can give an excellent match, but tends to create points of excessively high surface electric field. In the 8-Pack Project [7], the solution is an adiabatic blended arc taper from 0.400” to 1.435” which extends over four inches.

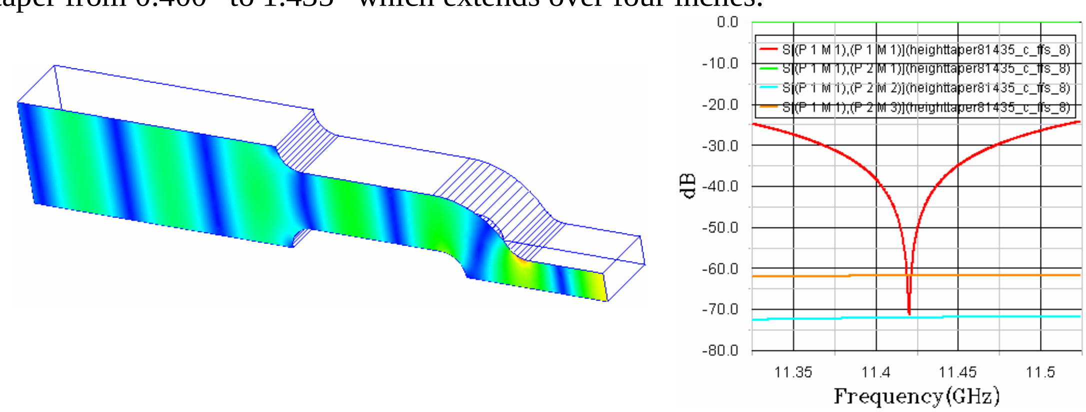

FIGURE 1. Upper quarter geometry of a height taper using a septum to suppress excitation of higher order modes with HFSS snapshot of fields. Also shown is a frequency plot of the scattering parameters.

A more compact way to make this transition is as follows. Call the standard WR90 height b_1 and the oversized height b_2. From the b_2 side, introduce a round-edged horizontal septum at mid height of thickness $(b_2–2b_1)/2$ and inward steps on the top and bottom identical to half the septum. This creates an intermediate section of two WR90 waveguides. The electric field symmetry across the horizontal midplanes of each of these single-moded guides (¼ and ¾ height planes of the overheight guide) is such that they cannot couple to the TM_{12} or TE_{12} mode in the overheight guide. The central septum is terminated and the new top and bottom walls brought smoothly inward the rest of the way through blended arcs to the b_1 height. The longitudinal position of this final height tapering relative to the rounded septum edge is adjusted to give the same amplitude mismatch as the transition at the other end of the septum. Finally, the length of the septum is set so that these mismatches cancel.

The resulting component, shown in Figure 1, is 1.711” long. The simulated reflection is better than −50 dB on frequency and below −30 dB over 100 MHz. With a slight compromise of the essentially perfect parasitic mode suppression, this could be reduced a half wavelength to 1.08”, at which point evanescent modes communicate the asymmetry across the septum region. By allowing a bit more length in the blended arc section, one can ease the 34% field enhancement over WR90.

Coaxial Tap-Offs

For efficient transmission of high-power rf over long distances, the TE_{01} mode in circular waveguide is ideally suited. Its attenuation drops rapidly as the waveguide diameter increases, quickly making it lowest-loss mode, it has no surface electric field to cause rf breakdown, and it has no longitudinal currents that require electrical continuity across flange joints. In a linear collider power distribution system, this mode will certainly be used. Power from one transmission line will need to be divided between multiple accelerator structures. One idea for extracting a fraction of the power from a circular waveguide without converting back and forth to a different waveguide mode, is the coaxial tap-off.

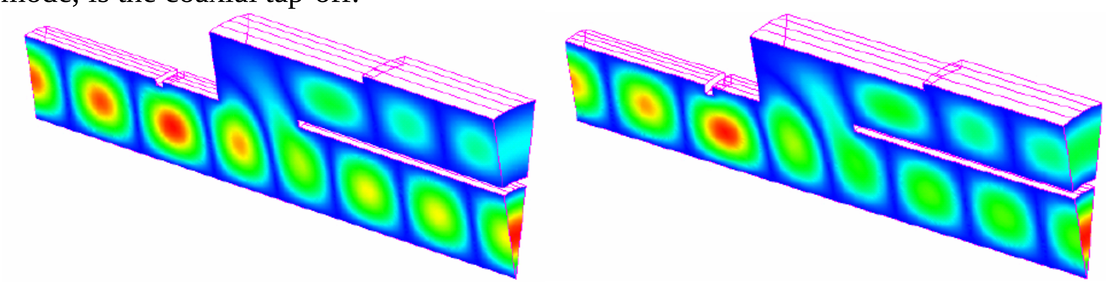

FIGURE 2. Electric field snapshots from HFSS simulation of wedges of coaxial tap-off designs for 1/3 and 1/2 power extraction.

Power Division

The input and output of this component propagate only the lowest TE_{0n} mode. The input waveguide is stepped up in diameter from 1.650” to 3.021”, above the cutoff of the TE_{02} mode (but below that of TE_{03}). The diameter ratio is chosen to equal the ratio of the first two non-zero roots of the Bessel derivative J_0', so that the wall of the smaller guide corresponds to the electric field null between lobes of TE_{02} in the larger guide. Incident TE_{01} power is thus made to split nearly equally between TE_{01} and TE_{02} after the step. As these modes move in and out of phase, power beats back and forth between the inner and outer region. After a short distance, a circular waveguide of the original diameter is introduced coaxial to the larger waveguide. The power is divided between this inner waveguide and the coaxial region between it and the outer wall. The division of power is determined by the distance between the step and the coaxial waveguide. Figure 2 shows designs for which either one third or one half of the power is coupled into the coaxial region. Anywhere from nearly zero to nearly a hundred percent is achievable. The finite thickness of the inner waveguide wall calls for a slight compensating step up in the outer diameter, a short distance into the coaxial waveguide, to perfect the match of the outer TE_{02} lobe from the open region. A small ridge in the input waveguide is used to cancel a fraction of a percent mismatch of the overall device.

Coaxial Wrap-Around TE_{01} Mode Converter

The coaxial TE_{01} mode must then be extracted into a waveguide which can bring it away from the main circular waveguide. This can be accomplished with a coaxial wrap-around mode converter, similar in concept to the circular TE_{01} mode launcher [8] now in common use at SLAC. The coaxial region is shorted with an end wall and coupled through nine radial slots, 40° apart, to a rectangular waveguide wrapped around it. The slots open at intervals of a guide wavelength through the broad wall of the rectangular guide. Eight slots would couple to the TE_{81} mode in the coaxial guide, and ten slots would require the wrapped waveguide to be overmoded to obtain the proper wavelength. The extracted power then exits this ring waveguide through an E-plane T-junction, matched with a bump, into a WR90 port. This device is illustrated in Figure 3.

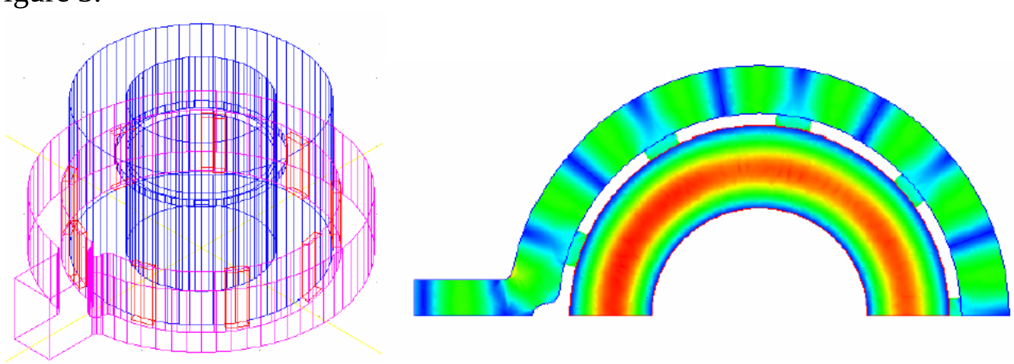

FIGURE 3. Geometry and field plot for coaxial wrap-around TE_{01} mode converter for extracting power from the coaxial region of the coaxial tap-offs.

TE_{01} 4-Way Power Divider

A component that splits the power from a TE_{01} mode circular waveguide into four rectangular waveguides was originally conceived as part of a 90° bend design for circular transmission lines. In that application, the rectangular waveguides would be bent in such a way that they fed into another circular waveguide at 90° to the first. Recently, this one-to-four transition, dubbed the "quadrapus", has found application in the 8-Pack project at SLAC. It is used to divide high-power rf pulses, carrying hundreds of megawatts, between four high-power loads.

The geometry of this device, illustrated in Figure 4, is quite simple. A circular waveguide of 1.500" diameter is terminated in a shorting plane. This plane also forms the side (narrow) walls of four WR90 waveguides radiating at 90° intervals from the circular waveguide axis. This four-fold symmetry is required to avoid reflecting into circular waveguide modes of higher azimuthal index, of which the highest propagating is TE_{31}. To minimize surface fields, the junctions of the WR90 broad walls and the circular waveguide wall are rounded as much as the geometry allows; each broad wall is flared out in an arc which is tangent to the cross section of the circular guide and to the near wall of the next WR90. This results in a junction with more than 96% power transmission at 11.424 GHz. The remaining 4% reflection is matched out by a small ridge in the circular port. The full geometry and cross-sectional fields are show in Figure 4 (with a step to 1.600” diameter to fit our system). Simulation shows the reflection to be about –57 dB at 11.424 GHz and better than –30 dB over 180 MHz.

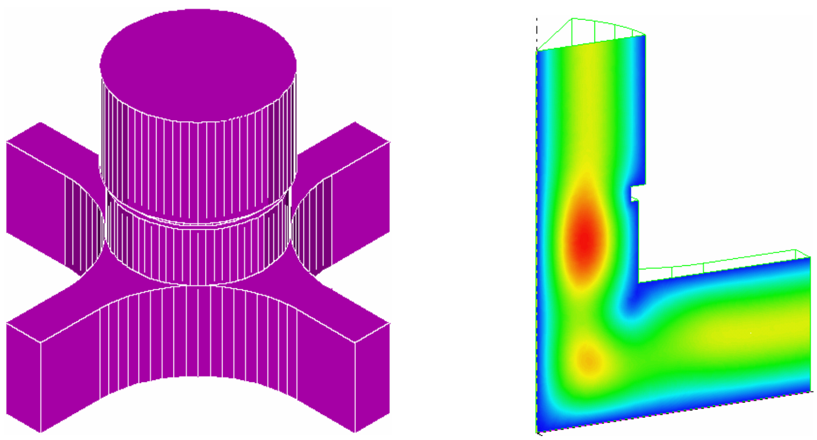

FIGURE 4. Geometry of the quadrapus TE_{01} power divider and an HFSS field plot of a cross-section.

Fractional Planar Directional Couplers

Using four-port directional couplers, with loads on the fourth ports, rather than three-port tap-offs to divide rf power between accelerator structures allows for the structures to be isolated, as well as providing a level of protection for the upstream system and klystrons. With reflected power being absorbed in the loads, such isolation avoids chain reaction multi-structure break downs, facilitating structure processing and improving operation. It is especially needed for standing-wave structures, which reflect some power by design during filling and after the pulse.

A novel “H”-shaped waveguide hybrid with planar symmetry was invented several years ago [5] and has been incorporated into high-power X-band rf systems at SLAC. The same design approach that gave us this hybrid can be used to achieve directional couplers with arbitrary coupling. Figure 5 shows the geometry of designs for a –6.0 dB (1/4) and a –4.8 dB (1/3) directional coupler. Together with a –3.0 dB (1/2) hybrid, these can be used in series to split power between four feeds by successively coupling the appropriate fraction of remaining power out of the main waveguide line.

The design and operation of these planar directional couplers is easy to understand. The ports are of the standard X-band waveguide width, 0.900”. (Height is arbitrary in these planar designs and can be increased for greater power handling.) The central waveguide is overmoded in width, allowing propagation of both the TE_{10} and TE_{20} modes. For the latter mode, a plane along the center of this waveguide satisfies an electric boundary condition. The upper half of the coupler can then be seen as two asymmetric mitered bends between the port waveguide and the half-central waveguide. Such mitered bends can be well matched. For the TE_{10} mode, the dividing plane has a magnetic boundary condition, and the junctions have a sizeable reflection. For certain lengths of the central guide, at intervals of π/β_{10} (the half guide wavelength) the mismatches cancel each other. With both the symmetric and asymmetric modes matched, the individual ports of the full device are matched and pairs on the same side of the "H" are isolated. The division of power between the two ports on the opposite side, however, depends on the overall relative phase slip between these two modes. The design thus comes down to finding a central width for which a reasonable TE_{10} matching distance coincides with the desired phase slip. Simple phasor analysis gives this angle as

$$\theta = \pm 2\sin^{-1}\sqrt{C} \pm 2n\pi, \qquad (1)$$

where C is the fractional power coupling and n an arbitrary integer. For C = 1/4, 1/3, and 1/2, respectively, θ = ±60°, ±70.52°, and ±90°, all modulo 360°.

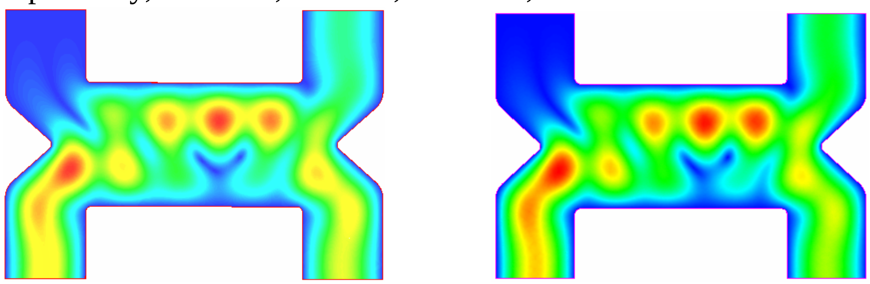

FIGURE 5. "H"-shaped planar rectangular waveguide directional couplers for tapping off 1/4 and 1/3 (upper right port) of the input power (lower left port) at 11.424 GHz. The ports are 0.900" wide.

	(P 1 M 1)	(P 2 M 1)	(P 3 M 1)	(P 4 M 1)
(P 1 M 1)	0.0005	0.8166	0.5772	0.0004
(P 2 M 1)	0.8166	0.0005	0.0004	0.5772
(P 3 M 1)	0.5772	0.0004	0.0005	0.8166
(P 4 M 1)	0.0004	0.5772	0.8166	0.0005

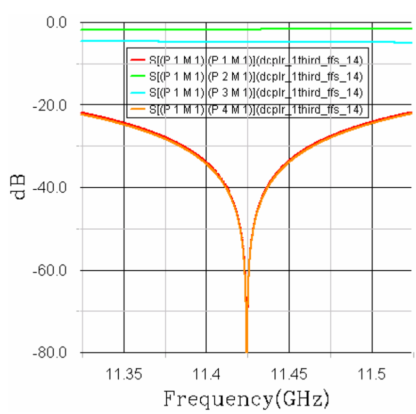

FIGURE 6. Scattering matrix at 11.424 GHz and frequency plot of the element amplitudes over 200 MHz for the 1/3 (–4.8 dB) directional coupler.

Of course the central waveguide width, typically around 1.4", is bound by the need to stay comfortably above the cutoff of TE_{20} and below the cutoff of TE_{30}. The designs shown in Figure 5 have all corners rounded to facilitate fabrication (concave corners) and to avoid potential pulsed heating problems (convex corners). The S parameters from HFSS simulation of the 1/3 coupler are shown in Figure 6.

TE_{02} Launcher

In the high power rf system currently under construction as part of the NLC development a component called a jog converter is employed to convert between the TE_{10} and TE_{20} modes in oversized rectangular waveguide. Its purpose is to interface between dominant mode waveguide and a rectangular-to-circular transition which converts the rectangular TE_{20} mode to the circular TE_{01} mode. The jog converter is typically preceded by a width taper from 0.900" waveguide and frequently, for topographical reasons, a 90° mitered bend. This combined structure is more than seven inches long.

Figure 3 shows an alternative component [9] developed to perform the same functions more compactly. It is basically the intersection of a 0.900" waveguide with a wider waveguide, with two ports shorted. The wide waveguide barely bulges out the far side of the narrow guide. The purpose of this feature is to achieve negligible coupling between the unshorted narrow waveguide and the TE_{10} mode in the open arm of the wide guide. With this condition satisfied, the position of the short in the far end of the narrow guide could be chosen to maximize coupling into the TE_{20} mode of the wide guide. Residual reflection is removed by the introduction of matching bumps, at the appropriate distance from the intersection, in the narrow guide side walls.

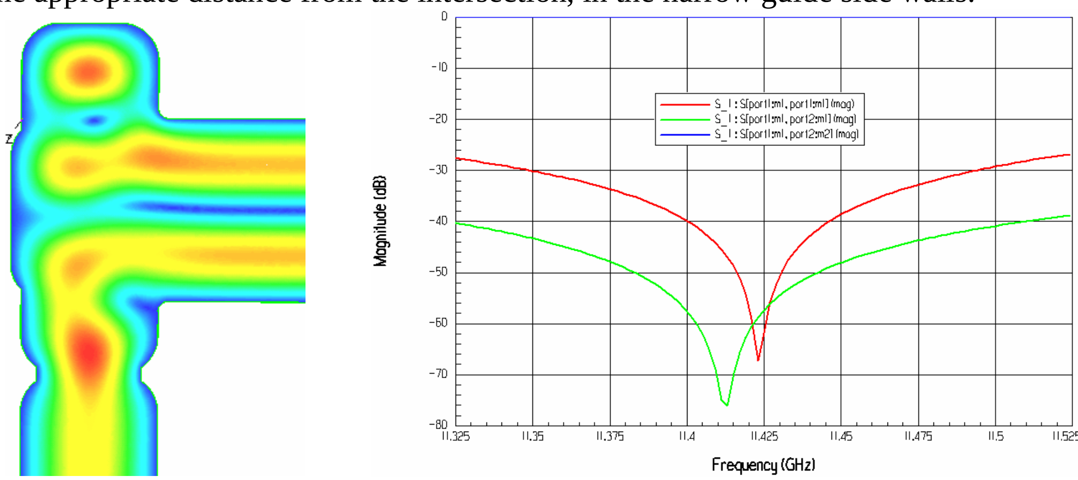

FIGURE 7. A compact, planar 90° $TE_{10} \leftrightarrow TE_{20}$ mode converter to interface between 0.900" waveguide and a rectangular-to-circular TE_{01} mode launcher. The geometry and field pattern are shown on the left. To the right is a plot of the scattering parameters.

Like the directional couplers described above, this TE_{20} mode launcher is a two-dimensional design, allowing for the use of overheight waveguide. The output width, as well as the height, was chosen to accommodate our rectangular-to-circular tapers, allowing a further width taper, currently incorporated into the input of the latter, to be eliminated. Thus, this component can reduce the size of an assembly by about 6.5" in the direction of the wide waveguide axis. Again corners are rounded for machinability and to avoid singularities. Although the peak electric field is enhanced relative to the jog converter, it is similar to the value in the directional couplers, compared with which it has nearly twice the bandwidth.

CONCLUSION

Several overmoded waveguide component designs have been presented. These have been developed to perform various functions specifically in high-power X-band systems for powering high-gradient accelerators. The priorities behind them are power handling and efficiency. Basic design strategies employed include exploiting symmetries, optimizing dimensions, adding matching elements, and avoiding slots, apertures and sharp edges. Descriptions of many other such components and the systems in which they are employed can be found in the papers referenced at the end of this one.

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