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Design of Compact Multi-Megawatt Mode Converter[1]

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Abstract. Experience gained during recent operation of high power 11.424 GHz rf sources for accelerators led to new, more strict requirements on system components. One of the basic components of such a system is a mode converter that transforms the rectangular waveguide mode into the TE_{01} mode in circular waveguide. With such a converter, it is possible to minimize the use of WR90 rectangular waveguide which was shown to be a weak part of the previous system at power levels higher than 100 MW and pulse lengths on the order of a microsecond. We used several methods to design a mode converter with extremely low parasitic mode conversion and compact size. These methods employ HFSS[4] and include multi-parameter searches, concurrent optimization with the mode-matching code Cascade[2], cascading of resulting S-matrices, and tolerance analysis using perturbation techniques. This report describes the design methods and presents results.

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INTRODUCTION

A multimoded X-band rf pulse compression system suitable for a TeV-scale electron-positron linear collider such as the Next Linear Collider (NLC) was built at SLAC [3]. This system was designed to feed several accelerating structures with 475 MW, 400 ns pulses at 11.424 GHz. Working with such high power necessitates the use of overmoded waveguide components. Such components have have better power handling capabilities and lower losses than single moded components. A key element of our multimoded system is a mode converter that transforms the TE_{20} and TE_{10} modes of overmoded rectangular waveguide into the TE_{01} and TE_{11} modes of a circular waveguide, respectively. These mode converters worked successfully at the full power of the pulse compressor. Based on this success and gained experience, we decided to create a new mode converter design. We need such a converter as a base element for a high power system that does not use single moded waveguide at all. During high power tests, the single moded waveguide was a weak link in the pulse compressor. This new mode converter should be more compact than the existing design and should have extremely low parasitic mode conversion.

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Design Requirements

We report on the design of two mode converters. The first transforms the TE_{20} mode of overmoded rectangular waveguide into the TE_{01} mode of circular waveguide. If we add to this mode converter a part that transforms TE_{10} in single moded WR90 into TE_{20} in the overmoded rectangular waveguide, we get a second mode converter that transforms TE_{10} of WR90 into TE_{01} of circular waveguide. The first one will be a base element for overmoded waveguide components such as power splitters, turns, *etc.*, and the second one will allow connecting these components to existing high power systems with WR90.

The main design requirements for these mode converters are good match (reflection of the TE_{10} or TE_{20} mode of rectangular waveguide and the TE_{01} mode of circular waveguide below –50 dB) and low parasitic mode conversion (below –50 dB). From our experience, the following requirements have to be satisfied for robust operation of high power waveguide components that have to guide 100 MW of rf power: surface electric field should be below about 45 MV/m (for μs - long pulses), and pulsed heating should be below about 30° C. Pulsed heating is the increase of the copper surface temperature during the rf pulse. While satisfying the above, we aimed to make the mode converter as compact as possible. We note here that since, in general, overmoded components cannot be tuned, they must be precisely designed and manufactured.

DESIGN PROCEDURE

We describe first the TE_{20} rectangular to TE_{01} circular mode converter, a base element for a system that has only overmoded components, and then the mode converter that transforms TE_{10} in WR90 into to TE_{20} in overheight rectangular waveguide. This mode converter will connect WR90 systems to overmoded systems. We finish with optimization of the complete TE_{10} WR90 to TE_{01} circular mode converter.

TE_{20} Rectangular to TE_{01} Circular Mode Converter

The TE_{20} rectangular to TE_{01} circular mode converter consists of five parts, as shown in Fig. 1. The input of the first part is a rectangular waveguide with dimensions 1.204 inch$\times$0.8 inch. The output of the fifth part is a circular waveguide with 1.5 inch diameter. The converter works as follows: rectangular TE_{20} enters the first part, a height taper with a constant width of 1.204 inch. The height taper is matched for TE_{20}. The mode is preserved in this height taper and in the straight section (second part) and then launched into the third part to create a mixture of TE_{21} and TE_{01} in a deformed circular waveguide. The relative phase of these two modes is adjusted in the fourth part, which has a constant cross-section. The fifth part transforms these TE_{21} and TE_{01} modes into a pure TE_{01} circular waveguide mode.

We have used a C++ code driving the HFSS[4] field solver to optimize the mode converter in an automated fashion. This C++ optimizer moves in the multi-parameter space of the converter dimensions, modeling and solving many iterations and saving the resulting S-paraments.

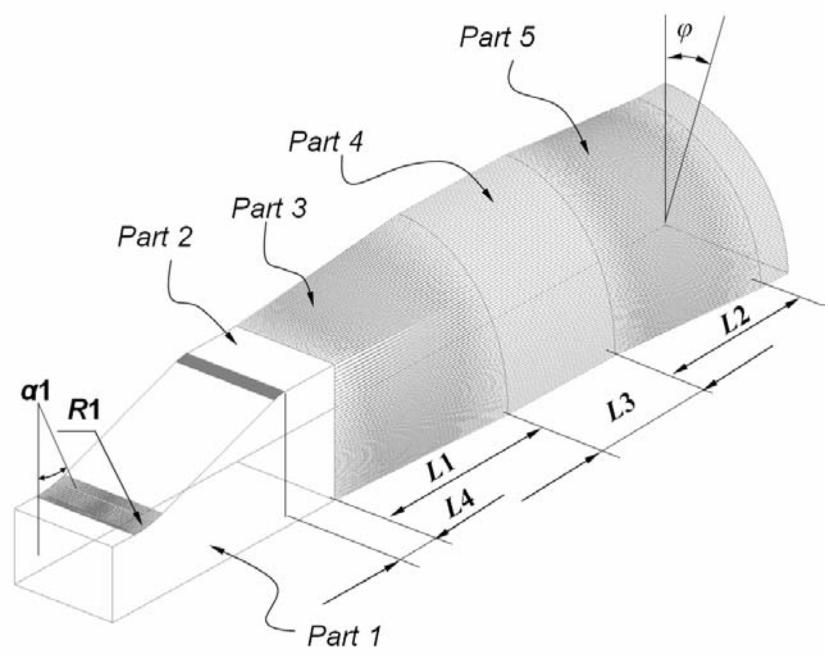

FIGURE 1. One quarter geometry of the TE_{20} rectangular to TE_{01} circular mode converter.

Part 1, the height taper with fixed input and output height, was designed using optimization of two parameters: the radius of rounding at the input end ($R1$) and its angle ($\alpha 1$). These two parameters create an array of possible solutions, so we selected one that has the shortest length.

The next step was optimization of parts 3, 4 and 5. The parts are designed to be cut by a wire from blocks of metal. To facilitate this fabrication method, we parameterized cross-sections for these parts with the azimuthal angle ϕ. The cross-section of part 4 is parameterized using the formula $R(\phi) = R_w(1-\beta\cos(2\phi))$. Here R is the distance from the axis of symmetry to the point on the edge of the cross-section, R_w is the output radius of part 5, and β characterizes deformation of the circle. Using the same ϕ we parameterize the shape of the input of part 3 as $R(\phi) = h/\cos(\phi)$ for $\phi < \phi_0$ and $R(\phi) = h\tan(\phi_0)/\sin(\phi)$ otherwise. Here h is the height of the rectangular waveguide, $\phi_0 = \arctan(w/h)$, and w is the width of the rectangular waveguide. $R(\phi) = R_w$ at the output of part 5.

Dimensions to be optimized are shown in Fig. 1. They are the length of part 3 ($L1$), the length of part 5 ($L2$), the length of part 4 ($L3$), and the deformation parameter β. The input of part 3 and output of part 5 have fixed dimensions R_w, h, and w. The optimization algorithm was as follows: for a fixed value of β, we found a combination of $L1$ and $L2$ that produced the same mixture of modes in part 4. Then we adjusted the length of part 3 to achieve perfect mode conversion. From the array of solutions for the fixed β, we found one with the minimum total length. Then we changed β and found another configuration with minimum length. Scanning β, we found the most compact mode converter for the given input and output dimensions.

During this optimization, we found that the converter which produces no parasitic

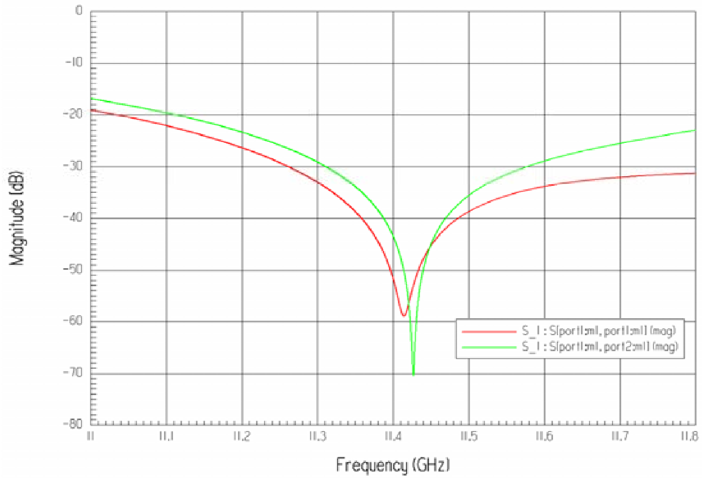

FIGURE 2. S-parameters of the TE_{20} rectangular to TE_{01} circular mode converter. The upper curve with sharp minimum is the parasitic mode conversion of TE_{20} rectangular into TE_{21} in the circular waveguide output. The lower curve is the reflection of the TE_{20} rectangular waveguide mode.

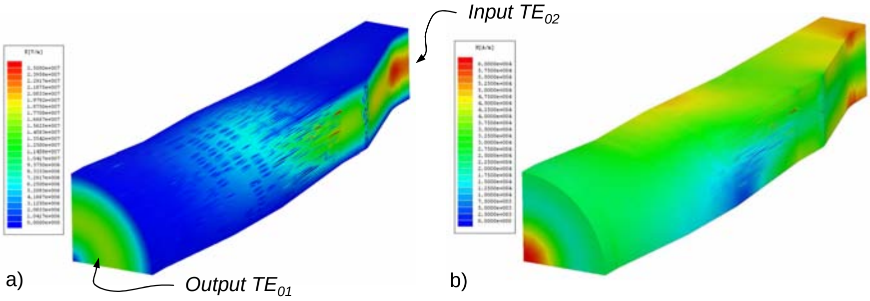

FIGURE 3. Fields in the TE_{20} rectangular to TE_{01} circular mode converter for 100 MW of transmitted power: a) the surface electric field, b) the surface magnetic field.

modes in the output gives a small backward scattered TE_{10} wave at the input port of part 3. This mode is reflected by the height taper (part 1) and propagates forward through the mode converter, spoiling the pure TE_{01} output.

To eliminate this TE_{10}, we used the following solution. First we changed length $L3$ so the mode converter started to produce a forward parasitic mode. Then we optimized the length of part 2 so the forward parasitic mode and the parasitic mode reflected from input cancel each other. Optimizing these two lengthes ($L3$ and $L4$), we were able to obtain a geometry with parasitic mode conversion below -50 dB.

Results of the optimization of the whole mode converter are shown in Fig. 2. The field distributions in the mode converter for 100 MW of transmitted power are shown in Fig. 3. The maximum electric field on the surface of the mode converter is 24.2 MV/m and the maximum magnetic field is about 50 kA/m.

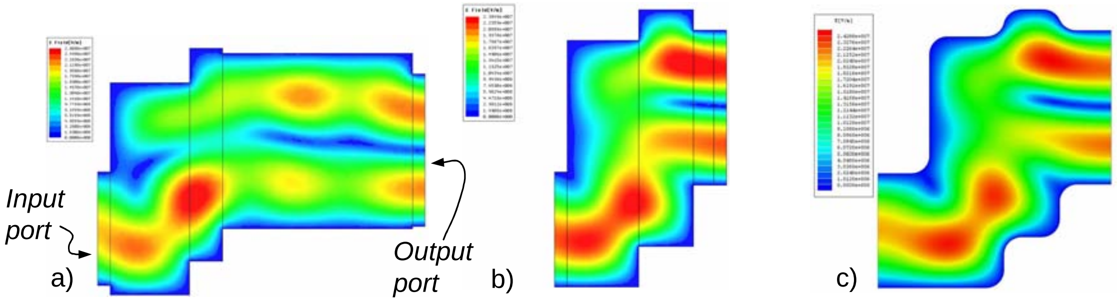

FIGURE 4. Geometries and surface electric fields in the TE_{10} to TE_{20} planar mode converter for 100 MW of transmitted power: a) a geometry made of five joined waveguides with seven optimization parameters; b) a geometry made of four joined waveguides with four free parameters; c) geometry with rounded edges.

TE_{10} WR90 to TE_{20} Overheight Rectangular Converter

To feed the mode converter described in the previous paragraph, we need a device that creates the TE_{20} mode in oversized rectangular waveguide from a TE_{10} mode in a WR90. This device should be compact and have very low parasitic mode conversion. The design consists of two parts: a planar TE_{10} to TE_{20} mode converter with height of 0.8 inch and height taper from W90 to rectangular waveguide with height 0.8 inch and width of 0.9 inch.

First, we describe the design of the planar TE_{10} to TE_{20} mode converter. The planar geometry allows us to use both a mode-matching code and HFSS for the optimization. For mode-matching we chose the commercial code CASCADE [2] by Calabazas Creek Research, Inc. This mode-matching code is fast and very accurate for geometries that consist of waveguide sections. It is a practical way to do multi-parameter optimization, since the calculation time for the converter geometry is a few seconds, compared to tens of minutes for HFSS (for solutions with comparable accuracy).

The design process consisted of several steps. First, a simple geometry was optimized. It consisted of five rectangular waveguide sections, shifted in the H-plane with respect to each other (see Fig. 4 a). This geometry had seven free parameters for optimization. We selected the shortest geometry out of an array of solutions. Then we analyzed the solution and reduced the number of free parameters to four (see Fig. 4 b). Again we took the shortest converter for further optimization. Then the rounding was introduced to avoid field amplification on sharp edges and for manufacturability (assuming that the converter will be cut by a 0.25 inch mill). This rounding is modeled in CASCADE by a stepwise approximation of the smooth boundary. After this geometry was optimized, we modelled it with HFSS. A C++ code that was used for the miltiparamter optimization read a file with a description of the geometry, and created input files for either CASCADE or HFSS. HFSS optimization started with an almost converged solution, so it converged in just 150 iterations. The resulting geometry is shown in Fig. 4 c. Both reflection and parasitic mode conversion were about -70 dB, as shown in Fig. 5.

While converging to the final solution the multiparamter optimization produced an array of solutions with close-to-optimal dimensions. Analysis of these solutions resulted

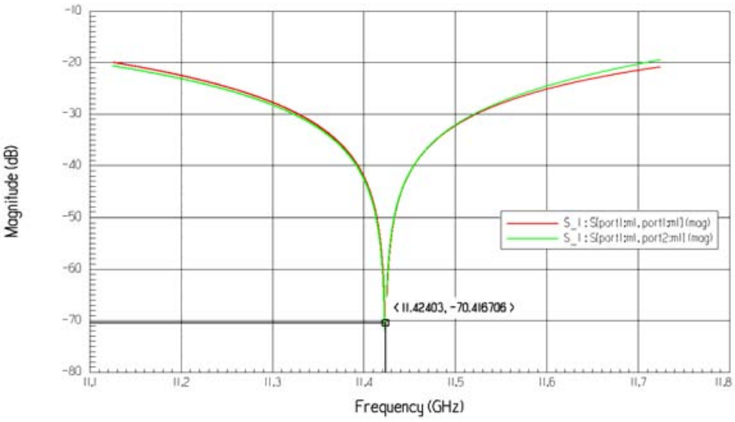

FIGURE 5. S-parameters of the TE_{10} to TE_{20} planar mode converter. The curve with lower attenuation at low frequency and higher attenuation at high frequency is TE_{10} reflection from input port. The other curve is parasitic mode conversion of TE_{10} from the input port to TE_{10} at the output port.

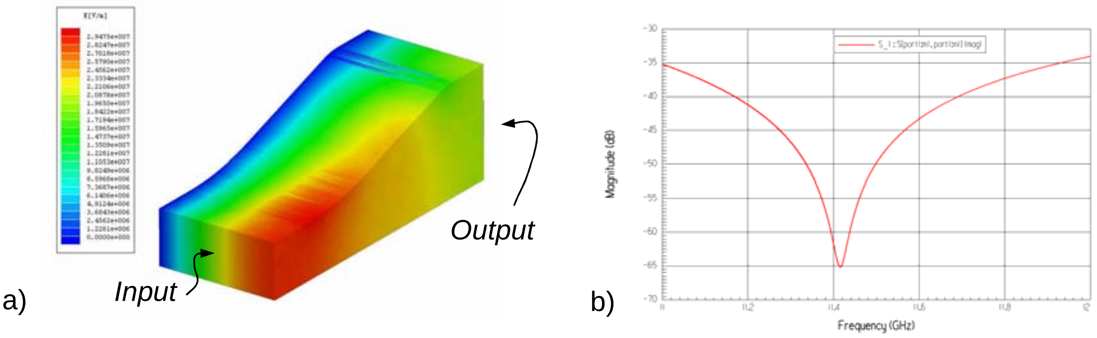

FIGURE 6. Height taper from WR90 to overweight waveguide: a) geometry and surface electric fields for 100 MW of transmitted power; b) TE_{01} reflection *vs.* frequency.

in tolerance requirements for the manufacturing of the converter. For the planar mode converter all critical dimensions have to be within ±30 μm for below -50 dB parasitic mode conversion.

To design the second part of this mode converter, the height taper, we used a two-parameter optimization similar to the one used to design the TE_{20} height taper from the previous section. The resulting geometry and match are shown in Fig. 6. The connection between the height taper and the planar TE_{10} to TE_{20} mode converter is described in the next paragraph.

Complete TE_{10} WR90 to TE_{01} Circular Mode Converter

We have now described all the elements for the complete mode converter: height taper, planar mode converter, and rectangular-to-circular mode converter. The next step is to

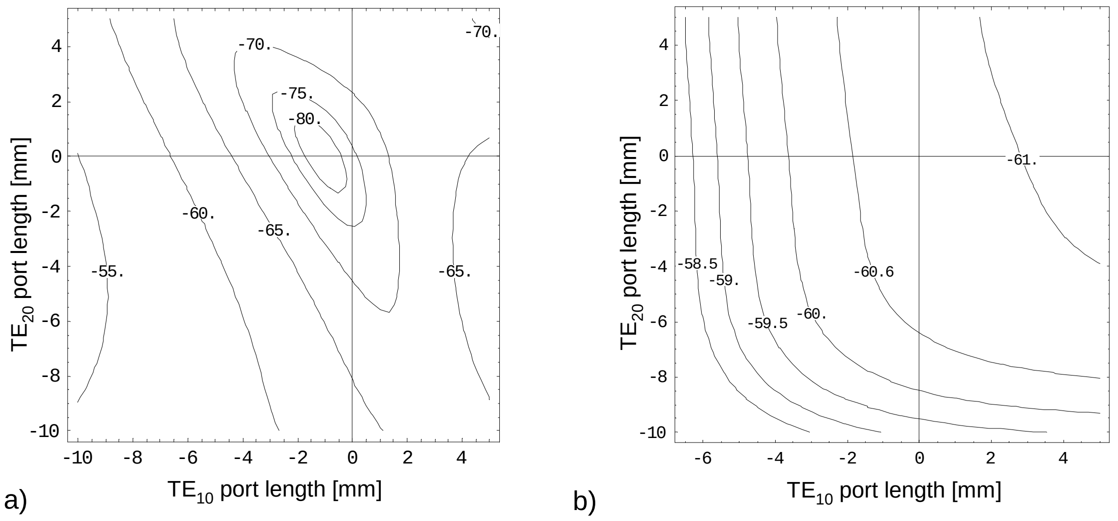

FIGURE 7. Results of port lengths optimization between WR90 height taper and TE$_{10}$ to TE$_{20}$ planar mode converter (TE$_{10}$ port length), and between the planar mode converter and TE$_{20}$ rectangular to TE$_{01}$ circular mode converter (TE$_{10}$ port length): a) WR90 TE$_{10}$ mode reelection; b) parasitic mode conversion from WR90 TE$_{10}$ mode.

combine these elements into one circuit and vary the lengths of waveguides between them to achieve optimal performance. To calculate S-parameters for the complete mode converter, we used analytical cascading of multimoded scattering matrices (see for example [2]) calculated for the separate parts of the converter.

The main reason for using cascading is stringent requirements on the accuracy of the simulations. To improve accuracy, we calculated quarters or halves of the parts of the converter with appropriate symmetry plane boundary conditions. The use of symmetries increases the number of tetrahedra per wavelength in the HFSS model. It is not practical with a full model of the converter to achieve the same number of tetrahedra per wavelength, and therefore the same accuracy, as for its parts. Multiple simulations of the complete converter for a two parameter scan of lengths of connecting waveguides does not look practical either.

We wrote a Mathematica [6] program to do the cascading. First we calculate a frequency scan of S-parameters for each element with each symmetry setting and save the data. The cascading program reads the S-parameter data for all the elements, changes analytically the length of the waveguide ports and cascades the corresponding transmission matrices. The results of the port length optimization are shown in Fig. 7. Reflection and parasitic mode conversion for the complete TE$_{10}$ WR90 to TE$_{01}$ circular mode converter are shown on Fig. 8.

SUMMARY

We designed two compact mode converters with lower than -50 dB parasitic mode conversion. The TE$_{20}$ rectangular to TE$_{01}$ circular mode converter could be a base part

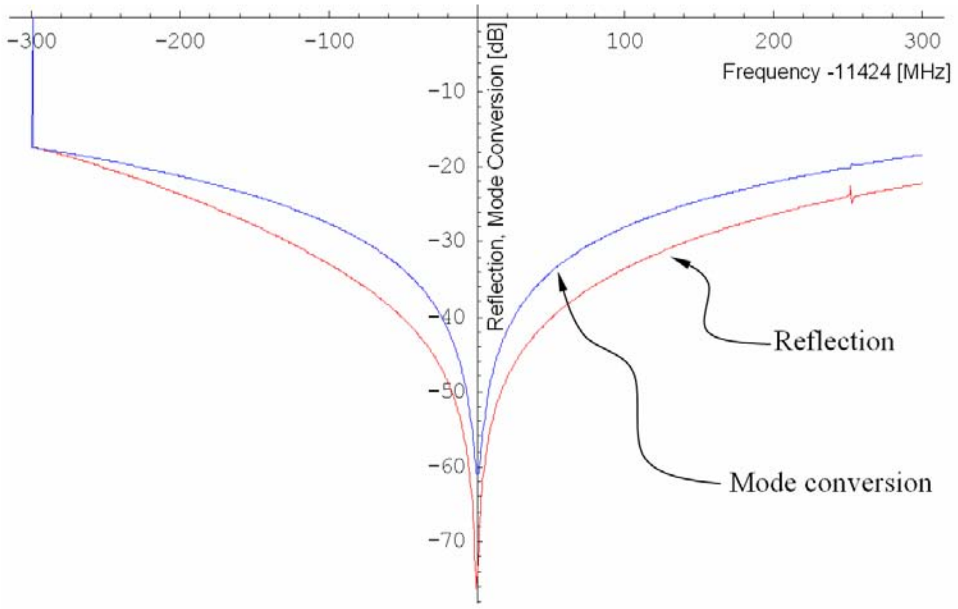

FIGURE 8. Reflection and mode conversion for complete TE_{10} WR90 to TE_{01} circular mode converter

for overmoded-only high power waveguide systems with performance superior to that of single-moded systems. The WR90 to TE_{01} circular mode converter could connect overmoded systems with single-moded inputs or outputs (based on WR90). The methodology that was successfully developed for the designs of the mode converters could be applied to create future overmoded systems, for example at different frequencies.

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