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Polarization-dependent TE_{11}-to-TE_{11}/TE_{01} waveguide mode converter for transmission line mode switching

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Introduction

Performance of microwave setups, such as ECR ion sources, may be affected by the selected type of the operating mode of microwave transmission line. The change of operating mode, if possible, is usually time-consuming process with substitution of some components and significant realignment. However, if we consider different modes of the same regular waveguide then mode switching can be made much easier and faster with the appropriate mode converters. In this work, we present the synthesized converter for switching between TE_{01} and TE_{11} modes of hollow smooth circular metal waveguide. Both modes are widely used, and in some cases it is hard to decide which one is preferable without experiments.

Synthesis of waveguide surface

Let us briefly discuss other elements of the transmission line first. Operating mode of the 45 GHz 20 kW CW gyrotron is converted into big converging Gaussian wave beam by output converter and matching optics unit. After several meters of insulating air gap, the beam is collected by the next converging mirrors and directed into synthesized waveguide taper. The taper converts Gaussian wave beam into linearly polarized TE_{11} mode of the circular waveguide with 22 mm diameter (see later). The next mode converter can conserve this mode or convert it into TE_{01}, being turned 90 degrees around its longitudinal axis. After the converter, there is one more taper to 32.6 mm waveguide diameter.

It is known that any non-symmetric mode may propagate differently in a serpentine converter, depending on its polarization relative to waveguide bend plane [1, 2]. This effect, controlled by the waveguide synthesizing code, allowed us to achieve high efficiency in both orientations.

The iterative synthesis method is based on the previous work made by authors [3, 4]. At the beginning of every iteration step the waveguide (Fig. 1) consists of the given input cross-section S_1, given output cross-section S_2 and initial conducting wall surface S_0. If we consider only one orientation, then conversion efficiency can be is increased after iteration by calculating two field distributions inside the waveguide. The first one is calculated using the given $\mathbf{E}_1$ and $\mathbf{H}_1$ fields at the input as a boundary condition, the second one by using the spatially reversed desired $\mathbf{E}_2$ and $\mathbf{H}_2$ fields at the output. Small and smooth deformation l orthogonal to waveguide wall affects the efficiency (mutual power) P according to formulas

$$\Delta P = \int_{S_0} l F dS, \quad F = -ik\left(\mathbf{H}_{\tau 1}\mathbf{H}_{\tau -2} + \mathbf{E}_{n1}\mathbf{E}_{n-2}\right) \quad (1)$$

where τ and n means tangential and normal field components, respectively. We can minimize the average square of deformation (i.e. norm) using real and imaginary parts of (1) as equality constraints with given ΔP, and in this simple case the deformation takes the form

$$l = \alpha \operatorname{Re} F + \beta \operatorname{Im} F \quad (2)$$

where constants α and β are expressed by ΔP and surface integrals of function F [4].

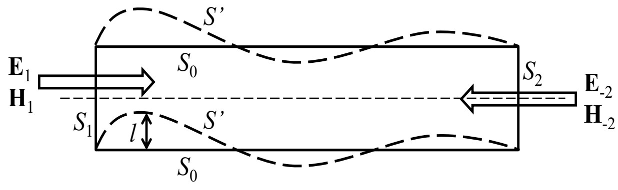

Fig. 1. Waveguide synthesis notations: two given waveguide cross-sections S_1 and S_2 (input and output, respectively), the waveguide surface before iteration S_0 and the surface after iteration S', the deformation value l at some point of the surface, the specified input fields $\mathbf{E}_1$ and $\mathbf{H}_1$, and the reversed desired output fields $\mathbf{E}_{-2}$ and $\mathbf{H}_{-2}$

To increase efficiency for both polarizations, two pairs of electromagnetic fields are calculated during the iteration and used in minimization. We used coupled-mode equations [1, 2] for field analysis, therefore we had to also add the condition of coaxiality of input and output cross-sections to allow rotation of the mode converter without realignment. This condition made the system solvable only numerically, which led to a slight decrease of the calculation speed.

Synthesized converter

We chose the waveguide diameter equal to 22 mm. It is high enough to pass the continuous power without arcing and overheating (with water cooling) and low enough to ensure adequate converter length. The length is 65 cm, which is only 10% more than then length of synthesized TE_{11}-TE_{01} converter with the same diameter and efficiency. After synthesis, the converter shape was tested numerically in CST Microwave Studio. Peak efficiency for both polarizations was well over 99.5%, but FDTD solver showed frequency shift for narrowband TE_{11}-TE_{01} conversion. However, few points calculated by frequency-domain solver showed good compliance with synthesis. It turned out that FDTD frequency shift depends on the mesh size. Power regression based on calculations with different mesh sizes suggests that the frequency shift tends to zero as mesh size approaches zero. Results for minimum cell size limited by the amount of available RAM are shown on Fig. 2.

One can see that efficiency in both orientations exceeds 99.5% in 400 MHz frequency band, which should be enough to cover the waveguide manufacturing tolerance and difference between actual and calculated gyrotron frequency. Fields in longitudinal cross-section in both polarizations are shown on Fig. 3a.

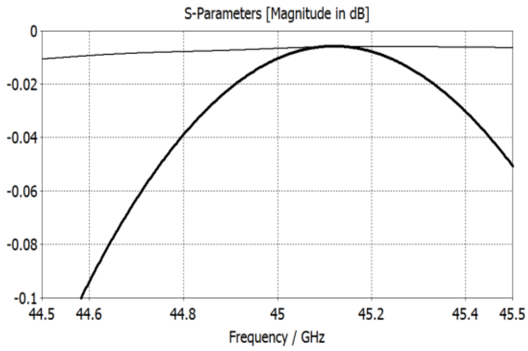

Fig. 2. CST Microwave Studio numerical test of conversion efficiency (FDTD solver): bold line corresponds to TE_{11}–TE_{01} conversion, thin line – to conservation of TE_{11} mode

The synthesized shape was split in two parts for manufacture and machined from copper. High-power measurements were done as a part of the complete setup. Output modes were observed using thermal paper and infrared imager. Thermal images presented in Fig. 3b illustrate overall efficiency of the transmission line, not only the mode converter. In spite of this, the level of spurious modes is very low.

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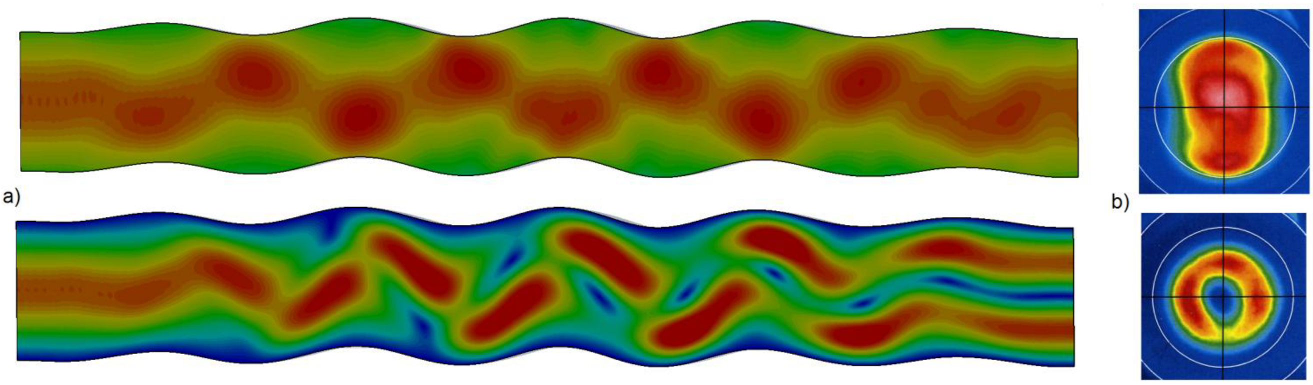

Fig. 3. a) Fields in longitudinal cross-section calculated by CST Microwave Studio (longitudinal coordinate compressed for better viewing), b) High-power thermal images of fields at the output cross-section. Top figures correspond to conservation of TE_{11} mode, bottom – to TE_{11}-TE_{01} conversion