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NEW COMPACT BROADBAND HIGH-EFFICIENCY MODE CONVERTERS FOR HIGH POWER MICROWAVE TUBES WITH TE_{0n} OR TM_{0n} MODE OUTPUTS*

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ABSTRACT

New shorter, broader bandwidth designs are discussed for TE_{03}-TE_{02} and TE_{02}-TE_{01} varying-radius mode converters and TE_{01}-TE_{11} serpentine mode converters for a 2.779 cm diameter circular waveguide for 60 and 140 GHz gyrotrons. Designs combining TE_{0n}-TE_{0n-1} converters with a 6.35-2.779 cm diameter taper are presented. A TM_{01}-TE_{11} serpentine mode converter design for a frequency of 8.6 GHz in a 4.76 cm circular waveguide is also discussed. Measured results are presented.

I. Introduction

Gyrotrons currently in use (and some being developed) for plasma heating have outputs in a TE_{0n} mode in a highly overmoded circular waveguide. Several other types of high-power tubes (the virtual cathode oscillator, certain relativistic BWO's, and magnetrons) in an advanced state of development in various laboratories generate power in TM_{0n} circular waveguide modes. TE_{0n} and TM_{0n} modes are not normally suitable for plasma heating or radiating into space with a useful pattern. They all have nulls in their radiation patterns on the waveguide axis and relatively low maximum gains. The electric fields of the TE_{0n} modes are purely azimuthal, (ϕ-polarized), while those of the TM_{0n} modes are purely θ-polarized. Thus these modes are commonly converted to the TE_{11} mode in a smooth-wall circular waveguide, the HE_{11} mode in a corrugated circular waveguide, or the TE_{10} in a rectangular waveguide. A typical mode conversion sequence for a gyrotron with a TE_{0n} mode output is shown in Fig. 1 [1].

In this paper, we present designs for mode transducers for 60 GHz and 140 GHz gyrotrons. The gyrotron's output mode is assumed to propagate in a 6.35 cm diameter circular waveguide which is commonly tapered to a 2.779 cm diameter. We will present designs for quasi-periodic and aperiodic varying-radius converters as well as serpentine converters. The quasi-periodic varying-radius mode transducers convert the TE_{0n} mode into the TE_{0n-1} mode and in some cases include part, but not all, of the taper. The aperiodic mode transducers convert the TE_{0n} mode into the TE_{0n-1} mode and include all of the 6.35 cm to 2.779 cm taper. A serpentine mode transducer converts the TE_{01} mode into the TE_{11} mode. Experimental results are be presented.

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A sequence of mode converters analogous to that shown in Fig. 1 can be used transform a TM_{0n} mode into an HE_{11} mode. In particular we will discuss an 8.6 GHz TM_{01}-TE_{11} mode converter in 4.76 cm diameter waveguide which is better than 98% efficient and uses only one perturbation period.

II. Varying-Radius Mode Converters

For varying radius mode converters, the coupled mode equations for the TE_{0n} modes can be written in the form [2]

$$\frac{dA_n}{dz} = -\gamma_n(z)A_n + \sum_{\substack{q \\ q\neq n}} K_{nq}(z)A_q \tag{1}$$

where

$$K_{nq}(z) = \frac{1}{a}\frac{da}{dz}\frac{x'_{0n}x'_{0q}}{(x'_{0n})^2-(x'_{0q})^2}\left[\left(\frac{\beta_n}{\beta_q}\right)^2+\left(\frac{\beta_q}{\beta_n}\right)^2\right]. \tag{2}$$

Here A_n is the complex amplitude of the TE_{0n} mode, normalized such that $|A_n|^2$ is the power transported in the z direction, a = a(z) is the radius of the converter (which is a function of z), x'_{0n} is the nth zero of $J'_0(x)$ excluding the one at x=0, and $\gamma_n(z) = \alpha_n+j\beta_n$ is the propagation constant of the TE_{0n} mode with $\beta_n = \beta_n(z) = \sqrt{k^2-(x'_{0n}/a)^2}$, k being the free space wavenumber. In the coupled mode equations, modes traveling in the -z direction have been neglected. Backward traveling modes, calculated by an invariant imbedding technique [3], have been shown to be negligible in all the cases considered here except in Sec. IV which has not been checked yet.

IIA. Quasi-Periodic Varying-Radius Mode Converters

For the quasi-periodic varying-radius mode converters, following Kovalev [4], we used a radial variation of the form

$$a(z) = a_1\{1 + \varepsilon_1/a_1[1+C_1\cos(H_2(z))][1\pm\cos(H(z))]\} \tag{3}$$

where ε_1/a_1 is the relative perturbation amplitude, $C_1\cos(H_2(z))$ is a small term used to

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suppress coupling to the TE_{0n+1} mode, and H(z) is approximately equal to $\int_0^z [\beta_{0n-1}(s) - \beta_{0n}(s)]ds$.

For a 1-1/2 period transducer, the plus sign in (2) is used and $0 \leq H(z) \leq 3\pi$. For a 2-period transducer, the minus sign in (2) is used and $0 \leq H(z) \leq 4\pi$. From 2-mode (TE_{0n} and TE_{0n-1}) constant beat wave number considerations, the relative perturbation amplitude, ε_1/r_1 can be shown to approximately satisfy the equation:

$$\frac{x'_{0n}x'_{0n-1}}{(x'_{0n})^2-(x'_{0n-1})^2} \begin{Bmatrix}4\pi\\3\pi\end{Bmatrix} \times \frac{\varepsilon_1}{a_1}[1 - \varepsilon_1/a_1 + 5/4(\varepsilon_1/a_1)^2] = \frac{\pi}{2} \qquad (4)$$

where the 4π term is for a 2-period device and the 3π term is for a 1-1/2 period device. Once ε_1/r_1 is determined, H(z) can be determined from 2-mode (TE_{0n} and TE_{0n-1}) variable beat wave number considerations by approximately solving the equation $\frac{dH}{dz} = \beta_{0n-1}(z) - \beta_{0n}(z)$. In the expression for $H_1(z)$, the plus sign is for the 2-period design and the minus sign is for the 1-1/2 period design. The solution was optimized by numerically integrating the coupled mode equations.

Using the method outlined in the previous paragraphs, we have designed 1-1/2 and 2-period 60 GHz mode converters both having a numerically calculated efficiency of 99.6% with losses taken into account. A graph of the modal modal amplitudes as a function of position as a function of position for the 2 period TE_{02}-TE_{01} converter is shown in Fig. 2. These shorter mode converters also have broader bandwidths than the older, longer designs as can be seen from Fig. 3 which compares the conversion efficiency as a function of frequency of the 2-period and 1-1/2 period converters with Moeller's pioneering 5-cycle design [5]. Preliminary measurements have been made on the 2-period converter in the reverse direction using the open-end radiation pattern method [6]. With a better than 99% pure TE_{01} mode input into the TE_{01} end (Fig. 4), a better than 99% pure TE_{02} mode was found at the output (Fig. 5).

IIB. Aperiodic Tapered TE_{0m}-TE_{01} Mode Converters

The basis for the aperiodic TE_{0n}-TE_{01} converter designs can be seen by examining Fig. 6. Figure 6a shows a taper and a 2-cycle mode transducer. Figure 6b shows the diameter variation of a conventional 1-1/2 cycle device "unfolded" with two flat sections one-half beat wavelength long inserted. The aperiodic device is substantially shorter than the combined length of the taper and 2-period mode transducer. Due to the constraint that the taper go from 6.35 cm to 2.779 cm, the ideal diameter variation of Fig. 6 was altered. Figure 7 shows the diameter variation of a 99.4% efficient 60 GHz TE_{02}-TE_{01} mode converter-taper which is only about half the length of the separate converter and taper which it replaces. In addition the combined converter-taper has a 30% greater 90% conversion efficiency bandwidth.

III. Serpentine TE_{01}-TE_{11} Mode Converters

A 60 GHz 98.8% efficient 3-period TE_{01}-TE_{11} serpentine mode converter was designed using an axial variation in one plane of

$$x(z) = \frac{\varepsilon_\ell(z)}{a}[1+c_{1,\ell}\cos(H_{2,\ell}(z))] \times [1-\cos(H_\ell(z))] + G(z) . \qquad (5)$$

where subscripted coefficients and functions change in different sections, $0 \leq H_\ell(z) \leq 2n\pi$, and G(z) is a small function introduced to suppress coupling to the TE_{12} mode. The TE_{01}, TE_{02}, TE_{11}, TE_{12}, TM_{11}, TE_{21}, TE_{22}, and TM_{21} modes were used in the numerical calculations. The TE_{01}-TE_{11} mode transducer is 86 cm. long. The mode amplitudes as a function of position are shown in Fig. 8 for the four most important modes.

IV. Serpentine TM_{01}-TE_{11} Mode Converter

A serpentine-type TM_{01}-TE_{11} mode converter has also been designed for a frequency of 8.6 GHz in a 4.76 cm diameter waveguide. For these parameters, only six modes can propagate (compared to 80 in the TE_{01}-TE_{11} converter above) and it is possible to obtain a mode conversion efficiency above 98% with a single "adjusted" period of about 50 cm as shown in Fig. 9. The reason that only one period is necessary here whereas three periods are necessary in Sec. III above is primarily that only six modes can propagate here whereas 80 modes can propagate in the converter of Sec. III. The conversion efficiency is limited to about 98% by the losses introduced primarily by the TM_{01} mode.

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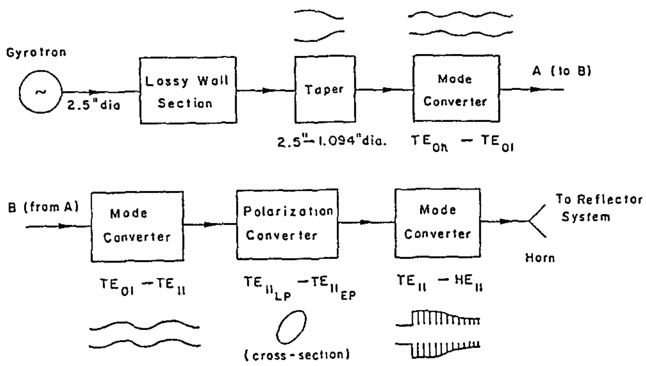

Fig. 1. A TE_{0n}-HE_{11} mode converter system. The gyrotron output mode could be any TE_{0n} mode. For a TE_{01} mode gyrotron output, the first mode converter (TE_{0n}-TE_{01}) is omitted. For a TE_{0n} gyrotron output with n > 2, the TE_{0n}-TE_{01} mode converter may have two or more stages. The minimum waveguide diameter after the taper was chosen to be 1.094". Larger minimum waveguide diameters are possible.

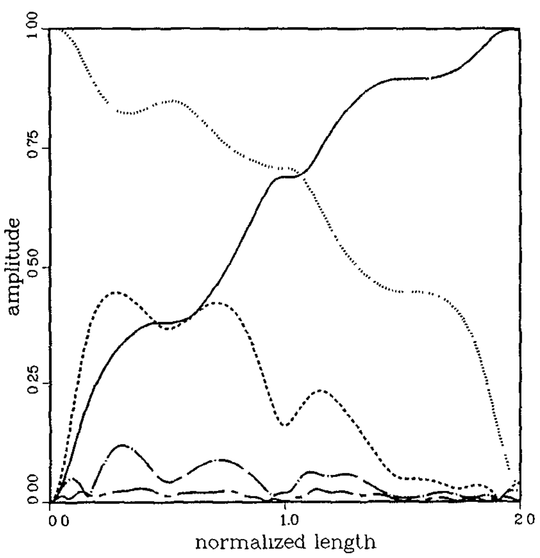

Fig. 2. Graph of amplitude as a function of longitudinal position for the first five TE_{0n} modes for a 2-period 60 GHz TE_{02}-TE_{01} mode converter. The length of the device is 24.9 cm. The device has a theoretical efficiency (including losses) of 99.6%.

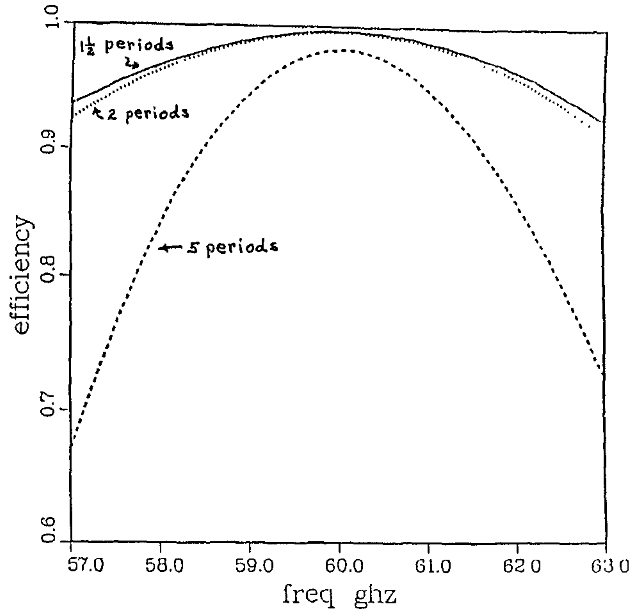

Fig. 3. Conversion efficiency of recent 1.5 and 2 period designs for TE_{02}-TE_{01} mode converters as a function of frequency compared with an older 5-period design of Moeller's. Notice the great improvement in the bandwidth as well as the small improvement in the center frequency conversion efficiency, both occurring in a more compact design.

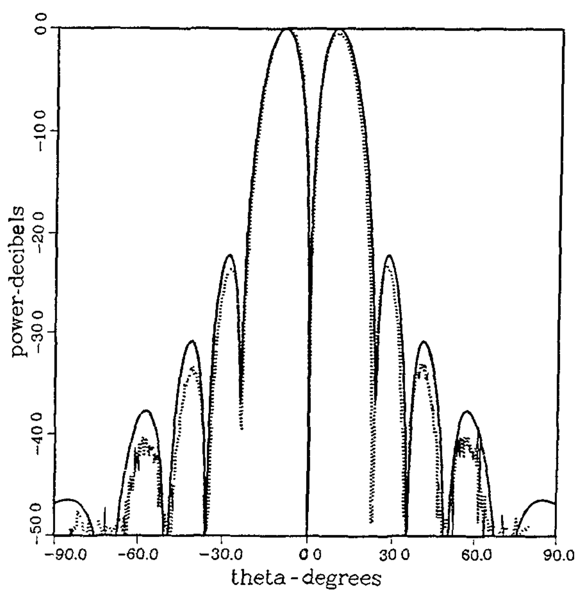

Fig. 4. Low-power open-end radiation pattern taken at a distance of 1.6 m for the TE_{01} mode input into the 2-period TE_{02}-TE_{01} mode converter. This input has a mode purity of greater than 99%.

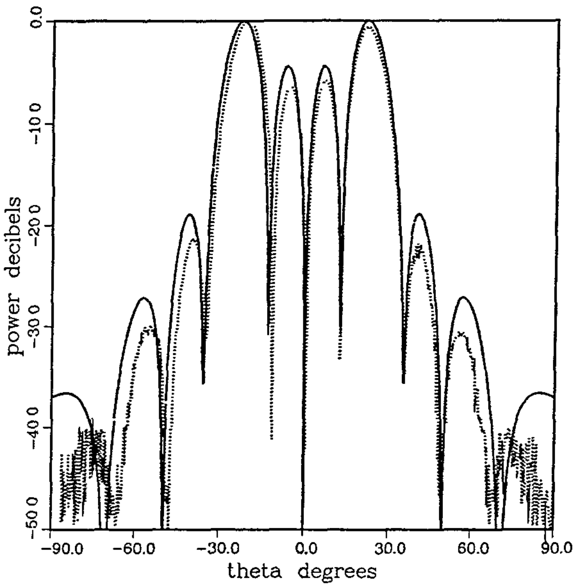

Fig. 5. Low-power open-end output radiation pattern taken at a distnce of 1.6 m for the TE_{02}-TE_{01} mode converter for the TE_{01} mode input of Fig. 4. This pattern indicates about a 99% TE_{02} mode output.

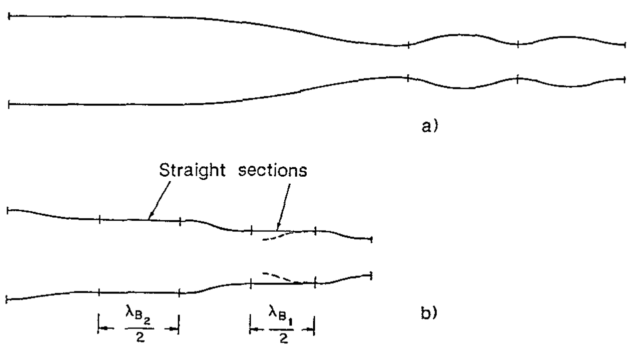

Fig. 6. (a) A downtaper and TE_{02}-TE_{01} mode converter compared with (b) an "unfolded" periodic perturbation mode converter combining both of these functions and having a shorter length than a previous downtaper alone.

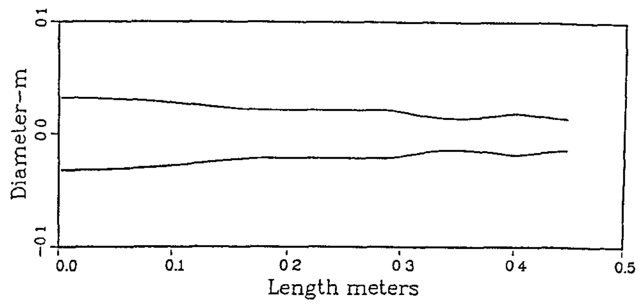

Fig. 7. Cross-sectional view of a 60 GHz TE_{02}-TE_{01} mode converter-taper. The device tapers from a 2.5" diameter waveguide to a 1.094" diameter waveguide. From two mode considerations, it can be shown that the flat section must be exactly one-half of a TE_{02}-TE_{01} beat wavelength long. The device has an efficiency (including losses) of 99.4% and is 44.75 cm long.

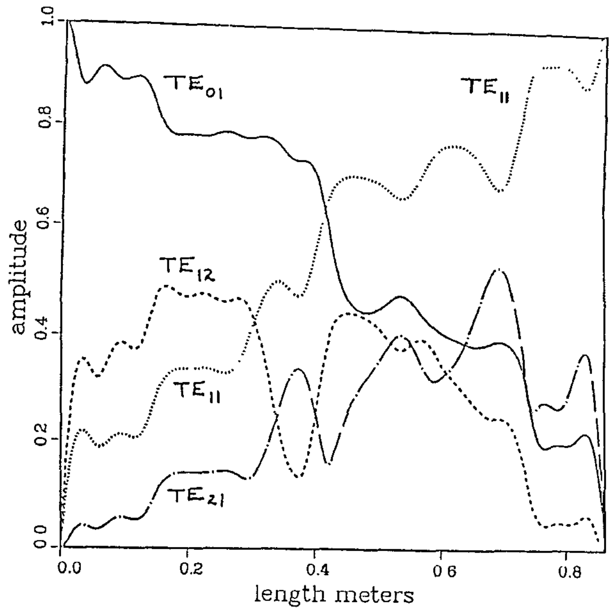

Fig. 8. Graph of amplitude versus longitudinal position for a 3-period 60 GHz TE_{01}-TE_{11} serpentine mode converter. The device is 86 cm long and has a diameter of 1.094 inches. The TE_{01}, TE_{11}, TE_{12}, and TE_{21} modes are plotted. The device is 98.88 % efficient (including losses). Eight modes, TE_{01}, TE_{02}, TE_{11}, TE_{12}, TM_{11}, TE_{21}, TE_{22}, and TM_{21} were used in the numerical calculations.

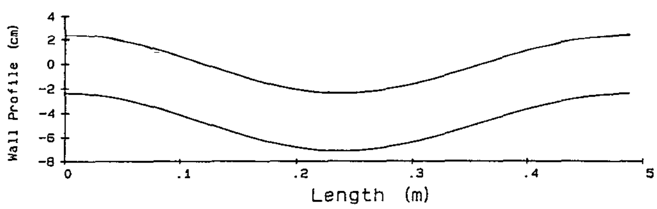

Fig. 9. Wall profile of a single period TM_{01}-TE_{11} serpentine mode converter for 8.6 GHz in a 4.76 cm diameter waveguide. The conversion efficiency is 98%.