

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 TE₀₃-TE₀₂ and TE₀₂-TE₀₁ varying-radius mode converters and TE₀₁-TE₁₁ 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 TM₀₁-TE₁₁ 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 TE₁₁ mode in a smooth-wall circular waveguide, the HE₁₁ mode in a corrugated circular waveguide, or the TE₁₀ 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 TE₀₁ mode into the TE₁₁ mode. Experimental results are 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 HE₁₁ mode. In particular we will discuss an 8.6 GHz TM₀₁-TE₁₁ 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]

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

where

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

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 γ_n(z) = α_n+jβ_n is the propagation constant of

the TE_{0n} mode with β_n = β_n(z) = √k² - (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

$$a(z) = a_1 \{ 1 + \epsilon_1/a_1 [1 + C_1 \cos(H_2(z))] [1 \pm \cos(H(z))] \} \quad (3)$$

where ε₁/a₁ is the relative perturbation amplitude, C₁cos(H₂(z)) is a small term used to

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 $0 < H(z) < 3\pi$. For a 2-period transducer, the minus sign in (2) is used and $0 < H(z) < 4\pi$. 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:

$$\frac{x'_{0n} x'_{0n-1}}{(x'_{0n})^2 - (x'_{0n-1})^2} \left\{ \begin{array}{l} 4\pi \\ 3\pi \end{array} \right\} \times \frac{\epsilon_1}{a_1} [1 - \epsilon_1/a_1 + 5/4(\epsilon_1/a_1)^2] = \frac{\pi}{2} \quad (4)$$

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 expres-

sion for H₁(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 TE₀₂-TE₀₁ 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 TE₀₁ mode input into the TE₀₁ end (Fig. 4), a better than 99% pure TE₀₂ mode was found at the output (Fig. 5).

IIB. Aperiodic Tapered TE_{0n}-TE₀₁ Mode Converters

The basis for the aperiodic TE_{0n}-TE₀₁ 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 TE₀₂-TE₀₁ 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 TE₀₁-TE₁₁ Mode Converters

A 60 GHz 98.8% efficient 3-period TE₀₁-TE₁₁ serpentine mode converter was designed using an axial variation in one plane of

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

where subscripted coefficients and functions change in different sections, $0 < H_{\ell}(z) < 2n\pi$, and G(z) is a small function introduced to suppress coupling to the TE₁₂ mode. The TE₀₁, TE₀₂, TE₁₁, TE₁₂, TM₁₁, TE₂₁, TE₂₂, and TM₂₁ modes were used in the numerical calculations. The TE₀₁-TE₁₁ 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 TM₀₁-TE₁₁ Mode Converter

A serpentine-type TM₀₁-TE₁₁ 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 TE₀₁-TE₁₁ 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 TM₀₁ mode.

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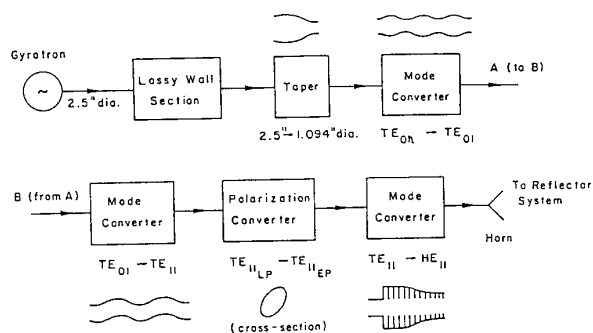


Fig. 1. A TE_{0n} - HE_{11} mode converter system. The gyrotron output mode could be any TE_{0n} mode. For a TE_{01} mode gyrotron output, the first mode converter (TE_{0n} - TE_{01}) is omitted. For a TE_{0n} gyrotron output with $n > 2$, the TE_{0n} - TE_{01} mode converter may have two or more stages.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

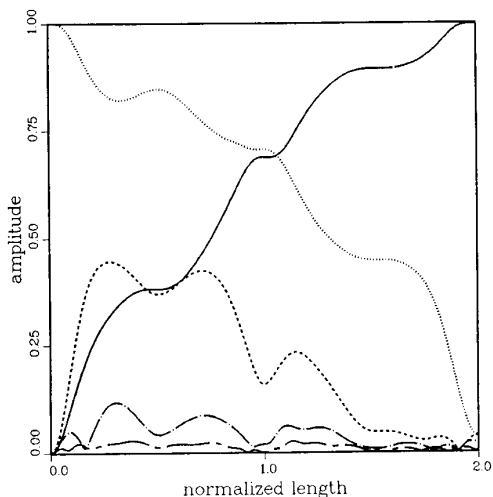


Fig. 2. Graph of amplitude as a function of longitudinal position for the first five TE_{0n} modes for a 2-period 60 GHz TE_{02} - TE_{01} mode converter. The length of the device is 24.9 cm. The device has a theoretical efficiency (including losses) of 99.6%.

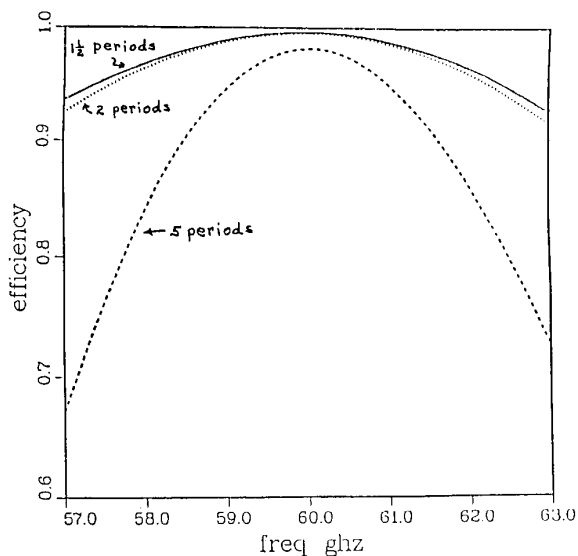


Fig. 3. Conversion efficiency of recent 1.5 and 2 period designs for TE_{02} - TE_{01} mode converters as a function of frequency compared with an older 5-period design of Moeller's. Notice the great improvement in the bandwidth as well as the small improvement in the center frequency conversion efficiency,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

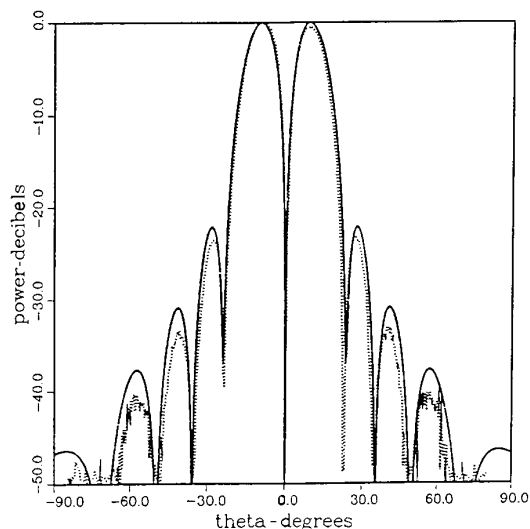


Fig. 4. Low-power open-end radiation pattern taken at a distance of 1.6 m for the TE_{01} mode input into the 2-period TE_{02} - TE_{01} mode converter. This input has a mode purity of greater than 99%.

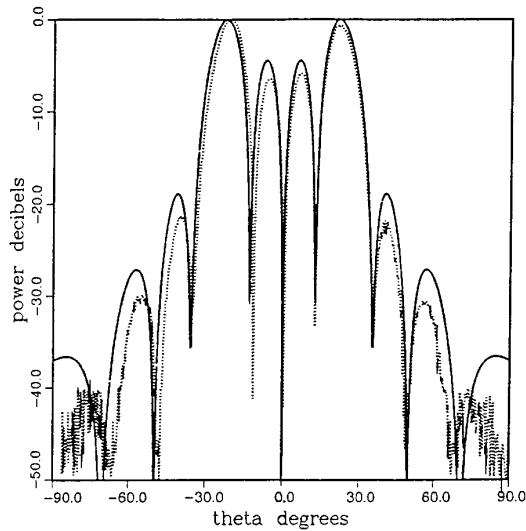


Fig. 5. Low-power open-end output radiation pattern taken at a distance of 1.6 m for the TE_{02} - TE_{01} mode converter for the TE_{01} mode input of Fig. 4. This pattern indicates about a 99% TE_{02} mode output.

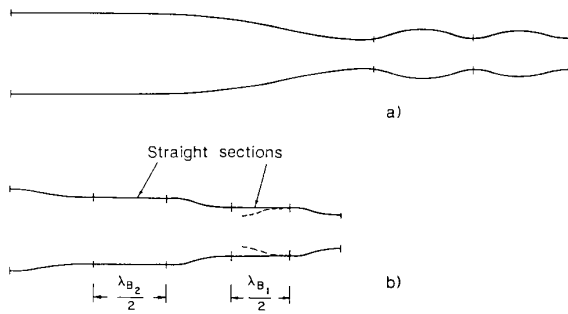


Fig. 6. (a) A downtaper and TE_{02} - TE_{01} mode converter compared with (b) an "unfolded" periodic perturbation mode converter combining both of these functions and having a shorter length than a previous downtaper alone.

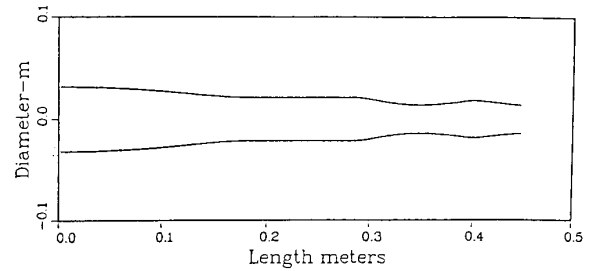


Fig. 7. Cross-sectional view of a 60 GHz TE_{02} - TE_{01} mode converter-taper. The device tapers from a 2.5" diameter waveguide to a 1.094" diameter waveguide. From two mode considerations, it can be shown that the flat section must be exactly one-half of a TE_{02} - TE_{01} beat wavelength long. The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

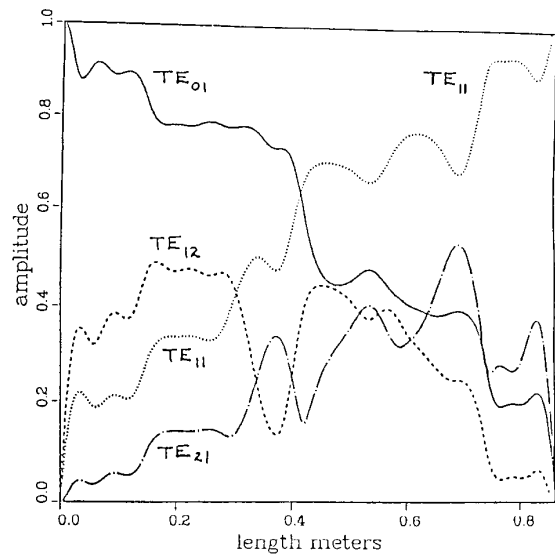


Fig. 8. Graph of amplitude versus longitudinal position for a 3-period 60 GHz TE_{01} - TE_{11} serpentine mode converter. The device is 86 cm long and has a diameter of 1.094 inches. The TE_{01} , TE_{11} , TE_{12} , and TE_{21} modes are plotted. The device is 98.88% efficient (including losses). Eight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

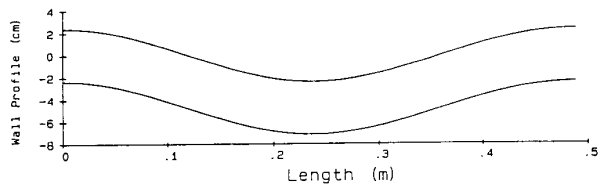


Fig. 9. Wall profile of a single period TM_{01} - TE_{11} serpentine mode converter for 8.6 GHz in a 4.76 cm diameter waveguide. The conversion efficiency is 98%.