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Converters for the TE_{11} Mode Generation from TM_{01} Vircator at 4 GHz

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The measurements and calculations (coupled mode equations) on the conversion of the transverse magnetic TM_{01} vircator (virtual cathode oscillator) mode at 4 GHz to the linearly polarized TE_{11} mode are presented by means of mode converter systems using a circular waveguide with curvature. The mode converter is composed of the 38.78° bend with 39.07 cm curvature and of the 50.78° inverse bend with 25.24 cm curvature in the circular waveguide of 9 cm internal diameter. The efficiency of conversion from TM_{01} to TE_{11} at 4 GHz exceeds 90%, and the overall efficiency from TM_{01} to TE_{11} exceeds 90% in the calculated range from 3.72 to 4.8 GHz.

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The virtual cathode oscillator, commonly referred to as the vircator, has a conceptual and mechanical simplicity compared to the other microwave sources. It produces high power levels (up to GW) and is conspicuously tunable. The vircator has been useful in many areas of intense beam physics, most notably light ion fusion and collective on acceleration.[1] The vircator usually generates one or more TM_{0n} transverse magnetic modes. Such a mode is good for power transmission in long runs of straight circular waveguides since they dissipate only small amounts of power in waveguide walls. However, they are unpolarized and can generate an undesirable conical radiation pattern without energy content on the axis from an open-ended waveguide. The almost linearly polarized TE_{11} mode, which produces a pencil beam with approximately 98% of the radiated power on the axis and a well-defined polarization from an open-ended waveguide, satisfies the requirement of the applications of the microwave. Therefore, we wish to consider converting power into the linearly polarized TE_{11} mode.

The TM_{0n}-to-TE_{11} mode converters suited for high-power applications can use a smooth circular waveguide with a curvature[2–5] and a constant cross section avoiding high power-flux densities and breakdown in waveguide. The converter is composed of a double back-to-back bend with differential curvature and is studied by using the modular analysis concept.[4] Using this method, it is possible to obtain almost complete power conversion between the two coupled modes of interest. This letter presents the measurements and calculations of the conversion of the transverse magnetic TM_{01} vircator mode at 4 GHz to the linearly polarized TE_{11} mode by the converter systems using a circular waveguide with a curvature.

In the overmoded circular waveguide, a selective transformation of one specific mode into another can be achieved by means of bending the circular waveguide with a proper curvature. When the waveguide distortions are small (low coupling per wavelength), the reflection can be ignored, and the requirements for the bending angle and converter length necessary for complete conversion can be deduced from the well-known modular analysis concept.[4] The set of simultaneously coupled differential equations for the complex forward-travelling wave amplitudes A of the two desired modes and all the other coupled undesired spurious modes are given by

$$\frac{\mathrm{d}A_m}{\mathrm{d}z} = -\gamma_m A_m - \mathrm{j}\sum_{n,m\neq n} C_{mn}A_n, \qquad (1)$$

where $\gamma_m = \alpha_m + \mathrm{j}\beta_m$ is the propagation constant of the mth mode (β_m being the wavenumber, and α_m the attention constant), and j indicates the imaginary part. The coefficients C_{mn} describe the forward mode-conversion coupling due to the bending of the waveguide. Even when the dissipation in the transmission lines is important, it is still assumed that the coupling mechanism is non-dissipative. This assumption is valid provided that the difference between the attenuation constants $(\alpha_n - \alpha_m)$ is small compared to the coefficient of coupling C_{mn}.[7]

The coupled mode Eq. (1) has to be solved numerically by using a differential equation solver but some features of the solution can be estimated from the coupled mode equations for the two modes of interest. Neglecting all spurious modes, we have

$$\frac{\mathrm{d}A_1}{\mathrm{d}z} = -\gamma_1 A_1 - \mathrm{j}C_{12}A_2,$$

$$\frac{\mathrm{d}A_2}{\mathrm{d}z} = -\gamma_2 A_2 - \mathrm{j}C_{21}A_1. \qquad (2)$$

In the lossless case, the propagation constants γ_1 and γ_2 are purely imaginary and have the form $\gamma_i = \mathrm{j}\beta_i$ $(i = 1, 2)$, where β_i is real. For the TM_{01}-to-TE_{11} transformation, the coupling coefficients can

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be deduced from Li's theory,[4] if we let A_1 and A_2 represent TM_{01} and TE_{11}, respectively; i.e.,

$$C_{12} = C_{21} = C = -\frac{\beta_1 + \beta_2}{\sqrt{2\beta_1\beta_2\left(\nu_{11}^2 - 1\right)\left(\nu_{11}^2 - u_{01}^2\right)}}\frac{k \cdot a}{R} \quad , \qquad (3)$$

where a is the radius of the waveguide, R is the curvature, k is the wavenumber, and ν_{11} and u_{01} are the roots of the Bessel function J_1' and J_0, respectively. Equation (1) is also a pair of coupled mode equations with two different effective phase constant $\beta_{1,2}$ (different phase velocity for both TM_{01} and TE_{11} modes) and uniform effective coupling coefficient C along the direction of the bent waveguide. When $A_1(0)$=1 and $A_2(0)$=0, the solution of Eq. (3) is very simple,

$$|A_2|^2 = \frac{C^2 \sin^2(\Omega Z)}{\Omega^2}, \qquad (4)$$

where $\Omega = \frac{1}{2}\sqrt{4C^2 + (\beta_2 - \beta_1)^2}$, $|A_1|^2 = 1 - |A_2|^2$, $Z = R \cdot \theta$, and θ is the bending angle.

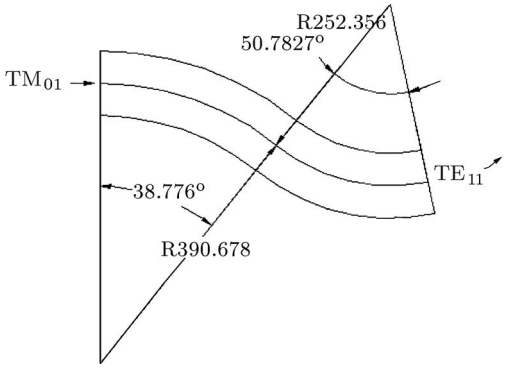


Fig. 1. Geometry scheme of the bent TM_{01}–TE_{11} mode converter.

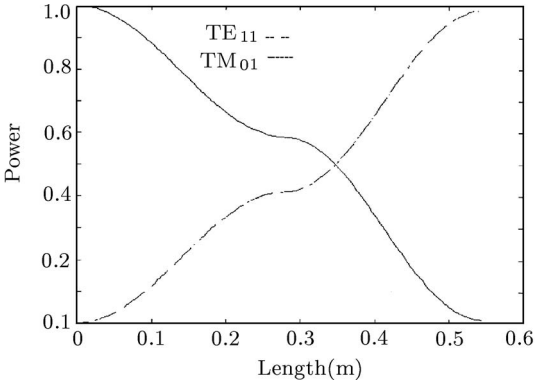


Fig. 2. Normalized wave power versus converter length.

If we let $\beta_1 = \beta_2$, for example, the TE_{01}-to-TM_{11} transformation, we can obtain the same results as Doane,[8] and may obtain a complete and cyclic power transfer between the two degenerated modes by using one bent circular waveguide. However, in our case, the β_1 did not equal β_2, the best bending angle is $\theta_1 = \pi/(2R\Omega)$, and the maximum amplitude of $|A_2|$ is C/Ω for one bent circular waveguide. Therefore one may not obtain a complete power transfer between the two modes of interest by using one bent circular waveguide.

If one bends the circular waveguide with the curvature R_2 on the other side of the axis of the waveguide at the same plane, as shown in Fig. 1, one can obtain $|y_2|^2$ from Eq. (2):

$$|A_2|^2 = \frac{1}{\Omega_2^2}\Big\{a_2^2\left(\beta_2 - \beta_1\right)^2 + 2a_1a_2C_2\left(\beta_2 - \beta_1\right) + 2\left(a_1^2 + a_2^2\right)C_2^2 - 2\Big[\left(a_1^2 - a_2^2\right)C_2^2 \; a_1a_2C_2\left(\beta_2 - \beta_1\right)\Big]\cos\left(\Omega_2R_2\theta_2\right)\Big\}, \qquad (5)$$

where C_2 is the coupling coefficient of the secondary bent waveguide, $\Omega_2^2 = (2C_2)^2 + (\beta_2 - \beta_1)^2$, a_1 and a_2 are the initial input wave amplitudes of TM_{01} and TE_{11} of the secondary bent waveguide, respectively. If we let $\Omega_2R_2\theta_2 = \pi$, where θ_2 is the secondary bend angle, we can obtain

$$|A_2|^2 = \frac{\left[a_2\left(\beta_2 - \beta_1\right) + 2a_1C_2\right]^2}{(2C_2)^2 + \left(\beta_2 - \beta_1\right)^2}. \qquad (6)$$

If we choose the initial value $a_2 = (\beta_2 - \beta_1)/\Omega_2$, we may obtain from Eq. (6) that $|A_2|^2 = 1$ and $|A_1|^2 = 0$, therefore we may obtain a complete power transfer between the TM_{01} and TE_{11} modes by using a circular waveguide bent back-to-back with differential curvature.

For our operating conditions, i.e. the wavelength of 7.5 cm and the waveguide radius of 4.5 cm, only TM_{01}, TE_{11} and TE_{21} are the transmission modes. The only undesired mode is TE_{21}. We even compile a general optimization program to solve Eq. (1), which includes these three modes. The results are examined by using the program provided by Li.[4]

The TM_{01}-to-TE_{11} mode converter is shown in Fig. 1, which was realized by two waveguide bends with constant curvatures. The two sections are linked up at the tangent point of the two arcs, while the input waveguides are also tangent to the arcs so that the junctures will not produce additional coupling or reflection. $\theta_1 = 38.78°$ and $\theta_2 = 50.78°$ are the bending angles of the two waveguide, respectively. Also, $R_1 = 39.07$ cm, $R_2 = 25.24$ cm is the curvature. The mode converter was made by a computer-controlling machine to suppress the ellipticity. The machined mode converter was electroplated with silver to reduce the loss of the microwave power.

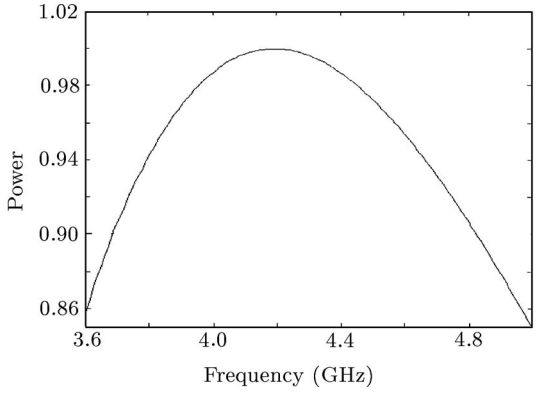


Fig. 3. Normalized power of TE_{11} versus frequency.

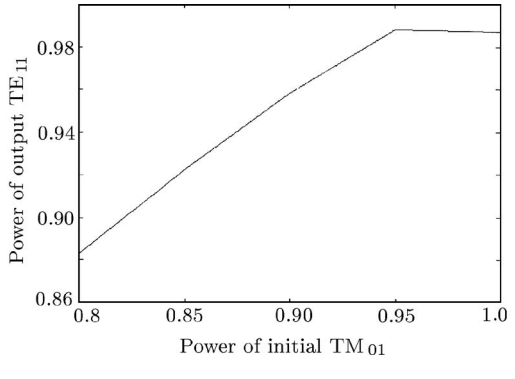


Fig. 4. Normalized power of TE_{11} versus initial power of TM_{01} mode.

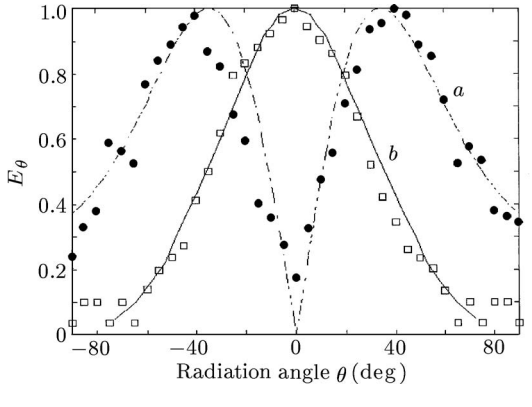


Fig. 5. (*a*) Measured (circle) and calculated (dot-dashed line) E-plane radiation pattern of the TM_{01} output from the straight circular waveguide. (*b*) Measured (square) and calculated (solid line) of the TE_{11} pattern in ideal mode converter at 4 GHz.

The calculation results of the mode converter are shown in Figs. 2 – 4. Figure 2 illustrates the normalized wave power of the two main modes of interest (TM_{01}, TE_{11}) versus the converter length. One can see from Fig. 2 that the calculated conversion efficiency exceeds 99%.

In order to check the sensitivity of the mode converter behaviour to the variable operation conditions, the calculations were also performed for different operation frequencies and different input power rates of TM_{01} to total power. Figure 3 illustrates the normalized power of the TE_{11} mode (or efficiency) versus the operation frequency. The mode converter operation frequency ranges from 3.72 to 4.84 GHz with the conversion efficiency exceeding 90%. Figure 4 illustrates the normalized power of TE_{11} versus the input power rate of TM_{01} to total power. One can see from Fig. 4 that, if the input power rate of TM_{01} to total power exceeds 80% and the rate of TE_{11} to total power is smaller than 20%, the mode conversion efficiency exceeds 90%.

The mode converter was tested at low power by means of far-field radiation pattern measurements. Centimetre waves were generated and measured by a HP 8510C network analyser. The pure TM_{01} mode at 4 GHz was produced by an electric field probe located at the axis of a straight circular waveguide with a radius of 4.5 and a length of 30 cm. Figure 5 illustrates the measured E-plane radiation pattern of TM_{01} (a) from a straight circular waveguide (indicated by the circles), and the measured E-plane radiation pattern (b) of the mode converter (indicated by the squares). The 4 GHz power was produced by a HP 8510C network analyser and detected by a centimetre open-end waveguide. The measured E-plane pattern is superimposed on the ideal far-field TM_{01} and TE_{11} radiation patterns in Fig. 5 (solid and dot-dashed lines). From these figures one can see that the TM_{01} mode was almost complete transferred into the TE_{11} mode.

In conclusion, there is good agreement between the calculated and measured performance of the devices. The calculation efficiency of the conversion from TM_{01} to TE_{11} at 4 GHz exceeds 99%, and the overall efficiency from TM_{01} to TE_{11} exceeds 90% over the calculated range of 3.72 to 4.8 GHz.

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