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A METHOD OF REMOTELY STEERING A MICROWAVE BEAM LAUNCHED FROM A HIGHLY OVERMODED CORRUGATED WAVEGUIDE

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A Method of Remotely Steering a Microwave Beam Launched from a Highly Overmoded Corrugated Waveguide

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A primary application of high power millimeter waves is electron cyclotron heating and current drive in magnetically-confined plasma research. Transmission of the power from generator to load, if skin effect losses, risk of microwave breakdown, and first wall penetration area are to be minimized, can best be accomplished by using corrugated waveguide having transverse dimensions »λ_0, where λ_0 is the free space wavelength. However, for a fixed frequency or even a step tunable source, such as a gyrotron, localization of current drive requires toroidal or poloidal steering, depending on electron temperature [1].

Although this steering can be accomplished by rotatable mirrors within the vacuum vessel, engineering details are challenging, and reliability remains a question [2]. A method of controlling the angle at which a microwave beam is launched from a corrugated waveguide is described which places the only moving parts many meters from the waveguide output. This approach was first developed as an alternative to the internal moving mirror baseline design for ITER [3].

Description and Results

The proposed scheme for remote beam steering requires the use of a square or rectangular corrugated waveguide. Designating b(z) as the waveguide height in the steering plane (y–z plane), and b_0 the waveguide height at the output, it is necessary that $b_0 > 10\lambda_0$ for this scheme to be useful. Designating the transverse dimension orthogonal to b as a (along x), the effective wave number in the y–z plane is $k_{||} = [(2\pi/\lambda_0)^2 - (\pi/a)^2]^{1/2}$. To avoid the complication of diffraction in the x–z plane outside the waveguide, we will let $a \to \infty$, so that the geometry is truly 2D and $k_{||} = 2\pi/\lambda_0 = k_0$.

A Gaussian-like beam will be emitted from the output of a square or rectangular corrugated waveguide at ϕ radians with respect to the waveguide (z) axis if the E_y-field component has the profile at the outlet: $\sin(\pi y/b_0)\ \exp(i\phi k_0 y$. This profile can be expanded in terms of the normal modes of the waveguide as $E_y = \sum_{n=1}^{\infty} B_n \sin(n\pi y/b_0)$, where the coefficients are given by:

$$B_n = \frac{-i4nu\left\{\exp\left[i\pi(u-n)\right]+1\right\}}{\pi\left[u^2-(n+1)^2\right]\left[u^2-(n-1)^2\right]} \quad , \tag{1}$$

where $u = \phi k_0 b_0/\pi$. If these mode amplitudes could be excited at some remote point such that the modes arrived at the waveguide output with the phases required by (1), remote steering would be achieved.

It is interesting to see which modes contribute to the far field radiation pattern for a given value of u in (1). A 2D far field pattern [4] for the case $u = 14$ (which corresponds to $\phi = 11.1°$ for $b_0 = 6.35$ cm at 170 GHz) is plotted in Fig. 1 for modes of index 14, 13–15, and 12–16. The five modes account for 99.3% of the total radiated power. When u is not an integer, the basic behavior is the same so that the output pattern shape only changes weakly with ϕ.

The required mode amplitudes can be excited most easily by the inverse process, e.g., launching a beam into the waveguide input at angle ϕ. In addition, the correct phases are given by (1), so with this excitation, it is "only" necessary for the relative phases to replicate at the waveguide output.

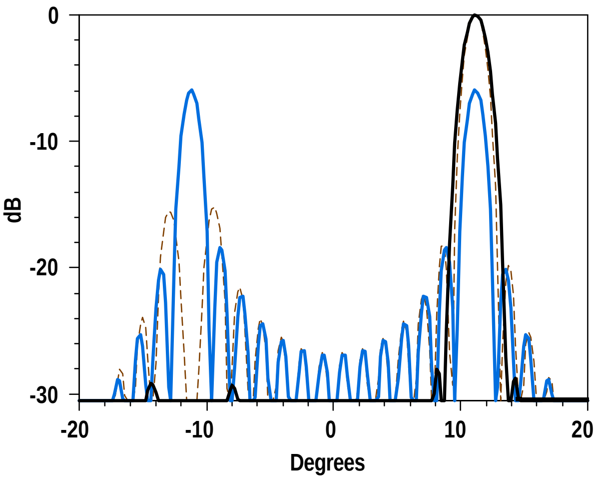

Fig. 1. The far field pattern of the $N = 14$, $N = 13$–15, and $N = 12$–16 modes having amplitudes given by Eq. (1) radiated from an aperture of height b_0 = 6.35 cm at 170 GHz. The corresponding power in the main lobe is 50%, 83.5%, and 99.3%.

The accumulated phase difference between any two modes of indices m and n along a waveguide of length L (which in general may be tapered) is given by:

$$\Delta\psi_{m,n} = \int_0^L \left(\left\{ k_0^2 - \left[m\pi / b(z/L) \right]^2 \right\}^{1/2} - \left\{ k_0^2 - \left[n\pi / b(z/L) \right] \right\}^{1/2} \right) dz \quad , \qquad (2)$$

$$= \frac{\pi^2}{2} \frac{k_0\, L\, I_1}{(k_0\, b_0)^2} \left(n^2 - m^2 \right) \left[1 + \frac{1}{4} \left(\phi_n^2 + \phi_m^2 \right) \frac{I_2}{I_1} + \frac{1}{8} \left(\phi_n^4 + \phi_n^2 \phi_m^2 + \phi_m^4 \right) \frac{I_3}{I_1} + \ldots \right]$$

where $I_p = b_0^{2p} \int_0^1 dt / b(t)^{2p}$, $\phi_p = p\pi/k_0 b_0$, and $b(t) \geq b_0$. Considering first only the lowest order term of (2), if we choose $k_0 L = (4/\pi)(k_0 b_0)^2/I_1$, so that $\Delta\psi_{1,2} = 6\pi$, then $\Delta\psi_{m,n} \approx 2\pi(n^2 - m^2)$. Therefore, if ϕ_n^2 and ϕ_m^2 « 1, so that the higher terms of the binomial expansion can be neglected, all the incident modes come back into phase over this length, and the tilted input beam is replicated at the waveguide output. It was pointed out by G. Denisov [5] that the tilted beam would also be replicated at $L/2$, but at $-\phi$, thereby reducing both the required waveguide length and the phase error. $k_0 L = (2/\pi)(k_0 b_0)^2/I_1$ will be used in all plots that follow. In particular, if $b(z/L) = b_0$, $k_0 L = 2(k_0 b_0)^2/\pi$.

Figure 2 shows examples of a 2D far field pattern of a beam steered through a uniform waveguide, which shows a useful range of about ±10°. The steering range can be extended to ±15°, as shown in Fig. 3 by reducing L by $-\Delta L$ where $\Delta L/L = 1 - 4N\pi/(\Delta\psi_{N,N+1} - \Delta\psi_{N,N-1})$ and N is chosen so that $N - 1/2 < u \leq N + 1/2$. $\Delta L/L$ varies approximately as ϕ^2. Varying the length with angle requires a line stretcher or a means of changing the effective position at which the input beam enters the waveguide.

Regarding any further steering range extension, for modes having significant amplitudes in Eq. (2), ϕ_n and $\phi_m \approx \phi$, so phase errors can only be reduced by reducing I_2/I_1 and I_3/I_1. The form of $b(z/L)$ that has been examined so far is $b(t) = b_0(R\text{-}(R - 1)t^k)$, where Rb_0 is the input height and b_0 is the output height. For $k = 1$, $k_0 L = 2R(k_0 b_0)^2/\pi$, and for $R = 3$, for example, $I_2/I_1 = 0.48$ and $I_3/I_1 = 0.30$.

For $k = 2$, $k_0 L = 4R(k_0 b_0)^2/\pi\{1 + \ln[(1 + \alpha)/(1 - \alpha)]/2R\alpha\}$, where $\alpha = \sqrt{(1 - 1/R)}$. For $R = 3$, $I_2/I_1 = 0.39$ and $I_3/I_1 = 0.22$, which further reduces the phase error, although unlike the linear taper, this parabolic taper has no set of normal modes, so mode mixing near $\phi = 0$ needs to be examined. Figure 4 shows that with $R = 3$ and $k = 2$, steering ±24° is possible.

The performance of various profiles with and without ΔL length correction is summarized in the Table 1 for the same $k_0 b_0$ as in the examples above. The last column in the table, "ohmic loss," is the ratio of the total attenuation in the taper to that of a uniform waveguide having the same $k_0 b_0$ and radiating at the same exit angle ϕ. Compared to the $HE_{1,1}$ mode, the $HE_{n,1}$ mode has n^2 times the loss, but still varies as $1/b^3$ locally.

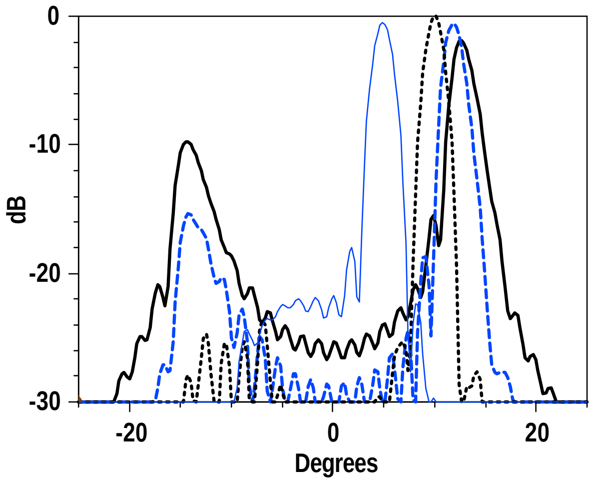

Fig. 2. Radiation patterns of a remotely steered Gaussian beam from a uniform waveguide of height b_0 = 6.35 cm at 170 GHz. Ratio of power in range (ϕ–5°, ϕ+5°) to total power: 5°: 97.3%; 10°: 98.6%; 12°: 93.6%; 13°: 78.7%; L = 8.996 m.

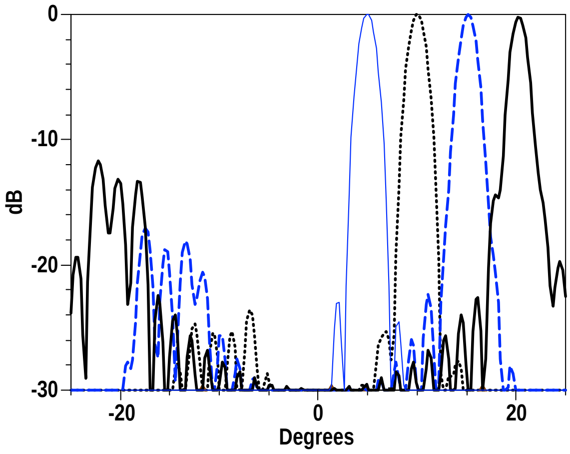

Fig. 3. Radiation patterns of a remotely steered Gaussian beam from a uniform waveguide of height b_0 = 6.35 cm at 170 GHz. Ratio of power in range (ϕ–5°, ϕ+5°) to total power: 5°: 99.8%: 10°: 98.6%; 15°: 95.5%; and 20°: 87.4%; L = 9.150 m, ΔL: –3.2, –15.1, –32.5, –57.0 cm.

Windows

A window is often required near the vacuum vessel to separate its vacuum from the waveguide vacuum. If the disk or plate thickness is chosen so that $\rho = 0$ for an incident angle θ, where ρ is voltage reflection coefficient, then as a function of steering angle ϕ:

$$\rho(\phi,\theta) \approx \frac{-i\left(\sqrt{\varepsilon} - 1/\sqrt{\varepsilon}\right)\tan\left[N\pi\left(\theta^2 - \phi^2/2\varepsilon\right)\right]}{2 + i\left(\sqrt{\varepsilon} + 1/\sqrt{\varepsilon}\right)\tan\left[N\pi\left(\theta^2 - \phi^2/2\varepsilon\right)\right]} \quad (3)$$

where ε is the relative dielectric constant of the disk and N is the number of half wavelengths in the dielectric. As an example, let $\varepsilon = 5.7$ (diamond) and $N = 5$. Then for $\theta = 0$, $\rho^2 \leq 2 \times 10^{-3}$ over $-11° \leq \phi \leq 11°$, while for $\theta = 10.5°$, $\rho^2 \leq 2 \times 10^{-3}$ over ±20°.

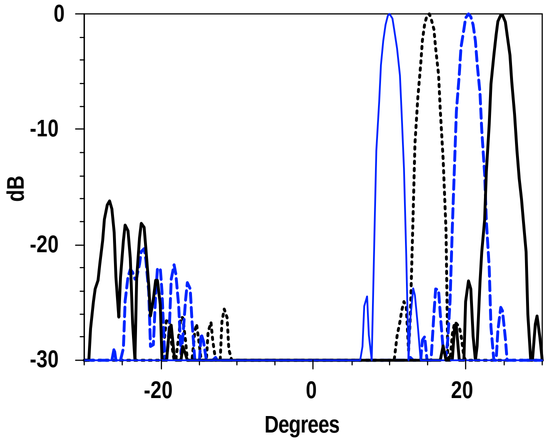

Fig. 4. Radiation patterns of a remotely steered Gaussian beam from a parabolically tapered (3:1 in:out) waveguide of output height b_0 = 6.35 cm at 170 GHz. Ratio of power in range (ϕ–5°, ϕ+5°) to total power: 10°: 99.7%; 15°: 99.0%, 20°: 97.2%; 24°: 95.2%; L = 37.380 m, ΔL: –23.8, –51.5, –90.5, –132.3 cm.

Conclusions

We have shown that it is theoretically possible to steer the exit angle ϕ of a Gaussian-like beam radiated from a highly overmoded rectangular corrugated waveguide as much as ±24° by injecting a similar beam in to the uniform or tapered waveguide at a specific distance from the exit (typically tens of meters). This distance takes the approximate form $L_0 \times [1 - (\phi/\phi_0)^2]$, where L_0 and ϕ_0 are constants dependent on the taper profile and $k_0 b_0$.

Table 1: Summary of Examples

Taper/ΔLength	φ°	η at φ	L m	ΔL at φ, cm	Ohmic Loss
uniform/ΔL = 0	12/13	93.6/78.7	8.996	0	1
uniform/ΔL ≠ 0	15/20	95.5/87.4	9.147	–32.5/–57.0	1
lin R = 2/ΔL = 0	15/16	95.6/87.3	17.984	0	0.75
lin R = 2/ΔL = 0	15/16	97.4/91.8	27.052	0	0.67
lin R = 3/ΔL ≠ 0	20/24	96.2/93.5	27.436	–84.7/–119.4	0.67
par R = 2/ΔL = 0	15/16	97.1/91.4	22.220	0	0.68
par R = 2/ΔL ≠ 0	20/24	96.3/93.5	22.536	–68.7/–99.3	0.68
par R = 3/ΔL ≠ 0	20/24	97.2/95.2	37.380	–90.5/–132.3	0.59

References

[1] R. W. Harvey, W. M. Nevins, G. R. Smith, B. Lloyd, M. R. O'Brien, and C. D. Warrick, Nucl. Fusion **37**, 69 (1997).

[2] R. Prater, H. J. Grunloh, C. P. Moeller, J. L. Doane, R. A. Olstad, M. A. Makowski, R. W. Harvey, in Electron Cyclotron Emission and Electron Cyclotron Heating," in Proc. 10th Joint Workshop on Electron Cyclotron Emission and Electron Cyclotron Resonance Heating, April 6–11, 1997, Ameland, The Netherlands (Work Science Publishing, Singapore, 1995), pp. 534–537.

[3] R. Prater, H. J. Grunloh, C. P. Moeller, J. L. Doane, R. A. Oldstad, M. A. Makowski, R. W. Harvey, *ibid* pp. 537–539.

[4] Microwave Antenna Theory and Design edited by S. Silver (Peter Peregrins Ltd., London, 1984), pp. 182–183.

[5] G. Denisov, private communication at the conference referenced in [3].