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THE USABLE REMOTE STEERING RANGE OF A MICROWAVE BEAM LAUNCHED FROM A HIGHLY OVERMODED CORRUGATED WAVEGUIDE

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The Usable Remote Steering Range of 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 plasmas research. Especially for current drive for either a fixed frequency source or a step tunable source, such as a gyrotron, local current drive requires toroidal or poloidal beam steering depending on the 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 was described in [3], 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 [4]. In the following, means of increasing the range of steering angles over which the radiation pattern is highly directional are described. Numerical data and approximate expressions for directivity versus launch angle are presented.

Discussion of Method

As discussed in Ref. 3, the basic concept of remote steering is to generate a mixture of HE_{1n} modes which are the normal modes of a square or rectangular corrugated waveguide which when superimposed at the exit of the waveguide with the proper phases excite a Gaussian-like beam propagating at an angle ϕ to the waveguide axis. Here the n index refers to the plane of steering. For a uniform waveguide, injecting a HE_{11} mode at the angle ϕ or $-\phi$ produces the required mode mixture. It was found that 85% of the power in the beam is carried by the modes of index $n-1$, n, and $n+1$, and 99.5% by the $n-2$ through $n+2$ modes, where n is the integer closest to $\phi k_0 b_0/\pi$. Here, k_0 is the free space wave number and b_0 is the waveguide height in the plane of steering. A specific distance L_0 was found that brings the modes back into phase for small angles ($\phi < 5°$); while for larger angles, the optimum L is a weak monotonically decreasing function of ϕ.

As discussed in Ref. 3, the phase shift at the exit due to the waveguide dispersion between two modes centered around mode n, expanded in a series in powers of $\phi_n^2 = (n\pi/k_0 b_0)^2$ and defining $r_q = (n+q)/n$, is

$$\chi_p - \chi_q \approx \frac{\pi^2}{2}\frac{k_0 L I_1}{(k_0 b_0)^2}\left(r_q^2 - r_p^2\right)\left[1 + \frac{\phi_n^2 (I_2/I_1)}{4}\left(r_q^2 + r_p^2\right) + \frac{\phi_n^4 (I_3/I_1)}{8}\left(r_q^4 + r_q^2 r_p^2 + r_p^4\right) + \frac{5\phi_n^6 (I_4/I_1)}{64}\left(r_q^4 + r_p^4\right)\left(r_q^2 + r_p^2\right)\right] \quad . \qquad (1)$$

If all the terms of the sum in (1) were 0 except the first, all modes would come back into phase at the exit if $k_0 L = 4(k_0 b_0)^2/I_1\pi$ or reverse phase and the sign of ϕ if L is half the distance. For a general taper profile $b(z/L)$, $I_m = \int_0^1 [b(t)/b_0]^{-2m} dt$. If the waveguide is uniform, all the quantities $I_m/I_1 = 1$ so that the modes do not come precisely back into phase as ϕ and, therefore, n increases. Simply increasing b_0 does not reduce the dispersion, because $\phi_n \approx \phi$. Some reduction of phase error can be obtained for a given ϕ by reducing L to αL where $\alpha = 4\pi n/(\chi_{n-1} - \chi_{n+1})$. With the integer n chosen to minimize $|\phi - \phi_n|$,

$$\alpha^{-1} \approx 1 + \left(\phi_n^2 + \phi_1^2\right)\left(I_2/I_1\right)\Big/2 + \left(\phi_n^2 + 3\phi_1^2\right)\left(3\phi_n^2 + \phi_1^2\right)\left(I_3/I_1\right)\Big/8 + 5\left(\phi_n^2 + \phi_1^2\right)\left(\phi_n^4 + 6\phi_1^2\phi_n^2 + \phi_1^2\right)\left(I_4/I_1\right)\Big/16 \quad .$$

With $L = \alpha L_0$, and for $\phi = \phi_n$ for an integer $n \geq 5$,

$$\frac{P_+}{P_{total}} \approx \frac{1}{4} + \frac{22}{9\pi^2} + \frac{2}{3\pi^2 n^2} - 5\phi_1^2\left(\frac{I_2}{I_1}\right)^2\phi_n^2 - 6\left(\frac{I_2}{I_1}\right)^2\phi_n^4 - 6\left[\left(\frac{I_2}{I_1}\right)^3 - 3\frac{I_2}{I_1}\frac{I_3}{I_1}\right]\phi_n^6 \quad ,$$

with an error of <0.2%. A more complex expression correct for arbitrary ϕ has also been derived.

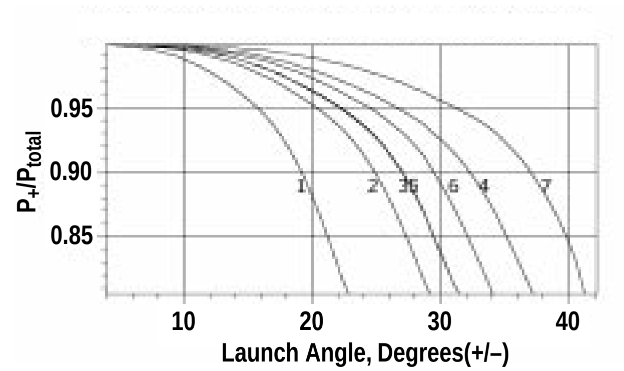
The only other way to extend the steering range is to reduce the I_m/I_1 terms in (1) by tapering the waveguide to a greater height away from the exit. b is assumed to have a power law profile $b(t) = b_0[R - (R-1)t^{pl}]$, where $pl = 1,2,\ldots 9$, $0 \leq t = z/L \leq 1$, b_0 is the waveguide height at its exit, and Rb_0 is the height at the taper input. The chosen profiles vary from a linear taper for pl = 1 to one that is almost uniform at height Rb_0 from the injection point to about $2/3L$ and then tapers rapidly to b_0 for pl = 9. Mode conversion between HE_{11} and HE_{13} is the first concern since the coefficients decrease for higher modes. In fact, the conversion is negligible for even the lowest modes for $0 \le pl \le 9$ and $R \le 3$ for the ITER parameters: k_0 = 35.63 cm^{-1} and b_0 = 6.35 cm. I_m/I_1 for some values of R and pl are given in Table 1.

Table 1. Values of I_m/I_1 for various tapers

pl	—	1	2	9	1	2	9
R	1	2	2	2	3	3	3
I_2/I_1	1	0.5833	0.4900	0.3361	0.4815	0.3911	0.2256
I_3/I_1	1	0.3875	0.2890	0.1409	0.2988	0.2216	0.0948
I_4/I_1	1	0.2835	0.1970	0.0766	0.2142	0.1534	0.0600

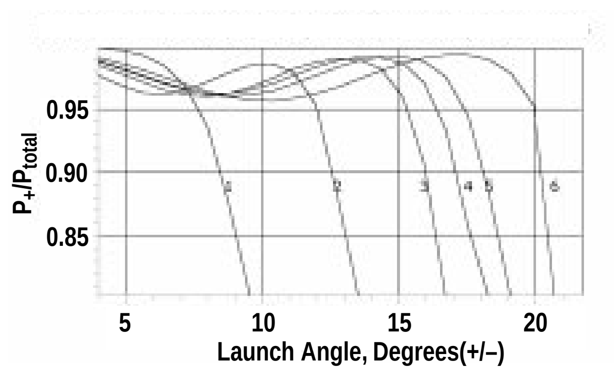
The greatest steering range, ±30°, is obtained when α is optimized for each value of ϕ, as shown in Fig. 1, which gives P_+/P_{total} for various tapers, where P_+ is the power in the beam centered around ϕ. Adjusting L requires a more complex steering mechanism than if L is constant, however. A steering range of as much as ±20° is possible by fixing α to maximize the useful steering range, as shown in Fig. 2, but at the cost of a longer taper than required for the same range in Fig. 1. In either case, the total waveguide run need not be a straight line because miter bends are permissible in the plane orthogonal to the plane of steering, while continuously curved bends having low HE_{11} – HE_{12} mode conversion are permissable in either plane.

At the time of writing, we have a section of uniform square corrugated waveguide and launcher assembled and have begun making measurements to compare with Figs. 1 and 2. We are also preparing to test the effect of miter bends on steering.



Taper No.	1	2	3	4	5	6	7
$R = B_{in}/B_{out}$	1	2	2	2	3	3	3
Power Law	–	1	2	9	1	2	9
L_0, m	9.146	18.293	22.539	31.169	27.439	37.384	62.248
$L_{96\%}/L_0$	0.968	0.968	0.968	0.968	0.968	0.968	0.969

Figure 1. P_+/P_{total} versus the launch angle ϕ when L = αL_0 is optimized for each value of ϕ. $L_{96\%}/L_0 = \alpha$ at which P_+/P_{total} = 0.96.



Taper No.	1	2	3	4	5	6
$R = B_{in}/B_{out}$	1	1	2	2	3	3
Power Law	–	–	2	9	2	9
L_0, m	9.146	9.146	22.539	31.169	37.384	62.248
L, m	9.146	8.986	22.230	30.795	36.917	61.589

Figure 2. P_+/P_{total} versus the launch angle ϕ for a fixed optimized L.

References

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