Mode Conversion Losses in ITER Transmission Lines

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***Abstract*—Mode conversion in miter bends and polarizers is the main contributor of loss in the transmission lines (TLs) for the ITER 170 GHz ECH system, which should transport one megawatt of power with the smallest possible loss. Previous loss estimates assumed that the power in the TL was carried by a pure HE_{11} mode; however, in practice, there is significant power in higher order modes (HOMs). It is shown that the mode conversion loss of the power in an HE_{11} mode at a miter bend is greatly altered by the presence of even a small proportion of HOMs in the TL, and is a strong function of both the magnitude of the HOM and its phase relative to that of the HE_{11} mode. The resulting total loss in the ITER transmission lines is expected to be very different from the loss previously predicted using single mode theory.**

I. Introduction

Very low loss in transmission lines (TLs) is an essential requirement for high-power millimeter-wave applications, such as ITER's 170 GHz electron cyclotron heating (ECH) and electron cyclotron current drive (ECCD) systems. To minimize losses, it is preferable to transmit power using the Gaussian-like HE_{11} mode in corrugated waveguides[1] with a large diameter (2a) to wavelength (λ) ratio ($a/\lambda = 18$ for ITER).[2] In such overmoded TLs consisting of sections of straight waveguide and miter bends, polarizers, etc., the loss in the straight sections is negligible if the system is constructed with sufficiently small tilt, offset, and sag errors.[3] Therefore, the majority of loss originates in the other components, mainly in the miter bends, and is primarily the result of mode conversion due to diffraction plus ohmic loss.[4] The mode conversion loss in these components has been previously evaluated under the assumption that the power in the TL is carried by a pure HE_{11} mode. In practice, there is significant power in higher order modes (HOMs). When a Gaussian beam from a gyrotron is injected into a corrugated guide, there is a minimum of about 2% of HOM generation.[5] More realistically, the HOM content is often several percent and can exceed 10%. A complete theory could be developed by determining the mode content using phase retrieval techniques.[6] To illustrate the effect of HOMs, we present numerical simulation results of the mode conversion loss in a miter bend for a simple model case of an HE_{11}/HE_{12} mode mix. This paper will only treat mode conversion loss; it does not treat ohmic loss.

II. Results

The theory of loss in a miter bend (Fig. 1A) is closely related to the theory of loss in a gap (two straight waveguide sections separated by a distance of one diameter).[4] For our calculations, an approximate geometry was used as shown in Fig. 1B.

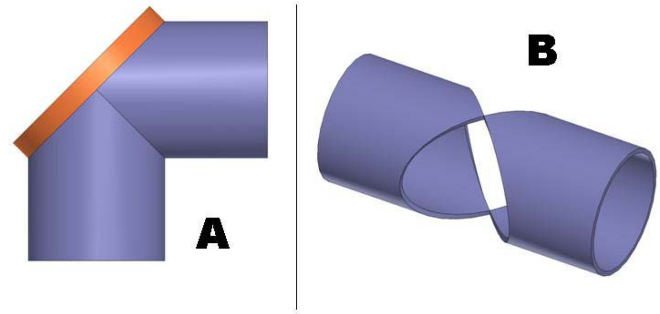

Fig. 1 A. Overhead view of a miter bend showing the two waveguide sections connected to a flat mirror B. Approximated miter bend geometry formed by cutting along the miter bend's overhead symmetry plane and rotating one of the sections around the mirror's vertical axis

To calculate the gap loss and the equivalent miter bend loss, the fields are propagated step-by-step from the input port to the output port using a scalar approximation. We employ the plane wave expansion and use a fast Fourier transform (FFT) to represent the fields as a superposition of the modes of a larger square area. Each plane wave in the expansion is propagated the length of one step and an inverse FFT is applied. The fields are then truncated outside of the waveguide boundary and the loss due to truncation is calculated. This process is repeated until the field at the output is obtained, which can then be represented as a superposition of HE_{mn} modes of the corrugated waveguide.

The power at the input is a superposition of a dominant HE_{11} mode and a parasitic HE_{12} mode with a particular phase relative to that of the HE_{11} mode. To determine the effects of this parasitic mode content on the mode conversion through a miter bend, we vary the magnitude and phase of the parasitic HE_{12} mode content. We also compared all simulation results with the losses calculated using the analytical expressions for the scattering coefficients between HE_{1n} modes derived by Doane and Moeller for the simple gap geometry,[4] and found the agreement to be very good.

Fig. 2 is generated using the scattering coefficients and shows how the transmission of an HE_{11} mode through a miter bend varies with the relative phase of a small percentage of a parasitic HE_{12} mode. As the HE_{12} mode content at the input is increased, the normalized HE_{11} transmission can diverge more and more from its value for a pure HE_{11} input. The normalized HE_{11} transmission also varies strongly with the relative phase of the HE_{12} mode. The results of Fig. 2 were checked with our FFT numerical code and the agreement was very good.

Even with as little as 2% HE_{12} mode content (approximately the minimum HOM content generated when injecting a pure Gaussian beam into a corrugated waveguide)[5], the actual loss

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can differ by up to 46% from the loss calculated when assuming a single mode input, depending on the phase of the parasitic HOM. This also means that a cold test or hot test experiment to measure loss at a miter bend will have a large uncertainty in the theoretical loss at the miter bend unless the amplitude and phase of all of the HOMs are known.

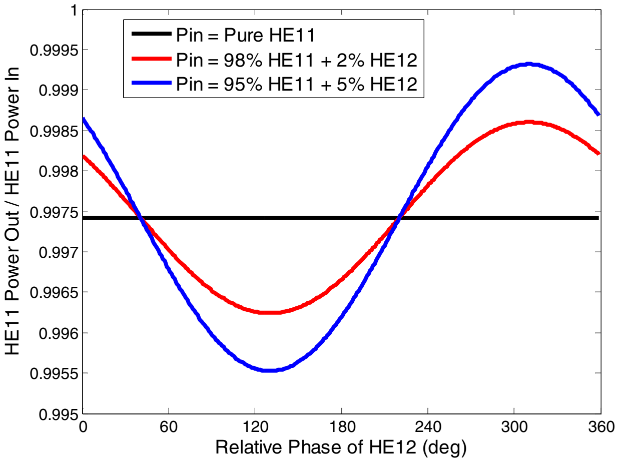

Fig. 2 The output HE_{11} mode power divided by input HE_{11} power at an ITER miter bend for three values of input HE_{12} power (0%, 2% and 5%) and as a function of phase of the HE_{12} mode relative to the phase of the HE_{11} mode.

In Fig. 3, we use our numerical simulation approach to show how much power is lost from the HE_{11} mode, assuming a total input power (HE_{11} power + HE_{12} power) of 1 MW. While the average power lost across all phases does remain roughly constant for a range of parasitic HE_{12} input, it is clear that the maximum power lost increases substantially with increased parasitic mode content.

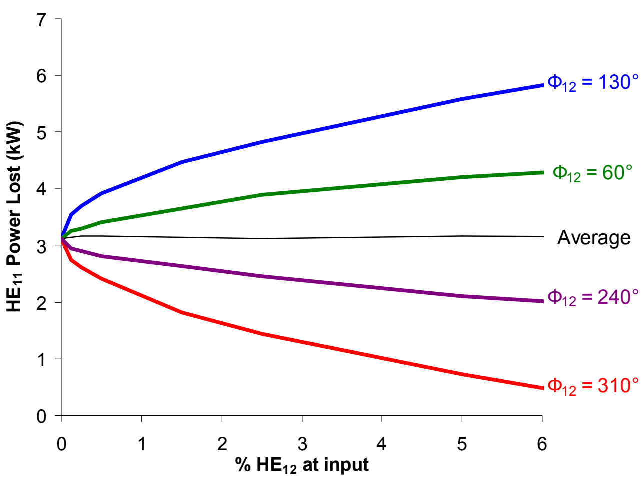

Fig. 3 Estimated power lost to higher order modes at an ITER miter bend as a function of the parasitic HE_{12} HOM mode content.

The power lost from a dominant HE_{11} mode at a waveguide gap has two terms: power that traverses the gap but does not couple to the HE_{11} mode and power that fails to traverse the gap. In a miter bend, the latter term generates power in very high order modes that are absorbed just upstream or downstream from the bend, causing significant heating. This has a major impact on the design of high power TL systems, such as ITER's ECH system, since the accompanying TL cooling systems should be designed to handle the expected maximum power to be absorbed in the line, and this value becomes much larger when there is any parasitic mode content in the TL.

We also computed the total mode converted output power in the first 20 HE_{1n} modes. We found that for a single mode input, the total power converted to HOMs (HE_{mn} modes with m or n >1) is approximately equal to the power failing to traverse the gap, which agrees with theoretical predictions[4]; however, in the presence of parasitic HOMs at the input, the average across all phases of the power failing to traverse the gap increases linearly with the proportion of parasitic HOM content. Thus when a parasitic HOM of random phase is present at the miter bend input, the heat loading around the miter bend will tend to increase. This further illustrates the need to consider the parasitic mode content's effect on the TL when designing a high power system.

III. Discussion and Conclusions

The results presented here clearly demonstrate that even small amounts of parasitic HOM power can significantly change the loss in low-loss miter bends. For certain HOM mode phases, the loss is greatly increased. The present calculation assumes a single HE_{12} HOM; though in a practical case, many HOMs will be excited at the input to the TL. The presence of HOMs will also affect the performance of other TL components such as polarizers, breaks, switches, windows, etc. Advanced miter bends, utilizing phase correcting mirrors or mode mixtures, will also yield results different from the predictions of single mode theory. Therefore, it is important to control the input power to the TL so as to generate a pure HE_{11} mode and to minimize as much as possible the HOM content.

Acknowledgements

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