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Low-Power Testing of Losses in Millimeter-Wave Transmission Lines for High-Power Applications

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Abstract

We report the measurement of small losses in transmission line (TL) components intended for high-power millimeter-wave applications. Measurements were made using two different low-power techniques: a coherent technique using a vector network analyzer (VNA) and an incoherent technique using a radiometer. The measured loss in a 140 GHz 12.7 mm diameter TL system, consisting of 1.7 m of circular corrugated waveguide and three miter bends, is dominated by the miter bend loss. The measured loss was 0.3±0.1 dB per miter bend using a VNA; and 0.22±0.1 dB per miter bend using a radiometer. Good agreement between the two measurement techniques implies that both are useful for measuring small losses. To verify the methodology, the VNA technique was employed to measure the extremely small transmission loss in a 170 GHz ITER prototype TL system consisting of three lengths of 1 m, 63.5 mm diameter, circular corrugated waveguide and two miter bends. The measured loss of 0.05±0.02 dB per miter bend may be compared with the theoretical loss of 0.027 dB per miter bend. These results suggest that low-power testing of TL losses, utilizing a small, simple TL system and a VNA, is a reliable method for evaluating performance of low-loss millimeter-wave TL components intended for use in high-power applications.

Keywords

Millimeter wave; Transmission line; Gyrotron; Miter bend; Corrugated waveguide; ITER

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1 Introduction

Extremely low loss in transmission lines (TLs) is an essential requirement for high-power millimeter-wave applications, such as electron cyclotron heating/current drive (ECH/ECCD) for fusion plasmas. According to the ITER Detailed Design Document Section 5.2 (DDD 5.2) [1], the transmission loss from the gyrotron power source to the plasma, which includes the transmission lines plus the ECH launcher, is limited to 17%. This loss of 17% is close to the theoretical value estimated by the ITER team, implying that the loss in every component must be kept to a value close to the theoretical, minimum value. As a consequence, it is very important to precisely determine transmission efficiency in high-power TL components.

To transmit high-power millimeter-waves with low loss, the ratio of waveguide diameter ($2a$) to wavelength (λ) should be large, and hybrid modes [2] in waveguides with corrugated walls or hollow dielectric waveguides [3] are preferred. The losses are roughly estimated by an approximate theory based on a waveguide gap theory [4], which needs further verification by experiments [5]. Direct measurements can provide reliable estimates of the losses, which are required for calculating transmission efficiency and designing cooling systems for high-power applications. For these reasons, high power tests have been used to obtain these losses [6-7]. However, high-power testing is a laborious process and requires a complicated setup including longer TLs and dummy loads. High power testing is also complicated by the use of a gyrotron source, which may not generate a pure hybrid mode of the transmission line. Low power techniques with pure modes and relatively simple configurations would be much more attractive to precisely measure the losses of hybrid modes in overmoded TL components.

In an overmoded corrugated waveguide TL consisting only of straight waveguides and quasi-optic waveguide miter bends with mirrors, the loss in the straight sections is negligible if the TL is constructed with sufficiently small tilt, offset and sag errors [8]. Thus the majority of loss originates from miter bends, especially in a simple configuration of TLs with short straight sections for low-power testing.

In this paper, we report TL loss measurements made by two methods [9]: one using a vector network analyzer (VNA) (coherent technique) and the other using a radiometer (incoherent technique). To evaluate our cold-test techniques, we used a commercial 140 GHz TL (built by Thomas Keating, UK) with a diameter of 12.7 mm, where the radius-to-wavelength ratio (a/λ) is ~ 3. This line was built for electron spin resonance experiments at the MIT Francis Bitter Magnet Lab. The experimental arrangements and the comparison of results are reported in Sec. 2-3.

In Sec. 4, we demonstrate a low-power measurement of loss in ITER-prototype TL components with a diameter of 63.5 mm (built by General Atomics, San Diego, USA), where a/λ is ~ 18. While low-power tests of corrugated transmission lines have previously been conducted [4, 10-11], the present approach differs in the use of the VNA, which should provide higher dynamic range and possibly higher accuracy. We discuss the accuracy and error bounds of this method by measuring the 183.3 GHz water vapor absorption line in the atmosphere and comparing with analytical results [12-13]. Sec. 5 is a Summary.

2 Coherent technique

An Agilent VNA, model PNA E8363B with WR8 (90-140 GHz) millimeter wave extension heads from Oleson Microwave Labs, was used to measure losses in a 140 GHz TL built by Thomas Keating (Fig. 1). Corrugated horns and waveguide adaptors (rectangular-to-circular) are employed to launch the HE_{11} mode from the TE_{10} mode in a WR8 rectangular waveguide.

Two hollow dielectric waveguides were inserted between the tapered horns and corrugated waveguides to preferentially damp unwanted higher order modes generated at the HE_{11} mode launchers and tapers. The hollow dielectric waveguides are tubes made from G10, with a 12.7 mm inner diameter, 2 cm wall thickness and 10 cm length. The Gaussian-like mode in the hollow dielectric waveguides is identical to that in the connecting corrugated waveguides (with the same inner diameter), provided the loss through the tube wall is large enough for the tube to be considered infinite in radial extent [3].

The baseline setup consisted of 1.5 m of straight corrugated waveguide, 1 miter bend, and 2 mode converters. The Device Under Test (DUT) consisted of three miter bends and three straight corrugated waveguide sections totaling 1.7 m in length.

Time domain filtering was employed for the transmitted signal (S_{21}) obtained in the frequency domain to reduce the interference due to mismatches [14]. To increase the number of data points for time domain filtering, a discrete sweep over a broad band (100-147 GHz) was used.

The loss measured for the DUT, consisting of 3 miter bends and 1.7 m of straight corrugated waveguide, was 0.9 dB at 140 GHz (Fig. 2). Since the loss in the straight sections is negligible, we estimate the loss per miter bend as 0.3 dB. The measured total loss was reproducible within ±0.2 dB in separate measurements, or ±0.07 dB per miter bend. The total error bar including systematic and random error is estimated at ±0.1 dB. The loss measured was therefore 0.3±0.1 dB per miter bend.

3 Incoherent technique

In the second TL loss measurement technique, a radiometer was used to measure transmission losses of incoherent thermal radiation, or equivalently the increase in radiometer noise temperature when the TL line was inserted into the radiometer field of view of a black body of known temperature. The radiometer consisted of a 137 GHz local oscillator and intermediate frequency (IF) amplifiers of 2 GHz bandwidth (Fig. 3), allowing us to measure (double sideband) the radiation between 135 and 139 GHz from a black body. The black body was a liquid-nitrogen (LN) cooled, 30 mm-thick, pyramidal-surfaced eccosorb sheet [15].

A commercial corrugated horn provided an HE_{11} mode field-of-view that was coupled to the DUT diameter by a hollow, acrylic, plastic, conical transition. A chopper and lock-in amplifier allowed stable phase-sensitive detection of the change in receiver noise temperature with and without the DUT. The change in measured receiver noise temperature is directly related to the insertion loss of the DUT.

By comparing the detected voltage with and without the DUT, we can determine the loss averaged over the frequency range of the radiometer. The loss measured was 0.22±0.1 dB per miter bend. This value agrees, within the error bounds, with the loss measured by the VNA, which was (0.3±0.1) dB per miter bend.

The measured loss per miter bend may be compared with the loss predicted by the approximate theory of Doane and Moeller [4], which is 0.17 dB per miter bend. The measured loss of (0.22 ±0.1) dB (radiometer) and (0.3±0.1) dB per miter bend (VNA) is somewhat larger, but the error bars are large enough that the experimental results may be consistent with the theory.

4 Low-power test of ITER prototype TL with VNA

A set of ITER-prototype TL components [16] were assembled on an optical table as shown in Fig. 4, where WR5 (140-220 GHz) millimeter wave extension heads from Oleson Microwave

Labs were incorporated with a VNA. The DUT consists of two miter bends and three straight corrugated waveguide sections, each one meter in length.

To evaluate the accuracy of this approach, a measurement of the well known atmospheric water vapor absorption at 183.3 GHz [13] was performed and is shown in Fig. 5. The theoretical fit shown in Fig. 5 is based on the millimeter-wave propagation model proposed by Liebe [12].

The excellent fit of the resonance with the theoretical calculation proves the validity of this method and exhibits an inherent systematic error of 0.02 dB at 170 GHz (see Fig. 5). This measurement also shows that TL loss measurements under atmospheric conditions need a correction of about 0.015 dB (~0.3%) due to the additional loss by the atmospheric effects using this configuration at 170 GHz.

Figure 6 shows an example of the loss measurements obtained in the ITER-prototype TL. The baseline measurement includes: the tapered waveguides, to convert the rectangular fundamental mode (WR5 waveguide) to the HE_{11} mode in a circular corrugated waveguide with a diameter of 20.32 mm and a dielectric filter to suppress unwanted modes. We were able to measure the low loss quantitatively at around the 170 GHz operation frequency with a relatively simple configuration because of the precision of the VNA method. By averaging several measurements and including the atmospheric correction for the DUT at 170 GHz, the loss per miter bend was estimated to be 0.05±0.02 dB. This measured loss is higher than the loss predicted by the Doane theory [8], which is 0.027 dB per miter bend. However, the difference between theory and experiment is about one standard deviation, so that further precision will be needed to verify whether the measured loss is indeed larger than theory.

5 Summary

A low-power test facility has been built at MIT to precisely measure small losses in overmoded millimeter-wave TL components. A coherent technique using a VNA and an incoherent technique using a radiometer were tested. To examine these techniques, the loss was measured in a 140 GHz, 12.7 mm diameter, corrugated TL. Correspondence between the results from the two techniques implies that both these techniques are useful for measuring small losses.

The VNA technique was employed in low-power measurements of loss in the 63.5 mm diameter ITER-prototype TL components. Accuracy of this method was evaluated by measuring the well known atmospheric water vapor absorption line (183.3 GHz). Excellent fit of the resonance with the theoretical calculation verified the validity of this method and showed an inherent systematic error of 0.02 dB at 170 GHz. The measured loss per miter bend was 0.05±0.02 dB, which is higher than the theoretical value of 0.027 dB per miter bend.

The accuracy of these measurements is dependent on the purity of the HE_{11} mode launched into the waveguide. It also depends on the sensitivity of the receiver to measure the HE_{11} mode and discriminate against High Order Modes (HOMs). In the 170 GHz system, the HE_{11} mode is generated and injected into a 20 mm diameter waveguide, filtered by a length of dielectric guide, then uptapered and launched into the 63.5 mm guide diameter. A series of scans of the mode field pattern at and near the entrance to the 63.5 mm guide indicated a high purity HE_{11} mode, containing about 99% of the power, with HOMs totaling only about 1%. This level of HOM content is small compared with the expected HOM content of a gyrotron beam injected into the ITER transmission line, but is larger than the mode conversion of the HE_{11} mode at a miter bend. The effect of the HOMs is somewhat reduced, but not totally eliminated, by the baseline subtraction, which measures transmission of the full mode content (the HE_{11} mode together with the HOMs) through the line without the DUT. The effect of the small HOM content on the waveguide loss is beyond the scope of this work, but will be investigated in future research. Further refinement of these techniques should reduce the error bar, resulting in a procedure for the complete test and qualification of TL components for ITER using a low power measurement system. In the future we hope to be able to compare the results of low power tests with high power tests, which are ongoing at JAEA [7] and are under preparation at the Oak Ridge National Lab.

Acknowledgments

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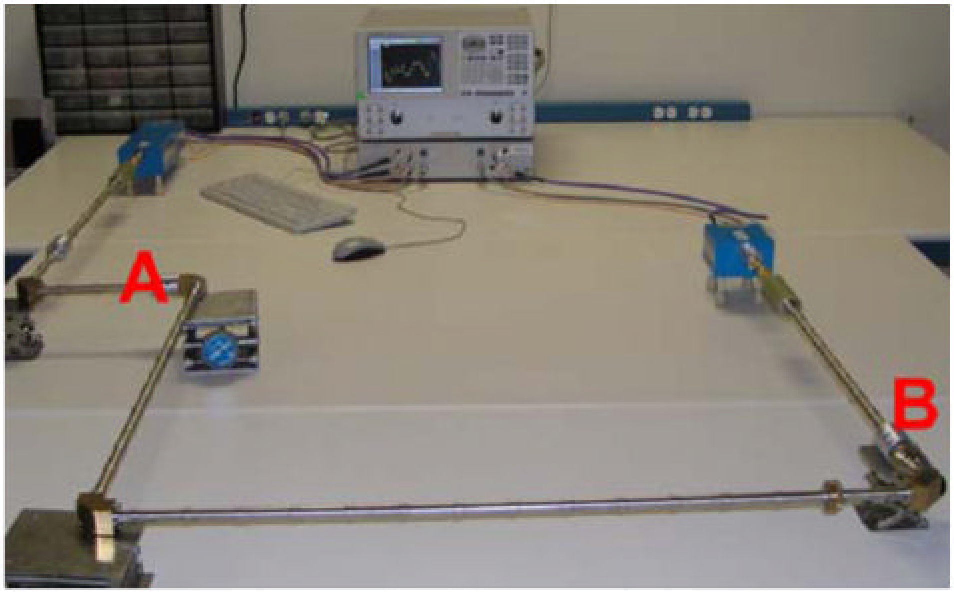

Fig. 1.

A 90-147 GHz band VNA and experimental setup; Device Under Test (three miter bends plus three straight corrugated waveguide sections totaling 1.7 m in length) spans between A and B. Each straight line of 12.7 mm-diameter waveguide is assembled by soldering 6 cm long sections that are connected to one another by clamps. For calibration, A and B are directly connected as a base line. The baseline measurement includes one miter bend, corrugated waveguide, and two launchers converting the rectangular fundamental mode to HE_{11} mode.

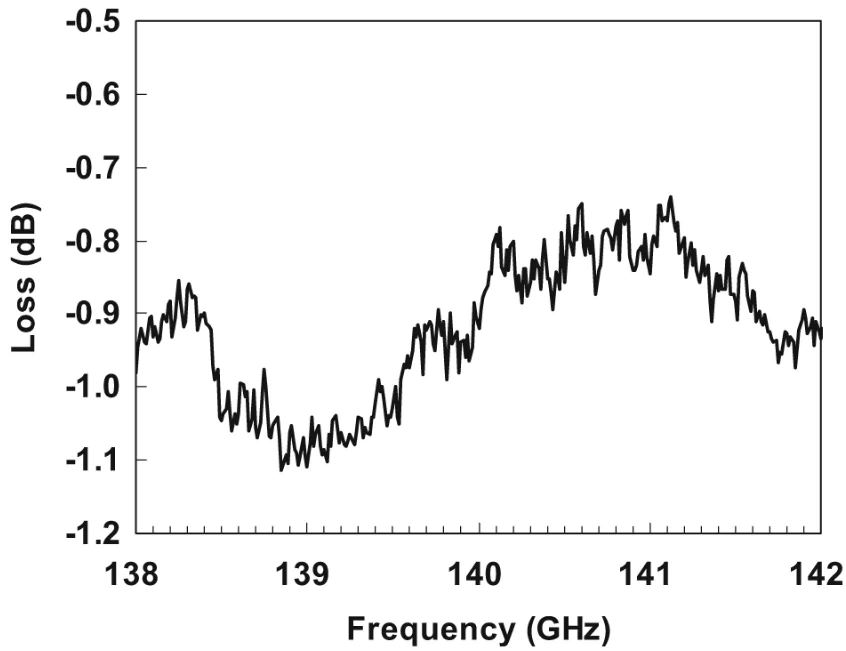

Fig. 2.
Loss of the 140 GHz, 12.7 mm diameter TL shown in Fig. 1 (1.7 m of corrugated waveguide and three miter bends) measured by a VNA.

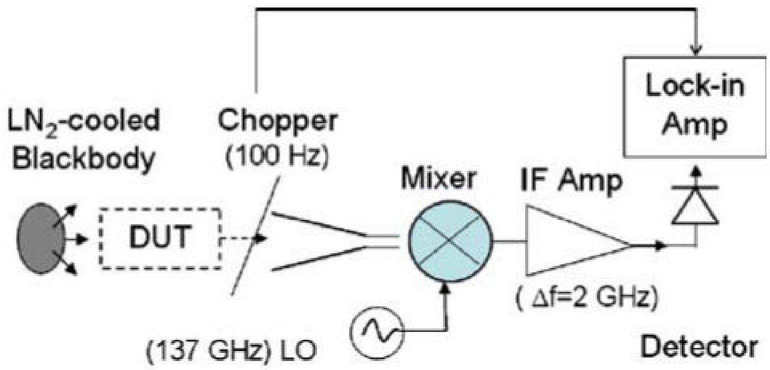

Fig. 3.

A schematic of the radiometer system; incoherent millimeter-wave blackbody radiation passing through the DUT is captured by a corrugated horn and directed to a mixer where the difference frequency with a 137 GHz local oscillator (LO) is generated and amplified for detection by a diode detector over a bandwidth ± 2 GHz centered on the LO.

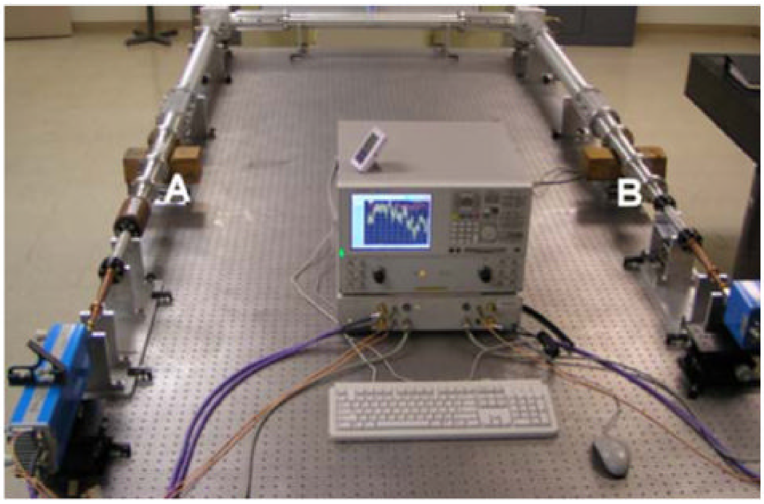

Fig. 4.
A 140-220 GHz band VNA and experimental setup; device under test (2 miter bends, 3 sections of 1 m corrugated waveguide, and 2 corrugated waveguide tapers changing the diameter from 20.32 mm to 63.5 mm) spans between A and B.

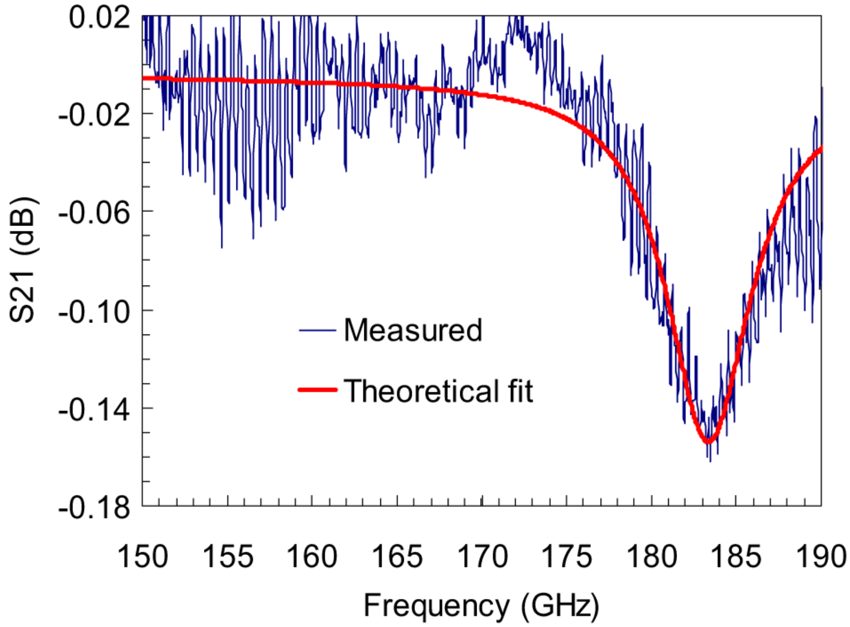

Fig. 5.

Water vapor absorption line (183.3 GHz) measurement. Theoretical fit of the resonance is calculated using the Liebe model based on lab measurements; 43% humidity, 22.5°C, and 106 kPa of atmospheric pressure.

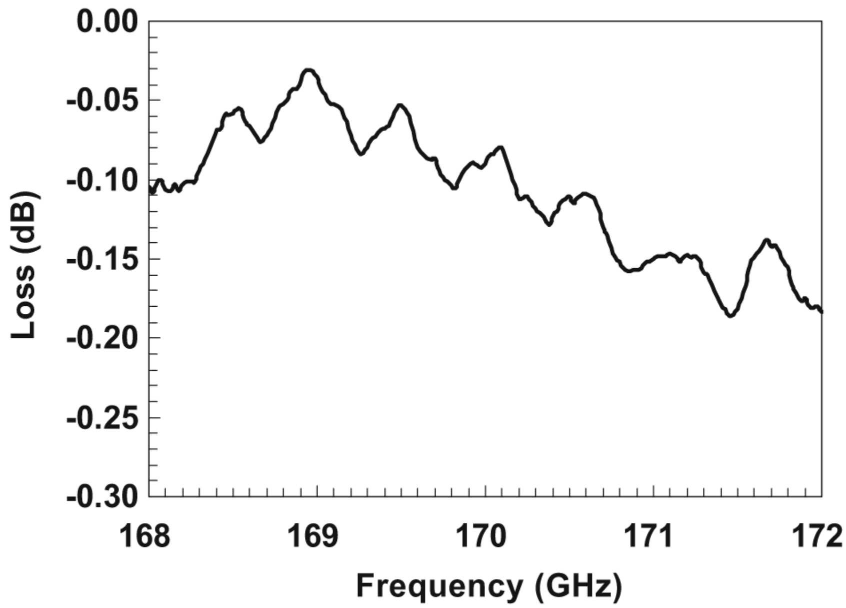

Fig. 6.

An example of losses measured for the DUT (2 miter bends, 3 sections of 1 m corrugated waveguide, and 2 corrugated waveguide tapers changing the diameter from 20.32 mm to 63.5 mm) by the VNA method.