Numerical and experimental investigations of a diplexer for power combination and switching of high-power millimeter waves

Wondwossen Wubie, Walter Kasparek, and Burkhard Plaum
Institut für Plasmaforschung, Universität Stuttgart, Pfaffenwaldring 31, D-70569 Stuttgart, Germany

Abstract—**We describe a four-port diplexer which is capable e.g. for power combination of two high-power gyrotrons in the millimeter wave range. Calculations and a conceptual design for a Mach-Zehnder-type diplexer for circular corrugated waveguides (diam. 63.5 mm) at 170 GHz are presented. Experiments with a slightly scaled mock-up version at 140 GHz are described.**

I. Introduction And Background

INTERFEROMETERS are used intensively in the millimeter and infrared region, e.g. for phase measurements, to combine signal and local oscillator, and as filters, usually for low-power experiments. For high-power applications like electron cyclotron resonance heating (ECRH) for nuclear fusion experiments, these devices, if operated as four-port diplexers, have attractive features[1]: (i) Combination of the power of two gyrotrons in large ECRH systems, e.g. on the international thermonuclear experimental reactor ITER, will effectively reduce the number of transmission lines and launchers. For this purpose, small (typ. 100 MHz) frequency differences of the sources are necessary. (ii) Fast toggling (typ. several kHz) of the power from a continuously operating gyrotron between two antennas maximizes the suppression of neoclassical tearing modes in tokamaks. The switching can be controlled by a small frequency-shift keying of the gyrotrons, initiated electronically by modulation of the acceleration or gun anode voltage. (iii) The arbitrary distribution of the power from one source between two launchers according to the needs of the experiment is possible either by frequency control of the gyrotron or slight movement of an optical component. (iv) The separation of forward and backward power is of interest in combined ECRH and ECE (electron cyclotron emission) experiments sharing the same launcher.

High-power diplexers can be designed in various forms[1], for integration into quasi-optical systems as well as for waveguide transmission lines. First high-power results for switching and power combination of gyrotrons have been obtained [2,3], and in-line ECE systems are in operation as well as planned[4]. In this paper, we describe the design of a diplexer based on a Mach-Zehnder–type interferometer[5] for circular corrugated wave-guide (HE_{11} mode) transmission, as well as measurements on a mock-up.

II. Diplexer Design

The principle design of the diplexer is shown in Fig. 1. It consists of two dielectric power splitters with power reflection coefficient R and power transmission coefficient T integrated into HE_{11} waveguide with a direct connection and a delay line with a length difference L with respect to the direct line. Neglecting losses, this results in a transmission given by

$$P_{1,4} = R^2 + T^2 + 2RT\cos(\varphi) \quad (1)$$

$$P_{2,4} = 2RT(1-\cos(\varphi)) \quad (2)$$

with the phase factor (for HE_{11} waveguide with diameter D)

$$\varphi = \frac{2\pi f}{c}\cdot L_{eff} + \varphi_0, \quad L_{eff} = L\cdot\sqrt{1-\left(2.405\,c/\pi f D\right)^2} \quad (3)$$

For $R = T = 0.5$, 100 % modulation of the output power as function of the frequency is obtained. An analysis of dielectric plan-parallel plates (Fabry-Perot etalons[5]) shows that 3-dB

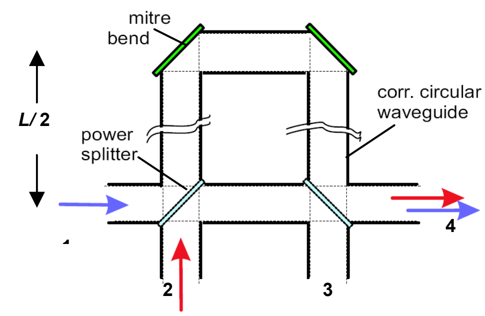

Fig. 1: Scheme of the circular waveguide diplexer. The arrows illustrate the use as power combiner.

splitters can be designed without any coating for an incidence angle of 45°, provided that the index of refraction n is $n > 1.84$ for s-polarization and $n > 3.34$ for p-polarization. For high-power cw applications and linear (s-) polarisation, CVD diamond ($n = 2.38$) is an appropriate material. Note that by coating the diamond disc with a wire-grid structure to increase the reflection coefficient for the p-polarized component, polarisation-independent characteristics are possible. For this case, the diamond disc is used simultaneously as a heat sink for the ohmic loss in the wires.

The design for the splitters may be derived from standard mitre bends installed back to back, with the diamond disc integrated instead of the mitre bend mirror with good thermal contact to the (cooled) body of the bend. Alternatively, a vacuum-window can be used as basis with waveguides sticked into it up to the disc.

The theoretical losses of the diplexer are very low, if highly oversized waveguides are used. Therefore, such a diplexer could be used in the ITER ECRH system for one or several tasks discussed in chapter I.

III. Conceptual Design For ECRH On ITER

The theoretical performance of a diplexer for the parameters of the ITER ECRH system was calculated. For this system, the waveguide diameter is $D = 63.5$ mm, and the frequency $f = 170$ GHz. Diamond splitters with a thickness of $d = 0.865$

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mm and a loss tangent of tan $\delta = 4\cdot10^{-5}$ were assumed. The analysis taking into account the various loss contributions[4,6] in eq. (1) and (2), which arise in the splitters (dielectric loss and diffraction), the mitre bends (diffraction and ohmic loss), and the waveguides (ohmic loss) yields a total transmission efficiency of > 99 %. This is shown in Fig. 2, where the transmission functions for the example with L = 0.75 m as well as the loss are plotted. By choosing L (mech. length $L \approx L_{eff}$ for highly oversized guides), the device can be easily matched to the frequency difference of two sources to be combined or to the frequency modulation characteristics of a gyrotron, the power of which is to be toggled between two launchers.

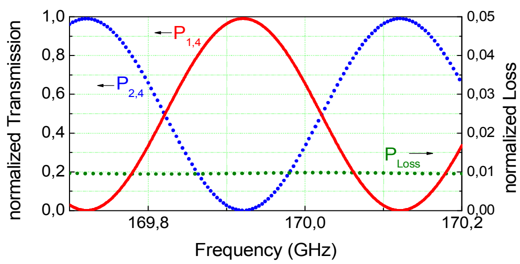

Fig. 2: Calculated power transmission as well as total insertion loss of the waveguide diplexer for D = 63.5 mm, f = 170 GHz, L = 0.75 m, and diamond splitters with d = 0.87 mm.

IV. Results of a Mock-up Diplexer

A waveguide diplexer mock-up was built up using 87-mm diameter corrugated waveguide[6], standard mitre bends and - due to availability - silicon nitride discs with refractive index of n = 2.784 and 2.758, thickness of 3.04 and 2.70 mm, and loss tangent of tan$\delta = 1.12\cdot10^{-3}$ and $2.16\cdot10^{-3}$, respectively. This results in a 3-dB splitting for frequencies around 141 GHz and 148 GHz. For the low-power investigations, lens-horns followed by mode filters to excite a pure HE_{11} mode were connected to input and output ports. A photograph is shown in Fig. 3.

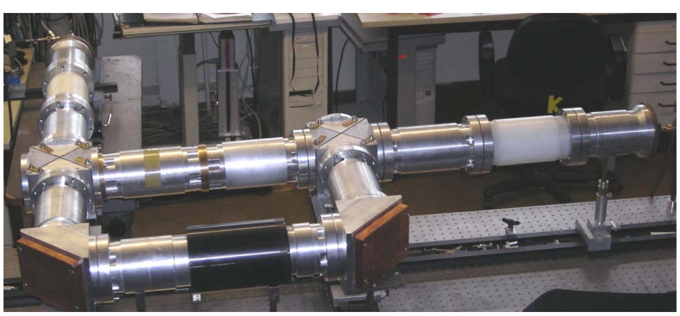

Fig. 3: Photograph of the diplexer mock-up.

For transmission and reflection measurements, a vector network analyzer was used; absolute transmission measurements were performed using a source and a calorimetric power meter. Fig. 4 shows a comparison of the calculated transmission and the corresponding experimental result. A good agreement is found. Note here, that the transmission loss is predominantly caused by the relative high loss of the Si_3N_4 plates. The amplitude and phase distributions at the outputs of the diplexer were recorded and analyzed with respect to mode spectrum, yielding an HE_{11} purity of 94 % and 96 % for the two outputs, respectively.

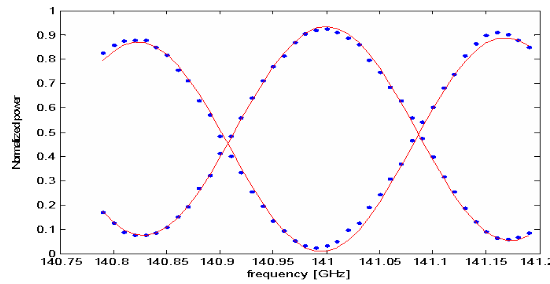

Fig. 4: Normalized power of the outputs of the diplexer mock-up. Solid curve is calculated, dots are measured.

V. Conclusions

High-power diplexers are a valuable component, which can strongly increase the performance and flexibility of ECRH systems. The progress obtained up to now in the development of several prototypes including the high-power demonstration of fast switching and power combination from two gyrotrons confirm the applicability of these devices.

The results obtained for the waveguide diplexer presented here and their extrapolation to a design using diamond splitters confirm the applicability of this type in high-power ECRH systems with the advantage of low transmission loss and easy system integration to corrugated waveguide transmission systems.

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