High-Power Diplexers for Plasma Heating and Diagnostic Systems: Developments, Experiments, and Prospects

Walter Kasparek[1] , Volker Erckmann[2], Michael Petelin[3], Alex Bruschi[4],
and research groups at IPF[1], IPP[2], IAP[3], IFP[4], KIT[5], TNO[6] and FOM[7]
[1]*Institut für Plasmaforschung, Universität Stuttgart, D-70569 Stuttgart, Germany*
[2]*Max-Planck-Institut für Plasmaphysik, EURATOM-Ass., D-17491 Greifswald, Germany*
[3]*Institute of Applied Physics, Russian Academy of Science, 603950 Nizhny Novgorod, Russia*
[4]*Istituto di Fisica del Plasma, EURATOM-ENEA-CNR Association, I- 20125 Milano, Italy*
[5]*Karlsruhe Institute for Technology (KIT), EURATOM-Ass., D-76021 Karlsruhe, Germany*
[6]*Dept. of Mechatronic Equipment, TNO Science and Industry, NL-2600 Delft, The Netherlands*
[7]*FOM Institute for Plasma Physics "Rijnhuizen", NL-3439 MN Nieuwegein, The Netherlands*
kasparek@ipf.uni-stuttgart.de

Abstract
High-power diplexers for millimeter waves can be used for various applications like power combination from gyrotrons, fast and slow switching between launchers in electron cyclotron heating experiments of plasmas, and for decoupling of low-level diagnostic signals from high-power radiation. This paper describes the design and development of various diplexers, especially concentrating on ring resonators. Results from low- and high-power tests are presented, and future applications are discussed.

1. Introduction

In the past years, high-power diplexers for millimeter waves have gained increasing attraction owing to their potential use in electron cyclotron resonance heating (ECRH) systems as well as for plasma diagnostics [1]. *Firstly*, oversized four-port diplexers can be used for power or beam combination (BC), the sources being implied to generate slightly different frequencies. Combining two (or more) conventional gyrotrons [2] would essentially reduce the number of transmission lines and launchers for ECRH systems of large tokamaks, e.g. ITER. *Secondly*, diplexers can be used as non-mechanical, fast directional switches (FADIS) to toggle the power from continuously operating gyrotrons between two transmission lines or launchers. In any gyrotron, modulation of a voltage results in a small (some tens of MHz) shift of the radiation frequency *f*. By using a diplexer with a steep slope at the transition frequency, this shift can provide switching of the (combined) millimeter wave power between output channels. In particular, such electronically controlled switching between two antennas - synchronous to the rotation of the magnetic islands in the tokamak plasma - would maximize the efficiency for stabilization of these neo-classical tearing modes (NTM) [3]. *Thirdly,* especially resonant diplexers (see Fig. 1b) are of interest for plasma diagnostics employing a combination of high-power sources and sensitive receivers. For the measurement of the ECRH power deposition zone in NTM stabilization experiments, the "Line-of-Sight" scheme [4] exploits the gyrotron transmission line in the reverse direction as an electron cyclotron emission (ECE) antenna, thus ensuring that the ECE observed originates from the same location as where the ECRH is deposited. Collective Thomson scattering (CTS) systems [5, 6] may as well benefit from this device, as the resonant channel can be used to purify the frequency spectrum of the gyrotron. In the following, designs of high-power diplexers are sketched, and detailed investigations of resonant diplexers are discussed. Options and plans for applications are explained.

2. Designs for high-power diplexers

Frequency diplexers can be designed in various forms. Here, we discuss three representative types as shown in Fig. 1, with the corresponding transmission characteristics, being periodic with $\Delta f_F = c/L$. By choosing L, the device can be matched to the application foreseen.

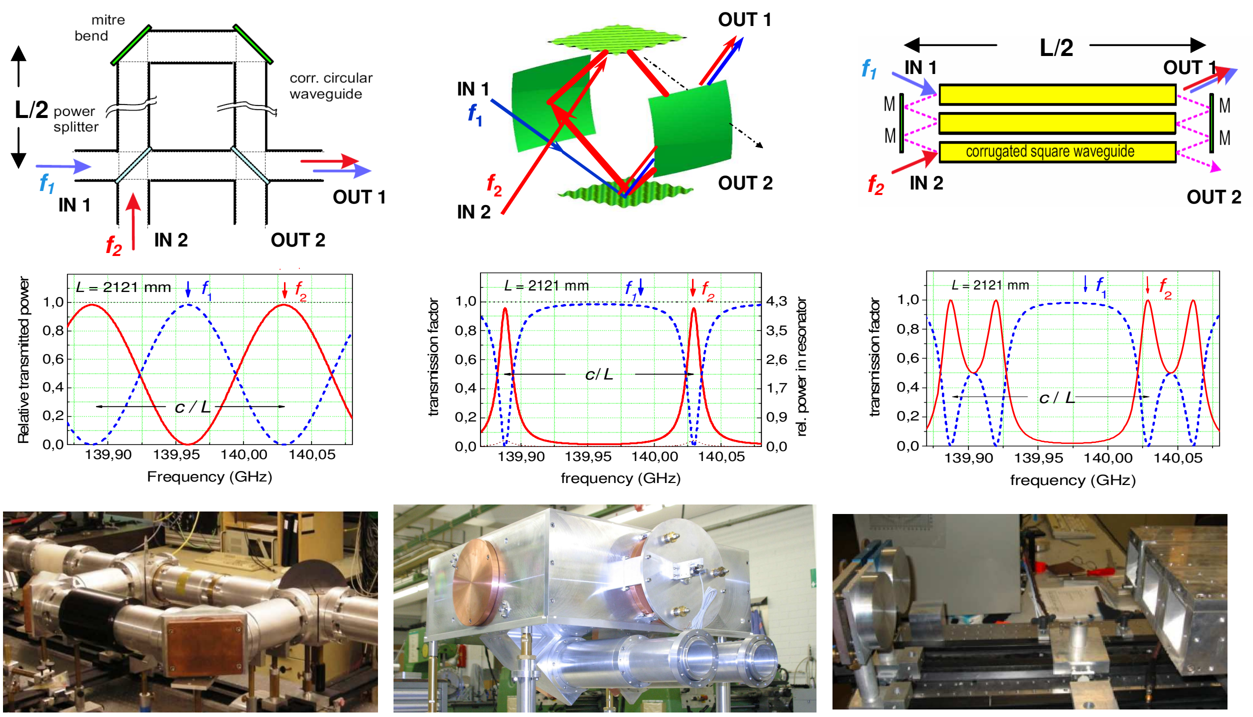

Figure 1: Some principle designs of high-power diplexers, together with the corresponding transmission function plotted for the inputs IN1 (blue, dashed) and IN2 (red, solid), and the (common) output OUT1, as well as photographs of corresponding pre-prototypes under investigation. For the other output OUT2, they have to be exchanged. In the calculation around f = 140 GHz, L = 2.121m was assumed. (a) Mach-Zehnder type interferometer in corrugated waveguide with dielectric beam splitters; (b) quasi-optical ring resonator (round-trip length L) with coupling gratings; (c) two-loop diplexer using square waveguide splitters.

The Mach-Zehnder type diplexer shown in Fig. 1, left consists of two dielectric power splitters integrated into HE_{11} waveguide with a direct connection and a delay line with a length difference L with respect to the direct line. This results in the well-known sinusoidal transmission characteristics. A mock-up of the waveguide Mach-Zehnder interferometer (Fig. 1a) has been investigated with low power [7]. The results were in good agreement with the calculations performed for the parameters (corr. waveguide diam. 87 mm, Si_3N_4 splitters, L = 0.87 m) of the experiment. For high-power applications, CVD diamond is an appropriate material for the 3-dB splitters. An analysis of a diplexer for the parameters of the ITER ECRH system (w.g. diameter D = 63.5 mm, frequency f = 170 GHz) taking into account the loss arising in the splitters, the mitre bends, and the waveguides yields a total transmission efficiency of > 99 %. Note that the operation at two frequencies is possible (e.g. 170 GHz and 136 GHz for a thickness of the diamond of 0.86 mm).

The two-loop resonant diplexer (Fig. 1c) consists of two nested loops [8] formed by square corrugated waveguides with length $2a^2/\lambda$ used as 3-dB hybrids [9], and the reflectors M. Additional mirrors provide matching of the inputs and outputs to the transmission system. The periodicity of the transmission function is determined by the overall length $L/2$ of the system. Special features are the steep slopes and the double-humped structure of the resonant channels. A mock-up of the two-loop diplexer was investigated at 105 GHz using available corrugated square waveguide with a width of a = 60 mm and a length of the splitting waveguides of L = 2.5 m. The measured transmission characteristics agreed well with the calculation, thus providing the proof-of-principle.

The resonant diplexer in Fig. 1b is a 4-mirror ring resonator [1,10], consisting of two focusing mirrors and two plane phase gratings for coupling of the incident beams to the resonator via the -1st diffraction order. Additional mirrors provide matching to the input and output beam or waveguide. If we denote the grating efficiencies for 0th order as R_0, for -1st order as R_1, and the round-trip efficiency of the unloaded resonator as R_q, then the power transmission coefficients from the input 1 to output 1 and 2, respectively, are given by

$$T_1(f) \quad = \quad R_0 \cdot \frac{1 + R_q - 2\sqrt{R_q} \cdot \cos(2\pi Lf/c)}{1 + R_0^2 R_q - 2\sqrt{R_q}R_0 \cdot \cos(2\pi Lf/c)} \qquad (1)$$

$$T_2(f) \quad = \quad \frac{R_1^2 \sqrt{R_q}}{1 + R_0^2 R_q - 2\sqrt{R_q}R_0 \cdot \cos(2\pi Lf/c)} \qquad (2)$$

with $R_0 + R_1 = 1$, and the resonator length L, frequency f and the speed of light c. The transmission characteristics are defined by the grating efficiency and the path length L of one round-trip in the resonator. Special features are the narrow resonant transmission channels separated by broad non-resonant bands, as known from the Fabry-Perot interferometer.

3. Experimental investigations

3.1 Low-power tests

Quasi-optical resonant diplexers for high-power applications were investigated in most detail. Up to now, 3 different prototypes (Mk I, Mk IIa and Mk IIb) were built, and measurements have been performed with low as well with high power. We present here low-power measurements on Mk I, which has a resonator length $L = 2386^{\pm 1}$ mm, coupling gratings with period $p = 2.14$ mm, grating efficiencies $R_0 = 0.78$ and $R_1 = 0.22$, and $R_q \geq 0.986$, respectively.

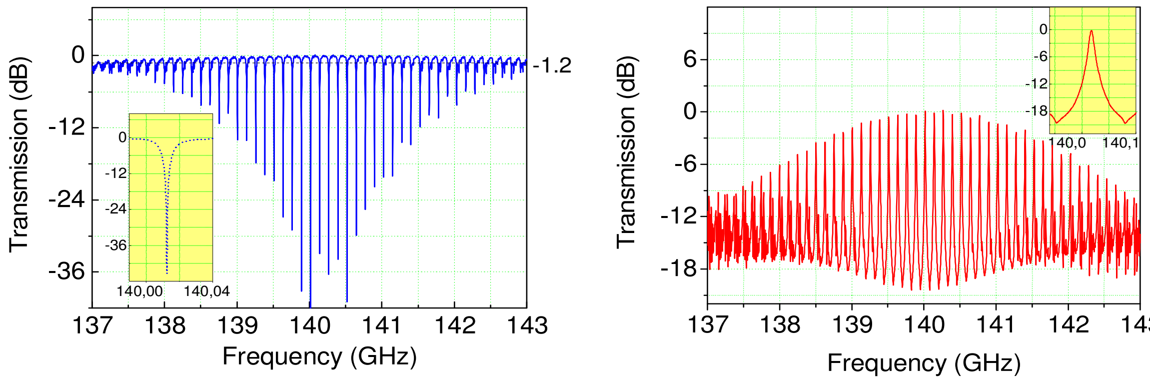

Figure 2: Transmission functions for the TEM_{00} mode measured over a broad frequency range. Left: non-resonant channel; right: resonant channel. The inserts show the detailed shape of a single notch or resonance, respectively.

Detailed low-power measurements using a vector network analyzer and calorimetry have been performed. The input beam was coupled by a scalar horn and a matched mirror. A good agreement with the calculations is achieved. Fig. 2 shows a measurement with a matched receiver; i.e. the transmission of the device in the nominal (TEM_{00}) mode is obtained. One can see, that the non-resonant output 1 provides narrow notches down to -40 dB near the design frequency, as expected from eq. (1). At frequencies above and below, the dispersion of the coupling grating leads to internal misalignment of the resonator, and the transmission factor approaches the 0^{th} order grating efficiency of 0.78. The resonant output 2 shows the resonances at a distance corresponding to $c/L = 125$ MHz. The envelope of the peaks is again determined by the grating dispersion. The 97-% bandwidth is at least 500 MHz, making the device tolerant to typical frequency uncertainties of gyrotrons.

For the measurement of the total power transmission (not regarding the modes), calorimetry was used. The result is plotted in the graph in Fig. 3 together with fitted transmission functions with the parameters given in the plot, yielding total efficiencies of about 93 % and 98 % in the resonant and non-resonant channel, respectively. In the resonant channel, the loss is governed by the round-trip loss in the resonator, which is near to the theoretical value of about 1% (determined by the ohmic loss, atmospheric attenuation, and beam truncation of the resonator mirrors). For the diplexer parameters, the mean number of round trips in the resonator is 4.5, which yields a total absorptive loss of < 5 % in the resonant channel. The second part of power loss of about 3 %, is due to the mode filtering effect. Higher-order modes in the resonator have other resonance frequencies, and the quality factor for these modes is lower. Therefore, higher-order modes in the input beam are not resonant at the nominal resonance frequency, and thus are transmitted to the non-resonant channel. This is clearly illustrated by the field patterns

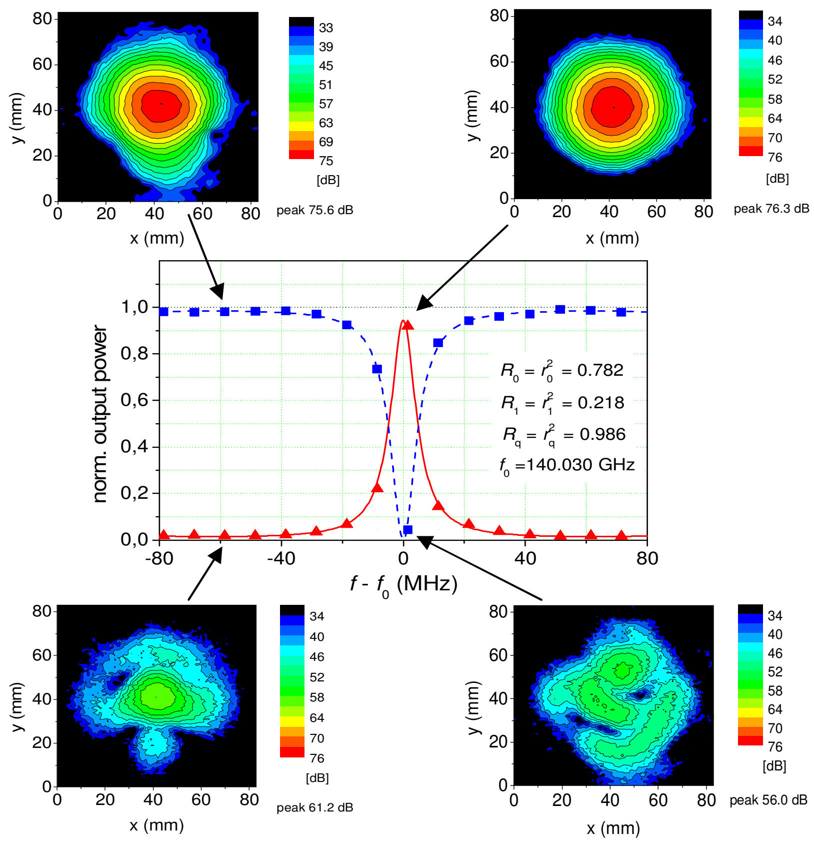

Figure 3: Center: Calorimetrically measured transmission functions (symbols) of the resonant diplexer Mk I with calculated transmission (lines) assuming a round-trip resonator loss of 1.2 % and a grating efficiency of 21.8%. Red solid line / triangles: resonant channel; blue dashed line / squares: non-resonant channel. Top and bottom: field patterns at the non-resonant and resonant outputs, respectively, at frequencies indicated by the arrows.

measured at various positions and frequencies: The field at the resonant output at resonance is a very pure gaussian mode (Fig. 3 top, right); the mode analysis (including the phase distribution) yields 99.8 % purity.

Higher-order modes from the input beam (TEM_{00} purity is typically 97 %) show up in the non-resonant output in form of a non-gaussian distribution (Fig. 3 bottom, right). The power in these modes as measured by calorimetry is about 4 %.

In the non-resonant channel far from resonance, the transmission loss is of the order of 2 %. Only a small contribution is due to absorptive loss as well as mode filtering of very high-order modes, leading to an output beam purity of 99.0 %. More significant is cross-talk to the resonant channel of 1.7 % as predicted from theory. The cross-talk power is mainly in TEM_{00} mode, as can be seen from the corresponding pattern (Fig. 3 bottom left).

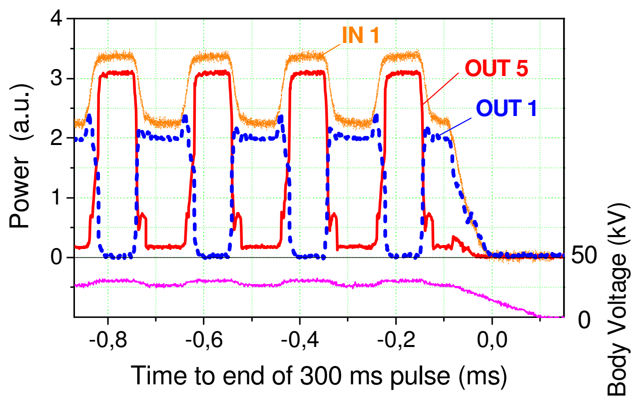

Figure 4: Power signals from output 1 (blue, dashed) and output 2 (red, solid), shown at the end of a 300 ms pulse with U_{acc} = 81.5 kV, ΔU_B = 4 kV, f_{MOD} = 5 kHz square wave. The enveloping trace (orange) is the signal from the gyrotron power monitor. The lower trace shows the body voltage.

3. 2 High-power experiments with ring resonators at W7-X

The Mk I prototype has been tested with high power in the 140 GHz ECRH system for the stellarator W7-X [11]. For this purpose, the diplexer was integrated into the beam duct with the help of matching optics, such that one or two gyrotrons (B1 and B5) could be fed into the inputs, and the outputs were connected to cw calorimetric loads. Experiments were performed with power around 500 kW and pulse lengths limited to several seconds by the un-cooled mirrors in the mock-up diplexer.

By modulating the body voltage U_B (square wave, $\Delta U_B \le 5$ kV, $f_{mod} \le 20$ kHz), frequency-shift keying of the gyrotron B1 with $\Delta f_{gyr} \le 30$ MHz could be obtained. This allowed to toggle the power in the rhythm of the frequency shift between the two outputs with a contrast of better than 90 %, as shown in Fig. 4 for the example for $f_{mod} = 5$ kHz [1].

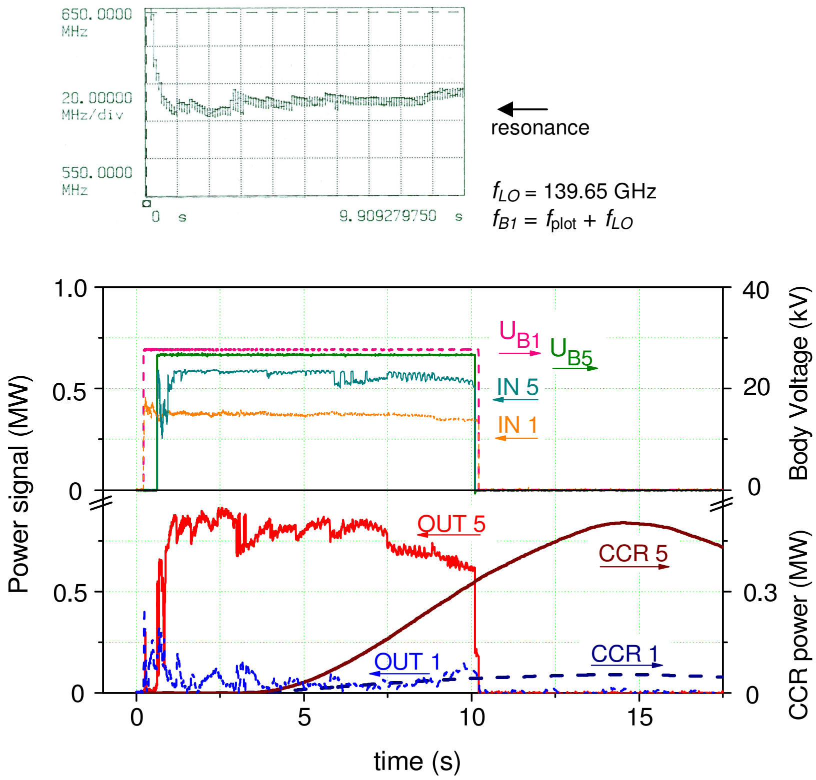

Figure 5: Top: Temporal variation of the frequency of gyrotron B1 (start frequency is about 780 MHz + f_{LO}). Bottom: Temporal variation of the body voltage U_{B1} and U_{B5}, the gyrotron power monitors IN1 and IN5, and the two outputs OUT1 and OUT5 of the diplexer, when gyrotrons B1 and B5 are pulsed at a power of 370 kW and 560 kW with pulse length of 10.0 s and 9.6 s, respectively. Additionally, the power signals from the CW loads (CCR1 and CCR5) are shown. Note that the scale for the load power applies only for the steady state case.

Power combination was demonstrated by feeding two gyrotrons into the diplexer [2]. It was tuned such that a resonance was coincident with the frequency of gyrotron B1 (after thermalization of the cavity, see Fig.5). The frequency of gyrotron B5 was set about 40 MHz below the frequency of B1 using the dependence of the cavity temperature and thus the frequency from the generated power. A 10 s pulse (Fig. 5) showed a power combination with an efficiency of about 90%. The weak frequency stability of the resonant gyrotron B1 as seen from Fig. 5 top, shows the limitation of the experiment. To cope with this problem, a mirror drive for automatic tracking of the resonator to the gyrotron frequency is developed. This drive is now implemented in the resonant diplexer Mk II, which features a compact design and corrugated waveguide interfaces (see Fig. 1 b). Long-pulse tests on transmission characteristics and fast switching are presently underway. First results include the high-power (typ. 500 kW) confirmation of the transmission functions, switching experiments with pulses up to 75 s, and a successful test of the automatic tracking of the diplexer resonance to the gyrotron frequency.

4. Applications

For the main applications of high-power diplexers, namely power combination, fast and slow switching, various concepts exist. A proposal for use of diplexers in the ECRH systems of ITER was made [12], and first investigations on integration of diplexers into large ECRH systems have been performed. Preparations for concrete experiments on synchronous NTM stabilization are going on. At the tokamak FTU in Italy, a diplexer is developed for fast switching between two launchers. At ASDEX Upgrade, the MK II device shown in Fig. 1b, which has very similar characteristics as discussed in chapter 3, will be integrated into the new ECRH system [13] in this autumn. The diplexers discussed here are of interest as well for plasma diagnostics, especially when a combination of high-power sources and sensitive receivers is employed.

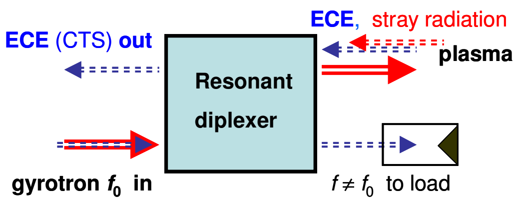

Fig. 6: diplexer set-up for in-line ECE

For the measurement of the power deposition zone in NTM stabilization experiments, the “Line of Sight” scheme [4] exploits the gyrotron transmission line in the reverse direction as an electron cyclotron emission (ECE) antenna, thus ensuring that the ECE observed originates from the same location as where the ECRH is deposited, see Fig. 6. The high-power beam can be fed via the resonant channel (corresponding to f_2 in figure 1b) of the diplexer to the launcher, while the ECE signal is coupled out in reverse direction via the non-resonant channel (f_1 in figure 1b) to the detection system. This scheme decouples the source from the detection system, and the notch-filter function of the non-resonant channel suppresses the gyrotron stray radiation in the sensitive ECE receiver with high efficiency in contrast to quartz plates used for this purpose in present systems. The distance of the notches in the receiver channel can be matched to the filter bank of the ECE receiver, i.e. they will not disturb the measurement. Moreover, with increasing distance from the centre frequency, the depth of the notches is reduced (*cf.* Fig. 2).

Collective Thomson scattering systems employing gyrotrons [5,6] may benefit from this device in several aspects: When feeding the high power through the resonant channel, possible spurious frequencies of the gyrotrons are absorbed in the load and do not reach the receiver. Thus, the dynamic range of the detection system is improved. As was seen from Fig. 3, the beam quality of the probing beam is very high, therefore the best possible spatial resolution can be obtained. Additionally, for a simple backscattering experiment, the set up like Fig. 6 can be used. It is understood that this set up provides no spatial resolution, however, it is at least useful for the commissioning of a CTS experiment and the test of the receiving system, as problems with alignment of a receiver beam are circumvented.

5. Summary and outlook

It has been shown, that high-power diplexers are a valuable component, which can strongly increase the performance and flexibility of ECRH as well as diagnostic systems. The results 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. An in-line ECE experiment on TEXTOR was successful, and its continuation at ASDEX Upgrade using a ring resonator diplexer aims at demonstrating the applicability of this technique in CW systems. CTS experiments employing gyrotrons can benefit from spectral and spatial mode purification of the probing beam. In conclusion, the results motivate the further development of power combiners and fast switches until maturity, especially in view to applications in ITER and other next step devices. This includes especially compact designs for direct connection of corrugated waveguide, which use an eigenmode in the resonator corresponding to the HE_{11} in waveguide, thus avoiding transition losses from HE_{11} to TEM_{00} and back.

Further research is aimed to study other multiplexing schemes and arrays of phase-controlled gyrotrons. Gyrotron developers are encouraged to continue the development of frequency or even phase controlled gyrotrons, the availability of which would further extend the application palette of high-power diplexers.

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References

[1] W. Kasparek et al., Nucl. Fusion 48 (2008) 054010.
[2] V. Erckmann et al., Fusion Sci. Technol. 55 (2009) 23-30.
[3] M. Maraschek, et al., Phys. Rev. Lett. 98, 025005 (2007).
[4] W. Bongers et al., Fusion Sci. Technol. 55 (2009) 188-203.
[5] S. Kubo et al., this conference
[6] T. Saito et al., this conference
[7] W. Wubie et al., Int. Conf. on Infrared and Millimeter Waves, Pasadena, 2008.
[8] A. Bruschi et al., Fusion Sci. Technol. 53 (2008), 97 – 103.
[9] S.V. Kuzikov, Int. J. Infrared and Millimeter Waves 19 (1998) 1523 - 1539.
[10] M. I. Petelin, AIP Conference Proceedings 691 (2003), 251-262.
[11] V. Erckmann et al., Fusion Sci. Technol., 52 (2007) 291.
[12] A. Bruschi et al., IEEE Transactions on Plasma Science, 2010, to be published
[13] D. Wagner et al., Fusion Sci. Technol. 52 (2007), 313 – 320.