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Controlled Mirror Motion System for Resonant Diplexers in ECRH Applications

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Abstract. High-power resonant diplexers for millimetre waves have various promising applications in ECRH systems. The round-trip resonator length of a diplexer needs to be accurately tuned to match its prescribed functionality. For this purpose one of the mirrors in the FADIS MkIIa diplexer has been mounted on a motion system, in order to control the mirror to its desired location despite the presence of substantial disturbances. The mechanical properties and control strategy for the mirror motion system have been designed such as to meet the overall system requirements. The performance of the motion system has been experimentally validated in various high power mm-wave tests.

1 Introduction

Recently, high-power diplexers for millimetre waves have been developed and experimentally validated for their potential use in ECRH systems as well as for plasma diagnostics; see [1] for the background and design considerations of these diplexers. A schematic diagram of a four-port diplexer is shown in Fig. 1 (left). The FADIS (FAst DIrectional Switch) diplexer is a quasi-optical ring resonator for millimetre waves that consists of 4 mirrors which are mounted in a rigid aluminum support structure. Two of the mirrors have gratings to serve as input and output couplers. The transmission properties of the FADIS diplexer can be modelled as [1]:

$$T_1(f, L) = r_0 \frac{1 - |r_q| \exp(j2\pi f L/c_0)}{1 - |r_q r_0^2| \exp(j2\pi f L/c_0)}; \quad T_2(f, L) = \frac{r_1^2 \sqrt{r_q} \exp(j\pi f L/c_0)}{1 - |r_q r_0^2| \exp(j2\pi f L/c_0)} \tag{1}$$

in which T_1 and T_2 are the amplitude transmission functions from input to output port 1 (non-resonant channel) and output port 2 (resonant channel) respectively, as a function of the mm-wave frequency f and the resonator round-trip length L. The coefficients r_0, r_1 and r_q represent the grating scattering coefficients for the 0th-order, the -1st order and the unloaded resonator respectively. It should be noted that this diplexer transmission model is only valid near the nominal values for frequency and round-trip length. For the FADIS diplexer (MkIIa) considered here, this is $f = 140$ GHz

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and L = 2.1 m. Furthermore, the grating scattering coefficients are such that the resonance width (FWHM power) equals 12 MHz. The range for which $T_1 < 0.1$ amounts to 1 MHz in gyrotron frequency or 12 μm in mirror position. The effective power transmission curves as a function of frequency are shown in Fig. 1 (right).

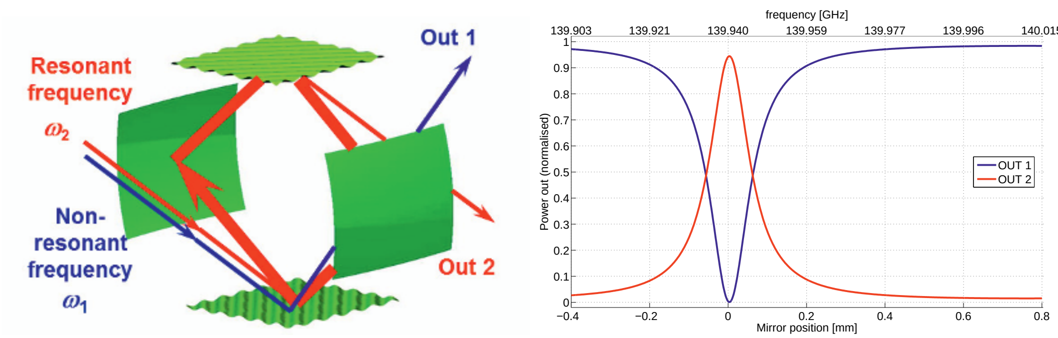

Fig. 1. Left: sketch of the FADIS ring resonator diplexer. Right: Diplexer power transmission as a function of frequency (with fixed L) and as a function of mirror position (with fixed f).

High-power, resonant diplexers have a large field of potential applications. These include the adjustable distribution of gyrotron power over the output ports (either by mechanical tuning of a diplexer mirror (slow) or by modulation of the gyrotron voltage (fast)), a mode purification device, a narrow band-pass filter to discriminate between low power ECE signals and high power ECRH in a line-of-sight ECE sensing configuration and a combiner of gyrotron power from two input ports into a single transmission line. Further details of the versatile application field can be found in [1–3].

2 Requirements on the mirror motion system

Following the mm-wave transmission properties (1) of the diplexer, its round-trip resonator length L is an essential parameter; more precisely the fraction of L and the wavelength λ. For a proper operation of the diplexer this round-trip length should be tuned to its desired value, despite the occurring disturbances. The main disturbances in an experimental setting of the diplexer are:

1. Gyrotron frequency variations.
2. Expansion of the diplexer cavity due to temperature gradients.
3. Structural vibrations; for instance induced by cooling pumps.

The variations in gyrotron frequency form the dominating disturbance source. Fig. 4 (top) shows characteristic time recordings of the temporal frequency behaviour of gyrotron at W7-X and AUG. Its main characteristics are the initial frequency drop mainly caused by thermal expansion of the gyrotron cavity and the irregular and fast frequency jumps, possibly caused by mm-wave reflections back to the gyrotron cavity. For the second disturbance a straightforward calculation shows that the thermal elongation of the round-trip length for FADIS MkIIa amounts to 5.10^{-5} mK^{-1}. So, already a step of 1 °C in ambient temperature will effectively move the diplexer far out of resonance; 50 μm of ΔL yields $T_1 > 0.5$. Regarding the structural vibrations acting on the cavity, measurements have shown that these may result in variations of the round-trip length in the order of several μm's.
To keep the diplexer round-trip length at its desired value during operation one or more mirrors in the resonator need to be made movable. This motion can be limited to a single mirror to restrict complexity, under the condition that by moving the mirror the effective beam displacement from nominal is negligible. Therefore, the mirror position should stay close to its nominal value. The main requirements for the active mirror motion system are shown in Table 1.

Table 1. Main requirements for the mirror motion system.

	characteristic	requirement	comment
a.	Single mirror control		the phase term $2\pi f L/c_0$ is set at the desired value
b.	Positioning precision	1 - 10 μm	to enable precise control to resonance: $T_1 < 0.1$
c.	Positioning stroke	> 1.5 mm	at least 1 period of the transmission curve
d.	Mirror rotation (3 DOF)	< 1 mrad	to keep correct angle of incidence
e.	Lateral motion	< 1 mm	to avoid contact with diplexer cavity
f.	Bandwidth	> 10 - 100 Hz	for gyrotron frequency tracking and 'slow' switching
g.	Motion response	linear	to facilitate control design

3 Mechanical design

Mechanically, the above requirements are fulfilled using an elastically deformable parallel leaf spring mechanism to guide the mirror and a voice coil actuator for the mirror positioning; see the schematic overview in Fig. 2. The voice coil actuator has zero stiffness, is contactless and its exerted force depends linearly on the driving current. It generates a force F_{act} between the frame and the mirror base. The leaf spring mechanism has a high stiffness in five degrees of freedom (DoF) of the mirror, whereas it is compliant for motion in the desired direction. This mirror movement will depend linearly on the voice coil force. To limit the required actuator force the first resonance of mirror motion is designed to be at 5 Hz. Parasitic tilting of the mirror as a result of mirror translations are due to the manufacturing accuracies. For this reason and to avoid the introduction of friction-based connections that will suffer from micro-slip, the mechanism is a monolithic component which is manufactured using wire electrical discharge machining (wire EDM). Note that the leaf spring mounting introduces a small lateral displacement to the mirror as a function of the translation. This effect is however negligible over the total positioning range and well within the requirement. To enable control of the position of the mirror relative to the casing a position sensor is added to the system. This optical encoder measures the displacement of the mirror base relative to the frame with a resolution of 0.1 μm.

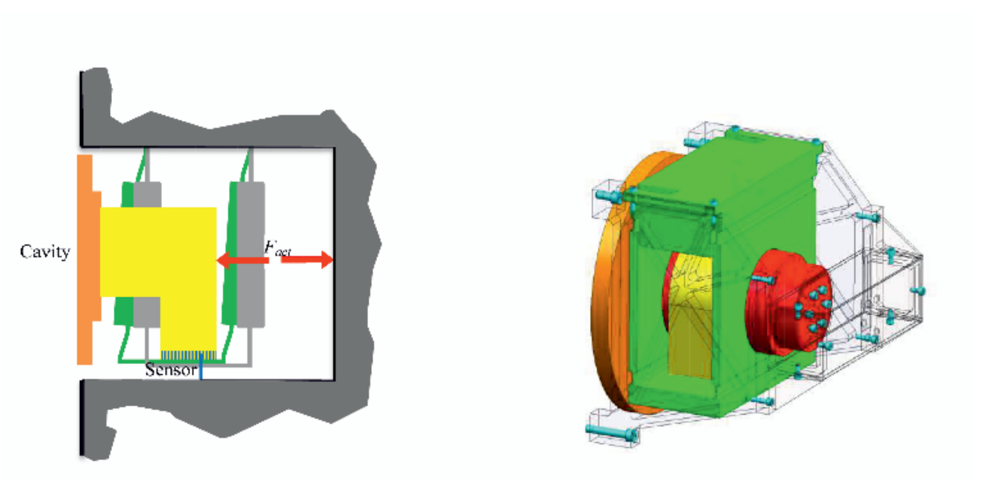

Fig. 2. Left: schematic overview of the cross-section of the elastically deformable parallel leaf spring guiding mechanism. The actuator force F_{act} moves the mirror by deflecting the leaf springs. The leaf springs in their equilibrium position are shown in grey, whereas the deformed leaf springs are colored green. Right: 3D overview of the most important components of the mirror mechanism; the frame (transparent), the voice coil (red), the leaf spring (green) and the mirror (orange).

4 Control design

4.1 Output power feedback

Given the mechanical design, the mirror motion system would have a limited bandwidth ($\approx$ 8 Hz). This is due to the large weight of the diplexer mirror (around 17 kg) and the stiffness of the parallel leaf spring construction. Using the encoder signal from the position sensor, a feedback control loop has been designed to enhance the mirror motion system bandwidth. Using this approach and a low-order position controller a closed-loop bandwidth of over 100 Hz has been realised.
Recall from the introduction that the main objective of the FADIS diplexer is to render a prescribed distribution of mm-wave output beams. In terms of output beam powers, this objective can be written as:

$$P_1 = \gamma P_2 \tag{2}$$

in which P_i is the beam power of diplexer output channel i and γ is an a priori determined, non-negative constant, which describes the functionality of the diplexer. For $\gamma \downarrow 0$ the diplexer is in resonance and the power at output 1 P_1 is (close to) zero. For the fast switching or power division function γ can be set to any value - say in the interval $0.1 < \gamma < 10$ - in which its default value is 1 for equal power distribution. γ can also be chosen as a time-varying parameter that describes a power switching function generated by mirror motion. Since the output beam powers P_1 and P_2 are the controlled variables (i.e. the variables that characterise the diplexer performance), it is most effective to use measurements of P_1 and P_2 as inputs to the controller. Moreover, output power feedback will render the required absolute accuracy to the motion system. The principle of the power feedback set-up is shown in the block diagram of Fig. 3. The particular error function generator corresponds to the objective (2).
The mirror mechanism with position feedback can be regarded as a linear, dynamic system. The relation between mirror position and beam output powers is non-linear however; see Fig. 1 (left). The output powers can be regarded as instantaneously reacting on changes of the mirror position (in relation to the measurement bandwidth of the system; 5 kHz) and so the dynamics of this relation can be neglected. However, the gain of the output powers response depends on the mirror position. That is: the effective gain is given by the derivative of the power curves in Fig. 1. Such non-linear behaviour complicates the design of the controller. For the power switching function (around $\gamma = \frac{1}{2}$, the gain can still be approximated by a constant. For the resonance function ($\gamma \downarrow 0$), however, the gain varies strongly and even changes sign around the optimum. This behaviour makes direct feedback of the output beam powers with a linear controller infeasible. As an alternative, an adaptive control approach has been selected. Consider the following gradient-type optimisation algorithm:

$$x(k+1) = x(k) - \alpha \frac{\partial J}{\partial x}|_{x=x(k)} \tag{3}$$

in which $x(k)$ is the mirror position at sampling instant k and J is the cost function to be minimised. The positive parameter α is a scale factor that influences the convergence speed of the algorithm. For the case of controlling the diplexer to resonance (P_1 is minimal), cost function J equals the measured value of P_1. To estimate the gradient of the cost function to the mirror position x, a control technique denoted as 'stochastic approximation' is used. The main principle of this technique is to add a small perturbation signal Δx_p to the actual x and consequently find the correlation of the change in the cost function ΔJ to the perturbation Δx_p. This will effectively yield an estimate of the gradient which can be inserted in the update rule (3). The perturbation signal must not be correlated to any other signal acting on the system and the update rate (scale factor α) should be restricted in order to get a proper estimate of the cost function gradient. This on-line gradient estimation and optimisation algorithm is very robust in the sense that it does not require any a priori information of the shape of the cost function. More details can be found in for instance [4] and [5]. Note that at each sampling instant the outcome of the algorithm (3) is used as a position command to the mirror system.

4.2 Frequency signal feedforward

The adaptive feedback control method is well capable of keeping the diplexer in resonance. A drawback of the algorithm is the potential of slow convergence. The on-line and recursive gradient es-

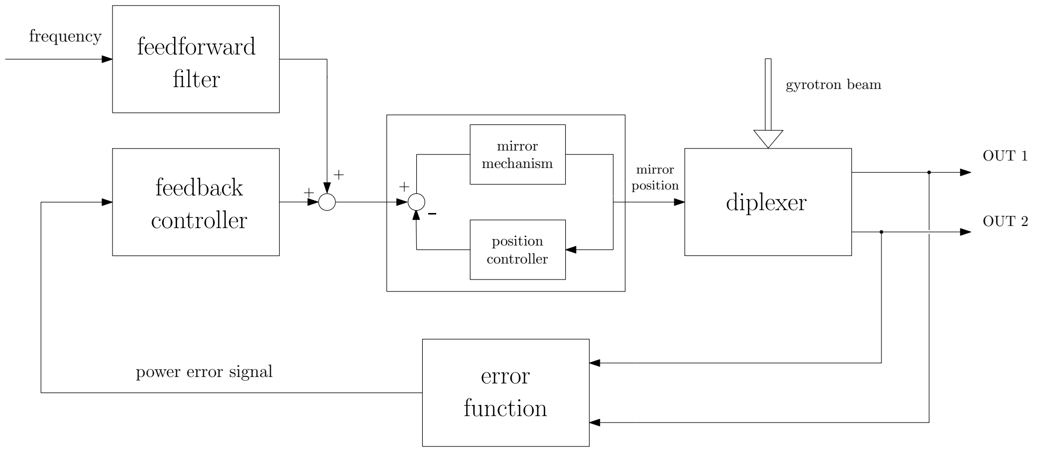

Fig. 3. Block diagram of diplexer mirror control system.

timation algorithm requires sufficient measurement data to converge to the correct value. This may hamper the performance especially in the case of fast gyrotron frequency variations. To enhance the tracking performance, the measured gyrotron frequency signal itself can be used as an additional feed-forward input to the mirror system. Inspection of the transmission expression (1) reveals that with known values of f, the right mirror position can be calculated to obey objective (2). This should give an instantaneous update of the mirror position, which is likely much faster than the adaptive feedback algorithm can produce. It should be stressed however, that the feedforward link requires highly accurate knowledge of both the gyrotron frequency f and the round-trip resonator length L. For instance, to get the diplexer into resonance based on the feedforward calculation rule only, L must be known with an accuracy better than 10 μm. Moreover, this resonator length will vary during operation of the diplexer due to thermal effects. Combined with the adaptive feedback control loop however, the frequency feedforward will improve the tracking speed of the mirror system, whereas the feedback loop will compensate for the errors induced by the feedforward link; see Fig. 3.

5 Experimental results

The controlled mirror motion system integrated with FADIS diplexers MkIIa and MkIII has been experimentally validated in various experiments; i.e. high-power tests with the W7-X ECRH (IPP-Greifswald) and at AUG (IPP-Garching) and low-power tests at IPF, University of Stuttgart. A selection of these experiments has been reported in a previous publication [6], in which the emphasis was put on the impact a controlled FADIS may have in ECRH applications. Here, we report on two fundamental high-power experiments with the controlled mirror system: (1) power equalisation and (2) control to resonance.

In Fig. 4 (left) the results are shown for a high-power experiment at W7-X, in which the powers of both output ports of the diplexer have to be equalised. This is the underlying functionality for slow and fast power switching. Control of the mirror position starts at $t = 0.2s$. Despite the strong variations in the gyrotron frequency, the system is well capable of maintaining an equal distribution over the output ports. The fast jumps in gyrotron frequency only give a temporary mismatch in power distribution. Note that the bandwidth of the mirror motion system is 100 Hz.

In Fig. 4 (right) the results are shown for a high-power experiment at AUG, in which the power of the output port 1 (non-resonance channel) of the diplexer is minimised in order to set the diplexer in resonance for the given mm-wave beam. This case represents the underlying functionality for power combination, mode filtering and 'in-line ECE'. Control of the mirror position starts at $t = 0$. The system both employs diplexer output power feedback and gyrotron frequency feedforward. It achieves a good performance over the entire time interval. The added perturbation signal on the mirror position Δx_p is not visible in the output power curves.

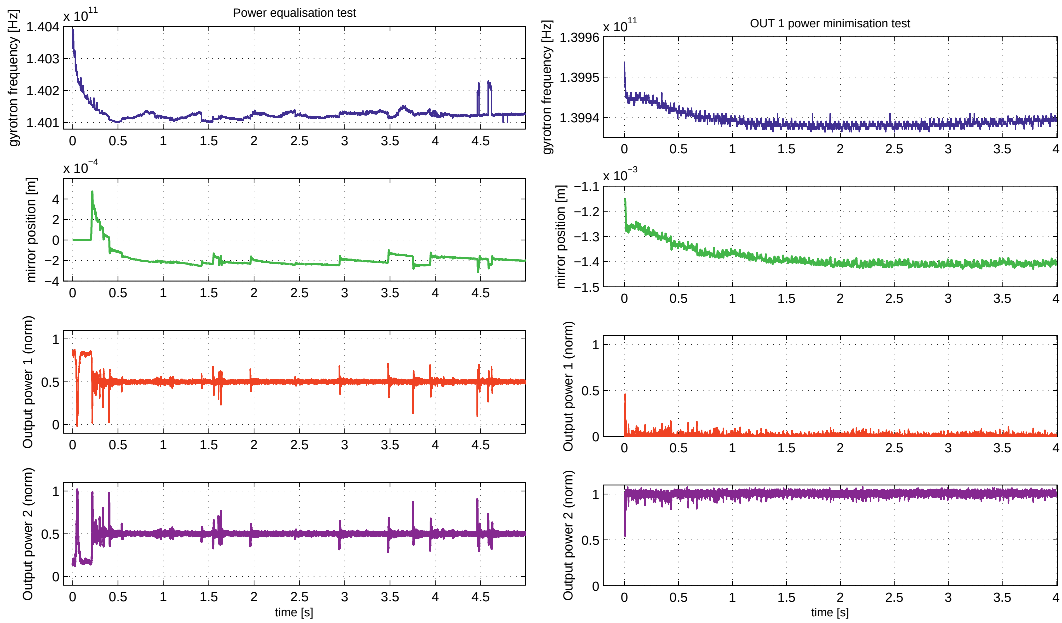

Fig. 4. Experimental results with the FADIS controlled mirror motion system; LEFT: output power equalisation (test with W7-X ECRH), RIGHT: P_1 control to resonance (AUG shot 27798).

6 Conclusions

A controlled mirror motion system for high-power mm-wave diplexers has been developed. Using a voice coil actuator with a leaf spring guidance the mirror positioning behaviour is linear and free of friction. To deal with the particular transmission characteristics as a function of the mirror position, a recursive optimization algorithm has been implemented which requires the injection of a small perturbation signal. The system is well capable of compensating for the temporal variations in the gyrotron frequency, the effects of thermal expansion and of structural vibrations. The performance of the controlled mirror mechanism fully meets the requirements. This has been validated in various high-power experiments with the W7-X and AUG ECRH systems.

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