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A Multifrequency Notch Filter for Millimeter Wave Plasma Diagnostics based on Photonic Bandgaps in Corrugated Circular Waveguides

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Abstract. Sensitive millimeter wave diagnostics need often to be protected against unwanted radiation like, for example, stray radiation from high power Electron Cyclotron Heating applied in nuclear fusion plasmas. A notch filter based on a waveguide Bragg reflector (photonic band-gap) may provide several stop bands of defined width within up to two standard waveguide frequency bands. A Bragg reflector that reflects an incident fundamental TE_{11} into a TM_{1n} mode close to cutoff is combined with two waveguide tapers to fundamental waveguide diameter. Here the fundamental TE_{11} mode is the only propagating mode at both ends of the reflector. The incident TE_{11} mode couples through the taper and is converted to the high order TM_{1n} mode by the Bragg structure at the specific Bragg resonances. The TM_{1n} mode is trapped in the oversized waveguide section by the tapers. Once reflected at the input taper it will be converted back into the TE_{11} mode which then can pass through the taper. Therefore at higher order Bragg resonances, the filter acts as a reflector for the incoming TE_{11} mode. Outside of the Bragg resonances the TE_{11} mode can propagate through the oversized waveguide structure with only very small Ohmic attenuation compared to propagating in a fundamental waveguide. Coupling to other modes is negligible in the non-resonant case due to the small corrugation amplitude (typically $0.05 \cdot \lambda_0$, where λ_0 is the free space wavelength). A Bragg reflector for 105 and 140 GHz was optimized by mode matching (scattering matrix) simulations and manufactured by SWISSto12 SA, where the required mechanical accuracy of ± 5 µm could be achieved by stacking stainless steel rings, manufactured by micro-machining, in a high precision guiding pipe. The two smooth-wall tapers were fabricated by electroforming. Several measurements were performed using vector network analyzers from Agilent (E8362B), ABmm (MVNA 8-350) and Rohde&Schwarz (ZVA24) together with frequency multipliers. The stop bands around 105 GHz (- 55dB) and 140 GHz (-60dB) correspond to the TE_{11}-TM_{12} and TE_{11}-TM_{13} Bragg resonances. Experiments are in good agreement with theory.

1 Introduction

Sensitive millimeter wave diagnostics are vulnerable to stray radiation from gyrotrons applied in Electron Cyclotron Resonance Heating (ECRH) systems at thermonuclear fusion plasma experiments. The output power of modern high-power fusion gyrotrons is typically in the megawatt range with pulse lengths from several seconds to continuous wave (CW). This means that even a small fraction of the total injected power has the potential to destroy sensitive millimeter wave diagnostic receivers. The stray radiation can originate from non-perfect coupling to the plasma (e.g. wrong polarization of the injected millimeter wave beam) or reflections at plasma density cutoffs. There are also heating schemes at harmonics of the electron cyclotron frequency with incomplete absorption of the injected millimeter wave power. For modern ECRH systems using multi-frequency or frequency step-tunable gyrotrons, filters with more than one stop-band are required. At the same time the stop band must be rather wide (several

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hundreds of MHz) in order to cope for the gyrotron frequency chirp, especially at the beginning of the pulse when the cavity expands due to Ohmic losses and the electron cyclotron frequency changes due to neutralization of the electron beam by residual ions. The stop band must also include slightly different oscillating frequencies in systems using more than one gyrotron. Both requirements are difficult to fulfill using the available filter technology (coupled cavity filters or quasi-optical resonance filters) [1]. A filter based on an oversized circular corrugated waveguide with a corrugation period satisfying the Bragg condition can provide several defined stop bands with steep frequency slopes and well defined width. Such a filter was successfully built and tested in Ka-Band [2]. We applied the same design principle for a filter which will protect a new inline Electron Cyclotron Emission (ECE) diagnostic at ASDEX Upgrade [3] where a multi-frequency ECRH system with several two-frequency gyrotrons (105 and 140 GHz) is in operation. The Bragg reflector was optimized by mode matching (scattering matrix) simulations and manufactured by SWISSto12 SA, where the required mechanical accuracy of ± 5 µm could be achieved by stacking stainless steel rings, manufactured by micro-machining, in a high precision guiding pipe (patent is pending) [4].

2 Notch filter principle

The principle scheme of the notch filter is sketched in Figs.1 and 2. A Bragg reflector that reflects an incident circular waveguide TE_{11} mode into a TM_{1n} mode close to cutoff is combined with two mode-conserving non-linear waveguide tapers to fundamental waveguide diameter. Here the fundamental TE_{11} mode is the only propagating mode at both ends of the reflector. The incident TE_{11} mode propagates through the taper and is converted to the high order TM_{1n} mode by the Bragg structure at the specific Bragg resonances (Fig. 2). The TM_{1n} mode is trapped in the oversized waveguide section by the tapers. Once reflected at the input taper it will be converted back into the TE_{11} mode which then can pass through the taper. Therefore at higher order Bragg resonances, the filter acts as a reflector for the incoming TE_{11} mode. Outside of the Bragg resonances the TE_{11} mode can propagate through the oversized waveguide structure with only very small Ohmic attenuation compared to propagating in a fundamental waveguide. Coupling to other modes is negligible in the non-resonant case due to the small corrugation amplitude (typically $0.05 \cdot \lambda_0$, where λ_0 is the free space wavelength).

$$\lambda_{Bragg} = \frac{2\pi}{k_{Bragg}} = \frac{2\pi}{k_{z1} + k_{z2}} \qquad (1)$$

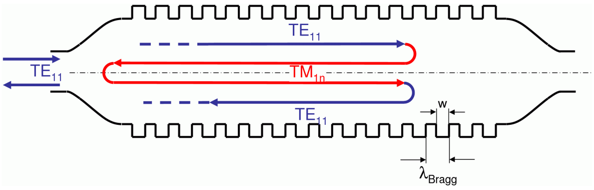

Figure 1. Principle scheme of the notch filter employing higher order Bragg resonances.

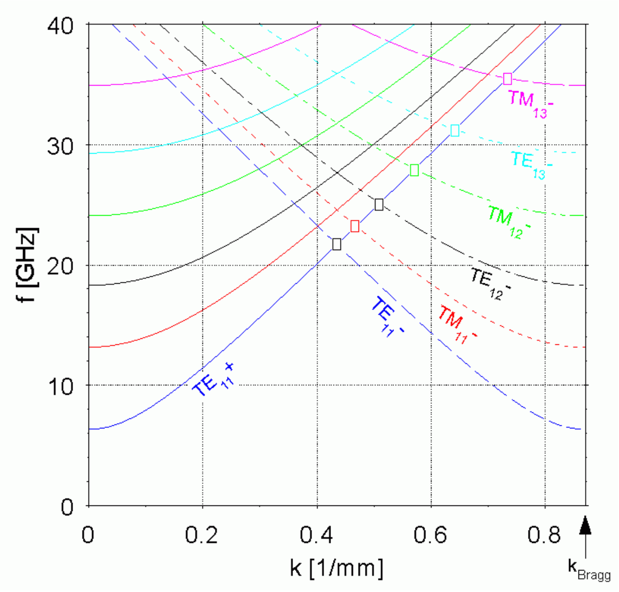

Figure 2. Dispersion diagram of higher order Bragg resonances. Incident modes are marked with '+' whereas reflected modes are tagged with '-'.

3 Notch filter design

The Bragg reflector has a tapered corrugation profile at both ends (Fig.3) to ensure high mode purity and minimum side bands in the frequency response [2]. The corrugation amplitude profile is given by:

$$h(z) = h_0 \cdot \frac{\sin\left(\pi \cdot \left(1 - \frac{z}{z_0}\right)\right)}{\pi \cdot \left(1 - \frac{z}{z_0}\right)} \qquad (1)$$

where h_0 is the maximum corrugation amplitude, z_0 is the total length of the tapered section of the corrugation.

The corrugations in the middle section of the Bragg reflector have a constant depth of h_0. To provide two stop bands at 105 and 140 GHz, the required waveguide radius is 3.47 mm (Fig. 4). The total number of Bragg corrugation periods is 250, where each period is 2.1 mm long. The design goal was to provide two stop bands, each with a width of ~800 MHz and a suppression of around 50-60 dB at the center frequencies of 104.75 and 139.75 GHz. The geometry of the complete filter, including optimized nonlinear tapers to fundamental waveguide at both ends is plotted in Fig.3.

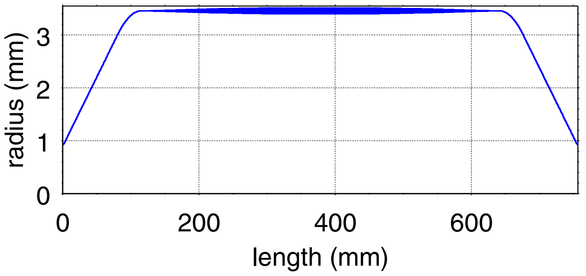

Figure 3. Bragg reflector with tapered corrugation depth and non-linear waveguide radius tapers at both ends.

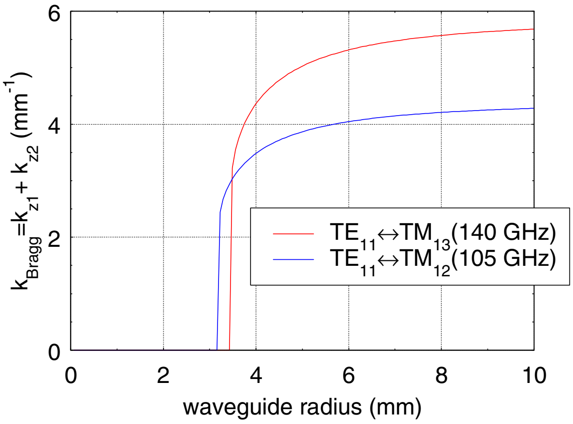

Figure 4. Determination of the waveguide radius 3.47 mm required for the 2-frequency notch filter.

4 Experimental results

The corrugated waveguide of the Bragg reflector was manufactured by SWISSto12 SA, where the required mechanical accuracy of ± 5 μm could be achieved by stacking stainless steel rings, cut by electric discharge machining, in a high precision guiding pipe (Fig. 5) [4]. The two smooth-wall non-linear tapers were fabricated by copper electroforming. The tapers are connected to the oversized Bragg reflector by collar flanges (Fig. 6). Additionally circular to rectangular standard waveguide transitions are connected to the smooth-wall tapers at both ends.

Fig. 7 shows calculated and measured transmission of the filter over the full D-Band. The stop bands around 105 and 140 GHz correspond to the TE_{11}-TM_{12} and TE_{11}-TM_{13} Bragg resonances. The suppression at the TE_{11}-TE_{13} and TE_{11}-TE_{14} resonances at 121 and 162 GHz is much less due to the low coupling of TE modes at the corrugations. Figs. 8 and 9 show measurements of the stop bands around 105 and 140 GHz. The measurements were performed with different setups: Agilent Vector Network Analyzer E8362B, Rohde&Schwarz Vector Network Analyzer ZVA24 and ABmm Vector Network Analyzer MVNA 8-350 with frequency multipliers. The measurements were probably somewhat limited by the spectral purity of the output signals. However, both center frequencies and stop band widths are in good agreement with the calculated values, proving a very high mechanical accuracy of the Bragg reflector. The suppression inside of the notch is somewhat less than theoretically predicted, but still shows a good performance of the filter. Further optimization is possible e.g. by avoiding parasitic reflections at waveguide flanges.

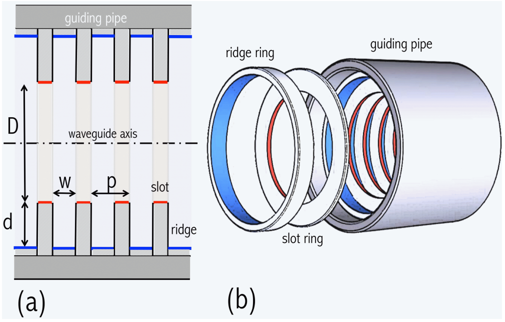

Figure 5. Corrugated waveguide made from stacked rings. (a) Schematic view of a corrugated waveguide with inner diameter D, corrugation period p, slot width w and slot depth d. (b) The corrugation is obtained by alternatingly piling up slot and ridge rings into a guiding pipe [4].

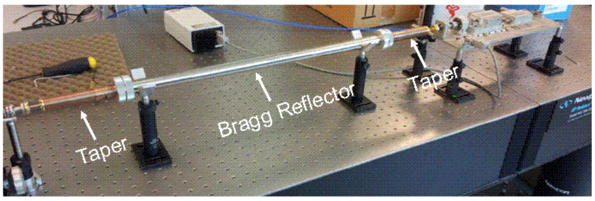

Figure 6. Multi-frequency notch filter setup with Bragg reflector and up-and down-tapers.

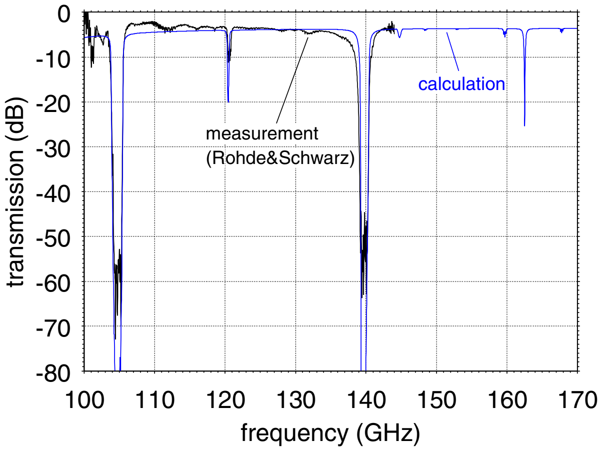

Figure 7. Calculated and measured transmission of the multi-frequency notch filter. Calculations were done using the mode matching method (scattering matrix calculations) [5,6]. Measurements were performed with the Rohde&Schwarz Vector Network Analyzer (ZVA24).

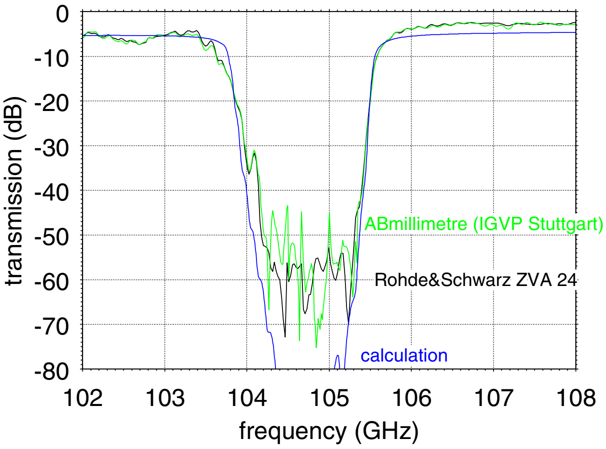

Figure 8. Comparison between calculated and measured transmission around 105 GHz.

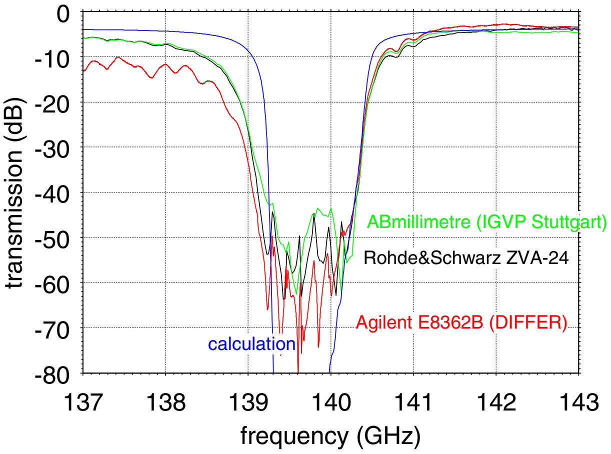

Figure 9. Comparison between calculated and measured transmission around 140 GHz.

5 Conclusions

Two-frequency Bragg reflector waveguide notch filters (105 and 140 GHz) for suppression of gyrotron RF stray radiation in nuclear fusion plasma diagnostics experiments (ASDEX Upgrade and Wendelstein 7-X in Germany) during ECRH with high power gyrotrons have been manufactured with high precision using the stacked rings technology. The filters show low insertion loss, steep frequency slopes and wide stop band. The center frequencies are in good agreement with theory. The 3 dB bandwidth is around 1 GHz. Further optimization can be achieved by improving/avoiding the waveguide flanges. The insertion loss can be further reduced by gold plating of the stainless steel rings.

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