Simple Feedback System for Passive Mode Locked Gyro-Devices at 263 GHz

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***Abstract* — A promising new source to generate a periodic series of coherent, ultra-short pulses in the millimeter and sub-millimeter frequency range is based on the method of passive mode locking [1]. The basic principle is well known from laser physics [2]. A realization for millimeter and sub-millimeter waves consists of an amplifier and a saturable absorber coupled in a feedback loop. In this paper, a coupling system for two single-window vacuum electron tubes in a mode-locked microwave oscillator is presented. Based on full-wave simulations, the key components of the proposed feedback system at 263 GHz (typical DNP-NMR frequency) are designed.**

***Keywords* — ultra-short pulses, passive mode locking, feedback system, quasi-optical.**

I. INTRODUCTION

In an ongoing joint RSF-DFG project led by the Institute of Applied Physics (IAP-RAS) in Nizhny Novgorod, Russia, and supported by the Institute for Pulsed Power and Microwave Technology (IHM-KIT), the generation of a periodic sequence of coherent, powerful, ultra-short RF pulses is studied [1]. Such powerful pulses of millimeter and sub-millimeter waves can be useful for a number of fundamental problems and practical applications, including novel pulsed Dynamic Nuclear Polarization (DNP)-Nuclear Magnetic Resonance (NMR) spectroscopy, diagnostics of plasmas, photochemistry and biophysics.

In [1], it is proposed to generate a periodic sequence of powerful, coherent pulses in the millimeter (mm)-wave frequency range by a feedback loop consisting of an amplifier and a non-linear, saturable absorber. The saturable absorber acts as a non-linear filter which is transparent for high intensity signals, while signals with low intensity are strongly attenuated. In such a feedback loop, the periodic signal is generated by the mechanism of passive mode locking, well known from laser physics [2].

For a realization of the proposed principle at mm-wave frequencies, appropriate technologies have to be identified. As shown in [3], a well suited technology for the high power RF amplifier and the non-linear saturable absorber are gyro-TWTs with helical interaction regions [4]. These devices provide a series of advantages compared to classical gyro-TWTs based on cylindrical interaction circuits with dielectric losses. The helical gyro-TWTs can operate at the 2nd cyclotron harmonic and, therefore, the required magnetic field is reduced by the factor of two compared to classical gyro-TWTs operating at the fundamental electron cyclotron harmonic. This is of particular interest for the development of a mode-locked oscillator in the sub-THz range, which is advantageous for a number of spectroscopy methods. Further advantages are the broader bandwidth and the lower sensitivity to velocity spread of the electron beam. The high available bandwidth is of special importance since it limits the minimal pulse length of the generated pulses.

As the amplifier and saturable absorber can only be realized in two separate gyro-TWTs, a feedback system is required to couple the amplifier and absorber devices with each other and to decouple the output signal from the feedback loop. The feedback system has to fulfill several requirements. As the output signal consists of ultra-short pulses (≈0.25 ns) with a high power (≈300 W at 263 GHz), the feedback system must provide a high bandwidth and low losses. To be on the save side, all components should resist a 1 kW CW signal. To provide as much flexibility as possible to the experimenter, a variable decoupling coefficient as well as a tunable delay time would be favorable. Low back-reflections into the amplifier are essential (S_{11}<-30 dB) to prevent the transition from the mode-locked regime to the generation of chaotic signals [5].

In the present paper, the general design of such a feedback system, developed under the aspect of simplicity, is presented. In section II, the feedback system is described and the basic ideas of the design are discussed. In the following sections III – V, detailed simulations of the key components of a feedback system for a mode locked pulsed source at 263 GHz are shown. Finally, a conclusion is given and the next steps in the project are outlined.

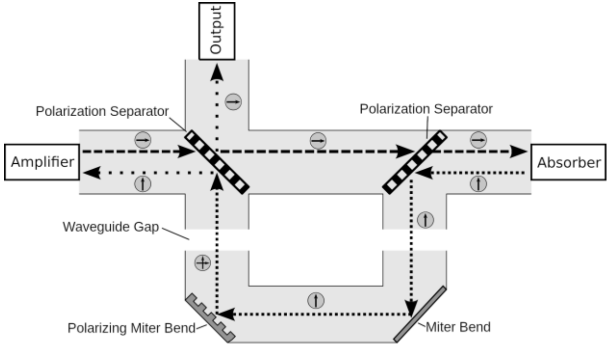


Fig. 1. Amplifier and absorber devices working with single input-output window coupled by corrugated, overmoded waveguides. The arrows symbolize the polarization of the HE_{11} mode.

II. Proposed Design of a Simple Feedback System for 263 GHz

In contrast to usual applications of gyro-TWTs, in the feedback loop both devices, amplifier as well as absorber must be able to be fed with a high power input signal. Therefore, both are realized as devices with a single window for the input and output of signals [6]. This feature allows high power input signals and it simplifies the design of the feedback system. In addition to previous discussed requirements: high bandwidth, low losses, low back-reflections, variable decoupling and tunable delay time, an additional requirement is essential for a stabile operation of the microwave oscillator. For optimum operation, the decoupling should take place only on the signal trail from the absorber to the amplifier. This requires a separation of the signal paths “amplifier-to-absorber” and “absorber-to-amplifier”. For this purpose, the polarization characteristic of helical gyro-TWTs in single window operation can be utilized. The output signal is cross-polarized to the input signal and therefore, a polarization splitter can be used to separate the input and output signals. A schema of the proposed design, fulfilling all requirements, is shown in Fig. 1.

For a simple alignment and handling, all components in the feedback system are oriented orthogonal to each other. This allows a realization of the feedback system with corrugated waveguides instead of a quasi-optical mirror system in free space, as proposed earlier [7]. In addition, the orthogonality allows the possibility for a tunable delay time (see section V) which is not possible in previous designs.

The input and output signals of the helical gyro-TWTs with single input-output window are cross polarized HE_{11} modes. With overmoded corrugated waveguides, the signals are transmitted to the polarization splitters. As shown in Fig. 1, the output polarization of the amplifier is chosen such that it is transmitted by the polarization separators, while the cross-polarized output from the absorber is reflected.

To decouple a fraction of the signal oscillating in the feedback loop, the polarization splitter is used in combination with a tunable polarizer miter bend.

As waveguide a usual overmoded corrugated waveguide for 263 GHz with 22 mm diameter, $\lambda/4 = 0.285$ mm corrugation depth, 0.38 mm corrugation period and 0.15 mm corrugation width is used.

III. Polarization Splitter

For the separation of cross-polarized linear HE_{11} modes several approaches are possible (a good overview can be found in [8]). While in previous proposed feedback-systems the signal paths are separated by sinusoidal corrugated mirrors [7], the favorable technology in the new proposed feedback system is a so-called wire-grid splitter. For contrast to wire-grid splitters in optical applications, an all-metal design is used here. The main advantage of the wire-grid splitter is that it can be directly used in a 4-port configuration as required in our application (see Fig. 2).

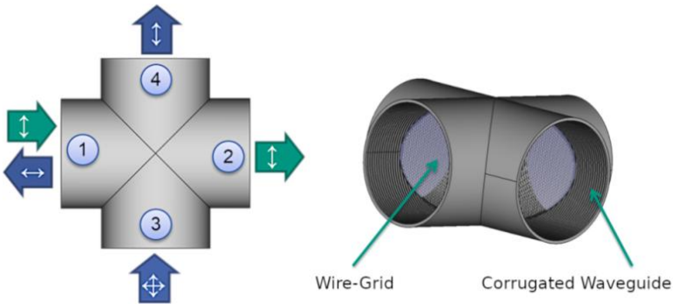
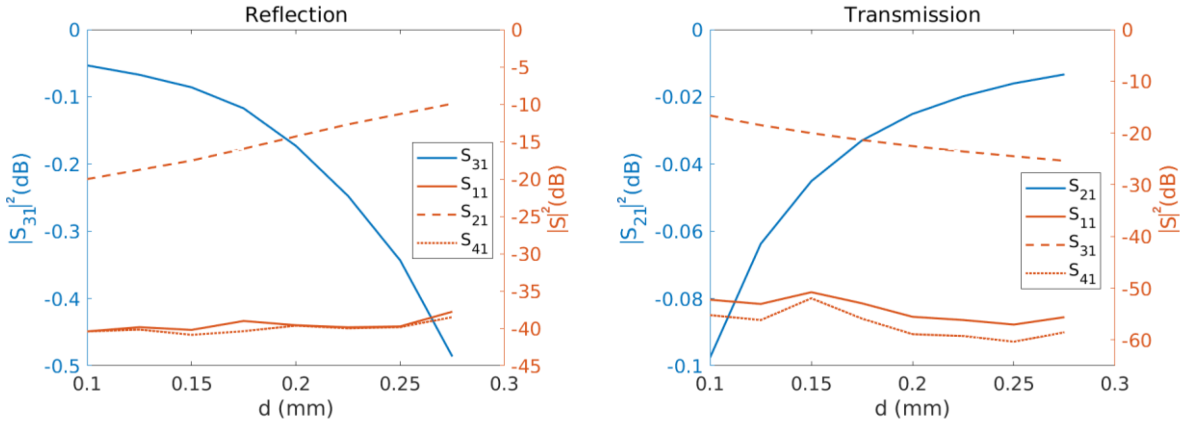


Fig. 2. Wire-grid polarization splitter in a 4-port configuration.

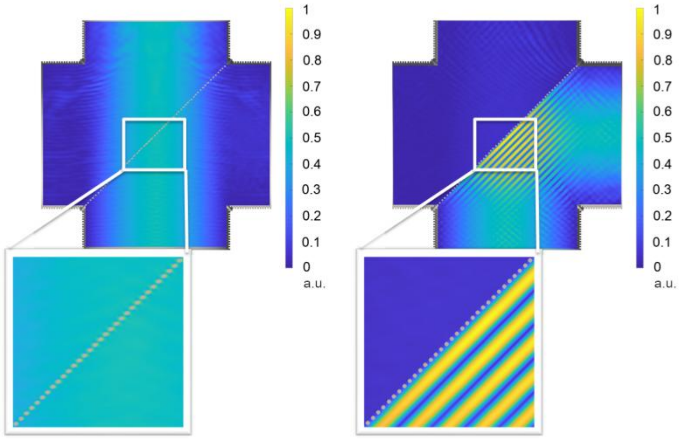
For a given waveguide diameter (22 mm) the remaining parameters are the wires’ diameter b and their spacing d. As the amplifier output signal has to be transmitted through two splitters before it is injected into the saturable absorber, the main focus in the optimization procedure is paid to a high transmission instead of an optimal signal-separation. Obviously, the transmission increases with decreasing wires’ diameter. As the wires’ diameter is mainly limited by the ohmic losses, it is set to a value of 0.1 mm which should be save for the maximum estimated signal power of 1 kW.

The optimization of the wires’ spacing d is performed on the basis of 3D full-wave simulations of the complete polarization spitter. For these simulations our in-house developed tool KarLESSS [9] is used.



(a) (b)

Fig. 3. Simulated S-parameter for a wire-grid polarization splitter in a corrugated waveguide with diameter of 22 mm for different wire distances d and a wire diameter of 0.1 mm. (a) for the reflection path; (b) for the transmission path



(a) (b)

Fig. 4. Electric field of a wire-grid polarization splitter, full-wave simulation: (a) transmission path; (b) reflection path

In Fig. 3, the interesting S-parameters of a parameter sweep of d are shown. As expected, the transmission increases with an increasing distance between the wires. This applies until d becomes too large and the grid acts as a diffraction grid.

Based on the parameter sweep over d and an additional sweep over the frequency (263±5 GHz) a wire distance of $d = 0.15$ mm is chosen as optimal. The optimized polarization splitter achieves a high transmission of -0.04 dB, a good reflection of -0.08 dB and a low back-reflection of always smaller than -30 dB. The power leak to the other ports is below -20 dB in the transmission path and below -17 dB in the reflection path.

In a final step, the maximal field strength is controlled to avoid breakdown. In Fig. 4, the electric field for the reflection and transmission path is shown. It is clear that in the reflection path the field strength is increased due to the interference of the incident and reflected beams. The simulation gives a value of 0.225 kV/m for a 1 W signal which corresponds to 7.2 kV/m at 1 kW.

IV. POLARIZER

To decouple a fraction of the signal oscillating in the feedback loop, the polarization splitter in combination with a tunable polarizer miter bend is used. The polarizer creates an elliptically polarized HE_{11} mode from the incident linearly polarized one. Since the elliptically polarized HE_{11} mode can be seen as a superposition of two cross-polarized, linearly polarized modes with a phase shift, the previously described polarization splitter separates these linearly polarized modes and a fraction of the signal can be decoupled in a simple way.

In the polarizing miter bend, the elliptical polarization is created by a reflective phase grid with rectilinear grating. The grating can be characterized by the grid width a, grid height h and grid period p. For a designated frequency, the optimal grid parameters can be chosen as [10]:

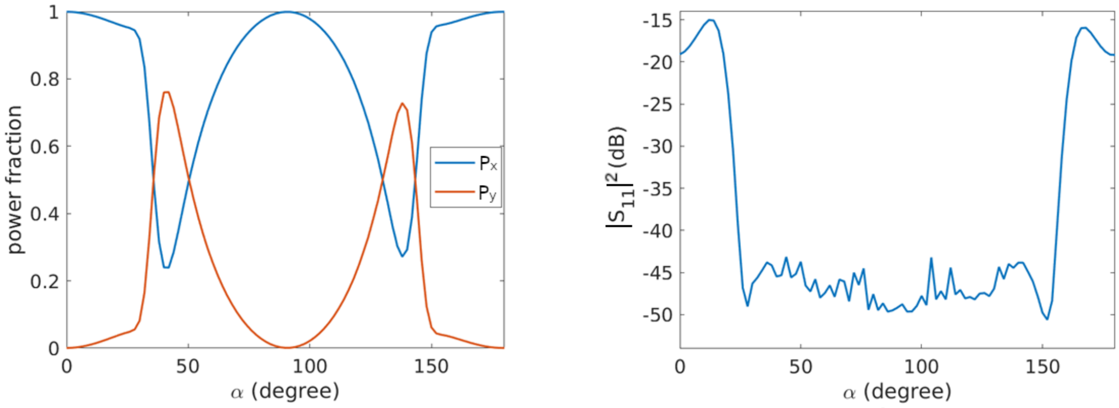
$$h = \frac{\lambda/8}{\cos\Omega} \tag{1}$$

$$p < \frac{\lambda}{1 + \sin\Omega\cos\alpha} \tag{2}$$

with the incident angle $\Omega = 45°$ and the angle α between the polarization plane of the incident linear polarized wave and the orientation of the grid.

To minimize dispersion effects of the polarizer at the ultra-short pulses, a bandwidth of 10 GHz is demanded. Because the optimal parameter for a phase grid with high bandwidth is not available from analytical formulas, a numerical optimization is performed. For simplification a plane wave approximation is used in the optimization procedure. The start parameters are chosen by the previous formulas for the center frequency of 263 GHz. As a result the optimized grid parameter: $p = 0.75$ mm, $a = 0.2$ mm and $h = 0.218$ mm are obtained.

By a variation of α, the fraction of power in the cross-polarized linear components can be controlled.



(a) (b)

Fig. 5. Full-wave simulations of the optimized polarizing miter bend for different orientations α of the reflective phase grid. (a) power in x- and y-polarized fractions; (b) back-reflected power

In our coordinate system, an angle of $\alpha = 45°, 135°$ corresponds to a circular polarized wave ($P_x = P_y$) and an angle of $\alpha = 90°$ does not change the polarization of the incident wave ($P_y = 1$, $P_x = 0$).

To verify the design based on the plane wave approximation, 3D full-wave simulations of the final polarizing miter bend are performed. In Fig. 5, selected examples of these simulations are shown. The fraction of power in the x- and y-polarized HE_{11} modes for various orientations of the tunable polarizing miter bend is shown in Fig. 5a. As in [3] described, an optimal operation of the feedback-loop is expected for a decoupling factor of ≈0.3. Therefore, with the designed polarizing miter bend a large flexibility is provided to operate in a wide range around the expected operation point. The result presented in Fig. 5b shows that only negligible back-reflections are expected in the operation range.

V. TUNABLE DELAY TIME

A preferable feature for the feedback system is a tunable delay time. The delay time is determined by the time a signal requires for a single pass through the complete feedback loop. A tunable delay time can be realized over a variable length of the transmission line. As the propagation velocity of a HE_{11} mode in an oversized waveguide is approximately the speed of light, an increase of the delay time of 1 ns corresponds to an increase of the signal path of 30 cm.

Due to the known fact that the HE_{11} mode can be transmitted very effectively over small gaps in the waveguide, the simples approach is to cut the waveguides in the signal path “absorber-to-amplifier” to create a gap which could be varied by moving the two miter bends (see Fig. 1). The transmission of a HE_{11} mode over a gap can be approximated with the following equation [11]:

$$S_{21} \approx -1.7 \left(\frac{L\lambda}{2a^2}\right)^{\frac{3}{2}} \text{dB} \qquad (3)$$

With the length L of the gap, the wavelength λ and the waveguide radius a. In Fig 6, equation (3) is plotted for the center frequency of 263 GHz and varying length of the gap. It can be clearly seen that for an increase of the delay time by 1 ns (two gaps of $L = 15$ cm), the attenuation would be unacceptable high. Therefore, this most simple implementation of a tunable delay time is not practicable for relevant delay tuning. Only a very minor tunability of ±0.25 ns is realizable with this concept. A more complex solution is necessary for a higher tunability.

VI. CONCLUSION

A new design for a system to couple two single-window vacuum electron tubes in a feedback loop is shown. The presented concept is simple to implement, save and flexible. Based on 3D full-wave simulations, the key components of a feedback system at 263 GHz (typical DNP frequency) were designed. In a next step, a measurement setup at 263 GHz will be build up to verify the designs.

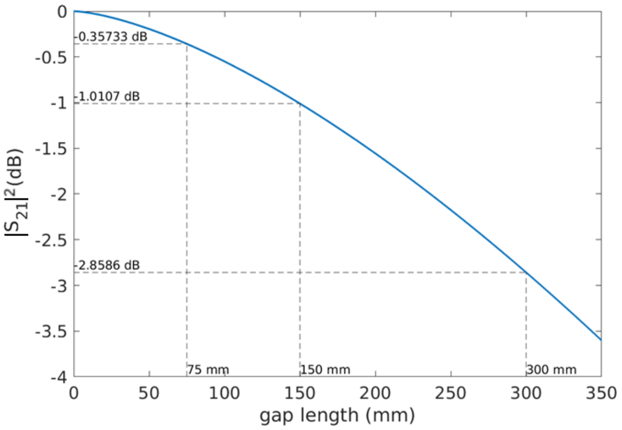


Fig. 6. Transmission of a HE_{11} mode at 263 GHz over a gap in a corrugated waveguide with diameter 22 mm.

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