Extended Feedback System for Coupled sub-THz Gyro-Devices to Provide New Regimes of Operation

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***Abstract*—A new type of high-power pulsed source in the millimeter and sub-millimeter frequency range, utilizing the method of passive mode locking, was proposed in 2015 by the Institute of Applied Physics (IAP-RAS) in Nizhny Novgorod. This principle, well known from laser physics, allows the generation of a periodic series of powerful, coherent, ultra-short pulses. In the millimeter and sub-millimeter wavelength range this can be realized using an amplifier and a saturable absorber coupled in a feedback loop. For the coupling of the two devices, a sophisticated feedback system is required. Such a system, based on simple overmoded waveguide components, was previously proposed by the authors. The present article shows how the proposed feedback system can be extended, allowing for a wide range of possible operation regimes for two coupled gyro-devices. Particularly noteworthy is the application of the modified feedback system for the realization of a two-stage amplifier in the sub-THz range. Furthermore, it seems to be possible to use two helical gyro-devices coupled in the proposed way as a source of coherent pulses, as a free-running or locked CW source, and as a two-stage amplifier. In all cases, no design changes of the feedback system are required.**

***Index Terms*—sub-THz, high power, ultra-short pulses, passive mode locking, feedback system, quasi-optical.**

I. Introduction

In a joint project of the Russian Science Foundation (RSF) and the Deutsche Forschungsgemeinschaft (DFG), 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 [2], [3], [4].

In [1], it is proposed to transfer the basic principle of a Kerr laser [5], [6] to the millimeter (mm)-wave frequency range to provide a novel source of a periodic sequence of powerful, coherent pulses for mm-waves. In this frequency range, gyro-devices promise the possibility of high power [7]. Therefore, the Kerr principle should be realized by a feedback loop consisting of two gyro-devices, acting as an amplifier and a non-linear, saturable absorber. The saturable absorber operates as a non-linear filter: 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 [8]. For the generation of powerful, sub-nanosecond pulses at sub-THz frequencies, the active devices, namely the amplifier and absorber, must fulfill a number of demanding requirements. Particularly challenging is the demand for high bandwidth at high power. Promising technologies for both the amplifier and the absorber are gyrotron traveling-wave tubes (gyro-TWTs) with a helical interaction circuit [9], [10], [11]. This type of vacuum electron tubes provide a series of advantages compared to classical gyro-TWTs based on cylindrical interaction waveguides with dielectric losses [12], [13]. The helical gyro-TWTs provide a larger bandwidth, are less prone to electron velocity spread and can operate at lower magnetic fields, since the electron-wave interaction takes place at the 2nd cyclotron harmonic [11]. This is of particular interest for the development of devices in the sub-THz range, where the required magnetic field strength for operation at the fundamental cyclotron harmonic can easily exceed 10 T.

As the amplifier and saturable absorber can only be realized in two separate gyro-TWTs, in [14] a feedback system for a passive mode locked pulsed oscillator at 263 GHz was already presented (see Fig. 1a). It couples effectively the two gyro-devices and enables the decoupling of the output signal. The design shown fulfills all the necessary requirements: high bandwidth (10 GHz), variable decoupling of the output signal, low losses and a separation of the signal paths "amplifier-to-absorber" and "absorber-to-amplifier" for an improved stability of the passive mode locked oscillator.

In the present paper, we propose an extension of the previously presented feedback system. This extension allows a range of new operating scenarios for the previously proposed system of two coupled helical gyro-TWTs. First of all, the operation of the passive mode locked pulsed oscillator in the hard excitation regime becomes possible. This could significantly improve the usability of the pulsed oscillator in real applications. Furthermore, the operation as a two-stage amplifier is possible. On the one hand, the amplifier can still be combined with the non-linear absorber, which can be used either as a pulse compressor or to reduce low power noise. On the other hand, the absorber can easily be operated as an amplifier. This would allow a two-stage high-power amplifier, similar to the systems in [15], however with

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the significant advantage of being able to inject the input signal via an overmoded waveguide. Finally, the system can be operated as a high-power sub-THz CW source. For this, one of the amplifiers must be operated as backward-wave-oscillator (BWO). In order to achieve higher frequency stability, the proposed feedback system additionally provides the possibility of injecting a locking signal.

The paper is structured as follows: First, a short review of the Jones calculus, used in this article to describe the different signal paths and polarization, is given. Then, the extended design is presented and its advantages for a passive mode locked pulsed oscillator are discussed. Next, the new alternative modes of operation are presented, namely two-stage amplifiers and CW sources based on BWOs. Finally, a conclusion is given and possible future steps in the project are outlined.

It should be noted that in this article we focus only on the fundamental functional principle of the proposed feedback system. The investigation and design of helical gyro-TWTs that support all the operating regimes discussed here will be the subject of future research.

A first proof-of-principle experiment of a coupled microwave amplifier and absorber to demonstrate the generation of ultra-short microwave pulses is under preparation at the IAP-RAS [16].

II. Jones Calculus

In the feedback system, power is transmitted via the balanced HE_{11} mode in overmoded corrugated cylindrical waveguides. Thus, for the separation of signal paths, the polarization characteristics of the HE_{11} mode is utilized. To describe the different polarization states in the feedback system in a simple way, the Jones calculus [17] is used, which is summarized in the following.. For a waveguide diameter of $D \geq 12\lambda$ (where λ is the free-space wavelength), a plane wave approximation can be used for the HE_{11} mode [18]. Therefore, we can describe the polarization of a HE_{11} mode in overmoded waveguides in a way similar to polarized light in optics by a Jones vector [17]. Assuming that the HE_{11} wave travels in the positive z-direction in a waveguide, the Jones vector represents the amplitude and phase of the electric field in the cross-section of the waveguide. In the local coordinate system of the waveguide, an HE_{11} mode linearly polarized in the x or y direction (in the following referred as horizontally and vertically polarized), is represented by

$$e_{\mathrm{x}} = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \quad (1)$$

$$e_{\mathrm{y}} = \begin{pmatrix} 0 \\ 1 \end{pmatrix}, \quad (2)$$

respectively, consequently left- and right-handed circularly polarized modes are given by

$$e_{\mathrm{l}} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ +j \end{pmatrix}, \quad (3)$$

$$e_{\mathrm{r}} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ -j \end{pmatrix}. \quad (4)$$

Here j refers to the imaginary unit. All components in the feedback system can be described by Jones matrices. The matrices for the transmission and reflection path of the polarizing beam splitters are given by:

$$S_{\mathrm{T}} = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}, \quad (5)$$

$$S_{\mathrm{R}} = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}. \quad (6)$$

In this discussion, we neglect the influence of the electron-tubes on the power of the signals and limit ourselves to their effect on the polarization. Since the input and output signals of the helical gyro-TWTs are cross-polarized with respect to each other, the Jones matrix for the tubes is given by:

$$D = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}. \quad (7)$$

Since tunable polarizing miter bends are realized as rotatable reflective phase grids, we can represent them by a Jones matrix which describes a delay in one component of the E-field. For simplicity, let us assume that for angle $\Theta = 0°$ the polarizer delays the x-component of the E-field by $\pi/2$ ($\widehat{=}\lambda/4$):

$$P_{\mathrm{x}} = \begin{pmatrix} e^{-j\frac{\pi}{2}} & 0 \\ 0 & 1 \end{pmatrix}. \quad (8)$$

For an arbitrary rotation angle Θ of the reflective phase grid, the Jones matrix for a polarizing miter bend is then given by the matrix product

$$P_{\Theta} = R_{\Theta}\ P_{\mathrm{x}}\ R_{\Theta} \quad (9)$$

with the rotation matrix

$$R_{\Theta} = \begin{pmatrix} \cos\Theta & -\sin\Theta \\ \sin\Theta & \cos\Theta \end{pmatrix}. \quad (10)$$

It should be noted that for a polarizer with a phase delay of $\lambda/4$ in a mode locked pulsed oscillator, only a maximum of $50\,\%$ of the oscillating signal can be decoupled. Therefore, the polarizer in [14] is designed to have an effective delay of $0.315 \cdot \lambda$, which allows an decoupling of up to $70\,\%$.

Although, strictly speaking, the Jones calculus is only valid for monochromatic waves, it allows an easy inclusion of the feedback system into interaction simulations based on the slowly varying amplitude approach (SVAA). The SVAA is common for the simulation of the electron-wave interactions in electron tubes and has been successfully used for first simulations of devices coupled in a feedback loop [10]. However, so far only simulations assuming a perfect feedback system have been performed. The derivation of new boundary conditions based on the Jones formalism, which allow the integration of non-ideal components, will be part of a further publication.

In the following, a superscript is added to all Jones vectors and matrices to clarify to which component the operator belongs. It should be mentioned that all potentially occurring effects of mode conversion are neglected in the following discussion.

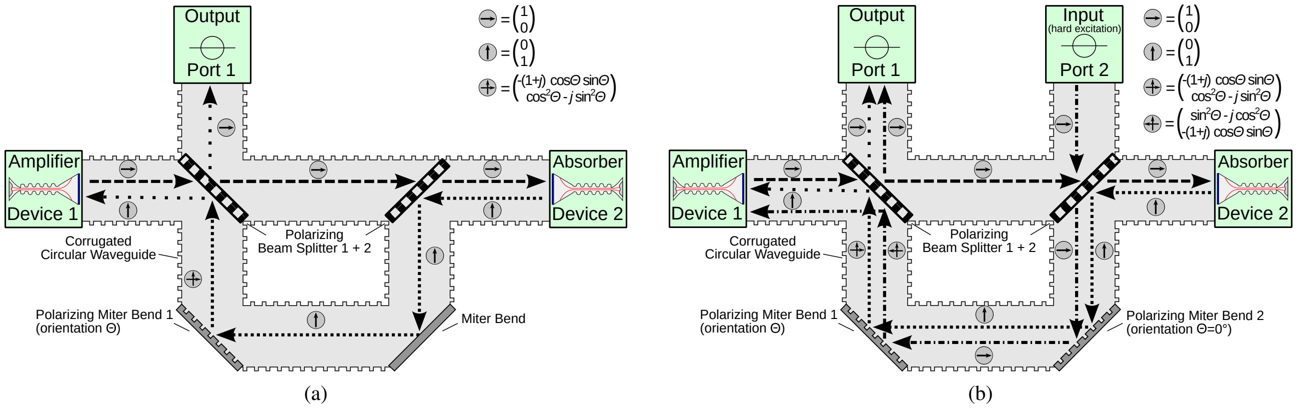

Fig. 1. Amplifier and absorber devices working with a single input-output window, coupled by corrugated, overmoded waveguides. The arrows represent the polarization (Jones vectors) of the HE_{11} mode. (a) Feedback system as proposed in [14]. (b) Extended design with an additional output/input port and a second polarizing miter bend. The extended design allows the input of a start-up signal to operate the passive mode locked pulsed oscillator in the hard excitation regime.

III. Feedback System for a Passive Mode Locked Pulsed Oscillator

A basic requirement for two passive mode locked gyro-TWTs coupled in a feedback loop is the possibility to feed high-power input signals into the tubes. This is a challenging requirement and in strong contrast to the usual applications of gyro-TWTs, where low-power input signals are amplified (see e.g. [19] for an appropriate input coupler). A solution can be found in a great attribute of helical gyro-TWTs: As long as the input and output signals are cross-polarized to each other, the input signal can be fed through the output port, which is able to handle high-power signals. Such a configuration with a single window for the input and output was first described in [20]. For our application, this allows the required input of high power signals and in addition, it simplifies the design of the feedback system. The design of the feedback system is primarily determined by the requirement to separate the signal paths ”amplifier to absorber” and ”absorber to amplifier”. Otherwise it is not possible to decouple a fraction of the oscillating signal only on the ”absorber to amplifier” path. As mentioned previously, this is important for the stability of the oscillator. The input and output signals of the helical gyro-TWTs in the usual single input-output port configuration is the linearly polarized HE_{11} mode. The linearly polarized HE_{11} mode of the output signal is cross-polarized to the linearly polarized HE_{11} mode of the input signal and therefore, a polarizing beam splitter can be used to separate the input and output signals [21].

To separate the signal paths ”amplifier to absorber” and ”absorber to amplifier”, a simple trick is used: while for the amplifier a right handed helical waveguide is chosen, for the absorber device a left handed helical waveguide is used. As a result, the output signals of amplifier and absorber are cross-polarized to each other. The output polarization of the amplifier is chosen such that it is transmitted by both polarizing beam splitters, while the cross-polarized output from the absorber is reflected. As a polarizing beam splitter, a so-called wire-grid splitter with a wire diameter of 0.1 mm and a wire distance 0.15 mm was found to be optimal for a system operating at a center frequency of 263 GHz [14]. The simulated transmission coefficient is always greater than $98.5\,\%$ for the considered 10 GHz bandwidth with a variation below $1\,\%$ over the complete bandwidth. The reflection coefficient is greater than $99.5\,\%$ with a variation below $0.1\,\%$.

For simple alignment and handling, all components in the feedback system are realized within corrugated circular waveguides. For a system operating at a center frequency of 263 GHz, a usual overmoded corrugated waveguide with 22 mm diameter, $\lambda/4 = 0.285$ mm corrugation depth, 0.38 mm corrugation period and 0.15 mm tooth width can be used. A waveguide of this type guarantees low ohmic losses (10^{-3} dB/m), a high bandwidth (> 10 GHz) and the possibility to transmit high power [22].

To decouple a fraction of the signal oscillating in the feedback loop, a polarizing beam splitter is used in combination with a tunable polarizing miter bend. 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 polarizing beam 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. As the optimal parameters for a phase grid with high bandwidth are not available from analytical formulas, a numerical optimization is performed in [14]. As a result, an optimized grid with a period of 0.95 mm, a tooth width of 0.75 mm and a tooth height of 0.218 mm is obtained. The change of the power decoupling factor over the 10 GHz bandwidth caused by the frequency dependence of the polarizing miter bend is in an acceptable range of $5\,\%$ around the center frequency. As the feedback system is intended for high-power operation, all components are designed with a capability for 2 kW continuous wave (CW) signals.

As mentioned in the introduction, two extensions to the feedback system shown in Fig. 1a, enable a variety of new operating regimes for a system of two coupled gyro-devices. First, the waveguide T-junction at the second polarizing beam splitter must be replaced by a crossover, and second, the normal miter bend must be replaced by a second polarizing miter bend, identical in construction to the existing polarizing miter bend. An extended feedback system, still operated as a passive mode locked pulsed oscillator is shown in Fig. 1b. Starting from the output of the amplifier, the output signal of the passive mode locked pulsed oscillator at the waveguide port 1 is given by

$$e_{\mathrm{out}}^{\mathrm{p1}}(e_{\mathrm{out}}^{\mathrm{dev1}}) = S_{\mathrm{T}}^{1}\ P_{\Theta}^{1}\ P_{0^\circ}^{2}\ S_{\mathrm{R}}^{2}\ D^{2}\ S_{\mathrm{T}}^{2}\ S_{\mathrm{T}}^{1}\ e_{\mathrm{out}}^{\mathrm{dev1}} \tag{11}$$

and the back-coupled signal reads as

$$e_{\mathrm{in}}^{\mathrm{dev1}}(e_{\mathrm{out}}^{\mathrm{dev1}}) = S_{\mathrm{R}}^{1}\ P_{\Theta}^{1}\ P_{0^\circ}^{2}\ S_{\mathrm{R}}^{2}\ D^{2}\ S_{\mathrm{T}}^{2}\ S_{\mathrm{T}}^{1}\ e_{\mathrm{out}}^{\mathrm{dev1}}. \tag{12}$$

As with conventional Kerr lasers, the passive mode locked pulsed oscillator can be operated in both soft and hard excitation. For the passive mode locked pulsed oscillator in the millimeter frequency range considered so far, only operation in soft excitation is planned. But as shown in [10], the highest pulse-to-pulse reproducibility is achieved in the hard excitation regime. Thanks to the extended feedback system, operation with hard excitation would be possible in principle (see Fig. 1b). For the operation in hard excitation, at the startup of the oscillator, an initial pulse is injected through the second waveguide port. The initial pulse must be horizontally polarized (e_{x}) so that it is transmitted by the polarization splitter 2. The polarizing miter bend 2 is still adjusted at $\Theta = 0^\circ$ so that the incident wave does not change its polarization at the polarizing miter bend 2. However, it is not possible to feed the complete power of an excitation signal into the oscillator. While in the soft excitation regime the polarizing miter bend 1 only determines the fraction $K_{\Theta}^{\mathrm{out}}$ of the oscillating signal which is decoupled from the oscillator, in the hard excitation it also determines the fraction K_{Θ}^{in} of the excitation signal that could be coupled into the oscillator. Thus, the following relation holds:

$$K_{\Theta}^{\mathrm{out}} = 1 - K_{\Theta}^{\mathrm{in}} \tag{13}$$

with

$$K_{\Theta}^{\mathrm{in}}(e_{\mathrm{in}}^{\mathrm{p2}}) = ||S_{\mathrm{R}}^{1}\ P_{\Theta}^{1}\ P_{0^\circ}^{2}\ S_{\mathrm{T}}^{2}\ e_{\mathrm{in}}^{\mathrm{p2}}||^{2}\,. \tag{14}$$

Since, up to now, in the sub-THz frequency range, only semiconductor amplifiers with very low power are available, it is unclear whether a realistic start-up scenario for a passive mode locked pulsed oscillator in hard excitation could be found. This question will be clarified in a future work.

IV. Two-Stage Amplifier

In addition to the original use as a pulsed oscillator, the operation as a two-stage amplifier is possible with the proposed modifications of the feedback system (see Fig. 2). On the one hand, the amplifier can still be combined with the non-linear absorber, which can be used either as a pulse compressor or to reduce low power noise. On the other hand, device 2 can easily be operated as an amplifier instead of an absorber. This would result in a two-stage high-power amplifier, similar to the systems proposed in [15], but with the considerable advantage of being able to inject the input signal via an overmoded waveguide. For sub-THz frequencies

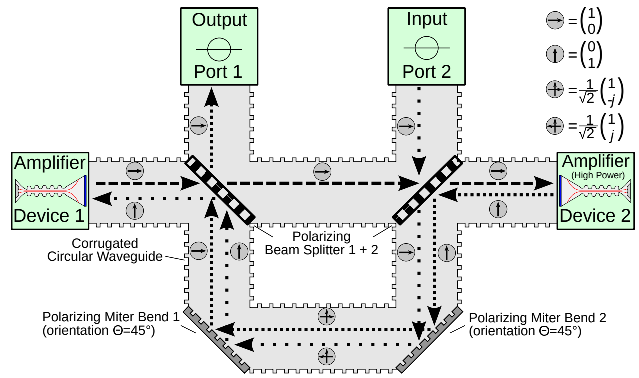

Fig. 2. Two coupled gyro-devices with single input-output window, operated as a two-stage amplifier system to achieve a higher gain and output power.

the manufacturing of a classical input coupler (e.g. [19]) with typical dimensions below the vacuum wavelength, can be a challenging problem. This is eliminated by the input through overmoded waveguides. Furthermore, even a highly optimized classical input coupler offers only a transmission in the order of -1 dB [19]. In addition, a second broadband vacuum window is necessary for the input coupler which leads to additional losses (transmission on the order of -0.5 dB [23]). Feeding via overmoded waveguides has the potential of achieving lower losses. Since existing high-power gyrotron amplifiers for sub-THz frequencies are mostly limited by the available power of the input signal (e.g. [24]), a reduction of the input losses could directly lead to a higher output power.

For the operation as amplifier system, the additional polarizing miter bend becomes necessary. As for the passive mode locked pulsed oscillator in the hard excitation, the low power input signal is injected through the second waveguide port. The Jones calculus for the input path is:

$$e_{\mathrm{in}}^{\mathrm{dev1}}(e_{\mathrm{in}}^{\mathrm{p2}}) = S_{\mathrm{R}}^{1}\ P_{45^\circ}^{1}\ P_{45^\circ}^{2}\ S_{\mathrm{T}}^{2}\ e_{\mathrm{in}}^{\mathrm{p2}}\,. \tag{15}$$

From (15) we can see that the input signal must be horizontally polarized ($e_{\mathrm{in}}^{\mathrm{p2}} = e_{\mathrm{x}}$) so that the wave is transmitted by the polarizing beam splitter 2. The two polarizing miter bends must be oriented in such a way that the polarization of an incident linearly polarized wave is rotated by 90° after the transmission through both polarizing miter bends. Then the wave is reflected at the first polarizing beam splitter. With this setup, a horizontally polarized input signal is completely fed into the amplifier (device 1 in Fig. 2). The output of device 1 is transmitted through both polarization splitters in the usual way and is fed into the second helical gyro-TWT. For device 2 there are two possible operation modes: It can still be operated as a saturable absorber or, since the saturable absorber is just a detuned amplifier [10], it can easily be operated as a second amplifier. Regardless of the operation regime, its output signal is first reflected by the polarizing beam splitter, after which the polarization is rotated 90° by the two polarizing miter bends. Therefore, the signal is now transmitted by the first polarization splitter. The Jones calculus for the complete signal path is:

$$e_{\mathrm{out}}^{\mathrm{p1}}(e_{\mathrm{in}}^{\mathrm{p2}}) = S_{\mathrm{T}}^{1}\,P_{45^\circ}^{1}\,P_{45^\circ}^{2}\,S_{\mathrm{R}}^{2}\,D^{2}\,S_{\mathrm{T}}^{2}\,S_{\mathrm{T}}^{1}\,D^{1}\,e_{\mathrm{in}}^{\mathrm{dev1}}(e_{\mathrm{in}}^{\mathrm{p2}})\,. \tag{16}$$

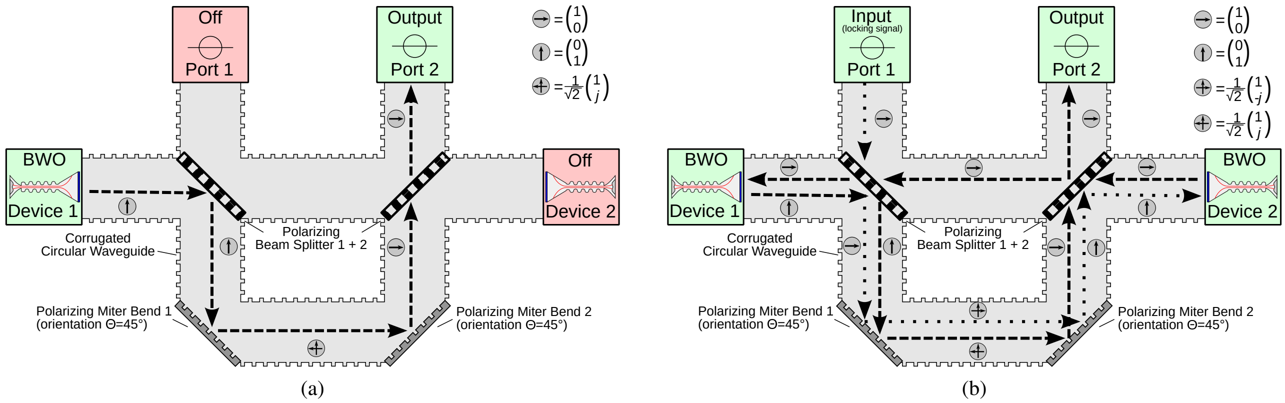

Fig. 3. Two coupled gyro-devices operated as a BWO to deliver a tunable high power CW signal. (a) Only device 1 is operated as a free running BWO. In a similar manner, device 2 can be operated as a free running BWO. (b) Both devices operated as coupled BWOs. An additional locking signal could be applied to run the BWOs as phase locked oscillators.

V. BACKWARD WAVE OSCILLATOR

In state-of-the-art DNP-NMR experiments, high power CW sources, namely gyrotrons [25], [4], are used. Gyrotrons are oscillators and therefore they provide the high power CW signals without the requirement of an external input source. It would be advantageous if our system of coupled gyro-TWTs could be also operated as a frequency tunable CW oscillator for CW DNP-NMR applications. For this purpose we can use the fact that a helical gyro-TWT can easily be operated as an electronically tunable gyro-BWO [20], [26]. Due to the helical symmetry of the waveguide and the use of the axis-encircling, large-orbit electron beam, the excitation of a wave with a negative group velocity (with respect to the motion of the electron beam) is possible. For the gyro-BWO configuration, the devices are operated with a static B-field of the inverse direction compared to the amplifier configuration [20]. The oscillation frequency can be varied smoothly by adjusting the magnitude of the B-field. Compared with the gyro-BWO based on a smooth waveguide, the use of a helical waveguide allows a broader frequency tuning band, on the order of the bandwidth of the amplifier operation [27]. Therefore, a CW source based on a helical gyro-BWO could be advantageous for DNP-NMR experiments compared to a gyrotron with a tunable frequency of only several hundred MHz [28].

The configuration for BWO operation of device 1 is shown in Fig. 3a. Special attention should be paid to the fact that the input and output ports have been swapped, compared to the amplifier and pulsed oscillator configurations. This results from the fact that in the BWO operation the generated output mode of a helical gyro-TWT is cross polarized to the usual output mode in the amplifier operation. Therefore, the Jones calculus for a BWO operation of device 1 is:

$$e_{\mathrm{out}}^{\mathrm{p2}}(e_{\mathrm{out}}^{\mathrm{dev1}}) = S_{\mathrm{T}}^{2}\ P_{45^\circ}^{2}\ P_{45^\circ}^{1}\ S_{\mathrm{R}}^{1}\ e_{\mathrm{out}}^{\mathrm{dev1}}. \tag{17}$$

In the configuration shown in Fig. 3a, device 1 is operated as gyro-BWO. However, it is also possible to operate device 2 as a BWO. In this case device 1 remains switched off. Since device 2 is designed in such a way that input and output signals are cross-polarized to the input/output signals of device 1, the generated RF power is first transmitted by the two polarization splitters and coupled into device 1. Also the electron beam is switched off, the polarization of the wave in device 1 is rotated by 90° and the wave leaves the system via port 2 as shown in Fig. 3a. Therefore, the Jones calculus for the operation of device 2 as a BWO is given by:

$$e_{\mathrm{out}}^{\mathrm{p2}}(e_{\mathrm{out}}^{\mathrm{dev2}}) = S_{\mathrm{T}}^{2}\ P_{45^\circ}^{2}\ P_{45^\circ}^{1}\ S_{\mathrm{R}}^{1}\ D^{1}\ S_{\mathrm{T}}^{1}\ S_{\mathrm{T}}^{2}\ e_{\mathrm{out}}^{\mathrm{dev2}}. \tag{18}$$

Aside from the operation as a simple BWO, our system offers the possibility to feed a locking signal. This makes it possible to operate a phase-locked oscillator instead of a free-running oscillator [29], [30], [31]. Due to the high frequency stability requirements of many spectroscopy applications, this could be an important feature. In Fig. 3b, it is shown how a locking signal is fed into the BWOs. Regardless of which device is used as a BWO, it is possible to lock it with the locking signal.

The interested reader will have noticed that in Fig. 3b both devices are active and operated as BWOs. This is a special case, where both components are operated as BWOs at the same time. Due to a lack of powerful RF sources in the sub-THz range, the generation of a locking signal could be challenging. Therefore, we propose to operate device 2 as a BWO-based amplifier [32], to pre-amplify the locking signal so that device 1 can be operated as an injection-locked BWO. It must be underlined that it is not possible to use device 2 as a normal amplifier operating with a forward traveling mode, because of the inverted requirements for the polarization of the input/locking signal in the BWO operation. The Jones calculus for the complete signal path from the input of the locking signal until the output is given by:

$$e_{\mathrm{in}}^{\mathrm{dev2}}(e_{\mathrm{in}}^{\mathrm{p1}}) = S_{\mathrm{R}}^{2}\ P_{45^\circ}^{2}\ P_{45^\circ}^{1}\ S_{\mathrm{T}}^{1}\ e_{\mathrm{in}}^{\mathrm{p1}}\,, \tag{19}$$

$$e_{\mathrm{in}}^{\mathrm{dev1}}(e_{\mathrm{in}}^{\mathrm{p1}}) = S_{\mathrm{T}}^{1}\ S_{\mathrm{T}}^{2}\ D^{2}\ e_{\mathrm{in}}^{\mathrm{dev2}}(e_{\mathrm{in}}^{\mathrm{p1}})\,, \tag{20}$$

$$e_{\mathrm{out}}^{\mathrm{p2}}(e_{\mathrm{in}}^{\mathrm{p1}}) = S_{\mathrm{T}}^{2}\ P_{45^\circ}^{2}\ P_{45^\circ}^{1}\ S_{\mathrm{R}}^{1}\ D^{1}\ e_{\mathrm{in}}^{\mathrm{dev1}}(e_{\mathrm{in}}^{\mathrm{p1}})\,. \tag{21}$$

Last but not least, it should be mentioned that an operation of both devices as BWOs without an external locking signal could also be of interest [33]. In such a configuration, the output of device 2 is always fed completely into device 1, while an arbitrary fraction of the first device's output can be coupled back into device 2. This fraction can be easily controlled via the adjustable polarizing miter bend 2 (P_Θ^2). Such a system of coupled, carefully adjusted oscillators could probably offer higher frequency stability compared to a free running BWO without the requirement of an external locking signal.

VI. Conclusion

A flexible feedback system based on state-of-the-art waveguide components for the coupling of two helical gyro-TWTs is presented. The feedback system enables a wide range of possible operation regimes of two coupled helical gyro-TWTs. Besides the original purpose as a passive mode locked pulsed oscillator, the developed feedback system allows the realization of a two-stage amplifier and the possibility of operating as a frequency tunable, phase-locked BWO. These new possibilities could make such a system of coupled helical gyro-TWTs a very interesting, new high-power RF source for spectroscopy applications. It is still an open question, whether all the described operation modes can be realized with the same helical gyro-TWTs. Therefore, in a next step, a simulation model should be developed for the simulation of two coupled helical gyro-TWTs. The introduced description of the different signal paths in the feedback system via Jones calculus will permit an easy inclusion of the feedback system into a simulation model of coupled devices. Of particular interest here is the effect of non-ideal components in the feedback system. For example, the output signal of a real helical gyro-TWT with a single input/output window is not perfectly linearly polarized but contains a small part of the cross polarization (see [34]). As a result, the two gyro-TWTs are coupled via both signal paths. The same effect occurs with non-ideal polarizing beam splitters. By simply replacing the Jones matrices of the ideal components with Jones matrices for the non-ideal components, this effect can be estimated and incorporated into the boundary conditions of a simulation.

The objectives for future research consist in evaluating the possibility of operating the passive mode locked pulsed oscillator in hard excitation, the possibilities offered by the operation of coupled BWOs and the impact of non-ideal components.

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