New Type of Pulsed High-Power sub-THz Source Based on Helical-Type Gyro-TWTs

A. Marek[1], L. Feuerstein[1], S. Illy[1], M. Thumm[1,2], C. Wu[1] and J. Jelonnek[1,2]
[1]IHM, [2]IHE, Karlsruhe Institute of Technology (KIT), Kaiserstr. 12, 76131 Karlsruhe, Germany

A new type of microwave source for the generation of high-power ultra-short coherent pulses at 263 GHz is presented. The source is based on the idea of passive mode-locking of two microwave tubes as it was first proposed in [1]. While passive mode-locking is well-established in laser physics, this idea is new for microwave electron tubes and was first experimentally demonstrated in [2]. As electron tubes, two helical gyro-TWTs are used that are coupled by a quasi-optical feedback system. The configuration proposed in this publication extends the original setup to enable the operation of the passive mode-locked oscillator in the hard excitation regime and to allow in addition the operation of the coupled helical gyro-TWTs as two-stage amplifier and as frequency-tunable, phase-locked backward wave oscillators. The performed simulation show an expected output power above 500 W and pulse widths below 0.1 ns for an operation as passive mode-locked oscillator.

I. Introduction

Systems which are capable to generate ultra-short radio frequency (RF) pulses coherently, and, at the same time, achieve a reasonable output power of more than a few Watts in the sub-THz frequency range are gaining fundamental interest in the research community. Those RF systems might become the key components of future THz diagnostic systems. Examples are novel pulsed Dynamic Nuclear Polarization (DNP)-Nuclear Magnetic Resonance (NMR) spectroscopy methods [3] and systems for the diagnostic of dense plasmas. In all cases, novel powerful RF sources of ultra-short coherent pulses in the millimeter and sub-millimeter frequency range would enable the scientific community to develop new instruments with improvements in sensitivity, resolution and data acquisition speed.

In this report, a new sub-THz source for the generation of trains of coherent high-power ultra-short pulses at 263 GHz is presented. The investigated frequency of 263 GHz is an established figure for continuous wave (CW) DNP-NMR (400 MHz) applications and, therefore, the investigated source could lead to the development of novel spectroscopy methods such as time-domain DNP-NMR [3].

The new pulsed source uses the mechanism of passive mode-locking of two helical gyro-TWTs [4] as it was first proposed in [1] and experimentally shown in [2] for the Ka-band. In a typical passive mode-locked laser, pulses are favored over CW signals by reducing the ohmic cavity losses for high intensities. At microwave frequencies, a similar behavior can be realized in a feedback loop of two electron tubes, one operated as amplifier, the other one as nonlinear saturable absorber [1]. The nonlinear absorber strongly attenuates low-power signals, while it is almost transparent at high-power levels. Therefore, it narrows the pulses and broadens the frequency spectrum. At every round trip, a fraction of the oscillating pulses is decoupled from the feedback loop. In this way, a train of coherent high-power ultra-short pulses is generated.

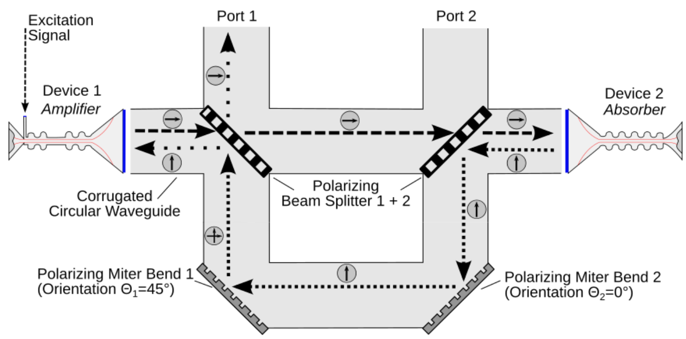

Fig. 1: Passive mode-locked oscillator consisting of an amplifier and a non-linear saturable absorber coupled in a feedback loop. The encircled arrows symbolize the polarization of the $HE_{1,1}$ mode.

The new pulsed source presented here is an extended version of the originally proposed setup in [1,2] with the aim to increase the possible fields of application. First of all, the usage of a high-gain helical gyro-TWT [5] instead of an ordinary helical gyro-TWT as amplifier will enable the operation of the passive mode-locked oscillator in the hard excitation regime, while the original proposal is limited to an operation in the soft excitation regime. Further benefits are provided by a novel feedback system [6]. The feedback system enables alternative operation regimes for the two coupled helical gyro-TWTs. Besides the original purpose as a mode-locked oscillator, the developed feedback system allows the realization of a two-stage amplifier and the possibility of operating the devices as frequency-tunable, phase-locked backward wave oscillators (BWO).

In combination, these extensions make such a system of coupled helical gyro-TWTs a promising new microwave source for future time-domain spectroscopy applications.

II. Feedback System

The feedback system has to fulfill several requirements to guarantee an optimal performance of the passive mode-locked oscillator, such as a high bandwidth, a low dispersion, low ohmic losses and a variable decoupling coefficient. In addition, the decoupling of the output signal should take place only at the signal path from the absorber to the amplifier. This is important because a decoupling of a fraction of the signal before the saturable absorber would decrease the saturation effect and, therefore, increase the total losses in the system.

In [6], a feedback system consisting of overmoded

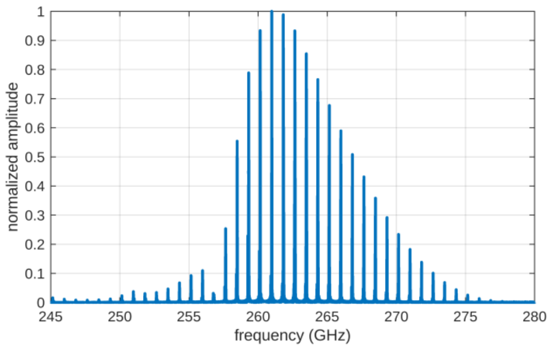

Fig. 2: Spectrum of the generated output signal.

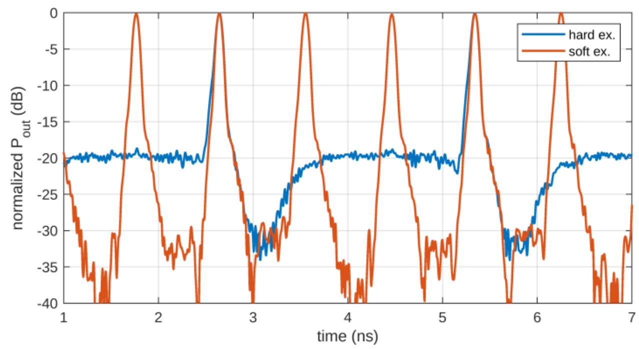

Fig. 3: Normalized output signals in logarithmic scaling of the passive mode-locked oscillator in the hard (blue) and soft (orange) excitation regimes.

cylindrical corrugated waveguides and fulfilling all these requirements is presented. The feedback system utilizes the polarization characteristics of the utilized single-window helical gyro-TWTs [7]. In these tubes, the same vacuum window is used for the output of the amplified signal and for the input signal. Since the input and output waves are cross-polarized to each other, a polarization splitter can be used to separate the signals [8].

In Fig. 1, the feedback system and the signal paths for an operation as passive mode-locked oscillator are shown. The output signals of the vacuum electron tubes are directly fed into the overmoded corrugated cylindrical waveguides. In the waveguides, the wave propagates as a linearly polarized $HE_{1,1}$ mode. 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 polarizing beam splitters, wire-grid splitters are used.

For the decoupling of a fraction of the signal oscillating in the feedback loop, the polarization splitter is used in combination with a tunable polarizer (polarizing miter bend 1 in Fig. 1). The polarizer creates an elliptically polarized $HE_{1,1}$ mode from the incident linearly polarized one. The elliptically polarized $HE_{1,1}$ mode is equivalent to a superposition of two orthogonal linearly polarized modes with a phase shift. Consequently, the polarizing beam splitter separates the linearly polarized modes and a fraction of the signal can be decoupled from the feedback loop, depending on the orientation of the polarizing phase grid in miter bend 1 [9].

As described in [6], a special feature of the feedback system is the possibility to additionally operate the coupled helical gyro-TWTs as a two-stage amplifier and as frequency-tunable, phase-locked BWOs. However, in the passive mode-locked oscillator configuration it is not possible to efficiently couple an external excitation signal into the feedback system (see [6]). A high-power (>100 W) sub-THz source would be required as excitation source for an operation in the hard excitation regime. In the absence of such a powerful sub-THz source (only a third vacuum electron tube could provide the required power), operation in the hard excitation regime is not possible and the oscillator must be operated in the soft excitation regime.

A solution to this problem is shown in Fig. 1. If the amplifier is realized as a high-gain helical gyro-TWT, it is possible to feed an external excitation signal directly into the tube via an additional input coupler. The high-gain helical gyro-TWT consists of two helically corrugated waveguide sections separated by a sub-cutoff drift region. The input signal is fed into the first helical section and modulates the electron beam. After the drift section, the pre-bunched beam induces a high-power wave in the second helical section. While an ordinary helical gyro-TWT in the single-window configuration cannot have an external input port, this is possible for the high-gain helical gyro-TWT since the input port is well separated from the high-power region by the sub-cutoff drift region. Therefore, a passive mode-locked oscillator consisting of a high-gain helical gyro-TWT, a second ordinary gyro-TWT operated as nonlinear absorber (see [10]) and the feedback system proposed in [6] offers the possibility for realizing a passive mode-locked oscillator at sub-THz frequencies that allows an operation in the hard excitation regime. Furthermore, the alternative operation modes of the coupled gyro-TWTs will also profit from the additional input port of the high-gain helical gyro-TWT.

III. Simulation Results

For the simulations of the coupled helical gyro-TWTs, a new self-consistent time-domain model is used [11]. The new model is a hybrid between classical methods based on slowly varying variables and 3D full-wave PIC solvers. It combines the classical theory of coupled circular waveguide modes for the description of the operating electromagnetic eigenmode in the helical interaction space with a 3D PIC representation of the electron beam. This allows the simulation of the beam-wave interaction over a broad bandwidth and at arbitrary harmonics of the cyclotron frequency, while the computing time is significantly reduced compared to full-wave 3D PIC codes [11].

In the following, simulation results of a passive mode-locked oscillator consisting of a high-gain helical gyro-TWT operated as amplifier and a second ordinary helical gyro-TWT operated as nonlinear saturable absorber are discussed.

In Fig. 2, the spectrum of the simulated output signal is shown. The envelope of the spectrum corresponds to the spectrum of a single pulse. The distance between the discrete frequency lines corresponds to the pulse repetition frequency

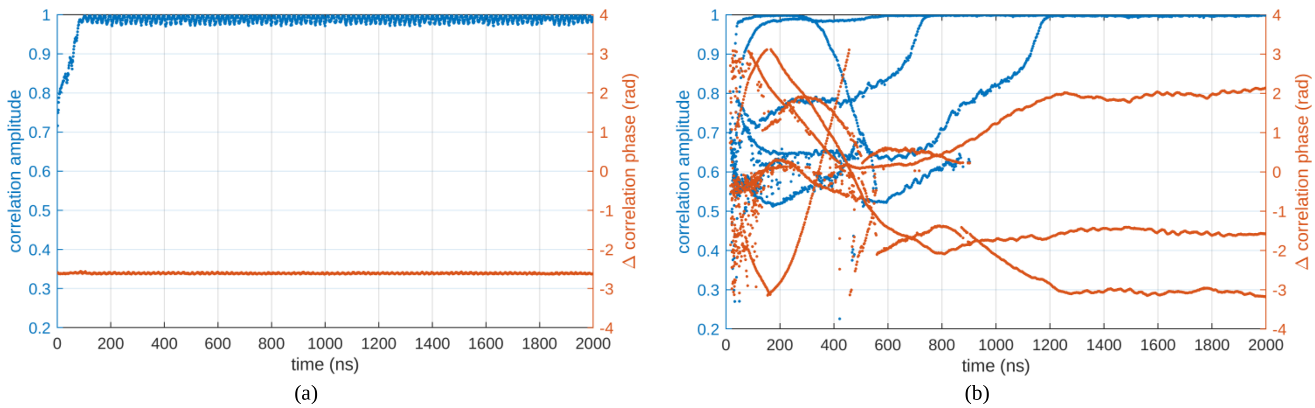

Fig. 4. Amplitude of the cross-correlation coefficient and the pulse to pulse change of the phase offset for an operation in the hard excitation regime (a) and the soft excitation regime (b).

(PRF) of 0.9 GHz. The spectrum, and therefore the minimal pulse length, is limited by the bandwidth of the amplifier.

In Fig. 3, the time-domain output signal is shown for an operation in the hard and the soft excitation regimes. The simulations show one of the advantages of the operation in the hard excitation regime. While in the soft excitation regime pulses are always generated with the maximal repetition frequency, which is limited by the latency of the amplifier, the repetition frequency can be controlled in the hard excitation regime. In the hard excitation regime, the repetition frequency is determined by the length of the feedback system (round-trip time of a single pulse in the feedback system) and the number of pulses oscillating in the feedback system. Because the high-gain gyro-TWT offers a higher gain than ordinary gyro-TWTs, even an input signal of 10-100 mW is sufficient as excitation signal. This is of particular importance for sub-THz frequencies, where even the generation of 100 mW is a challenging problem.

Future pulsed spectroscopy applications will require pulses with a high temporal coherence. For the investigation of the coherency of the generated pulses, a continuous cross-correlation function was used in [12]. However, such a continuous cross-correlation function is not optimal for the investigation of a pulsed signal because it results in a pulsed correlation coefficient that complicates the interpretation. Therefore, the usage of a discrete cross-correlation function

$$C_{m,n} = \frac{\int_{T_m-\tau_p}^{T_m+\tau_p} A(t)A^*\big(t-(T_m-T_n)\big)\mathrm{d}t}{\sqrt{\int_{T_m-\tau_p}^{T_m+\tau_p}|A(t)|^2\,\mathrm{d}t\cdot\int_{T_n-\tau_p}^{T_n+\tau_p}|A(t)|^2\,\mathrm{d}t}} \tag{1}$$

is proposed in this work. It defines a single cross-correlation value for two pulses m and n with a pulse length of τ_p, located at T_m and T_n. Here, $A(t)$ is the simulated complex output signal of the passive mode-locked oscillator.

In general, $C_{m,n}$ is a complex number. Its amplitude corresponds to the correlation of the transient distribution of the two pulses m and n, while the phase of $C_{m,n}$ corresponds to the relative phase between the two pulses. For an evaluation of the coherence, the cross-correlation function $C_{m,n}$ between an arbitrary reference pulse m and all other pulses n in the output signal is evaluated. In addition, the phase change from pulse to pulse

$$\Delta C_{m,n} = \arg\big(C_{m,n-1}\big) - \arg\big(C_{m,n}\big) \tag{2}$$

is evaluated. The results for an operation in the hard and the soft excitation regime are shown in Fig. 4.

For the hard excitation case (Fig. 4a), the absolute value of the cross-correlation coefficient remains above 0.97 after the oscillator has reached a quasi-steady state. This proves a high reproducibility of the generated pulses. Also $\Delta C_{m,n}$ is almost constant in the region of a quasi-steady state operation. Therefore, the phase of the pulses changes by a constant value from pulse to pulse and the generated signal is equivalent to a single pulse that is repeated continuously and that has its phase shifted by a constant value with each repetition.

In Fig. 4b, the same quantities are shown for the case of an operation in the soft excitation regime. After the oscillator has reached a quasi-steady state ($t > 1300$ ns), the amplitude of the cross-correlation coefficient indicates again a good reproducibility of the generated pulses. However, it can be seen that the final output signal is created by three different pulses that have been formed during the start-up process. This origin of the total output signal from three different pulses is also reflected in the pulse to pulse change of the phase offset $\Delta C_{m,n}$. The formation of the three discrete lines in $\Delta C_{m,n}$ implies that the output signal consists of three pulses with similar pulse shapes and phase distributions but with a different phase offset. The reason for this can be found in the start-up scenario. In the soft excitation, the passive mode-locking regime is created from noise and, therefore, the initial phases of all signals that contribute to the quasi steady state solution are arbitrary and not correlated with each other.

In the existing literature about the coherence of the signals generated from passive mode-locked oscillators at microwave frequencies, the investigation of phase offsets was neglected until now. Although in [12-14] the coherence of the generated pulses was already investigated by a continuous version of the cross-correlation function (1), all considerations were limited to the amplitude of the cross-correlation coefficient while its phase was neglected. As a consequence, the present work concludes with a different result than previous investigations: While the shape of the generated pulses from passive mode-locked oscillators is independent of the excitation regime, the phase is sensitive to the excitation regime. Only in the hard excitation regime the maximal coherency and reproducibility can be reached. In the soft excitation regime, an arbitrary phase offset between the pulses occurs. This offset is unpredictable and will change for every start-up of the oscillator because the pulses are created from noise. In the shown case with a relatively short delay time in the feedback system of 2 ns, only three different phase offsets are observed. Nevertheless, the number of contributing pulses and consequently phase offsets will increase for longer delay times.

IV. Conclusion

For the first time, it was shown that an excitation of the passive mode-locking in the soft excitation regime will lead to arbitrary phase offsets in the generated pulses. To maintain the phase coherency, the passive mode-locked oscillator should be operated in the hard excitation regime.

Because of a lack of the required high-power sub-THz sources an operation in the hard excitation was unrealistic up-to now. Here, for the first time, a solution for the operation in the hard excitation regime was proposed and verified by simulations: The usage of a high-gain helical gyro-TWT will enable the hard excitation of passive mode-locking with input signals of only tens of milliwatt.

Furthermore, the proposed hard excitation operation could enable the development of new operation modes, such as an operation with specific pulse sequences. Such an operation could be especially of interest for novel pulsed DNP-NMR spectroscopy methods where well-defined pulse sequences are required.

Finally, the feedback system allows additional operation regimes of the coupled helical gyro-TWTs, such as a two-stage amplifier or frequency-tunable, phase-locked BWOs.

References

[1] N. Ginzburg, G. Denisov, M. Vilkov, I. Zotova, and A. Sergeev, “Generation of a periodic sequence of powerful ultrashort pulses in a traveling wave tube with bleachable absorber in the feedback loop,” *Tech. Phys. Lett.*, vol. 41, Art. no. 9, Sep. 2015, doi: 10.1134/S1063785015090047.

[2] N. Ginzburg, S. Samsonov, G. Denisov, M. Vilkov, I. Zotova, A. Bogdashov, I. Gachev, A. Sergeev, R. Rozental, “Ka-band 100-kW subnanosecond pulse generator mode-locked by a nonlinear cyclotron resonance absorber,” *Phys. Rev. Applied*, vol. 16, no. 5, p. 54045, Nov. 2021, doi: 10.1103/PhysRevApplied.16.054045.

[3] K. Tan, C. Yang, R. Weber, G. Mathies, and R. Griffin, “Time-optimized pulsed dynamic nuclear polarization,” *Sci. Adv.*, vol. 5, Art. no. 1, 2019, doi: 10.1126/sciadv.aav6909.

[4] G. Denisov, V. Bratman, A. Phelps, and S. Samsonov, “Gyro-TWT with a helical operating waveguide: New possibilities to enhance efficiency and frequency bandwidth,” *IEEE Trans. Plasma Sci.*, vol. 26, Art. no. 3, Jun. 1998, doi: 10.1109/27.700785.

[5] S. Samsonov, G. Denisov, I. Gachev, and A. Bogdashov, “CW operation of a W-band high-gain helical-waveguide gyrotron traveling-wave tube,” *IEEE Electron Device Lett.*, vol. 41, Art. no. 5, 2020, doi: 10.1109/LED.2020.2980572.

[6] A. Marek, K. Avramidis, N. Ginzburg, S. Illy, J. Jelonnek, J. Jin, M. Thumm, “Extended feedback system for coupled sub-THz gyro-devices to provide new regimes of operation,” *IEEE Trans. Electron Devices*, vol. 67, Art. no. 12, 2020, doi: 10.1109/TED.2020.3028531.

[7] G. Denisov, A. Bogdashov, I. Gachev, S. Mishakin, and S. Samsonov, “New radiation input/output systems for millimeter-wave gyrotron traveling-wave tubes,” *Radiophys. Quantum Electron.*, vol. 58, Art. no. 10, 2016, doi: 10.1007/s11141-016-9649-y.

[8] S. Samsonov, V. Belousov, A. Bogdashov, G. Denisov, S. Mishakin, and D. Sobolev, “Quasi-Optical Orthomode Splitters for Input-Output of a Powerful W-Band Gyro-TWT,” *IEEE Trans. Electron Devices*, vol. 65, Art. no. 10, Oct. 2018, doi: 10.1109/TED.2018.2866030.

[9] A. Marek, K. Avramidis, N. Ginzburg, D. Haas, S. Illy, J. Jin, M. Thumm, J. Jelonnek, “Simple feedback system for passive mode locked gyro-devices at 263 GHz,” in *2020 German Microwave Conference (GeMiC)*, 2020, pp. 56–59, doi: 10.5445/IR/1000119937

[10] N. Ginzburg, G. Denisov, M. Vilkov, A. Sergeev, I. Zotova, S. Samsonov, S. Mishakin, “Generation of trains of ultrashort microwave pulses by two coupled helical gyro-TWTs operating in regimes of amplification and nonlinear absorption,” *Phys. Plasmas*, vol. 24, Art. no. 2, 2017, doi: 10.1063/1.4975084.

[11] A. Marek, K.A. Avramidis, L. Feuerstein, S. Illy, M. Thumm, C. Wu, and J. Jelonnek, “Time-domain simulation of helical gyro-TWTs with coupled modes method and 3-D particle beam,” *IEEE Trans. Electron Devices*, pp. 1-7, 2022, doi: 10.1109/TED.2022.3182292.

[12] N. Ginzburg, E. Kocharovskaya, M. Vilkov, A. Sergeev, and S. Fil’chenkov, “Dissipative solitons in electron oscillators with a saturable absorber,” *Phys. Plasmas*, vol. 25, Art. no. 9, 2018, doi: 10.1063/1.5046651.

[13] N. Ginzburg, E. Abubakirov, M. Vilkov, I. Zotova, and A. Sergeev, “Generation of a Periodic Sequence of High-Power Ultrashort Pulses in a Chain of Coupled Backward-Wave and Traveling-Wave Tubes Operating in the Regimes of Amplification and Nonlinear Kompfner Suppression,” *Technical Physics*, vol. 63, Art. no. 8, 2018, doi: 10.1134/S1063784218080078.

[14] N. Ginzburg, G. Denisov, M. Vilkov, A. Sergeev, S. Samsonov, A. Malkin, I. Zotova, “Nonlinear Cyclotron Resonance Absorber for a Microwave Subnanosecond Pulse Generator Powered by a Helical-Waveguide Gyrotron Traveling-Wave Tube,” *Phys. Rev. Applied*, vol. 13, no. 4, p. 44033, 2020-04, doi: 10.1103/PhysRevApplied.13.044033.