New Type of sub-THz Frequency-Doubling Gyro-TWT with Helically Corrugated Circuit

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***Abstract*— A novel type of frequency doubling gyrotron traveling wave amplifier (FD-GTWT) for applications that require high-power microwave in the sub-THz frequency range is presented. The proposed FD-GTWT delivers high power and high gain over a broad bandwidth and simultaneously doubling the frequency of the input signal. Simulations of a first 263 GHz FD-GTWT design are presented, which show for a 10 mW driving signal at 131.5 GHz an RF output power of 250 W at 263 GHz and a gain of >40 dB over a bandwidth of 17.5 GHz. The basis of the FD-GTWT are two interaction circuits separated by a long drift section. In the first circuit, the electron beam is pre-bunched at the fundamental cyclotron harmonic. In the second one, high-power RF is induced by the pre-bunched electron beam at the 2nd cyclotron harmonic. Both sections consist of helically corrugated waveguides that efficiently suppress parasitic interactions and allow broad bandwidth.**

***Index Terms*— Gyro-TWT, helically corrugated waveguide, sub-THz, frequency doubling amplifier.**

I. Introduction

BROADBAND high-power amplifiers at sub-THz frequencies are of considerable interest for novel spectroscopy and diagnostic applications. For example, future time-domain dynamic nuclear polarization (DNP) nuclear magnetic resonance (NMR) spectroscopy methods will require broadband high-power microwave sources at frequencies of 250 GHz and above [1], [2]. While first prototypes have been successfully demonstrated [3], their development is still part of current research [4], [5]. A promising candidate are gyrotron traveling wave tubes with a helically corrugated interaction space (H-GTWTs) [6]–[9]. H-GTWTs can provide high power and broad bandwidth at the same time. Furthermore, in H-GTWTs with three-fold helically corrugated waveguide (HCW) circuit, the electron beam interacts at the 2nd cyclotron harmonic with the eigenwave of the HCW which reduces the required magnetic field strength by a factor of two. This is of particular interest at sub-THz frequencies above 250 GHz where the magnetic field strength would exceed 10 T for a gyro-device operated at the fundamental cyclotron harmonic. However, the saturated gain of H-GTWTs usually does not exceed 30 dB because of parasitic reflection-induced oscillations [10]–[12].

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A solution for this problem was proposed in [11]: sectioning the interaction region into two short HCW parts, separated by a long below-cutoff drift region, allows higher net gain. The low-power RF input signal is fed into the first HCW and causes a small velocity modulation in the electron beam. In the long drift section, ballistic bunching of the velocity-modulated electron beam occurs. The bunched electrons finally induce a high-power RF signal in the second HCW section. The shortness of the individual HCW sections ensures the prevention of parasitic reflection-induced oscillations, and a high saturated gain of >40 dB becomes possible.

A high-gain H-GTWT allows the usage of low-power drivers (10-100 mW), which are readily available at frequencies up to the W-band. However, generating 10 mW at frequencies of 250 GHz and above is still a challenging problem.

In this letter, a modification of the high-gain H-GTWT concept is proposed, which solves this problem. For this, the 2nd harmonic operation of H-GTWTs is utilized. While in a high-gain H-GTWT the bunching and amplification process (in the first and second HCW circuits) both occur at the 2nd harmonic, we propose the usage of an electron-wave interaction at the fundamental of the cyclotron harmonic for the bunching process. As a result, an input signal at the half frequency of the generated output signal is sufficient. This allows the use of readily available D-band solid-state amplifiers (e.g. [13]) as driving RF sources for the generation of high-power RF signals at frequencies from 220-340 GHz.

The main goal of this letter is the presentation of the novel idea of a frequency doubling gyrotron traveling wave amplifier (FD-GTWT) and the proof of the proposed concept by full-wave 3D PIC simulations. Therefore, a basic design of the interaction circuit for a broadband 263 GHz FD-GTWT with a gain of >40 dB over a bandwidth of 17.5 GHz and an output power of up to 250 W is presented.

II. Principle of a Helical FD-GTWT

In a H-GTWT, the beam-wave interaction takes place in a three-fold HCW with an inner surface

$$r(\phi, z) = R + \tilde{r}\cos\left(3\phi - 2\pi z/\tilde{d}\right) , \qquad (1)$$

where R is the mean waveguide radius; $\tilde{r}$ and $\tilde{d}$ are the amplitude and period of the corrugation, respectively. In those HCWs, two counter-rotating modes $\mathrm{TE}_{-1,1}$ and $\mathrm{TE}_{2,1}$ are coupled with each other (see [6], [14] for details). The resulting eigenmode of the HCW allows a resonant interaction with a gyrating electron beam over a broad bandwidth.

In H-GTWTs, it is utilized that the HCW eigenmode has a $\mathrm{TE}_{2,1}$ structure and is therefore able to resonantly interact with an axis encircling electron beam, so-called large orbit beam (LOB), at the 2nd cyclotron harmonic. Since a LOB resonates only with co-rotating TE modes with an azimuthal index equal to the cyclotron harmonic [15], a parasitic interaction at the fundamental harmonic is effectively suppressed.

For a FD-GTWT, this is problematic because the input signal is supposed to interact with the electron beam at the fundamental cyclotron harmonic. However, a simple solution for this problem is possible: If the first HCW section, used for pre-bunching, is shifted relative to the beam guiding center axis, the LOB looses its strong mode selectivity and allows a resonant interaction with the HCW eigenmode at the fundamental cyclotron harmonic.

In Fig. 1, a schematic of this approach is shown. The LOB is created by a cusp-type electron gun [16]–[18]. Through a side-wall input coupler [19], [20] the low power input signal at half the output frequency is coupled into the tube ($f_{\mathrm{in}} = 0.5 f_{\mathrm{out}}$). The HCW bunching section is shifted from the gyration center of the beam by Δy which allows a resonant interaction of the input signal with the electron beam at the fundamental cyclotron harmonic. Since the bunching section is short ($< 10\tilde{d}$), no significant amplification occurs and the driving RF signal can be absorbed by a short lossy dielectric section at the end of the buncher circuit.

The bunching section is followed by the drift section where the ballistic bunching of the modulated electron beam occurs. This mechanism is similar to conventional gyrotron-type klystrons. To prevent the excitation of parasitic oscillations, the drift section should have a radius below $0.3\lambda_{\mathrm{out}}$, such that the fundamental $\mathrm{TE}_{1,1}$ mode is in cut-off. Since the LOB with typical parameters (pitch factor of 1.0-1.5 and kinetic energy of < 60 keV) will have a radius of around $0.1\lambda_{\mathrm{out}}$, there are strict requirements to the quality and alignment of the beam. Therefore, the FD-GTWT should be operated with a low current electron beam (similar to high-gain H-GTWTs).

In the second HCW, the bunched electron beam interacts with the HCW eigenmode at the 2nd cyclotron harmonic and induces a high-power RF signal at the double frequency of the input signal ($f_{\mathrm{out}} = 2 f_{\mathrm{in}}$). Because of the bunched beam, this section can be significantly shorter ($< 25\tilde{d}$) than the HCW in ordinary H-GTWTs ($\approx 40\tilde{d}$). Based on the experimental results for high-gain H-GTWTs [21], it is assumed that this provides a sufficient suppression of reflection-induced oscillations.

Finally, the wave is converted into a linearly polarized hybrid $\mathrm{HE}_{1,1}$ mode which can be decoupled from the device.

III. Sub-THz Helical FD-GTWT

As prove-of-concept, a basic design of the beam-wave interaction circuit for a target output frequency of 263 GHz (typical DNP-NMR frequency) was designed and simulated with the PIC Solver of CST Microwave Studio Suite [22]. The objective of this prove-of-concept design is the demonstration of a frequency-doubling amplification of a 10 mW input signal to more than 100 W with a bandwidth of at least 15 GHz around the center frequency of 263 GHz.

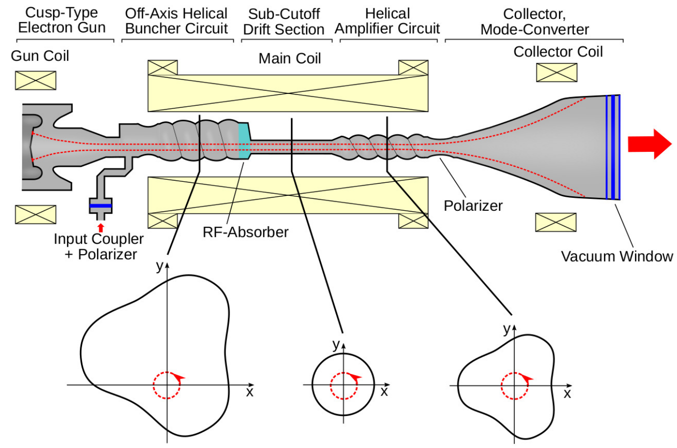

Fig. 1. Schematic of the FD-GTWT with off-axis HCW buncher circuit.

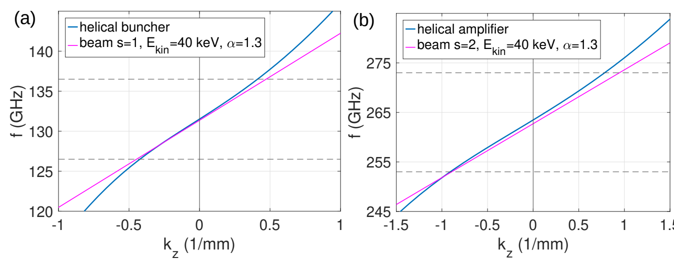

Fig. 2. Wave dispersions and beam lines at the fundamental and 2nd cyclotron harmonic in the HCW buncher (a) and amplifier (b) circuits.

Initial investigations of a suitable cusp-type electron gun have shown that a LOB with a kinetic energy of 40 keV, a pitch factor of 1.3 and a beam current of 0.25 A appears feasible. In a static magnetic field of ≈ 5 T, this beam allows a cyclotron interaction at the target frequencies of 131.5 GHz and 263 GHz at the fundamental and 2nd cyclotron harmonic, respectively.

The waveguide parameters of the HCW buncher and amplifier circuits are chosen such that the beam line and the wave dispersion intersect for the desired bandwidths (Fig. 2). For the buncher circuit, a HCW with $R_{\mathrm{b}} = 1.06$ mm, $\tilde{r}_{\mathrm{b}} = 0.17$ mm and $\tilde{d}_{\mathrm{b}} = 2.06$ mm was found. The corresponding HCW for the amplifier circuit has $R_{\mathrm{a}} = 0.53$ mm, $\tilde{r}_{\mathrm{a}} = 0.09$ mm and $\tilde{d}_{\mathrm{a}} = 1.00$ mm. Fig. 2 shows that the wave dispersions match well with the beam lines at the fundamental and 2nd cyclotron harmonic in the buncher and amplifier circuits, respectively.

In the final design step, 3D full-wave PIC simulations are performed with CST. For these prove-of-principle simulations, an ideal LOB is used, and an interaction circuit of OFHC copper is assumed. The corresponding ohmic losses were taken into account in the simulations. The optimal lengths of the three circuit sections were found to be $L_{\mathrm{b}} = 7\tilde{d}_{\mathrm{b}} = 14.42$ mm, $L_{\mathrm{d}} = 42$ mm and $L_{\mathrm{a}} = 20\tilde{d}_{\mathrm{a}} = 20.0$ mm.

In Fig. 3a, the simulated output power over the frequency of the output signal is shown for different input powers. The frequency dependence is obtained by simulations at discrete frequency points with $f_{\mathrm{in}} = 0.5 f_{\mathrm{out}}$. For the designated input power of 10 mW, the simulations indicate a gain of more than 40 dB over a bandwidth of 17.5 GHz. The FD-GTWT is fully saturated and reaches its maximal output power of 390 W for

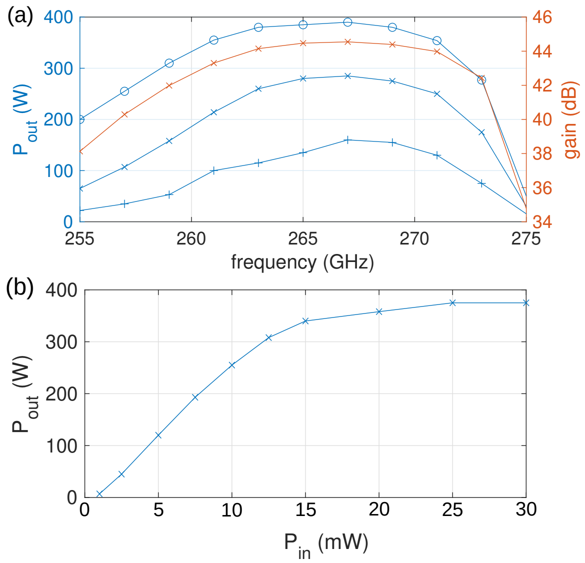

Fig. 3. (a) Simulated output power versus the output frequency for an input signal at half the output frequency and different powers (+ = 5 mW; × = 10 mW; ○ = 30 mW). For a 10 mW input signal the gain is given (red). (b) Simulated output power versus the input power at $f_{\mathbf{out}}$=263 GHz.

input powers of more than 25 mW (see Fig. 3b).

A comparison of the designed FD-GTWT with proposed and realized W-band high-gain H-GTWTs [11], [21], [23] shows that buncher and drift sections have a similar length. However, the amplifier section of the FD-GTWT is with $20\tilde{d}$ significantly longer than in the high-gain H-GTWTs ($\approx 12\tilde{d}$). The reason is the initial bunching of the electron beam at the fundamental cyclotron harmonic. In Fig. 4b, the particle density, in the cross-section of the tube, directly after the drift-section, is shown. It can be seen that the initial energy modulation took place at the fundamental cyclotron harmonic, which resulted in a single electron bunch. For an initial energy modulation at the 2nd cyclotron harmonic, a 2nd electron bunch would occur at the opposite of the fundamental harmonic bunch. Because a 2nd bunch is missing, the efficiency of the 2nd harmonic beam-wave interaction in the amplifier circuit is reduced. This reduction can be compensated by an increased length of the amplifier section. The induced wave with a frequency of $2f_{\text{in}}$ causes an energy modulation and consequently a bunching of the unbunched beam fraction. The resulting formation of a 2nd electron bunch can be seen in Fig. 4a. To allow the creation of the 2nd bunch, the length of the amplifier section must be increased. However, from Fig. 4a and Fig. 4c it can be seen, that at the end of the amplifier circuit, the fundamental bunch is already slightly overbunched. At the same time, the electrons in the second bunch have still not transferred the maximal amount of energy to the wave. As a consequence, the maximal efficiency of the FD-GTWT is with 3.9 % significantly lower than in a high-gain H-GTWT (e.g. 7.5-8.5 % in [21]).

IV. Discussion

To assess the feasibility of the proposed FD-GTWT, a comparison with existing H-GTWTs can be made. Well suited for this comparison is the W-band high-gain H-GTWT presented in [21]. This H-GTWT has shown a high gain (>40 dB) and

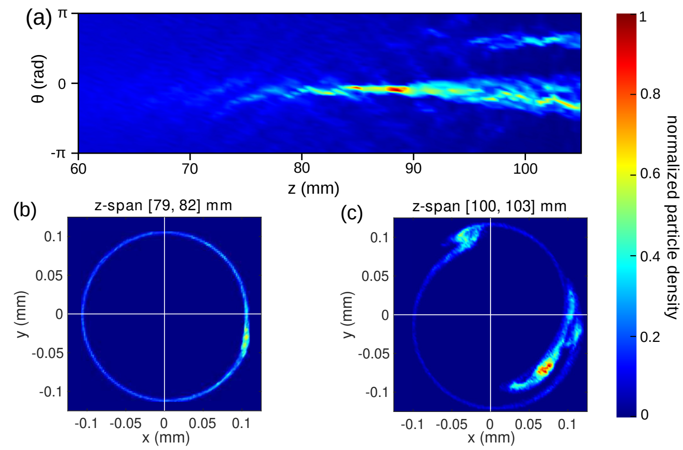

Fig. 4. Electron bunching along the amplifier circuit (a) and in the coss-section at the beginning (b) and the end (c) of the amplifier circuit.

a peak output power of 3 kW in CW operation for frequencies in the upper W-band (94.5-98.0 GHz). This frequency range is close to the input frequencies of the proposed 263 GHz FD-GTWT. Therefore, the dimension and tolerance requirements of the input coupler and the HCW buncher circuit of the W-band H-GTWT and the 263 GHz FD-GTWT are comparable, and those components can be considered as non-critical.

Manufacturing the 263 GHz HCW for the amplifier circuit is a more challenging task, and to date no H-GTWT has been realized at these high frequencies. However, the fabrication and cold measurements of a HCW for 370 GHz are presented in [24]. This makes a HCW for 263 GHz very feasible.

Most critical are the required high-quality electron beam and the strict alignment limits of the tube in the static magnetic field to allow the beam transmission through the long sub-cutoff drift section. Already for the W-band high-gain H-GTWT this was considered the most critical part [21]. However, the challenge of beam creation can be simplified if the beam current is sufficiently low [11]. Therefore, the beam current was reduced to 0.25 A, which is significantly lower than the 1 A in [21], used for the W-band high-gain H-GTWT. Based on the theoretical investigations in [11], we expect that a transverse velocity spread of up to 10 % can be tolerated and will cause only a moderate reduction of the bandwidth from 17.5 GHz to 15 GHz. Since cusp electron guns have already demonstrated excellent performances at even higher magnetic fields [25], we are optimistic that the beam can be generated with the required quality.

It should be also mentioned that the increased length of the amplifier circuit probably reduces the stability against reflection-induced parasitic oscillations compared to high-gain H-GTWTs, which should be investigated in future studies.

V. Conclusion

In conclusion, the presented approach of a FD-GTWT is a promising new type of high-power and broadband sub-THz amplifier. High gain and frequency doubling allow the usage of readily available D-band solid-state amplifiers as driving RF sources. Furthermore, the manufacturing of critical structures such as the input coupler with sub-wavelength dimensions is simplified because of the halved input frequency.

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