Project of a Third Harmonic W-band Gyroamplifier

Sergey V. Mishakin*, Sergey V. Samsonov*, and Gregory G. Denisov*†
*Department of Electron Devices, Institute of Applied Physics, RAS, Nizhny Novgorod, Russia
Email: mishakin@appl.sci-nnov.ru
†Nizhny Novgorod State University, Nizhny Novgorod, Russia

***Abstract*—In this paper we present design of a broadband third-harmonic operating gyro-amplifier with helically corrugated interaction circuit. An analysis of stability of the gyro-TWT with respect to parasitic wave-beam interactions has been performed and the range of parameters at which the gyro-TWT is zero-drive stable is found. According to 3D simulations, the amplifier yields a 6% amplification bandwidth with the maximum output power/gain of 80 kW / 25 dB for a 10-A, 70-kV electron beam.**

I. Introduction

DEVELOPMENT of wideband gyrotron traveling amplifiers (gyro-TWTs) with high continuous-wave/average output power in millimeter and sub-millimeter frequency bands has drawn considerable attention in recent years. Presently, the scheme of gyro-TWT with high distributed Ohmic losses and traditional circular waveguides as the interaction circuit has enjoyed the widest spread for millimeter-wave high-power wideband gyro-amplifiers [1]–[4]. However, among the reported experimental results only a limited number pertains to high CW/average power operation regimes, which may be attributed to strict thermal requirements on lossy materials at high-powers.

For a number of years, a different type of gyro-TWT is being investigated at IAP RAS [5]–[7]. The key element of gyro-TWTs of this type is the interaction circuit having the form of a waveguide with helical corrugation of its inner surface. Using of helical corrugation allows one to have a control over the eigenwaves dispersion properties. In particular, by choosing proper parameters of the corrugation it is possible to create an eigenwave with almost constant group velocity and close-to-zero longitudinal wave number, allowing one to combine broadband characteristics of a device with traveling waves with a weak dependence of the generation efficiency on the electron beam velocity spread inherent to gyrotrons.

Presently, a number of Ka-band second-harmonic operating gyro-TWTs of this type were created [7] and a great deal of effort is aimed at advancing the concept to the higher frequency bands, in particular, to the W-band. A straight-forward scaling of Ka-band gyro-TWT to the W-band would require utilizing of superconducting magnetic systems, which would reduce reliability and mobility of the device. A different path consists in utilizing of higher cyclotron harmonics interactions. In this paper we investigate a new configuration of gyro-TWT with helically corrugated waveguide operating in W-band at the third cyclotron harmonic and employing axis-encircling electron beam.

II. Interaction circuit design

The key problem of the gyro-TWT design consists in choosing of the geometry of the interaction circuit. A typical interaction circuit comprises the part with regular corrugation and two transition section from helical to circular waveguides for radiation input and output. The surface of the regular part can be described by the formula

$$r(\varphi, z) = r_0 + l_0 \cdot \cos(m_B\varphi - 2\pi/d) \qquad (1)$$

where m_B is the number of corrugation folds, r_0 – mean radius, d – corrugation period and l_0 – corrugation depth. The helical corrugation effectively couples smooth waveguide modes having azimuthal numbers differ by the number of the corrugation folds, m_B.

The number of corrugation folds, m_B, is determined by the considerations of efficiency and selectivity of the interaction between the electron beam and the operating wave. An axis-encircling electron beam can only effectively interact with the modes having the same azimuthal number as the cyclotron harmonic. Thus, one of the partial modes forming the helical waveguide operating eigenwave should be a $TE_{3,n}$ mode. From the selectivity and efficiency of the electron-wave interaction point of view, it is expedient to use the lowest mode of this set, namely, the $TE_{3,1}$ mode. The second partial mode, firstly, should have a high enough group velocity and secondly, be selectively coupled with the $TE_{3,1}$ by the helical corrugation. The analysis shows, that using of counter-rotating $TE_{-2,1}$ mode and, correspondingly, five-fold helical corrugation ($m_B = 5$) provides best result. The choice of the rest of the helical corrugation parameters is driven by the necessity of ensuring of a broadband synchronism between the operating eigenwave and the electrons in the beam.

For the current study we chose a 70 keV/10A electron beam having mean pitch-factor of 1.2 and spread of 40%. Through an optimization procedure the corrugation parameters ensuring broadband beam-wave synchronism (which is evident by the closeness of the electron-cyclotron wave dispersion slope and the operating wave dispersion slope in a wide frequency range (Fig. 1)) were found.

In order to ensure zero-drive stable single mode operation of the gyro-TWT, investigation of possible disruptive parasitic interaction was performed. The analysis revealed that the proposed configuration of the interaction circuit guarantees stability within the designed amplification band.

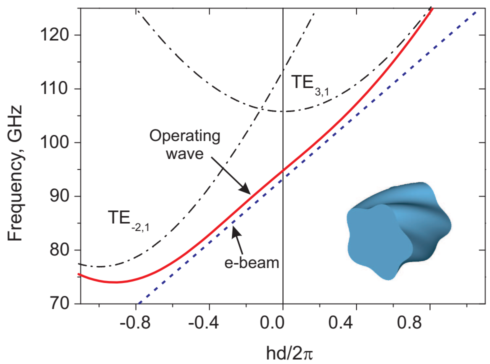

Fig. 1. Dispersion characteristics of the operating eigenwave

III. Large signal regime

In order to investigate large-signal performance of the gyro-TWT, 3D finite-difference time domain particle-in-cell (FDTD-PIC) simulations were performed. For the FDTD-PIC simulations results to be close to a physical device performance, a realistic model for the e-beam and the electrodynamic system were used. The electrodynamic model consisted of an input mode converter, sections of up- and down- tapered corrugations with length of four periods, the section with regular corrugations (with its length being optimized) and a cone at the end of the interaction circuit. The interior of the electrodynamic system was embedded in a conducting metal with conductivity two times worse than that of pure copper. The geometry of the input converter was optimized so as to provide high efficiency and wide bandwidth. With the found parameters, the power efficiency of the radiation coupling was more than 90% in the frequency range of 90–100 GHz.

For the current study we assume the power level of the input signal of 250 W, as a reasonable compromise between the power level of state-of-art and widely available linear-beam amplifiers. The simulations showed, that at length of the interaction circuit of approximately 65 mm, the amplifier reliably reached its saturation and this length may be considered as optimal. The instantaneous bandwidth of the gyro-TWT (for a fixed optimal magnetic field of 1.28 T) in this case was about 6% at –3 dB level and value of the output power amounted to 80 kW (corresponding to 25 dB gain) at the maximum (Fig. 2).

It is important to note that weakening of the beam-wave interaction strength at high harmonics leads not only to negative effect such as a relatively low electron efficiency (about 11 %) but also results in a relatively small amount of the energy spread in the beam after the interaction. According to the 3D PIC simulation, the minimum energy of the electrons in the "waste" beam amounts to 40 keV, which opens up the possibility of using a single stage energy recovery system (depressed collector) with the main power supply voltage decreased down to 30 kV and, correspondingly, the electron efficiency increased up to 27 %.

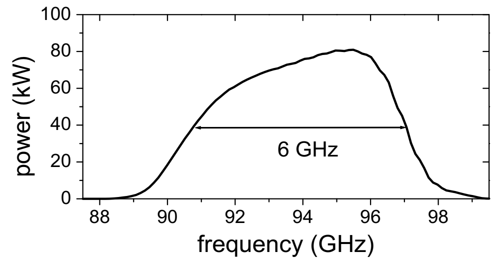

Fig. 2. Instantaneous amplification band of the gyro-TWT.

IV. Conclusion

A configuration of third-harmonic W-band gyro-TWT with helically corrugated interaction circuit was suggested. According to 3D simulations, the gyro-TWT can deliver output power of 80 kW, gain of 25 dB and –3-dB instantaneous bandwidth of 6%. The use of the third harmonic makes the value of the required magnetic field low enough to employ non-superconducting magnetic systems with reasonable power consumption. It also should be noted, that electron efficiency of the device can be increased from 11% to 27% through the use of a single-stage depressed collector.

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