Terahertz High-Harmonic Gyrotrons and Gyro-Multipliers

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***Abstract*—Progress on the study of a 3rd-harmonic Large Orbit Gyrotron with the radiation frequency of 1 THz and a prototype of a promising gyro-multiplier at the 4th harmonic are presented.**

I. Introduction

THOUGH the maximum frequency of gyrotrons has been increased from 0.3 to 1.3 THz during last 35 years, these devices are not wide-spread yet. The main reasons are the strong magnetic field required for conventional THz gyrotrons when operating at fundamental and second cyclotron harmonics, and severe mode competition when operating at higher harmonics. These problems can be significantly mitigated in the so-called Large Orbit Gyrotron (LOG), where all the electrons describe helical trajectories with the axes coinciding with the cavity axis or close to it [1]. Due to such a configuration stronger coupling with operating modes and better mode selectivity at high harmonics can be obtained.

Frequency multiplication is an attractive alternative method for realization of THz gyro-devices. In gyro-multipliers, smaller operating currents in comparison with high-harmonic gyrotrons can be used because it is not necessary to exceed the starting current of the high-harmonic (HH) mode. In addition, gyro-multipliers possess higher selectivity at high cyclotron harmonics [2]. The realization of conventional gyro-multipliers is restrained at THz waves in particular because of necessity of a high-frequency external signal. However, in self-exciting gyro-multipliers the same electron beam excites both low-harmonic (LH) and HH modes, therefore an external signal is not needed. Among various possible versions of such devices single cavity schemes [3, 4] have some advantages in providing a well defined frequency multiplication factor for LH- and HH-modes; the starting current for the LH-mode can be greatly exceeded and this mode may reach saturation.

II. 1-THz Large Orbit Gyrotron

A 3rd-harmonic LOG with a 250 kV, 3 A, 10 μs electron beam has recently demonstrated power up to 10-20 kW in single-mode regimes at the modes $TE_{3,5}$, $TE_{3,8}$ and $TE_{3,9}$ with high radial indices and frequencies 0.37-0.41 THz [5]. As a development of this method, a new 3rd-harmonic LOG with significantly lower voltage of 80 kV and higher operating frequency of 1 THz at kilowatt power level in 10-μs pulses has been designed and manufactured at the Institute of Applied Physics. To decrease particle spread the new oscillator exploits a cusp electron gun where the electrons transverse velocity is seeded near the cathode, in the region of a sharp reverse of the magnetic field. The transverse velocity achieves the operating value by compression in a magnetic field increasing 3,000 times up to 13.7 T. According to simulations and preliminary low-current modeling experiments (Fig. 1), a beam with current 0.7 A, pitch-factor 1.5 and satisfactory velocity spread 0.3 can be obtained in such a system. A rather long cavity should provide sufficient mode separation and single-mode operation at the operating mode $TE_{3,7}$ (Fig.2) with output power 0.5 kW. A pulse duration of about 10-μs with repetition rate of up to 1 Hz is expected.

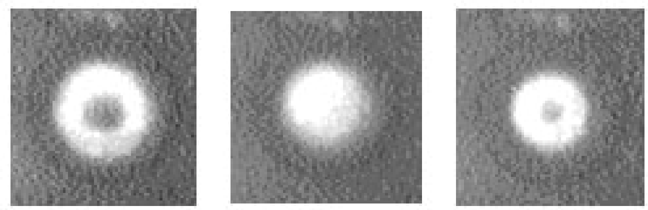

Fig. 1. Scintillator images of electron beam for positive, zero and negative (cusp configuration) cathode magnetic field; outside diameter of the dark ring is equal to 1 mm.

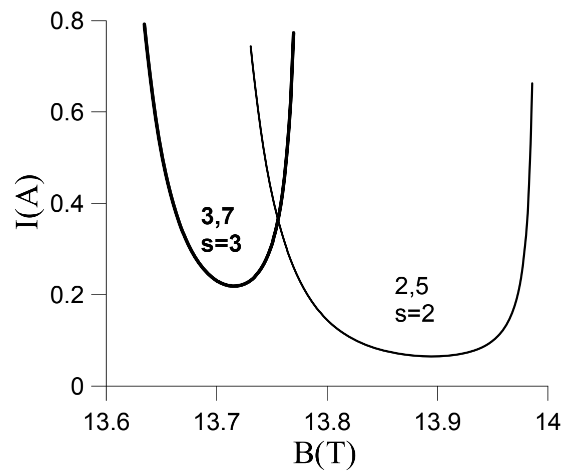

Fig. 2. Calculated starting currents for the operating 3rd-harmonic mode $TE_{3,7}$ and the nearest parasitic 2nd-harmonic mode $TE_{2,5}$ with frequencies of 1.0 and 0.7 THz respectively.

III. Single-cavity gyro-multiplier

The authors have previously shown that in the case when both the LH and HH waves in a gyro-multiplier are radiated by the same electron beam in a single cavity, larger efficiency than in the klystron-type schemes can be attained, since one may use a more effectively bunched beam. The most perceptible problem presented by this design is the difficulty of separation of LH- and HH-waves at the output, which is

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especially severe when the levels of generated power differ by several orders of magnitude. Here we propose a design that promises high power efficiency and simultaneously allows convenient separation of the output signals. The most efficient high-harmonic interaction is provided when a near cut-off (gyrotron) mode is used for generation. A cut-off mode should be also used for electron beam modulation at a low cyclotron harmonic, because it is the only case when the both operating waves can be in resonance with the beam in a uniform magnetic field. However, a traditional axis-symmetrical gyrotron cavity usually does not provide a pair of eigenmodes applicable for frequency multiplying. The cavity mode spectrum can be altered to the desired one by exploiting an azimuthal corrugation of the wall. Such a corrugation may significantly shift the frequency of the HH-mode while keeping the frequency of LH-mode practically unperturbed. Namely a 2m-fold corrugation cancels the frequency degeneracy of the two transverse standing $TE_{m,p}$ modes (Fig. 3) and results in a splitting of their frequencies, one is upshifted and the other is downshifted.

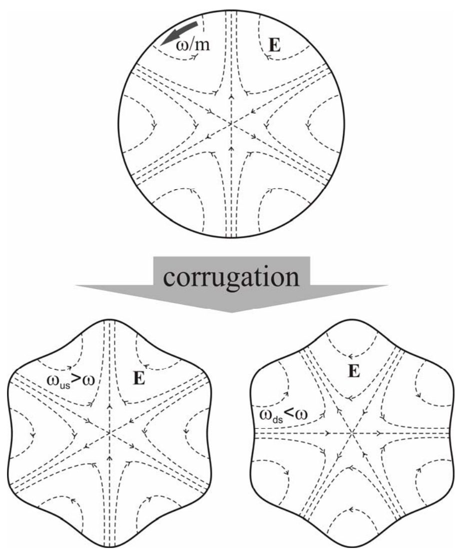

Fig. 3. Splitting of the $TE_{m,p}$ mode (at frequency ω) under the 2m-fold azimuthal corrugation of the cavity into two modes with upshifted, ω_{us}, and downshifted, ω_{ds}, frequencies.

It should be mentioned that the corresponding field structures are bound to the corrugation and hence not rotating. This leads to the halving of the coupling strength between the beam and each of the two split modes. Choosing the corrugation amplitude, it is possible to make one of the frequencies exactly *n* (integer) times higher than the frequency of the LH-wave and thus provide effective high harmonic generation. In addition, the difference between the cut-off frequencies of corrugated and axis-symmetrical waveguides allows the trapping of the LH-wave inside the cavity, so that only a monochromatic HH-wave is radiated through the output. The radius of the output waveguide may be such that the frequency of the LH-mode is lower than the cut-off value for this waveguide, whilst the HH-mode may still propagate if the initial relation between the frequencies of the HH- and LH-modes in the circular waveguide is less than *n* (Fig. 4).

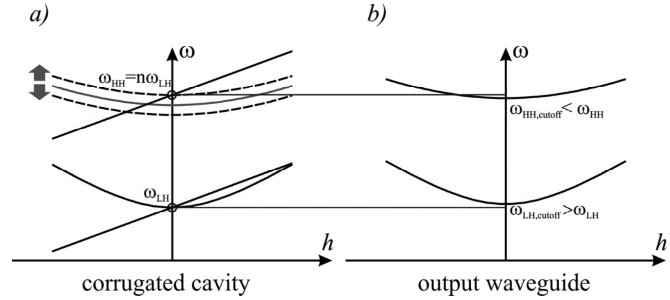

Fig. 4. Difference in the mode spectrum in azimuthally corrugated (a) and circular (b) waveguides allows separation of the HH-wave at the output of the self-exciting single-cavity gyro-multiplier.

A demonstration mm-range experiment utilizing this approach is currently being prepared at the Institute of Applied Physics. It is planned to double the frequency of the $TE_{2,2}$ gyrotron mode, which is self-excited at the 2^{nd} cyclotron harmonic, to produce output radiation from the 4^{th} cyclotron harmonic. The high-frequency operating mode is derived from the $TE_{4,3}$ mode of the circular waveguide using an 8-fold wall corrugation. An axis-encircling 60 kV/5 A electron beam has already been obtained from a cusp gun and successfully exploited in a preliminary experiment with a 2^{nd}-harmonic LOG. According to simulations, in a relatively weak magnetic field of 0.7 T the proposed scheme of the self-exciting gyro-multiplier can produce up to several kW of output power at a frequency of 70 GHz. After some modifications such a method may be used for obtaining radiation in the sub-THz and THz frequency range.

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