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Gyrotron Frequency Control by a Phase Lock System

G. Yu. Golubiatnikov[a],*, A. F. Krupnov[a], L. V. Lubyako[a], A. G. Luchinin[a], A. B. Pavelyev[a], M. I. Petelin[a], and A. Fernandez Curto[b]

[a] *Institute of Applied Physics, Russian Academy of Sciences, Nizhni Novgorod, Russia*

[b] *Associación Euratom–CIEMAT para Fusión, 28949 Madrid, Spain*

* *e-mail: glb@appl.sci-nnov.ru*

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Abstract—The idea of controlling gyrotron frequency by means of voltage variation on an insulated "current-free" anode [1] has been implemented. A gyrotron phase-locked to an external stabilized low-power oscillator exhibits a more than tenfold narrowing of the output spectrum width as compared to that in the free running regime.

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High-precision control over gyrotron frequency in the short-wavelength part of the millimeter range is of interest for various applications, including (i) molecular spectroscopy (where unstabilized gyrotrons are only suited for the investigation of rather broad lines [2], while frequency-stabilized gyrotrons have good prospects for use in solving some problems of nonlinear spectroscopy [3, 4]); (ii) experiments with the phase conjugation of gyrotron radiation on resonant transitions of molecules in the gas phase [5]; (iii) investigations into plasma turbulence spectra [6]; and (iv) adaptive suppression of hydrodynamic instabilities in plasma traps [7].

One possible approach to high-precision gyrotron frequency stabilization is through its feedback adjustment to a frequency-stable low-power reference oscillator. Recently, Idehara et al. [8] demonstrated a method of phase locking for a millimeter-range gyrotron, in which the control voltage was applied to a cavity that was insulated from the collector. However, a relatively large capacitance between the collector and cavity imposes additional requirements on the final stage of the control circuit: in order to provide a diode-gun gyrotron frequency control in a bandwidth of about 1 MHz, it is necessary to use a control amplifier with a power of several kilowatts.

A more effective frequency control can be achieved in a triode-gun gyrotron (Fig. 1) with variable voltage on the insulated anode possessing a small capacitance relative to the other electrodes [1]. In this case, the electron energy (determined by the cathode potential relative to the cavity) is fixed and a change in the anode voltage influences only the ratio of rotational and translational electron velocity components (pitch factor). This variation of the pitch factor is accompanied by a change in both active and reactive components of the electron-beam conductance for the cavity working mode, which leads to a change in the oscillation amplitude and frequency (the latter is retained within the frequency band determined by the Q value for the cavity working mode).

In the proposed scheme (Fig. 2), the frequency and phase difference between the gyrotron and the refer-

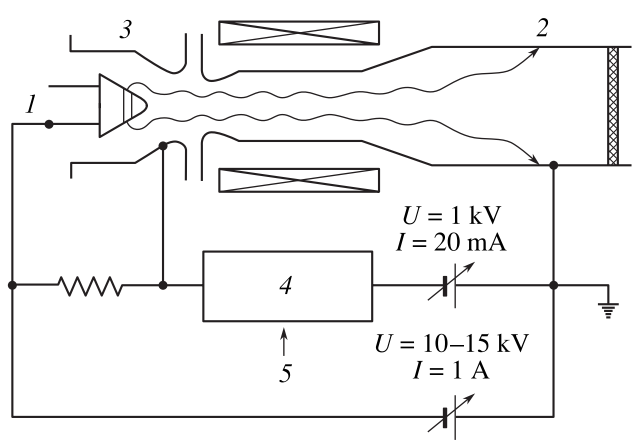

Fig. 1. Schematic diagram of the triode-gun gyrotron frequency control system: (*1*) cathode; (*2*) collector; (*3*) current-free anode; (*4*) high-voltage video amplifier; (*5*) error signal from phase-frequency detector.

ence microwave synthesizer is monitored by a frequency-phase detector. The error signal is proportional to the frequency or phase (for a phase-lock regime) detuning. This signal is applied to the control anode that shifts the gyrotron frequency toward that of the reference signal. An analogous scheme has been used for high-precision frequency stabilization of backward-wave oscillators [9] for the millimeter and submillimeter wavelength ranges.

The experiments were performed with a gyrotron operating in a fundamental cyclotron resonance regime with a frequency of 12.3 GHz and an output power of 300 W. The working $TF_{2,1}$ mode had a loaded Q value of 400. The triode electron gun operated at 20 kV and produced an electron beam with a total current of 1 A. The control voltage on the insulated anode was varied within 0.5–6 kV, and the working current changed within 5–10 mA. The limiting electron pitch factor was about 2. Depending on the initial voltage on the triode gun anode (i.e., on the initial pitch factor), the gyrotron frequency tunability varied from 1 to 10 MHz/kV, which was in good agreement with theoretical estimates. The gyrotron oscillation spectrum in the free-running regime had a width (FWHM) of about 400 kHz (Fig. 3a) that was determined mostly by the power supply voltage pulsation.

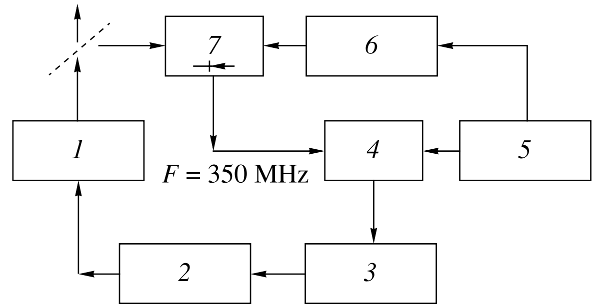

Fig. 2. Schematic diagram of the triode-gun gyrotron phase-lock loop (PLL): (*1*) gyrotron; (*2*) high-voltage power supply unit; (*3*) high-voltage video amplifier; (*4*) frequency-phase detector; (*5*) 5 MHz quartz crystal oscillator (reference clock); (*6*) reference microwave (8–17 GHz) synthesizer; (*7*) diode mixer.

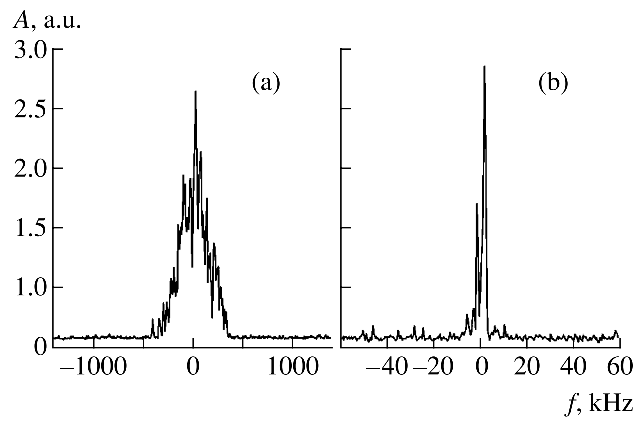

Fig. 3. Averaged spectra of gyrotron oscillations in the (a) free running and (b) PLL-controlled regimes.

In experiments with the phase-lock frequency stabilization (Fig. 2), a fraction of the gyrotron output signal and the signal from a microwave (8–17 GHz) synthesizer (RCh6-03, Kvarts Co., Nizhni Novgorod) were fed to a diode harmonic mixer (Ch5-13). The intermediate frequency (IF, 350 MHz) signal taken from the mixer was fed to a frequency-phase detector, and the error signal, which is proportional to the phase difference between the IF signal and harmonics of a 5 MHz reference clock, was fed to a video amplifier. The video amplifier had an output circuit based on a GMI-83 high-power tetrode with a gain factor of 30 and a control bandwidth of about 10 kHz. These characteristics were sufficient to suppress the influence of 50 Hz mains pulsation (and its harmonics) in the high-voltage power supply unit of the gyrotron.

Figure 3 shows the average spectra of gyrotron oscillations measured by an S4-27 spectrum analyzer (the analyzer output signal was digitized by an analog-to-digital converter and averaged). The gyrotron spectrum width in a regime with phase-lock loop (PLL) control does not exceed 10 kHz, which is 40 to 50 times narrower than that in the free running regime.

Thus, the results of our experiments demonstrated the possibility to stabilize the gyrotron frequency and to provide its fast and precise control. In the case of a triode-gun gyrotron, the problems were successfully solved using a PLL with relatively low control power consumption. Since the proposed frequency control scheme does not depend on the gyrotron frequency (the upper frequency limit as determined by the diode mixer is on the order of 1 THz), it offers a promising general solution for gyrotrons operating in the short-wavelength part of the millimeter range.

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