Improving Frequency Stability of a 0.67 THz Gyrotron by Delayed Reflection

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***Abstract*— Effect of delayed reflection from a remote load on operation of a gyrotron is considered. Improving of frequency stability by the wave reflected from the load is demonstrated. Theoretical analysis for quasi-linear model of a gyrotron are presented. The theoretical results are in good agreement with numerical simulations for the high-power 0.67 THz gyrotron.**

I. INTRODUCTION

CONTINUOUS-WAVE (CW) gyrotrons covering sub-THz and THz frequency range are of great importance for dynamic nuclear polarization (DNP) spectroscopy as well as for other scientific applications [1]. Such a source should provide a stable signal with smooth frequency tuning and moderate output power (tens of watts). The gyrotron operation frequency may fluctuate owing to voltage power-supply instability or to thermal expansion of the cavity. In particular, in the experiment with the 140 GHz gyrotron [2] step frequency tuning owing the cavity heating and thermal expansion had been observed. It is supposed that the step-wise character of the frequency variation is caused by reflections.

For many microwave and optical oscillators, stabilization of oscillation frequency by a signal reflected from an external high-Q resonator has been demonstrated. However, this method has never been applied for gyrotrons. It is essential to note that operation depends not only from amplitude of the reflected signal but also from its phase, which is determined by the propagation time from the gyrotron cavity to the window (long-line effect). In this paper, we present the results of theoretical analysis and numerical simulation of self-injection-locking by the delayed reflected signal for a gyrotron. This method is much simpler and faster than frequency stabilization by control of the beam voltage or magnetic field.

II. THEORY

We start from the well-known quasilinear model of a gyrotron using the quasi-linear approximation of the electron susceptibility by cubic polynomial [3-5]. Using this approach, we obtain the following delay-differential equation (DDE) for slowly varying complex amplitude A:

$$\frac{dA}{dt} + i\Delta A = \left(\sigma - (1+i\beta)|A|^2\right)A + \rho e^{-i\psi}A(t-\tau). \qquad (1)$$

Here, Δ is the normalized detuning between cold cavity eigenfrequency and generation frequency, σ is the mode increment, β is the parameter of reactive phase nonlinearity.

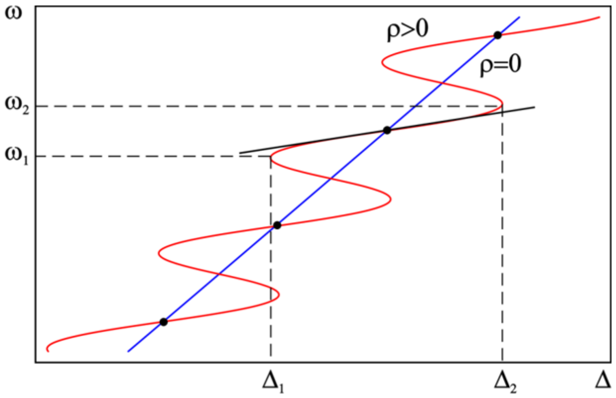

Fig. 1. Frequency vs. detuning in the case without ($\rho = 0$) and with ($\rho > 0$) reflection.

The last term in the right-hand side of (1) stands for the influence of the reflected signal, $\rho\exp(-i\psi)$ is the normalized parameter of reflections and τ is the normalized delay time (see [5] for details). In [6], we derived analytically the conditions of stability of steady states of (1) and checked the results of stability analysis by numerical simulation of transient processes. In this paper, we extend the results of this analysis to the problem of frequency stabilization.

Seeking for single-frequency steady-state solutions of (1), $A = A_0\exp(i\omega t)$, we obtain

$$\begin{gathered} |A_0|^2 = \sigma + \rho\cos(\omega\tau + \psi), \\ \Delta = \omega + \beta|A_0|^2 + \rho\sin(\omega\tau + \psi). \end{gathered} \qquad (2)$$

In Fig. 1, frequency vs. detuning is plotted. Without reflections, the oscillation frequency is proportional to the detuning Δ. With the increase of reflections, the slope of ω(Δ) curves decreases and they tend to nearly horizontal “shelves,” i.e., self-injection-locking takes place.

From (2) we derive the equation for the locking bandwidth

$$\Delta_1 - \Delta_2 = \frac{2\left[\pi - \arccos(1/\rho\tau) + \sqrt{(\rho\tau)^2 - 1}\right]}{\tau} \qquad (3)$$

and the frequency-stabilization rate

$$K_\omega = (d\Delta/d\omega)_{\omega_{st}} = 1 + \rho\tau, \qquad (4)$$

which is the slope at the central frequency of a locking band ω_{st}. The theoretical formulas are in good agreement with numerical solution of the DDE (1).

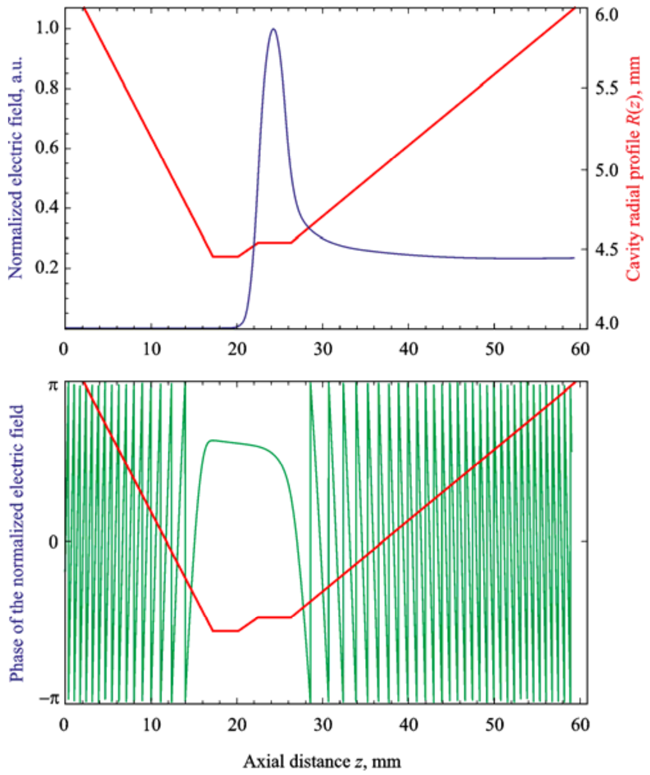

Fig. 2. Radial profile of the 0.67 THz gyrotron circuit and normalized electric field magnitude and phase profiles for the $TE_{31,8}$ cavity mode.

III. NUMERICAL RESULTS

We confirm the theoretical results by numerical simulation using the well-known non-stationary gyrotron theory with fixed axial field profile [4]. For this simulation, we take the parameters of the 0.67 THz gyrotron developed in [7]. First, we calculated cold characteristics of the cavity. For $TE_{31,8}$ operation mode, eigenfrequency is $f = 670.164$ GHz, and Q-factor $Q = 1948.85$. In Fig. 2, radial profile of the gyrotron circuit, as well as axial profiles of magnitude and phase of the $TE_{31,8}$ cavity mode are presented. This profile was used in the numerical simulations.

Detailed simulations of frequency stabilization of the 0.67 THz gyrotron were performed. In Fig. 3, plots of generation frequency versus cold cavity eigenfrequency are presented. Results of numerical simulation shown by circles are in good agreement with the theory. In particular, the frequency-stabilization rate K_ω increases with the increase of reflection magnitude and delay time. When a steady state becomes unstable, hopping transition to the nearest stable steady state occurs. These transitions are shown by arrows in Fig. 3. Such a behavior is in good agreement with the results of stability analysis presented in [6].

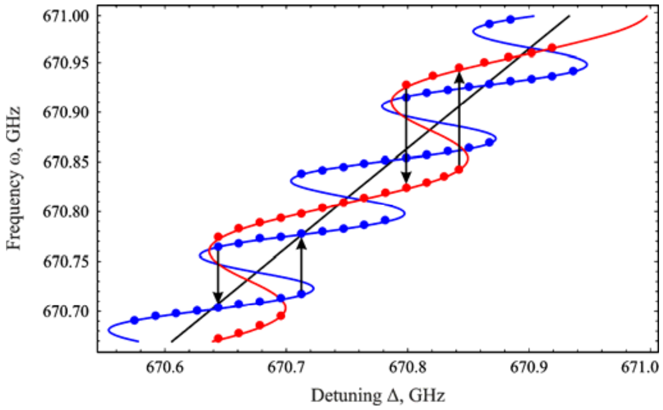

Fig. 3. Frequency vs. detuning for 2.25% reflected power. Cavity-to-reflector distance is 1 m (red) and 2 m (blue). Theoretical and numerical results are shown with solid lines and circles, respectively.

IV. SUMMARY

In this paper, we present the results of theoretical analysis and numerical simulations explaining gyrotron frequency stabilization by partial reflection of the output signal from a remote load. A simple quasi-linear model is studied, and formulas for the frequency-stabilization rate and locking bandwidth are derived. The theoretical predictions are confirmed by using time-domain gyrotron numerical simulation. The results for the 0.67 THz gyrotron [7] are presented. These results allow interpretation of the experiment [2] where step frequency tuning has been observed.

V. ACKNOWLEDGEMENTS

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REFERENCES

[1]. E.A. Nanni, A.B. Barnes, R.G. Griffin, and R.J. Temkin, “THz dynamic nuclear polarization NMR,” *IEEE Trans. Terahertz Sci. Technol*., vol. 1, pp. 145-163, September 2011.

[2]. W. Kasparek, M.I. Petelin, D.Y. Shchegolkov, et al., “A fast switch, combiner and narrow-band filter for high-power millimetre wave beams,” *Nucl. Fusion*, vol. 48, 054010, 2008.

[3]. G.S. Nusinovich, “Mode interaction in gyrodevices,” *Int. J. Electron.*, vol. 51, no. 4, pp. 457-474, 1981.

[4]. G.S. Nusinovich, Introduction to the Physics of Gyrotrons, Baltimore, *MD: Johns Hopkins University Press*, 2004.

[5]. M.M. Chumakova, S.A. Usacheva, M.Y. Glyavin, Y.V. Novozhilova, and N.M. Ryskin, “Mode competition in a two-mode gyrotron with delayed reflections,” *IEEE Trans. Plasma Sci.*, vol. 42, no. 8, pp. 2030-2036, August 2014.

[6]. Y.V. Novozhilova, N.M. Ryskin, and S.A. Usacheva, “Nonstationary processes in an oscillator with delayed reflection from the load,” *Tech. Phys.*, vol. 56, pp. 1235-1242, 2011.

[7]. M.Yu. Glyavin, A.G. Luchinin, G.S. Nusinovich, J. Rodgers, D.G. Kashyn, C.A. Romero-Talamas, and R. Pu, “A 670 GHz gyrotron with record power and efficiency,” *Appl. Phys. Lett.*, vol. 101, 153503, 2012.