Nonlinearly Driven Oscillations in the Gyrotron Traveling-Wave Amplifier

Chen C. Chiu [a], Kuo F. Pao [a], Yin C. Yan [a], Kwo R. Chu [a], Larry R. Barnett [b] and Neville C. Luhamnn, Jr. [b]
[a] Department of Physics, National Tsing Hua University, Hsinchu, Taiwan
[b] Department of Applied Science, University of California, Davis, CA 95616

Abstract—**A new phenomenon in the gyrotron traveling-wave amplifier (gyro-TWT) in the form of nonlinearly driven oscillations was reported. A zero-drive stable gyro-TWT is shown to be susceptible to considerably reduced dynamic range at the band edge, followed by a sudden transition into driven oscillations, and then a hysteresis effect. An analysis of this unexpected behavior and its physical interpretation are presented.**

I. INTRODUCTION

The gyrotron is a powerful millimeter-wave source operating on the principle of the electron cyclotron maser instability. Demonstration of the gyrotron oscillator for fusion plasma heating and current drive has led to its development for large-scale fusion reactors. The gyroklystron amplifier has been implemented in a W-band advanced radar for low observable control. More recently, significant progress has been made on the gyro-TWT, which is being developed as a broadband driver for space radars.

As a common requirement for all types of gyrotrons, the wave frequency ω and the initial electron cyclotron frequency Ω_c (or its harmonic) must be matched in order to maintain synchronism between the bunched electrons and the electromagnetic wave. For the gyrotron oscillators, the synchronism time need only be comparable to the electron transit time through the interaction structure. This allows some freedom of frequency mismatch, or magnetic field detuning, which can be exploited for efficiency optimization and mode control. The frequency mismatch results in a finite transit angle Θ. For optimum linear interaction with the lowest start-oscillation current (I_{st}), Θ falls in the neighborhood of π. Nonlinearly, to favor energy-losing electrons whose cyclotron frequency increase in time, the transit angle is tuned to a higher value in the neighborhood of 2π in order to achieve maximum saturated efficiency. This is significantly off the optimum range for I_{st} and thus often leads to a situation in which the operating current I_b for maximum efficiency is lower than I_{st}. The system is then in a "hard excitation" state so that priming is required to start the oscillations [1].

The hard excitation is characterized by a nonlinear interaction efficiency which increases with the RF field faster than the linear rate. This is because the synchronism time is shortened by the frequency mismatch. Consequently, rapid energy extraction at a stronger field keeps the favorable electrons in the energy-losing phase for a longer time. More energy is thus delivered to the wave than predicted by the linear theory.

II. NONLINEARLY DRIVEN OSCILLATIONS

In this study, we show that there is a regime in which the linear amplification of a zero-drive stable gyro-TWT prematurely reaches a nonlinear stage, with enhanced gain, well before the normally expected saturation level. Upon further increase of P_{in}, it then suddenly transitions to nonlinear oscillations with a steep jump in output power. This is an anomalous effect which substantially reduces the linear dynamic range as well as completely spoiling the saturated operation.

The physical reasons can be seen in the ω-k_z diagram in Fig. 1 below. The waveguide mode is a parabolic line, whereas the beam-wave resonance line is straight. Because of the broad instantaneous bandwidth of the gyro-TWT interaction, there is always a region of significant frequency mismatch at the lower edge of the operating band despite a good match at the band center. This therefore provides the requisite condition for enhanced nonlinear gain at band-edge frequencies. Furthermore, in addition to the common form of self-sustaining oscillations which are triggered by an input wave, the amplifier also accommodates a new form of oscillations, which are nonlinearly driven by the input wave, but which then terminate when the drive wave is turned off. Both types of oscillations occur under zero-drive-stable conditions, under which the system is expected to work as a normal amplifier.

A hysteresis effect also takes place. This is because the nonlinear oscillations, once driven to start, tend to linger on for a short time even at a drive power which is insufficient to initiate it.

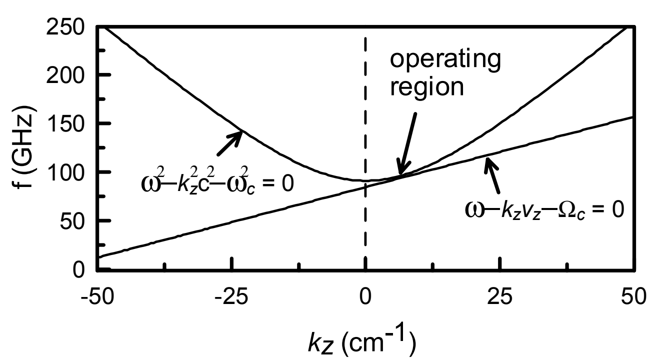

Fig. 1: f vs k_z diagram showing the waveguide dispersion curve and the beam wave resonance line.

REFERENCE

[1] A. H. McCurdy, and C. M. Armstrong, IEEE Trans. Plasma. Sci. **36**, 891 (1988).

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