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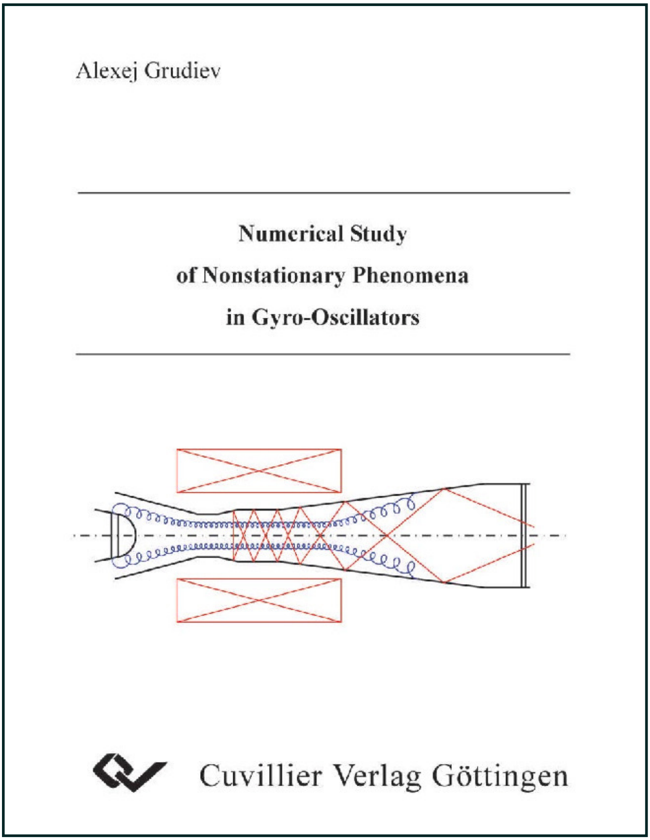
Numerical Study of Nonstationary Phenomena in Gyro-Oscillators



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$u(t)$	Step-function $u(t) = \begin{cases} 0 & \text{for } t < 0 \\ 1 & \text{for } t \geq 0 \end{cases}$
$\boldsymbol{v}$	Electron velocity vector
$\boldsymbol{v}_\perp$	Electron transverse velocity vector
v_{gr}	Wave group velocity
v_{ph}	Wave phase velocity
v_z	Electron axial velocity
V	Complex amplitude of the electric field along the axis
V_l	Complex eigenvector of the l-th eigenmode of open cavity
V_b	Electron beam voltage or kinetic energy of the beam electron
V'_m, V''_m, V_m	Waveguide voltage functions of TM, TE, and TE+TM modes, respectively
$\mathbf{z}^{(i)}$	Unit vector in the outward axial direction at i-th aperture
$z^{(2)}$	Axial location of the right aperture
Z_0	Wave impedance of vacuum
α	Pitch factor of the electron beam: $\alpha = \lvert\boldsymbol{v}_\perp\rvert/v_z$
β	$\lvert\boldsymbol{v}\rvert/c$
$\beta_\perp$	$\lvert\boldsymbol{v}_\perp\rvert/c$
γ	Relativistic factor
γ_0	γ at the entrance to the interaction space
$\delta()$	Dirac delta-function
δ_{nm},$\delta_{\alpha\beta}$,$\delta_{\lambda\mu}$	Kronecker deltas
Δ	Normalized frequency mismatch from [1]
Δf	Frequency pulling
Δf_B	Width of the passband in the presence of reflections
Δf_L	Locking bandwidth
Δf_0	Mismatch of the central frequency of the locking band and the free running frequency
Δf_M	Frequency separation due to modulations
Δf_R	Frequency separation due to reflections

ΔL_R	Variation of the distance to the reflecting load
ΔP	Variation of the output power
ΔT	Temperature increase of the load in the experiments
ε	Electric permittivity of media
ε_0	Electric permittivity of vacuum
η	Efficiency
$\eta(z)$	Efficiency versus z-coordinate
$\eta_\perp$	Perpendicular efficiency
$\eta_\perp(z)$	Perpendicular efficiency versus z-coordinate
θ_{tr}	Transit angle
λ	Wavelength
$\Lambda'_{\alpha m}, \Lambda''_{\alpha m}$	Coupling coefficients between the cavity electric irrotational eigenfunctions and the waveguide electric eigenfunctions for TM and TE mode, respectively
$\left[\Lambda_{\alpha m}\right]$	Matrix of coupling coefficients $\Lambda'_{\alpha m}, \Lambda''_{\alpha m}$ for all modes at all apertures
μ_0	Magnetic permeability of vacuum
ρ	Electric charge density
ξ_l	Normalized length of the interaction space from [2]
ω	Wave frequency
ω_c	Waveguide mode cutoff wave frequency
${\omega_c}'^{(i)}_{m}, {\omega_c}''^{(i)}_{m}$	Cutoff wave frequency of TM and TE modes, respectively, at the i-th aperture
Ω	Electron cyclotron frequency
τ_C	Delay time due to wave propagation in the cavity
τ_R	Delay time due to wave propagation to the reflecting load

Chapter 1

Introduction

1.1 What is a Gyro-Device ?

1.1.1 Coherent Radiation of Electrons

Gyro-devices are relative newcomers to the microwave tube family. This family is big and is usually divided into three classes according to three basic kinds of electromagnetic radiation by charged particles: Cherenkov or Smith-Purcell radiation, transition radiation, and bremsstrahlung radiation [3]. Microwave tubes based on the first kind of radiation, including traveling-wave tubes (TWTs), backward-wave oscillators (BWOs), orotrons, and others, are often called Cherenkov devices. Klystrons and monotrons are typical examples of devices based on coherent transition radiation. Finally, gyro-devices or cyclotron resonance masers (CRMs), free electron lasers (FELs), and vircators form the last but not least class of microwave sources based on coherent bremsstrahlung radiation of electrons.

In contrast to the first two types of radiation, bremsstrahlung occurs when electrons perform an oscillatory motion with varying velocity $\boldsymbol{v}$. To force the electrons to oscillate, different means are used. In gyro-devices, the electrons gyrate in a constant magnetic field. Periodic external fields are used in FELs. Finally, in vircators, the electrons oscillate in a potential well formed by an electrostatic field. In all three cases, the electrons radiate waves whose Doppler-shifted frequencies coincide with the frequency of the electron oscillations Ω or one of its harmonics:

$$\omega - k_z v_z \cong s\Omega \tag{1.1}$$

Since (1.1) can be satisfied for any wave phase velocity v_{ph}, it follows that the radiated waves can be either fast (i.e., $v_{ph} > c$) or slow (i.e., $v_{ph} < c$). However, it is preferable to radiate fast waves, because, in this case, the interaction can take place in a smooth metal waveguide and does not require the periodic variation of the waveguide wall that is required to support slow waves. Fast waves have real transverse wavenumbers, which means that the waves must not be localized near the walls of the interaction structure. Correspondingly, the interaction space can be extended in transverse direction, which makes the use of fast waves especially advantageous for millimeter- and submillimeter-wave generation, since the use of larger waveguide or cavity cross sections reduces wall losses and breakdown restrictions, as well as permits the passage of larger, higher power electron beams. Moreover, it also relaxes the constraint that the electron beam in a single cavity can only remain in a favorable rf phase for half of a rf period (as in klystrons and other devices employing transition radiation). In bremsstrahlung devices, the reference phase for the waves is the phase of the electron oscillations. Therefore, the admissible mismatch of synchronism of the type defined by (1.1), which is given by the condition

$$|\theta_{tr}| \lesssim 2\pi, \tag{1.2}$$

where $\theta_{tr} = (\omega - k_z v_z - s\Omega)T_{tr}$ is the transit angle and $T_{tr} = L/v_z$ is the transit time, can now be satisfied even in cavities or waveguides that are many wavelengths long.

1.1.2 Electron Bunching

The relativistic dependence of the electron cyclotron frequency on energy

$$\Omega = \frac{eB_0}{mc\gamma} \tag{1.3}$$

where e is the electron charge, B_0 is the applied magnetic field value, m is the electron rest mass, and γ is the relativistic factor ($\gamma = 1 + eV_b/mc^2$, where eV_b is the electron kinetic energy and mc^2 is the electron rest energy) is the fundamental basis of gyro-device operation [4]. This effect leads to bunching of the electrons in gyrophase and, due to this, to coherent bremsstrahlung radiation. The instability resulting from this effect, known as the cyclotron maser instability, was found by R. Q. Twiss [5], J. Schneider [6], and A. V. Gaponov-Grekhov with V. V. Zheleznyakov [7] in the late 1950's. It is interesting to note that this relativistic effect is important even for a weakly relativistic electron ($eV_b \ll mc^2$). Indeed, from (1.3) it follows that changes in electron energy and cyclotron frequency are related as

$$\frac{\Delta\Omega}{\Omega} = -\frac{\Delta\gamma}{\gamma} \tag{1.4}$$

Therefore, according to (1.2) and (1.4), when electrons interact with an electromagnetic wave with a small axial wavenumber ($k_z v_z \ll \omega$, such a wave can easily be excited in open resonators as discussed below), all of the kinetic energy of the electrons may be withdrawn without significantly disturbing the cyclotron resonance. This occurs when the number of electron orbits in the interaction space, $N_{tr} = \Omega T_{tr}/2\pi$, and the electron beam voltage are properly matched:

$$\frac{eV_b}{mc^2\gamma} \sim \frac{1}{sN_{tr}} \tag{1.5}$$