Cyclotron-resonance maser in a magnetic mirror

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A cyclotron-resonance maser (CRM) experiment is performed in a high-gradient magnetic field using a low-energy electron beam (~10 keV/1 A). The magnetic field exceeds 1.63 T, which corresponds to a 45-GHz cyclotron frequency. The CRM radiation output is observed in much lower frequencies, between 6.6 and 20 GHz only. This discrepancy is explained by the finite penetration depth of the electrons into the growing magnetic field, as in a *magnetic mirror*. The electrons emit radiation at the local cyclotron frequency in their reflection point from that magnetic mirror; hence, the radiation frequency depends mostly on the initial electron energy. A conceptual *reflex gyrotron* scheme is proposed in this paper, as a CRM analogue for the known reflex klystron. [S1063-651X(99)00808-9]

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I. INTRODUCTION

Cyclotron-resonance masers (CRM's) [1] have been studied and developed in a variety of schemes. These include gyrotrons [2], cyclotron autoresonance masers [3], and gyroanalogues of linear microwave tubes (i.e., gyroklystrons, gyro traveling-wave tubes, and gyro backward-wave oscillators) [4]. This paper presents a preliminary experiment that may lead to the development of the *reflex gyrotron*, a gyrodevice resembling the reflex klystron.

The tuning relation of the CRM interaction, in general, is given by $\omega=\omega_c+V_\parallel k_\parallel$, where ω and $k_\parallel$ are the [electromagnetic (em)] em-wave angular frequency and axial wave number, respectively. The cyclotron angular frequency is $\omega_c=eB_0/\gamma m$, where e, m, γ, and $V_\parallel$ are the electron charge, mass, relativistic factor, and axial velocity, respectively, and B_0 is the axial magnetic field. The CRM interaction is characterized by the normalized tuning parameter,

$$\hat{\theta}=(\omega-\omega_c-V_\parallel k_\parallel)\tau, \tag{1}$$

where $\tau=L/V_\parallel$ is the electron time of flight along the interaction length L. The CRM interaction occurs near resonance, in the vicinity of $|\hat{\theta}|\leqslant\pi/2$.

The progress in super-conducting-magnet technology enables the development of gyrotrons at the submillimeter range [5] toward the terahertz regime. The availability of strong magnets leads also to the development of CRM devices at lower frequencies, such as the CRM device in a magnetic mirror presented here in which the electrons radiate while they are reflected back from a high-gradient magnetic field.

In a magnetic mirror [6], the moving electrons are reflected back when their magnetic moment, $\mu\equiv W_\perp/B_0$, attains

$$\mu\geqslant\frac{W}{B_p}, \tag{2}$$

where W and $W_\perp$ are the electron (total) kinetic energy and its transverse component, respectively ($W_\perp=mV_\perp^2/2$), and B_p is the axial magnetic field at the reflection point.

An adiabatic variation is assumed for $|\partial B_0/\partial z|\ll\omega_c B_0/v_\parallel$. The magnetic moment varies then as $\Delta\mu/\mu=A\exp(-D\Delta z/r_L)$, where Δz corresponds to a ΔB_0 variation, $r_L=V_\perp/\omega_c$ is the Larmor radius, and A and D are constants [7]. The velocity component $V_\parallel$ is converted then adiabatically to $V_\perp$, until Eq. (2) is satisfied. At this point the electrons are reflected back.

A conceptual scheme of the proposed *reflex gyrotron* is shown in Fig. 1. The static magnetic field varies along the axis, as in a magnetic mirror. The rotating electrons stay longer near the reflection point; hence, the CRM emission at the corresponding cyclotron frequency is enhanced and its spectral linewidth is sharpened [in view of Eq. (1), near the reflection point $V_\parallel\rightarrow 0$ and $\omega\rightarrow\omega_c$]. The reflex gyrotron can be tuned by varying the electrons' penetration depth by their initial energy. [This frequency tuning by varying the electron energy resembles the free-electron laser (FEL) tunability feature.]

II. EXPERIMENTAL SETUP AND PRELIMINARY RESULTS

A general view of the CRM device and its diagnostic setup is shown in Fig. 2. It employs a 3-T pulsed solenoid

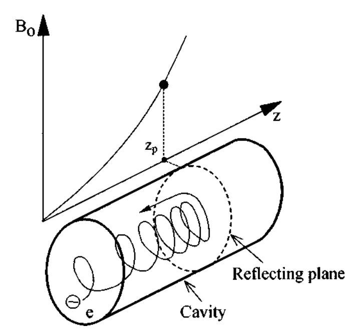

FIG. 1. A conceptual scheme of the reflex gyrotron. The penetration depth of the electrons into the growing magnetic field is denoted by Z_p.

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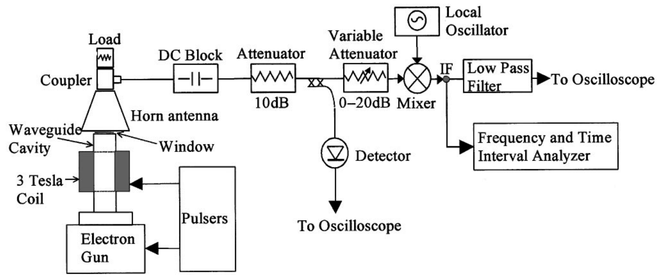

FIG. 2. The CRM experimental setup.

TABLE I. Experimental parameters.

Electron energy	<10 keV
Current	<1 A
Waveguide (WR90)	$0.9\times-0.4\ \mathrm{in}^2$
Magnetic field (peak)	1.63 T
Cyclotron frequency (peak)	45 GHz
em frequency	6.6–20 GHz
Output power	$\sim$1 W
Pulse width	$\sim$1 ms

(intended originally for a short-wavelength gyrotron experiment). The tube consists of a Pierce electron gun and a uniform rectangular waveguide (WR90) cavity. The low-energy electron beam (<10 keV) is injected into the cavity and interacts with the em wave. The experimental parameters are listed in Table I.

The output rf signal is received by a horn antenna (10-dB gain) followed by a dc block, a 10-dB attenuator, and a 3-dB coupler. In one arm, the signal is detected by a HP424*A* power detector. In the other arm, the signal is mixed by a HP5364*A* mixer with the local-oscillator (LO) output (HP83752*A*). The mixer includes an internal 20-dB variable attenuator. The mixer output is filtered by a 20-MHz low-pass filter in the Tektronics Digital Oscilloscope (TDS 540). The spectrum is measured by a frequency-time interval analyzer (HP5372*A*).

The CRM device was operated first at a 1.63-T solenoid field, which corresponds to a 45-GHz cyclotron frequency. The output radiation was observed in much lower frequencies, below 20 GHz. Typical results of the CRM oscillator experiment are shown in Figs. 3(a)–3(d). Figure 3(a) shows the electron gun voltage variation during one pulse (the dots are discrete, digitized measurements; the line is their linear fit). Figure 3(b) shows the corresponding microwave output, which consists of several bursts. Figures 3(c) and 3(d) show the microwave heterodyne detection for $f_{LO}=6.6\,\mathrm{GHz}$ and the instantaneous frequency variations, respectively. A frequency sweep (i.e., chirping) is observed in Fig. 3(d). This sweep follows the electron energy variation shown in Fig. 3(a).

The radiation frequency was measured in various shots in the range 6.6–7.0 GHz, as accumulated in Fig. 4. A slight dependence of the frequency on the electron gun voltage is observed. Figure 5 shows the spectral content in various pulses for fixed electron gun voltage and magnetic field (8 kV and 1.63 T, respectively). The dots represent rms values

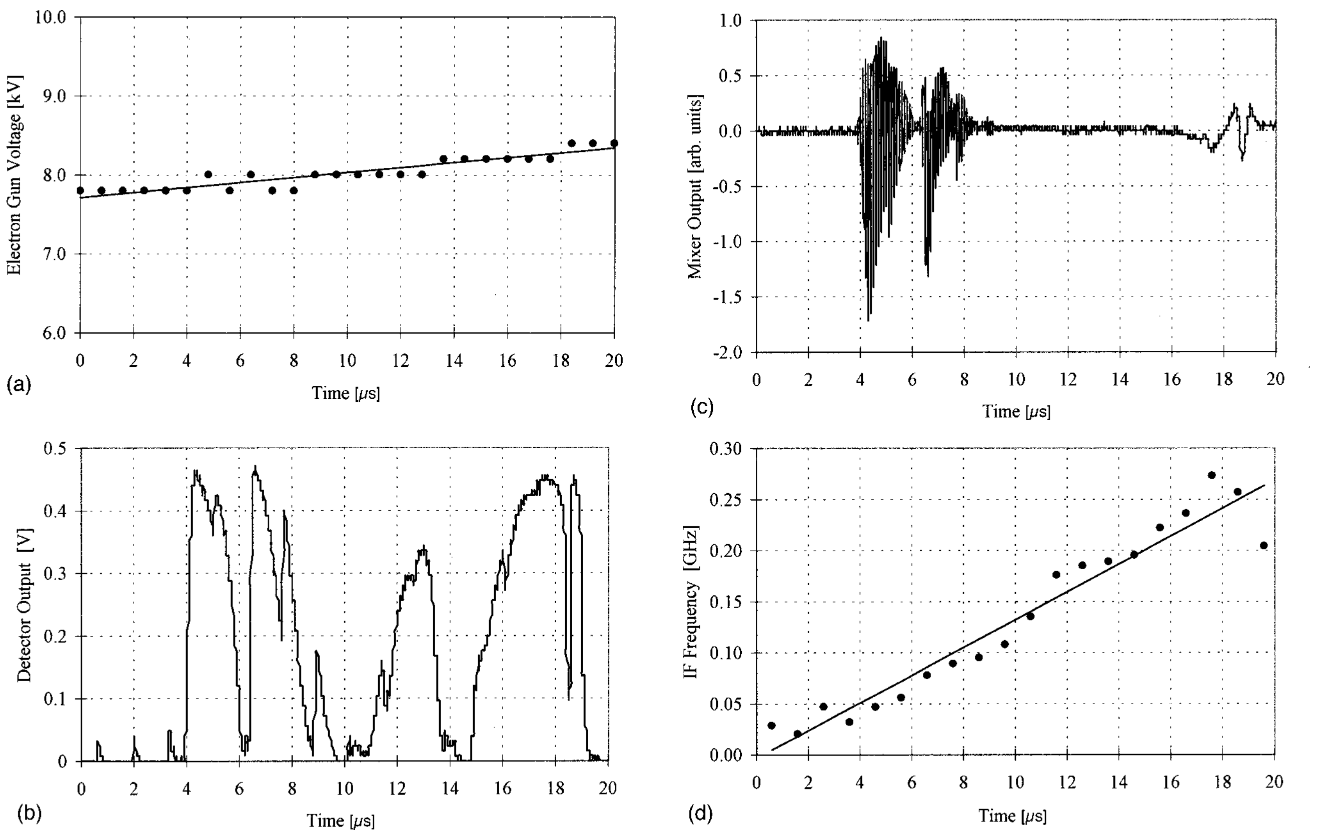

FIG. 3. Experimental results for a 1.63-Tesla solenoid (45-GHz cyclotron frequency). (a) The electron gun voltage. The dots indicate discrete experimental samplings and the solid line is their linear fit. (b) The microwave detected power. (c) The heterodyne mixer output for an LO frequency of 6.6 GHz. (d) The intermediate frequency for an LO frequency of 6.6 GHz.

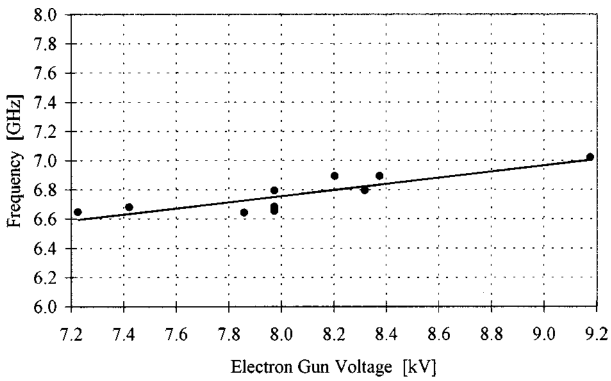

FIG. 4. Center frequencies of the CRM output vs the electron gun voltage in several runs.

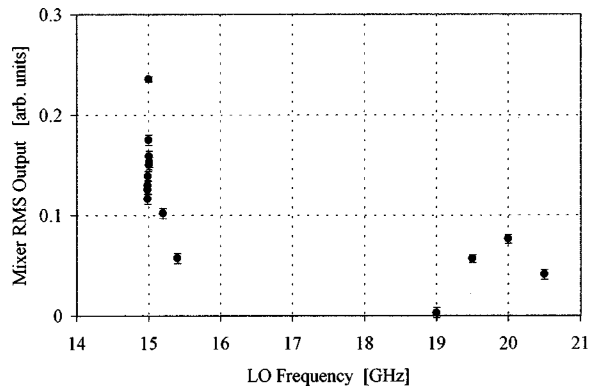

FIG. 5. Spectral content near 15 and 20 GHz. The dots represent rms values of i.f. outputs at different LO frequencies in various shots.

of the mixer output at different LO frequencies between 14 and 21 GHz. This spectral content was measured also by the frequency-time interval analyzer (HP5372*A*). This analysis yielded a sharp spectral line at 15 GHz, while around 20 GHz the spectrum is spread in a ~1-GHz width. These results may indicate oscillations at higher modes. All signals were observed in a vertical polarization (as of the TE_{10} waveguide mode).

III. DISCUSSION

The CRM experiment in a magnetic mirror yielded microwave emission at discrete frequencies, between 6.6 and 20 GHz, in a solenoid field corresponding to a 45-GHz cyclotron frequency. The magnetic-mirror effect was confirmed by electron-trajectory simulations. Similar reflections were found in other magnetic cusps [8,9] but, to the best of our knowledge, this is a first observation of a CRM radiation in such a scheme.

The reflex-gyrotron concept proposed here requires an ''excessive'' magnetic field, as compared to other CRM's, but, on the other hand, it enables a wide tunability by low-energy electrons. The magnetic field can be kept fixed in this device.

The preliminary results presented here may motivate further theoretical and experimental studies in order to characterize the reflex-gyrotron concept in a wide parametric range. In particular, a reflex-gyrotron experiment is designed at Tel-Aviv University using an existing 19-T magnet [10].

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