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Cyclotron resonance maser experiment in a non-dispersive waveguide

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Abstract

A cyclotron-resonance maser (CRM) experiment with a transverse electromagnetic (TEM) wave is presented in this paper. A nonrelativistic electron beam is spiraling in this device in a non-dispersive parallel-line waveguide. The CRM oscillator output frequency is tuned by the axial magnetic field in the range of 3.2–4.8 GHz.

1. Introduction

The cyclotron resonance interaction with transverse electromagnetic (TEM) modes is known to be weaker than cyclotron interactions with other waveguide modes [1,2]. Ref. [3] describes a CRM oscillator experiment operating in a Fabry–Perot cavity. The condition for amplification in this case is defined as [3]

$$V_\perp^2 > 2V_z c, \tag{1}$$

where $V_\perp$ and V_z are the electron perpendicular and axial velocity components. Other CRM experiments in Fabry–Perot resonators are reported in Refs. [4,5]. Theoretical studies of CRM interactions with TEM waves are devoted mainly to quasioptical devices with open resonators [6,7].

The tuning relation of the cyclotron interaction is given in general by

$$\omega = \omega_c \pm V_z k_z, \tag{2}$$

where ω is the em wave angular frequency, and k_z is the axial wavenumber. The $\pm$ signs correspond to interactions with forward and backward waves, respectively. The angular cyclotron frequency is

$$\omega_c = \frac{e}{\gamma m} B_0, \tag{3}$$

where e, m, and γ are the electron charge, mass, and relativistic factor, respectively, and B_0 is the axial magnetic field. The approximate tuning relation of the TEM-CRM interaction results from Eq. (2) for $k_z \cong$ k as

$$\omega = \frac{\omega_c}{1 \mp V_z/c}. \tag{4}$$

For a nonrelativistic electron beam ($|v| \ll c$), the amplification condition in Eq. (1) dictates a very small axial velocity of the electron beam. Hence, the Doppler shift in Eq. (4) is relatively small, and $\omega \cong \omega_c$. In addition, the slow electron velocity increases the effective space-charge density.

In this paper we describe a nonrelativistic table-top CRM oscillator in which a long-wavelength TEM wave is supported by a nondispersive parallel-line waveguide [8]. Radiation is observed in the cyclotron frequency whenever the electron beam acquires a large transverse velocity by a magnetic kicker.

3. Experimental setup

The TEM cyclotron device used in our experiment is shown in Fig. 1. The metallic waveguide consists of a WR90 rectangular tube with two parallel wires along it. They support odd and even TEM modes in frequencies below the empty waveguide cutoff. A low-energy electron beam is orbiting in an externally applied axial magnetic field. The orbiting motion of the electrons couples them synchronously to the electromagnetic wave in the non-dispersive waveguide.

The experimental apparatus is based on the setup of the periodic-waveguide CRM experiment at Tel Aviv Univer-

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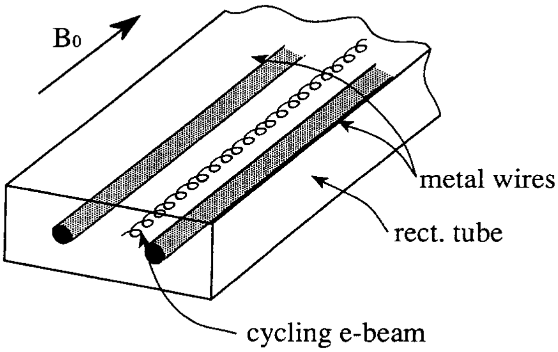

Fig. 1. Schematic of the TEM-mode cyclotron maser device.

sity [9,10]. The oscillator tube consists of a planer-diode electron gun, a non-dispersive parallel-line waveguide (shown in Fig. 1), a solenoid, and a kicker coil. A low-energy, low-current electron beam (< 5 keV, < 1 A) is injected into the waveguide and interacts with the TEM wave. The uniform solenoidal magnetic field maintains the electron cyclotron motion along its axis. The electron beam is dumped at the exit of the interaction region onto a collector which is also used to measure the electron current.

Three synchronized pulsers generate the solenoid, the e-gun, and the kicker pulses, as described in Ref. [10]. The electron gun high-voltage pulser (1 ms pulse width) [11] and the high-current kicker pulser are triggered at the peak of the 25 ms width solenoid pulse.

The impedance of the parallel-line waveguide in the odd TEM mode is ~ 200 Ω. The waveguide is terminated in the CRM oscillator cavity by two partial mirrors at both ends. The mirror near the electron gun has a hole at the center for the electron beam entrance. The mirror at the collector has an SMA (50 Ω) RF connector attached to each wire. These terminations form a cavity with a low qaulity factor ($Q < 200$).

The low-energy solid electron beam is generated by a simple planar diode electron gun, which consists of a

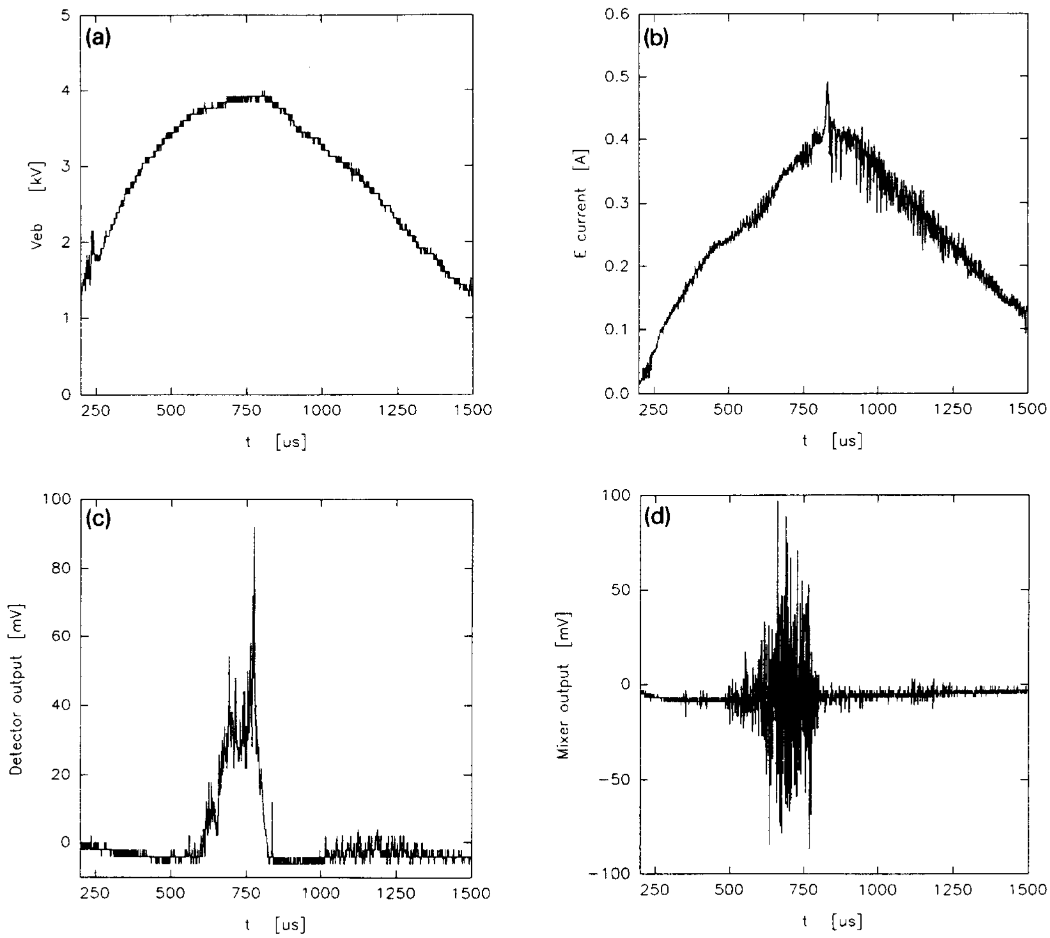

Fig. 2. Typical experimental results of the TEM-CRM oscillator. (a) The electron gun voltage. (b) The electron beam current measured in the collector. (c) The microwave detected output power. (d) The heterodyne mixer output.

dispenser thermionic cathode (Spectra-Mat, STD200) and a planar anode. The electron beam diameter is 4 mm and its filling factor for the odd TEM-mode is estimated to be 2.5%. A kicker coil spins up the electron beam at the entrance to the solenoid. The axial solenoid field is 1–2 kG. The waveguide is terminated by a collector section connected to ground by a 10 Ω resistor which measures the electron current.

The RF power generated in the cyclotron oscillator is coupled by a small dipole antenna into a WR187 waveguide section which acts as a high-pass filter (its cutoff frequency is 3.15 GHz). The signal is coupled out by a coaxial probe and is split into two arms, as in Refs. [9,10]. In the power measurement arm, the signal is attenuated and detected by an HP424A power detector. In the heterodyne measurement arm, the signal is mixed with a fixed LO signal from an external RF oscillator. The mixer output is filtered by the internal 20 MHz low-pass filter of a Tektronix TDS 540 digital oscilloscope. This heterodyne measurement shows the spectral contents of the CRM oscillator output shifted by the LO frequency. Typical output signal measurements are presented in the next section.

4. Experimental results

Typical results of the TEM-CRM oscillator experiment are shown in Figs. 2a–2d. Figs. 2a and 2b show the electron gun voltage variation during the pulse and the corresponding electron beam current measured in the collector section, respectively. Figs. 2c and 2d show the detected microwave power and the corresponding microwave heterodyne detection output, respectively.

The output signal of the mixer shown in Fig. 2d is observed with an LO frequency of 4.5 GHz and a solenoid field of ~1.6 kG. Hence, the corresponding cyclotron frequency is close to the radiation frequency within the accuracy limit of the experimental setup. According to the tuning relation of Eq. (4), the result $\omega \cong \omega_c$ indicates that $V_z \sim 0$, and, consequently, the CRM operates with a large pitch ratio $V_\perp \gg V_z$. The total electron velocity in this experiment is $0.12c$, and it turns out that most of it is imparted to the transverse cyclotron motion.

The oscillator frequency is tuned by varying the solenoid field. The heterodyne results in Fig. 3 show the mixer output (RMS) for various LO frequencies, with different solenoid fields. The CRM tunability in this setup is demonstrated in the frequency range of 3.2–4.8 GHz. Lower frequencies are measured as well without the high-pass filter at the exit of the cavity. The spectral contents of the TEM-CRM emission for each value of the solenoid field is close to the corresponding cyclotron frequency (3), with some line widening. The bandwidth observed is ~10%. It is considerably larger than expected from the axial velocity spread of the spiraling electron beam (~2% to satisfy the condition in Eq. (1)). This line widening is explained by the nonuniformity of the solenoid field at its ends, and by the narrow spikes observed in the oscillator output. A tunability range of over one octave in the range 2–5 GHz is observed in this experiment without the high-pass filter.

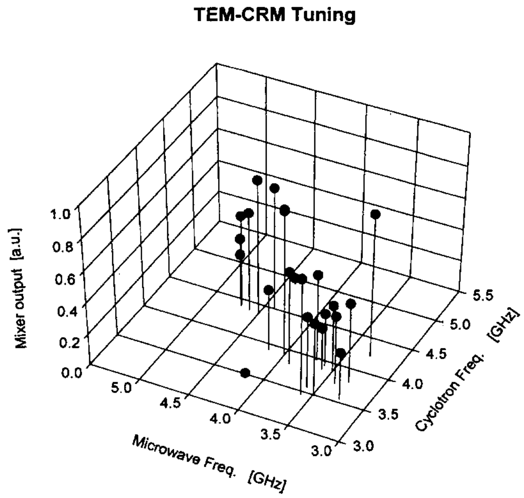

Fig. 3. Output heterodyne signal (RMS) measurements for various LO and cyclotron frequencies.

5. Conclusions

The cyclotron maser oscillator experiment presented in this paper shows a strong cyclotron interaction between a low-energy electron beam orbiting in an axial magnetic field and a TEM wave propogating in a nondispersive waveguide. The coupling occurs only with a considerable kicker field. The kicker induces a large transverse electron velocity component, as required by Eq. (1). A wide tunability of the TEM-CRM is demonstrated in this experiment.

Further studies of the TEM-CRM device are needed in order to investigate the effects of the electron velocity spread, and to examine novel kicker mechanisms. Our recent experimental results show, however, the feasibility of a long-wavelength nonrelativistic CRM device in a non-dispersive metallic waveguide.

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