V. Conclusions

The performance of a 10-GHz balanced FET FMCW transceiver has been investigated and compared with a similar unbalanced transceiver. The FETs in the transceiver are operated simultaneously as amplifiers and FET resistive mixers. This circumvents the need for separation between the transmitted and received signals, thus making it suitable for integration in MMIC technology.

The use of a balanced circuit topology improves the AM noise performance by typically 20 dB. The output power is 14 dBm at 7-dBm input power. Similar to the unbalanced transceiver, the balanced circuit is very robust against bias variations.

Acknowledgment

The authors thank Dr. N. Rorsman, Department of Microelectronics, Chalmers University of Technology, Göteborg, Sweden, for fruitful discussions and the reviewers for valuable comments and suggestions.

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A Microwave Gyro Amplifier With a Ferroelectric Cathode

Moshe Einat, Eli Jerby, and Gil Rosenman

***Abstract*—A ferroelectric cathode is employed for the first time as the electron-beam source in a microwave amplifier tube. A PLZT 12/65/35 ferroelectric ceramic with a high dielectric constant ($\varepsilon_r \sim 4000$) is used in a form of a hollow cathode. The tube is operated in poor vacuum conditions (2×10^{-5} Torr) at room temperature, in a mechanism of a cyclotron-resonance maser amplifier. The device operates near the waveguide cutoff frequency at 6927 MHz. A 22-dB electronic gain and a 25-W output power are measured in this experiment.**

***Index Terms*—Cold-cathode tubes, electron emission, electron guns, ferroelectric materials, gyrotrons.**

I. Introduction

The electron gun and, more specifically, the cathode, are key elements in the design of any microwave tube [1]. In particular, cyclotron-resonance masers (CRMs) and gyro-devices can be further developed if new types of cathodes would be available. Recent records of gyro-amplifier studies, presented in [2]–[5], encourage the investigation of new types of cathodes for these devices. This paper presents a study of a ferroelectric cathode operating for the first time as an electron source for a gyro-amplifier.

The ferroelectric cathode has useful features, such as a high-density electron emission at room temperature in poor vacuum condition ($\sim 10^{-5}$ Torr). Its turn-on time is short, and it does not need any activation process. The ferroelectric cathode is easy to fabricate and it is made of low-cost materials. On the other hand, ferroelectric cathodes have a limited lifetime [6]. Studies of the electron-energy spectrum of the PLZT 12/65/35 ferroelectric cathode showed that its electron-energy spread is as large as $\sim$100 eV [7]. However, demonstrations of practical applications based on ferroelectric cathodes are still rare.

Early observations of electron emission from ferroelectrics induced by a polarization switching [8], and subsequent reports on generation of high electron current densities by ferroelectric ceramics (reaching 10^3 A/cm^2) [9], [10], stimulated development of ferroelectric cathodes by several research groups [11]–[17]. Detailed studies showed that the strong emission evolves surface flashover plasma generation, which damages the cathode surface [6], [14]–[17].

The first microwave oscillator using a ferroelectric cathode was demonstrated in our previous study [18], [19]. In the present experiment, the ferroelectric cathode serves as a hollow electron-beam source in a CRM gyro-traveling-wave tube (TWT) amplifier experiment. This CRM amplifier, operating in the fundamental gyrotron mode [20] near the cutoff frequency of the circular waveguide, tolerates the wide electron energy spread of the ferroelectric cathode. Demonstration of such a microwave amplifier may motivate the development of various low-cost devices based on ferroelectric cathodes.

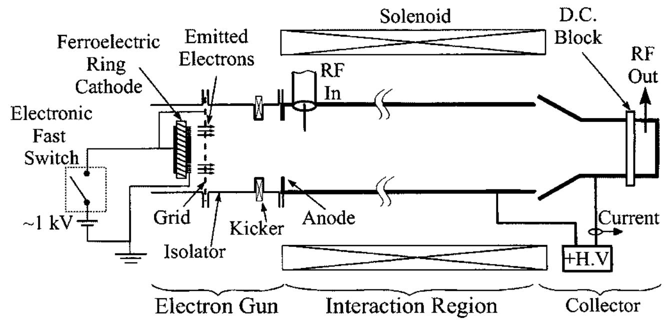

Fig. 1. Experimental gyro-amplifier device with a ferroelectric cathode.

II. Experimental Setup

The experimental device is shown in Fig. 1. It is comprised of an electron-gun section, a CRM interaction region, and a collector section. The electron gun is based on a ferroelectric ring cathode made on a $10 \times 10 \times 1$ mm^3 PLZT 12/65/35 ceramic plate [7]. The contact is made by silver paint at the rear (nonemitting) side of the ferroelectric plate. In the front (emitting) side, the electrode is made of a stainless-steel grid, in a ring shape of 5 and 8 mm inner and outer diameters, respectively. A metallic electrode covers the inner circle of the ring surface. The rear electrode is activated by a positive pulse of $\sim$1 kV, $\sim$0.25 μs, where the front side is grounded. The first accelerating electrode is placed 5 mm in front of the cathode emitting side. This electrode, made of a stainless-steel grid, is electrically connected to the rear electrode. A dc accelerating voltage in the range of 8.5–12.5 kV is applied on the accelerating anode, at the entrance to CRM interaction region.

Manuscript received May 3, 2000; revised April 30, 2001.

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Publisher Item Identifier S 0018-9480(02)03025-9.

TABLE I
EXPERIMENTAL PARAMETERS

Experimental Parameters		
Waveguide		
Diameter	26	[mm]
Interaction length	400	[mm]
Electron beam		
Emitting voltage	1	[kV]
Accelerating voltage	8.5-12.5	[kV]
Beam current	0.1-0.4	[A]
Pulse width	0.25	[μs]
Magnetic field	~2.5	[kG]
Pitch ratio ($v_\perp/v_z$)	~4	
Amplified signal		
Frequency	6,927	[MHz]
Electronic gain	22	[dB]
Output power:		
beam off	0.16	[W]
beam on	25	[W]
Electronic efficiency (small signal)	1-2 %	

Two significant limitations of the ferroelectric cathode are the development of voltage breakdowns and the electrons' relatively large velocity spread, both due to the plasma involved in the emission process. The electron gun is designed to overcome plasma breakdown problems by several means. The electrons are emitted and pulled out of the ferroelectric ceramic by a relatively low-voltage pulse ($\sim$1 kV) simultaneously with the short trigger pulse. The electrons are then accelerated to the required energy ($\sim$10 keV) by the accelerating anode. Breakdowns between the cathode and anode are not developed because the grid electrode in the middle is grounded immediately after the pulse. Also, the energy spread of the electrons is limited by the emission extracting voltage from the cathode. The two-stage accelerator enables to extract the electron at a low voltage and, therefore, with a low energy spread (determined only by the first stage). Since the main acceleration is obtained by a dc voltage separated from the cathode, this voltage and, thus, the acceleration, are stable during the current pulse. Hence, the energy spread is reduced to an acceptable level for the gyrotron interaction. Without this separating arrangement, no signals were obtained.

The CRM interaction section is made of a copper cylindrical waveguide (26-mm diameter). The input microwave signal is fed by a coaxial transmission line. The operating waveguide mode is TE_{11}. The output is terminated to a horn tapered to a WR-90 rectangular waveguide. The waveguide is connected to the high dc voltage, which accelerates the electrons at the entrance to the tube. In the collector section, the rectangular waveguide is connected to the same potential as the waveguide. The microwave output is fed through a dc block to microwave attenuators and diagnostic elements. The electron-beam current is dumped and measured in the collector section.

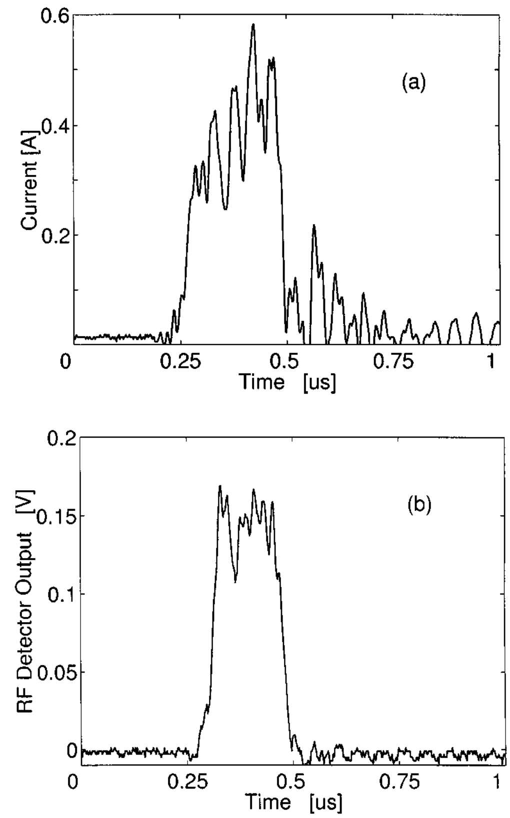

Fig. 2. Typical CRM experimental run with the ferooelectric cathode. (a) Current pulse measured at the collector. (b) Amplified microwave signal.

A solenoid generates the axial $\sim$2.5 kG magnetic field. A short kicker coil induces a strong gradient in the magnetic field; thus, the electrons acquire a transverse velocity component. A pitch ratio of $v_\perp/v_z \cong 4$ (where $v_\perp$ and v_z are the transverse and axial electron velocity components, respectively), as calculated by the EGUN simulation code [21], was needed to obtain a reasonable amplification. The cathode, solenoid, and kicker geometries were determined according to the simulation results. The cylindrical waveguide is located inside the solenoid, whereas the collector is outside the solenoid bore. The electron-beam current is measured by a Rogovsky coil.

The diagnostic section is comprised of attenuators, a power divider, a spectrum analyzer, and a calibrated crystal detector ($\pm$1 dB). The output voltage of the crystal detector is traced by an oscilloscope. The spectrum analyzer is operated in a zero-span mode for the input signal frequency (6927 MHz) with a 3-MHz bandpass filter. The video signal detected by the spectrum analyzer is also traced on the oscilloscope. A cold measurement of the transmission through the device (without the electron beam) indicates a 10-dB transmission loss (i.e., the 1.6-W continuous wave (CW) microwave signal at 6927 MHz injected into the device appears as a 0.16-W signal at the output). Table I summarizes the experimental parameters.

III. EXPERIMENTAL RESULTS

A typical run of the CRM amplifier with a ferroelectric cathode is presented in Fig. 2(a) and (b). The current pulse emitted by the ferroelectric cathode is shown in Fig. 2(a), as measured at the collector for an accelerating dc voltage of 12.5 kV, and an axial magnetic field of 2.5 kG (the current loss and reflection were not measured). Since the electron emission is a plasma-assisted effect, the current pulse is not as smooth as obtained from a thermionic cathode. The amplified microwave signal, at a frequency of 6927 MHz, is presented in Fig. 2(b).

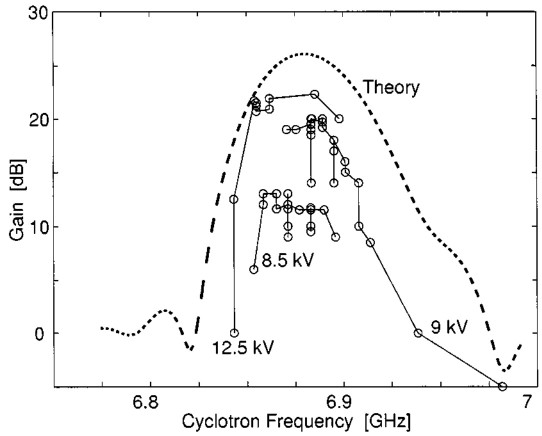

Fig. 3. Amplifier gain dependence on the cyclotron frequency for three different accelerating voltages of 8.5, 9, and 12.5 kV. The dashed curve shows the theoretical result for 12.5 kV.

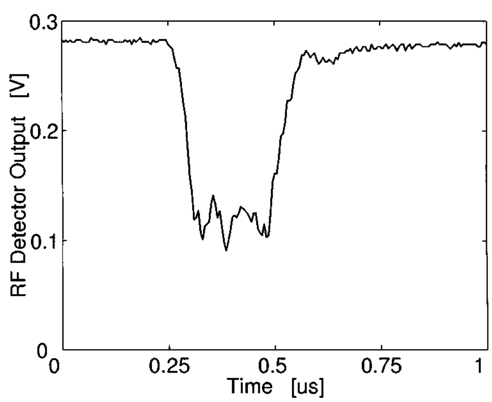

Fig. 4. CRM absorption measured in a slight off-tuning CRM operating condition.

The output signal level measured without the electron beam is 22-dBm CW. During the current pulse, the output signal increases to 44 dBm. This amplification corresponds to an electronic gain of 22 dB. Similar results were measured in these conditions in many shots. Furthermore, no output signals were measured during similar shots in which the input signal was turned off.

An accumulation of $\sim$50 runs of the CRM amplifier form its gain dependence on the cyclotron frequency (i.e., on the axial magnetic field), as presented in Fig. 3. (The theoretical result shown in the dashed line is discussed later.) The experimental upper curve was obtained in an accelerating voltage of 12.5 kV and an input signal frequency of 6927 MHz in various magnetic fields (varying from shot to shot). Thus, the output power versus the cyclotron frequency is obtained. A maximal gain of 22 dB is measured in a $\sim$50 MHz band of the cyclotron frequency. The gain in two other accelerating voltages (8.5 and 9 kV) at the same frequency is also shown. Since the input signal was small, the device operated in the linear regime where the electronic efficiency was a few percent.

Another confirmation for the CRM interaction is obtained by a slight shift in the magnetic field, out of the CRM amplification tuning range. As expected, a CRM absorption of the input microwave signal is observed. Typical signal absorption is shown in Fig. 4. In this result, a CRM absorption of 5 dB is measured at a 9-kV accelerating voltage, a 2.54-kG magnetic field, and a 6927-MHz cyclotron frequency. A larger shift in the magnetic field, outside the CRM tuning range, results in no variation in the output signal during the electron-beam pulse.

IV. Conclusions

This experiment demonstrates the first implementation ever reported of a ferroelectric cathode in any microwave amplifier tube. The CRM amplifier yielded a 22-dB amplification and a 25-W output power at 6927 MHz in a 0.25-μs pulse. A verification of the CRM amplification (rather than oscillations) was done by a spectrum analyzer tuned to the input signal frequency. Measurements at the CRM operating frequency $\omega = \omega_c + k_z v_z$ and at slight and large deviations from it, verified the amplification mechanism as a CRM, operating in a gyro-amplifier mode, near the waveguide cutoff frequency. The Doppler shift measured ($\sim$80 MHz) coincides with the axial velocity ($v_z \cong 0.05c$, where c is the speed of light) for the calculated pitch ratio $v_\perp/v_z \cong 4$.

The theoretical gain curve in Fig. 3 was calculated by a linear CRM gain equation [22] for a cold electron beam. The electron-beam current in this calculation, i.e., 0.1 A, is smaller than measured in the collector in order to compensate for the cold electron-beam model. The calculation for 6927-MHz and 12.5-kV accelerating voltage results in a maximum gain of $\sim$25 dB without including the electron energy spread. The theoretical gain curve resembles the experimental results shown in Fig. 3, whereas the pitch ratio of $v_\perp/v_z \cong 4$ found by an electron trajectory simulation is verified. The smaller gain in the experiment can be attributed to the electron-beam spread.

The practical CRM device might be limited, however, by the known ferroelectric cathode restrictions, i.e., only a short pulse operation is available and the repetition rate is limited, as well as the lifetime of the cathode [23]. Considering these limitations, in view of the advantages, it seems that the ferroelectric cathode can fit into a new niche of low-cost microwave devices operating in short pulses for a limited lifetime. This understanding leads us to the new concept of disposable microwave tubes [24].

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A Novel Tap Input Coupling Structure for a Narrow Bandpass Filter Using TM_{010} Mode of a Microstrip Circular-Disk Resonator

Kenneth S. K. Yeo and Michael J. Lancaster

***Abstract*—This paper discusses a new method to couple into the TM_{010} mode of a microstrip circular-disk resonator. This method can achieve reasonably strong input coupling, which is useful for narrow-band filters with fractional bandwidths of approximately 0.5% and above. A comparison between this newly proposed input coupling structure and the conventional gap input coupling structure will be addressed. A decision threshold for using either the tap input or the conventional gap-coupled input is also explained. Experimental results of a filter fabricated using this novel input coupling structure is also presented.**

***Index Terms*—Disk resonator, filter, HTS.**

I. Introduction

The TM_{010} mode of a microstrip circular-disk resonator is a very promising structure for high-power high-temperature superconductor bandpass filters because of its edge-free current distribution [1]. This paper presents a new input coupling structure for the TM_{010} mode of microstrip disk resonator, which can achieve the required input coupling for narrow-band filter design. This input coupling is controlled by tapping between the open- and short-circuit points along the radius of the microstrip circular disk.

Conventionally, input gap coupling is used to couple into the disk resonator [2]. The disk filter in [2] employs the TM_{110} mode instead of the TM_{010} mode, which is discussed here. Since the charge density of the TM_{110} mode of circular disk is maximum at the edge [3], reasonably strong coupling can be achieved using the gap-coupled input. However, gap coupling for the TM_{010} mode is very weak because charge density is not maximum at the edge. Therefore, it can only be used to design very narrow-band filters, i.e., smaller than 0.5% of fractional bandwidth (FBW).

Another method to couple into the TM_{010} mode of circular disk is to use a coupling pin, which is inserted onto the top of the disk (without touching) [4]. This method provides similar coupling strength compared to the gap-coupled input because the coupling mechanism is through the charge density (or electric field). This method has its advantages over the gap-coupled input because no perturbation of the disk is introduced. However, the pin-coupled input is difficult to control because positioning of the pin is subject to mechanical machining tolerance. Furthermore, the external Q factor using this method is also difficult to determine using planar electromagnetic (EM) simulators. It should be pointed out here that the input coupling and the external Q factor are inversely proportional [5] and both terms are used extensively in this paper.

The newly proposed method in this paper also has a disadvantage, which is the slight perturbation of the disk, but it can provide reasonably strong input coupling. Furthermore, the external Q factor can be easily determined using a planar EM simulator. Due to this factor, this method is useful for practical filter design.

II. Input Coupling

A microstrip disk resonator is a circular conducting disk patterned onto a dielectric substrate with a ground plane on the opposite side. The tap input coupling can be easily achieved by making a via through the dielectric substrate and ground plane to the patterned disk resonator. However, for a high-temperature superconductor thin film, which grows on a single crystal substrate, i.e., magnesium oxide (MgO), lanthanum–aluminate ($LaAlO_3$), or sapphire, making a via through the ground plane cannot be easily achieved. For this case, the tap input can only be achieved by making a notch into the disk resonator and inserting the 50-Ω feed line into the disk, as shown in Fig. 1(a).

The external Q factors of the input feed can be varied by changing the tap location T along the radius of the disk. The current distribution flows radially with the minimum at the center and the edge of the disk and the peak at about one-half the radius. A plot of the normalized current distribution is shown in Fig. 2. This plot is based upon the theoretical model for the field equations [6] of the microstrip circular-disk resonator. The X- and Y-axes are normalized to the radius R of the disk.

The external Q factor of the new tap input structure is simulated using ***em*** Sonnet [7]. To make comparison between the new tap input and the conventional gap coupled, a similar structure is also simulated, as shown in Fig. 1(b). The simulation results are shown in Fig. 3. The insertion point t is normalized to the radius of the disk, i.e.,

$$t = \frac{T}{R} \tag{1}$$

Manuscript received August 9, 2000. This work was supported by the Engineering and Physical Sciences Research Council, U.K.

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Publisher Item Identifier S 0018-9480(02)03027-2.