Experimental Observation of Coherent Millimeter Wave Radiation in a Folded Waveguide Employed with a Gyrating Electron Beam

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The first experimental observation of a strong millimeter wave radiation from a gyrating electron beam propagating through an *H*-plane bend rectangular folded waveguide is reported. Measurements of power, frequency, and relative phase change of both forward- and backward-wave radiations verified that the oscillation originated from an absolute instability near a stop band of the second space harmonic. A high power radiation of 5.5 kW which corresponds to an electronic efficiency of 24% was observed at 32.8 GHz. [S0031-9007(96)00363-8]

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Developments of coherent high power, millimeter wave radiation sources are continuing in many institutions throughout the world; to name a few of the leading institutions, there are Naval Research Laboratory, National Tsinghua University, Institute of Applied Physics of the Russian Academy of Science, MIT, UC Davis, and the University of Maryland. Fastwave gyrodevices which have the phase velocity of the guided wave greater than the speed of light are particularly attractive because of large transverse dimension and thus high power handling capability. Recently, a high power (~8 kW) broadband (bandwidth ~20%) Ka-band gyrotron traveling-wave-tube (gyro-TWT) amplifier has been successfully demonstrated at Naval Research Laboratory using a tapered two-stage waveguide and a precise nonlinear tapered magnetic field [1]. As a continuing effort on the development of compact and robust circuits applicable for system use, hybrid circuits such as an *H*-plane bend rectangular folded waveguide circuit [2] and a staggered coupled cavity circuit [3] were invented and are currently under both theoretical and experimental investigations. Although the *H*-plane bend folded waveguide circuit looks similar to an *E*-plane bend serpentine waveguide operating with a Pierce-type linear beam [4], there is a notable difference that the rf electric field orientation in the *H*-plane bend folded waveguide is perpendicular to the gyrating beam propagation direction so that the beam-wave interaction takes place between the transverse electric field and an electron transverse momentum. The gyrating electron beam passes through the narrow wall of the rectangular serpentine waveguide and periodically interacts with the transverse electric field. The beam-wave interaction of the *H*-plane bend folded waveguide circuit is based on an electron cyclotron resonance (ECR) instability in which an azimuthal phase bunching of the gyrating beam dominates. It has some advantages over other devices in that the circuit is compact and robust, and it is easy to use a depressed collector due to natural beam separation from radiation. In this Letter, we report the first experimental observation of coherent millimeter wave radiation in the *H*-plane bend folded waveguide circuit from the gyrating beam produced by a magnetron-injection gun (MIG).

An experimental layout of the proof-of-principle folded waveguide tube is shown in Fig. 1. The interaction circuit is a periodic (12 periods), *H*-plane bend, rectangular folded waveguide which supports the lowest TE_{10} mode. A conventional double anode MIG was used to produce an electron beam of 31.3 kV and 0.8 A. Metal and ceramic rings (80% BeO, 20% SiC) were inserted into the beam compression region between the electron gun and the circuit in order to suppress undesired oscillations. A capacitive probe located right before the circuit entrance was used to measure a beam axial velocity and thus a beam velocity ratio, $\alpha = v_t/v_z$, where v_t and v_z are beam transverse velocity and axial velocity, respectively. A three-sector (120° apart, and electrically isolated) beam position monitor was placed between the capacitive probe and the circuit in order to align beam axis with circuit axis. Note that the two waveguide ends of the folded waveguide circuit can be used for monitoring both a backward growing wave and a forward growing wave simultaneously. The radiations extracted from the two open waveguide ends of the

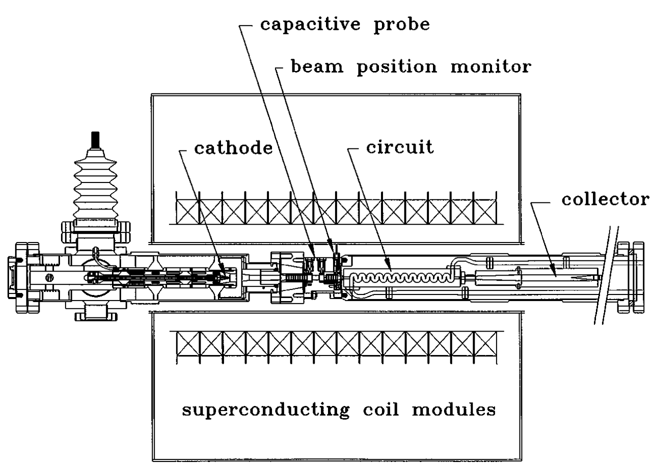

FIG. 1. Experimental layout of a 12 period folded waveguide tube.

circuit were guided through standard Ka-band waveguides (WR-28) to vacuum windows made of 0.001" thick mica followed by an integrated millimeter wave diagnostic system. The two guided radiations were attenuated through several directional couplers and attenuators, and they were combined through a matched magic tee with a phase shift. Power and frequency were measured by the use of peak power meters and reactive cavity-type frequency meters.

Like other periodic structures [5], the folded waveguide circuit has space harmonics originating from the periodic nature of waveguide bends and beam holes. A circuit dispersion diagram obtained from an equivalent circuit model [6] is shown in Fig. 2. The first stop band near 27 GHz was eliminated by a mode coalescing technique [6]. Therefore, the second stop band near 33 GHz becomes the lowest stop band in this circuit.

Experiments were carried out to examine beam-wave interaction near the second stop band by adjusting a beam cyclotron mode to the second space harmonic of the waveguide mode. Here, the beam cyclotron mode is given by $\omega = \Omega_c/\gamma + k_z v_z$ and the uncoupled space harmonic waveguide mode is written as $\omega^2 = \omega_{\mathrm{co}}^2 + (k_{zm}c)^2$, where Ω_c is the cyclotron frequency, γ is the relativistic factor, k_z is the propagation constant along the beam direction, ω_{co} is the cutoff frequency of the rectangular waveguide, $k_{zm} = k_z + 2\pi m/\ell$, ℓ is the periodicity length, m is the space harmonic number, and c is the speed of light. Strong oscillations of both the forward wave and the backward wave were simultaneously observed. This observation is different from the previous gyrotron-backward-wave oscillator (gyro-BWO), where the oscillation amplitude grows in the backward direction only [7]. Typical oscilloscope traces of beam voltage, collected current, and radiation pulse shapes are shown in Fig. 3, where the cathode voltage is 31.3 kV, the current is 0.42 A, and an external magnetic field is 12.27 kG. From total waveguide attenuations of 61.21 $\pm$ 0.5 dB for the forward wave and 60.56 $\pm$ 0.5 dB for the backward wave, the forward- and backward-wave powers were measured at 0.7 and 0.8 kW, respectively. The radiation frequencies identified by the frequency meters and a mixer were both 32.8 GHz. In order to make a cross-check of the power and frequency measurements, a phase interferometer composed of the matched magic-tee and the phase shift was used to combine the forward- and backward-wave powers and to measure the total radiation power. Taking into account insertion losses of the phase shift and the magic tee, the total attenuation of the combined signal was 61.69 $\pm$ 0.5 dB. The combined power as a function of relative phase difference between two coplanar arms of the magic tee is shown in Fig. 4. It clearly shows a sinusoidal variation of the combined power with a maximum power of 1.4 kW (sum of individually measured forward and backward powers) when the two incoming radiations are in phase and a zero power when they are 180° out of phase. The absence of beat wave of the combined radiation in Fig. 3(e) confirms that the forward and the backward waves have the same frequency at 32.8 GHz. The *in situ* measurements of power and frequency of the forward- and backward-wave radiations and relative phase change of the combined power suggest that the measured oscillation attributes to an absolute instability. When the absolute instability takes place close to zero group velocity near the second stop band, rf power at a given frequency grows with time at every point in space [8]. Hence, the waveguide carries equal power in both the forward and backward waves having the same frequency.

Figure 5 shows combined radiation power and efficiency as a function of the beam current. The radiation power grows as the beam current increases and saturates at an efficiency of ~10% at ~0.5 A. When the current

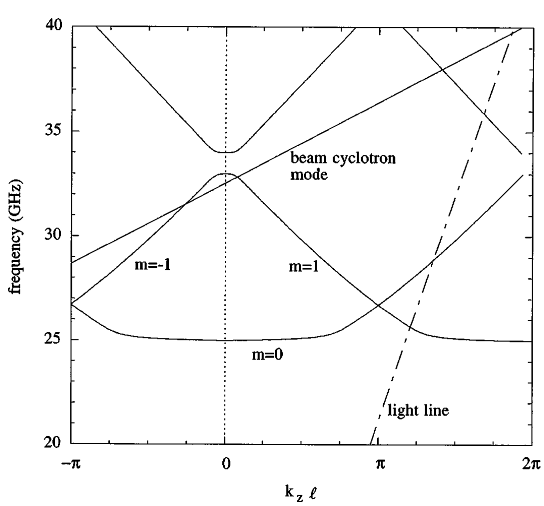

FIG. 2. Dispersion diagram of the folded waveguide circuit.

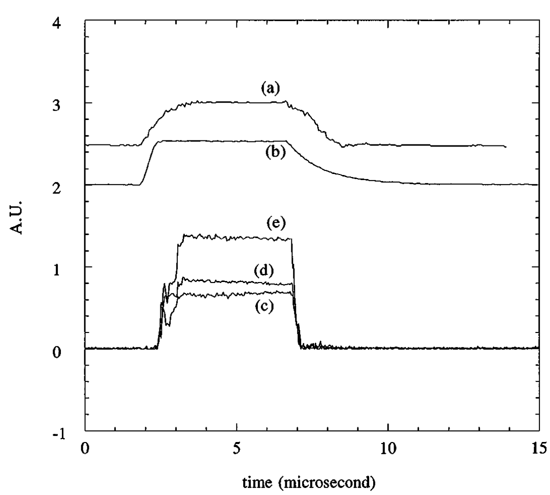

FIG. 3. Typical oscilloscope traces of (a) collected beam current (0.42 A), (b) beam voltage (31.3 kV), (c) forward wave power (61.21 dB attenuation), (d) backward wave power (60.56 dB attenuation), and (e) combined power from a magic tee (61.69 dB attenuation).

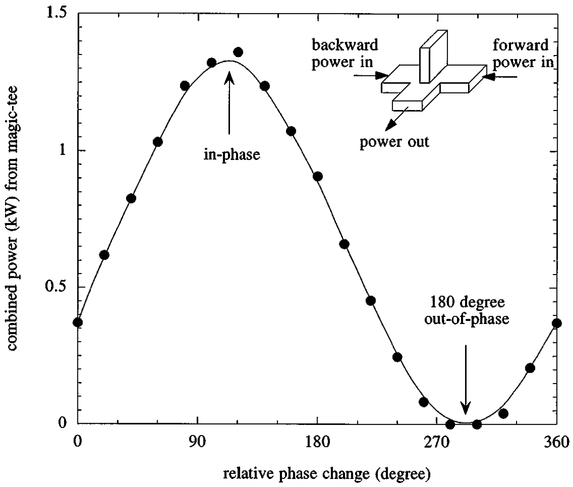

FIG. 4. Combined power variation as a function of phase change in the magic tee.

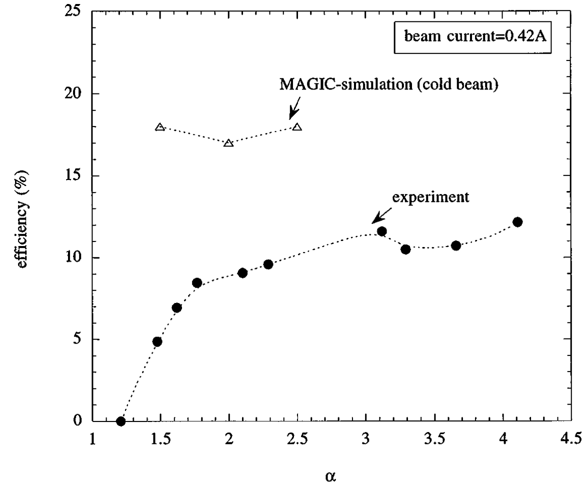

FIG. 6. Efficiency dependence of the beam velocity ratio, α.

increases further, the collector current decreases, indicating that a strong azimuthal modulation leads to a beam loss in the circuit. Note that the backward wave power continuously grows as the beam current increases above 0.5 A, whereas the forward-wave power remains constant. This is probably due to the fact that the backward-wave interaction takes place mainly in the first part of the circuit, and therefore the beam loss in the middle of circuit does not affect the power growth of the backward wave [9]. Figure 6 shows a plot of efficiency dependence on the beam velocity ratio, α, where the beam velocity ratio was changed by varying a modulated anode voltage and the beam current was fixed at 0.42 A. A fully relativistic $2\frac{1}{2}$-dimensional particle-in-cell code, MAGIC [10] was used to compare with the experiments where a cold electron beam emission was assumed in all MAGIC simulations. The discrepancy between the measured and simulated efficiencies is believed to be due to the large beam velocity spreads in experiments. An electron trajectory code, a modified Herrmannsfeldt code [11], was used to compare with the measured beam velocity ratio and estimate the beam velocity spread. Figure 7 depicts the beam velocity ratio and the axial velocity spread, $\Delta v_z/v_z$, as a function of the modulated anode voltage measured with respect to the cathode voltage of 31.3 kV. The measured velocity ratio agreed reasonably well with the prediction, and the estimated axial velocity spreads were 17% and 50% at $\alpha = 2$ and 3, respectively. This large spread is due to a large magnetic field compression (compression ratio = 12) to reduce a beam size for achieving a 100% beam transmission through the beam tunnel. The compression was about twice as large as the original design of the MIG. To

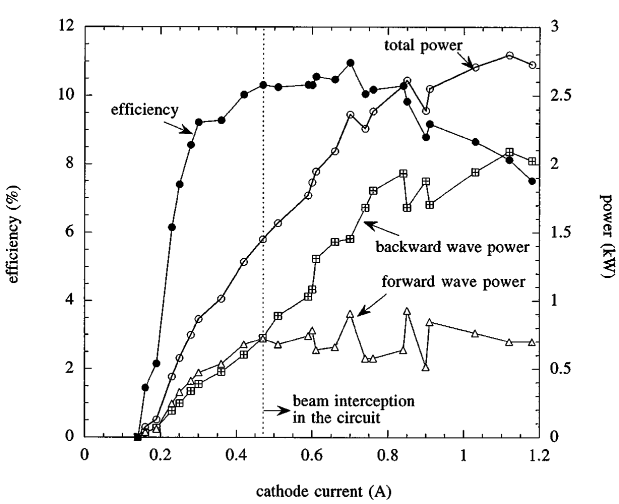

FIG. 5. Radiation power and efficiency as a function of beam current.

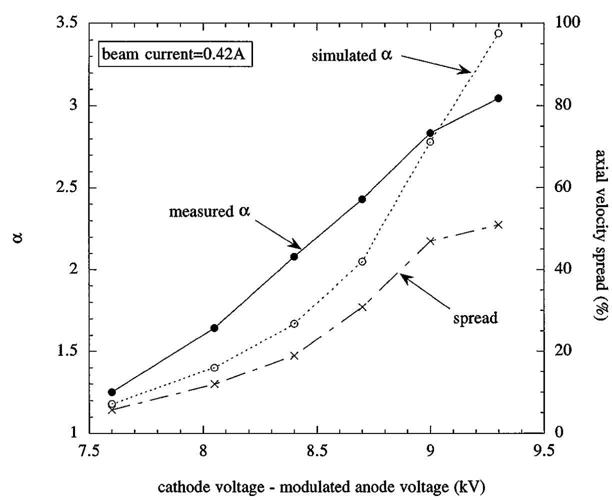

FIG. 7. Beam velocity ratio and axial velocity spread as a function of modulated anode voltage measured with respect to cathode voltage, where cathode voltage is 31.3 kV.

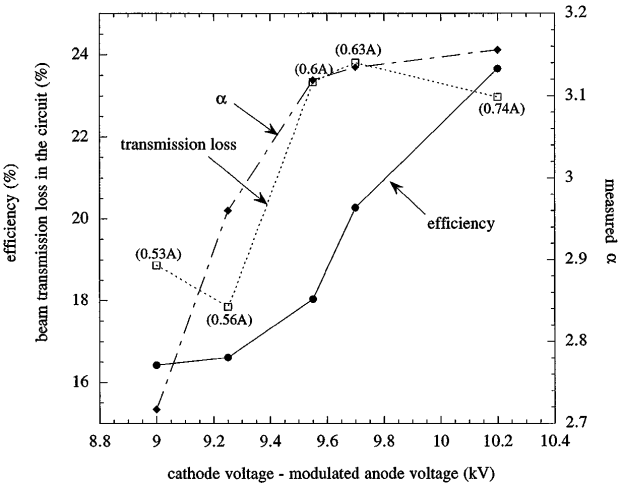

FIG. 8. High power operation with higher current and higher α. The values in the parenthesis are cathode currents.

demonstrate a high radiation power, both the beam current and the velocity ratio were raised. As shown in Fig. 8, a peak combined radiation power of 5.5 kW, corresponding to an efficiency of 24%, was observed at $\alpha = 3.15$ and a cathode current of 0.74 A (collected current = 0.57 A). As the velocity ratio and the cathode current increased, the beam interception in the circuit was large. When the collected beam current was used for efficiency measurements, the energy conversion efficiency was more than 30%.

In summary, a high power millimeter wave radiation of more than 5 kW power (efficiency $>$20%) was experimentally observed for the first time from an *H*-plane bend rectangular folded waveguide circuit with a gyrating electron beam. The oscillation was confirmed to originate from the absolute instability by measuring the frequency and power of the forward and backward growing waves, and the phase variation of the combined power. Differently from other gyrodevices, the folded waveguide circuit is realized to be useful in operating as an oscillator based on the absolute instability because the two growing waves carrying same phase, frequency, and power are naturally separated from the electron beam, and therefore one can easily combine the two radiation powers through the magic tee. In addition, the circuit can be operated as a broadband amplifier when the beam line is tuned to be tangential with the first space harmonic mode ($m = 0$). In order to operate the device as an amplifier, however, an axis-encircling beam is required because beam propagation of the small orbit MIG beam becomes difficult at a low magnetic field. Developments of such a high quality axis-encircling beam are currently underway at various U.S. tube industries in collaboration with the Naval Research Laboratory [12].

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