A High-Power Backward-Wave Oscillator Driven by a Relativistic Electron Beam

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Abstract—**A high-power backward-wave oscillator (BWO) has been constructed that is driven by a relativistic electron beam (REB). A typical electron beam of 2–4 kA is accelerated across a diode potential of 650–800 kV and then guided through a section of corrugated transmission line by an axial magnetic field of 5–15 kG. Peak microwave powers of 100–200 MW have been observed in the circular TM_{01} mode at the predicted frequency of 8.4 GHz. The basic principles and parameters of operation will be discussed, along with the dependence of peak microwave power on applied axial magnetic field.**

Introduction

Although intense electron beams and slow-wave structures have long been employed in the production of bursts of high-power microwave radiation [1], [2], a renewed interest in such sources has fostered a new generation of increasingly practical ultra-high-power microwave radiation sources. In addition to providing a high-power microwave radiation source, the backward-wave oscillator (BWO) experiments also verify theories of beam–slow-wave structure interactions [3], [4]. In a BWO experiment, an electron beam passes through a slow-wave structure in such a way that the negative-energy space-charge wave of the beam grows and couples energy into the electromagnetic modes of the structure. In our idealized geometry, shown in Fig. 1, a negative group velocity wave (antiparallel to the beam) grows in the region of the slow-wave structure, reflects from the section of waveguide below cutoff, and leaves the system as microwave output. At this point, a variety of diagnostics are used to measure microwave power, frequency, and pulse length.

Theory of BWO Operation

In the BWO or any other type of slow-wave traveling wave tube (TWT), an electron beam traverses and interacts with a periodic slow-wave structure in a way that allows energy to be transferred from the negative-energy space-charge wave (density wave) in the electron beam to a propagating electromagnetic wave (mode) in the slow-wave structure. The frequency at which energy transfer occurs is the frequency where the space-charge wave and slow-wave structure mode have the same wavenumber (are in synchronization). The classical BWO, as opposed to the general TWT, is characterized by the slow electromagnetic mode having a group velocity $d\omega/dk_z$, in opposition to its propagation wavenumber k_z ($d\omega/dk_z$ is opposite in sign to k_z), so that energy can flow back toward the entrance point of the electron beam, providing positive feedback for the start of oscillation.

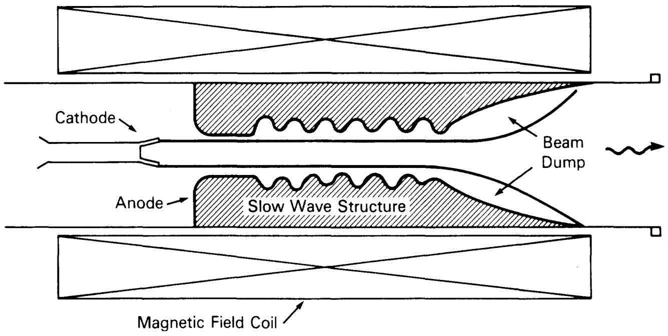

Fig. 1. Idealized BWO geometry.

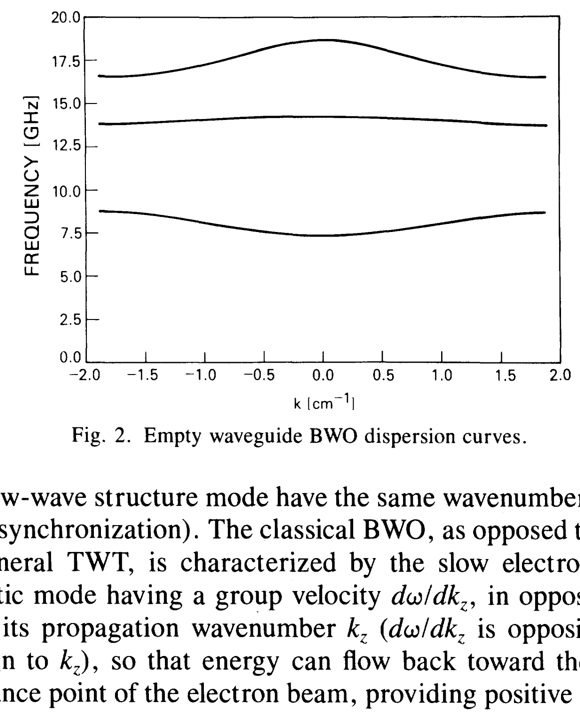

Fig. 2. Empty waveguide BWO dispersion curves.

Three steps are used to analyze the operation of the BWO, or any TWT. The first step is to determine the dispersion relation $\omega(k_z)$ and fields associated with the empty slow-wave structure modes. This calculation has been performed [3], and the results for the slow-wave structure used in the experiment are shown in Fig. 2. Note the small extent of the passbands, which indicates that $|d\omega/dk_z| << c$ everywhere within the passband, implying large E_z fields and good coupling to beam space-charge waves. The second step is to plot the space-charge wave dispersion relation

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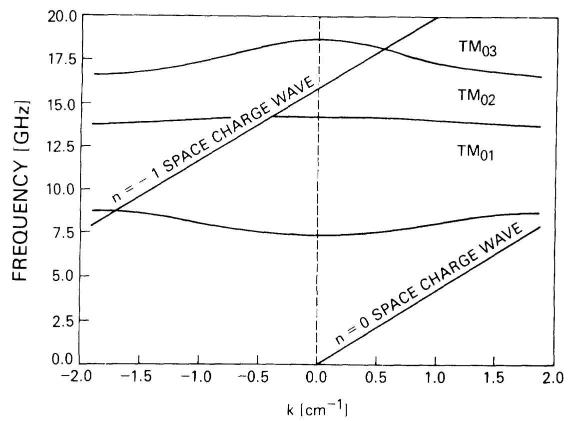

Fig. 3. Superposition of beam space-charge waves and slow-wave structure dispersion relation.

$$\omega = V_{\parallel}(k - 2\pi n/L) \tag{1}$$

where $V_{\parallel}$ is beam axial velocity, n is spatial harmonic, and L is the period of ripples in a slow-wave structure, on the same axes as the empty slow-wave structure dispersion relation (Fig. 3). The operating frequency of the BWO is well-approximated by the intersection of the $n = -1$ spatial harmonic of the space-charge wave with the $n = 0$ spatial harmonic ($-\pi \leq k_zL \leq \pi$) of the empty waveguide mode. Note that this point is equivalent to the operating point determined by the intersection of the $n = 0$ spatial harmonic of the space-charge wave and the $n = -1$ spatial harmonic ($\pi \leq k_zL \leq 3\pi$) of the empty waveguide mode in the sense that the frequency, fields, and beam quantities associated with each operating point are identical. The third step is to use the linearized relativistic beam fluid equations and the inhomogeneous Maxwell equations to couple the beam space-charge currents to the empty waveguide modes and solve the resulting set of homogeneous equations to determine a) the coupled beam-wave dispersion relation and b) the beam perturbed fields in the slow-wave structure [4]. If the slow-wave structure is terminated in its characteristic impedance (no reflections at the input or output), the starting current can be calculated for oscillations in a structure of given length.

However, the matched structure starting current is of not much utility in the experiment due to the severe mismatch at the output end of the slow-wave structure. Until end conditions are included in the theory, the only relevant prediction that can be made is the operating frequency of the oscillator. This analysis is in progress. At the BWO operating frequency the slow-wave structure group velocity is less than 0.1 c, while in the output waveguide the group velocity is 0.8 c. In this situation, which is currently being analyzed, the reflection at the output end is approximately 80 percent, and could easily be more important than the backward electromagnetic wave, in the absence of reflections, in causing the device to oscillate.

Experiment

For BWO experiments, the DRAGON [5] relativistic electron beam (REB) generator is used to drive an explosive field-emission diode. The resulting electron beam is then guided through a slow-wave structure to a beam dump area by an applied axial magnetic field. Microwave diagnostics are used to determine the power, frequency, and duration of the resulting radiation.

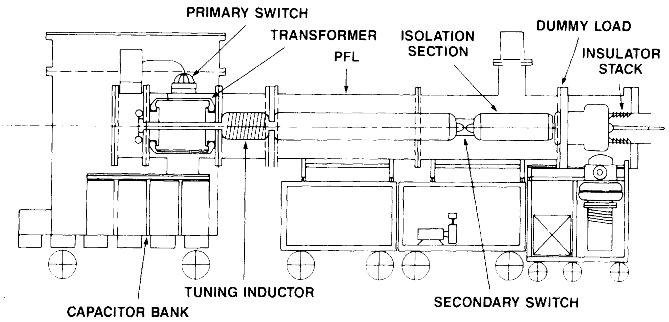

Fig. 4. DRAGON relativistic electron beam generator.

The DRAGON REB generator is used to produce several kiloamperes of electrons with energies approaching 1 MeV. As shown in Fig. 4, energy is first stored in two sets of capacitors which are charged in parallel to +V and −V. When the primary switch is triggered, the capacitors discharge through the transformer to the transmission line. When sufficient voltage has built up on the transmission line, the secondary switch breaks down and the stored energy flows through the diode. (It should be noted that DRAGON was designed as a 7-Ω machine and that most of the output energy is being absorbed by the dummy load.) In this configuration, the actual load or diode represents only a small fraction of the total load seen by the discharging transmission line, and thus changes in the diode impedance during pulse evolution do not result in serious changes in the output pulse. This enables us to construct an electron beam with reasonably constant energy.

The hollow knife-edged axially symmetric stainless-steel cathode is tapered to reduce shank emission and has an outer radius approximately equal to the inner radius of the carbon anode structure. Thus electrons with a high component of transverse velocity are "shaved off" by the anode structure. The resulting beam is well-approximated by a cold one-dimensional model.

The slow-wave structure shown in Fig. 1 was designed for operation at 8.4 GHz. As described earlier in this paper, the slow-wave structure defines the interaction region in which electron beam energy can be coupled into electromagnetic radiation. The actual structure was constructed by first machining (numerically) a piece of aluminum to the inside shape of the slow-wave structure. A thin layer of copper was then deposited on the aluminum, and the whole piece was potted in epoxy. Finally, the aluminum was etched away with a sodium hydroxide solution.

The magnetic-field lines cross the vacuum system walls and form a beam dump in a region (see Fig. 1) just beyond the slow-wave structure. Applied axial magnetic fields are typically 5–15 kG. The diode and beam drift-tube regions

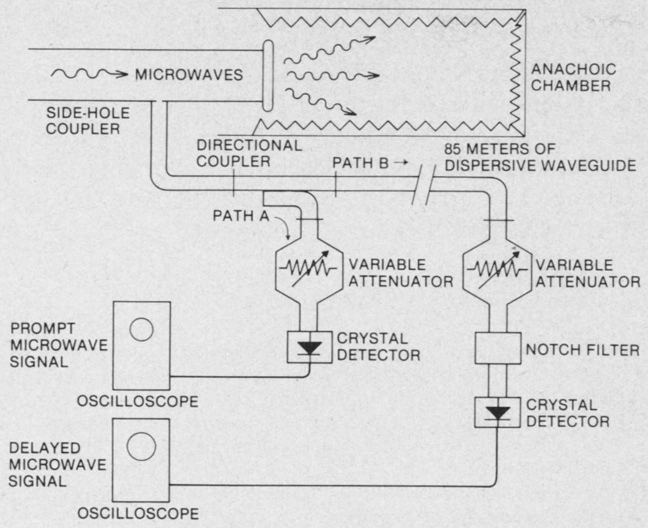

Fig. 5. Microwave diagnostic system.

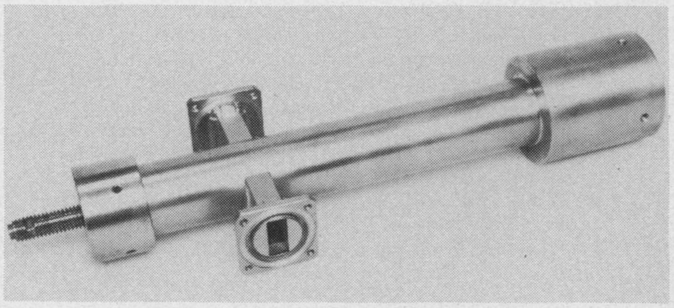

Fig. 6. TM_{01} mode launcher.

are pumped down to a pressure of 5×10^{-5} torr. In our experiment, electromagnetic radiation propagates out of the BWO in the circular TM_{01} mode and enters a region of microwave diagnostics.

The basic system of microwave diagnostics is shown in Fig. 5. In this scheme, TM_{01} mode radiation (propagating down an evacuated drift tube) is coupled through a small hole into the TE_{10} mode propagating in *X*-band (8–12 GHz) rectangular waveguide. The hole coupler was calibrated *in situ* by launching a TM_{01} cylindrical waveguide mode in the output waveguide by feeding it (the cylindrical waveguide) with diametrically opposed rectangular *X*-band waveguides (Fig. 6). The *X*-band guides are fed from a power divider and phased so that the TM_{01} mode is the only one allowed by symmetry in the cylindrical guide, while the TE mode excitation was suppressed by the same symmetry considerations. All other modes were below cutoff in mode launcher for the calibration frequencies used. The calibration mode generated was verified as TM_{01} by measuring the BWO output waveguide antenna pattern when driven by the mode launcher. The hole coupler was then calibrated by measuring power incident on and reflected from the mode launcher and output from the coupling hole for frequencies in the passband of the slow-wave structure. This radiation is then split into two parts. Along path A the radiation is further attenuated, detected, and displayed on an oscilloscope. In path A, the length of waveguide is relatively short and the signal is a good indicator of the microwave power versus time at the side hole coupler. Path B, however, contains an additional 85 m of dispersive waveguide which acts to spread the signal versus time when detected and viewed on an oscilloscope. Path B also contains a notch filter with a center frequency of 8.4 GHz which severely attenuates higher- and lower-frequency signals. In our actual situation, both notch and bandpass filters were used in either, both, or neither paths depending on which aspects of the experiment were under study. Some type of filter is necessary for low-frequency (8–12-GHz) studies because the higher-frequency components of the signal are not affected by directional couplers, attenuators, and detectors in any easily manageable fashion. The restriction of the output (via filters) to a narrow frequency range is essential for accurate measurements with the hole couplers. On future experiments we will include both calorimetry and far-field horn receivers as diagnostic tools.

Results

Some typical voltage, current, and microwave power oscilloscope traces are shown in Fig. 7. The microwave shown in Fig. 7(b) has passed through a coupling hole, 100 m of WR90 waveguide, a rotary vane attenuator, a notch filter (centered at 8.4 GHz), and a crystal detector. The 100-MW peak power is typically associated with the 9.5-kG applied field.

The variation of peak output power (at 8.4 GHz) versus applied magnetic field is shown in Fig. 8 for this experiment and for a similar experiment by Denisov *et al.* [6], and is the only example outside of the USSR where this behavior has been observed. As the applied magnetic field is increased, beam quality improves and the radiated power increases until a plateau is reached at about 25 kG. The dip in the output power which is common in these devices is due to resonant reradiation into a fast cyclotron wave on the electron beam [7].

The electron beam current in the Harry Diamond Laboratory (HDL) experiments was slightly higher than the current used by Denisov. Thus one would expect to see slightly higher output power levels from the HDL experiments. Unfortunately, we were limited to an applied magnetic field of 16 kG and could not verify the increase in output power that should accompany higher applied magnetic fields.

Conclusions/Summary

In addition to validating the computer simulations described in [3] and [4] and complementing the results of Denisov *et al.*, these experiments demonstrate that the REB-driven BWO is an excellent source of high-power microwave radiation. By adjusting the structure and beam parameters, one may achieve single-mode operation over a wide range of frequencies, and the BWO scheme should easily work in a repetitively pulsed mode of operation.

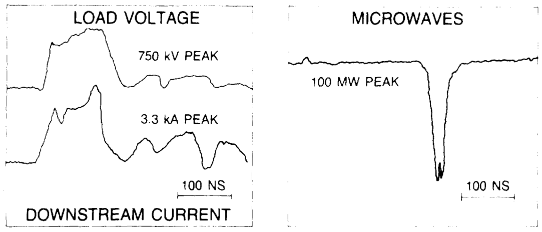

Fig. 7. Typical oscilloscope diagnostic traces.

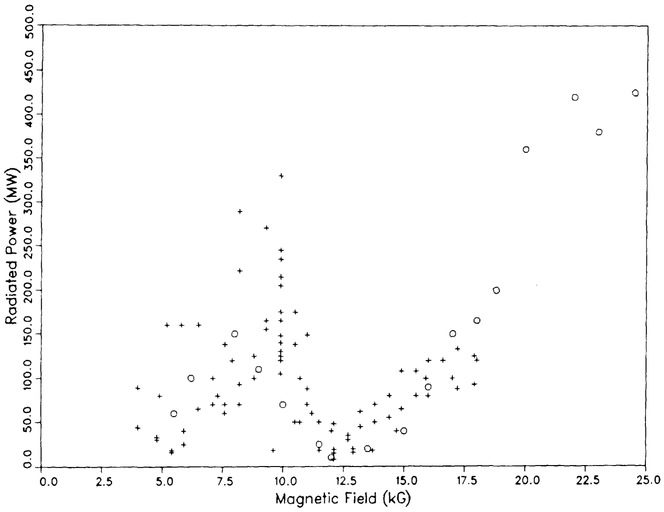

Fig. 8. Comparison of radiated power versus magnetic field from HDL (+) and Denisov *et al.* (○).

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