A COHERENT VERY HIGH POWER MICROWAVE SOURCE USING A VIRTUAL CATHODE OSCILLATOR*

M. V. Fazio, and R. F. Hoeberling, AT-5, MS H827
Los Alamos National Laboratory, Los Alamos, NM 87545

Summary

An oscillating virtual cathode produced by a multikiloampere relativistic electron beam can generate microwave power at levels from several-hundred megawatts to one gigawatt. This type of source can operate from 500 MHz to 40 GHz. To become useful as an accelerator driver, it is essential that we control the frequency and phase of the microwave radiation. To accomplish this, it may be possible to use the resonant interaction between the oscillating virtual cathode and a microwave cavity that is pumped with a klystron-injected signal to produce a microwave source capable of very high power, narrow bandwidth, narrow-band frequency tunability, and phase controllability.

Dynamics of the Virtual Cathode Oscillator

A virtual cathode is formed when the electron current from an electron-beam diode, greater than the space-charge limiting current,[1] is injected into a cylindrical waveguide, as shown in Fig. 1. A propagating electron beam produces a negative potential because of its own space charge, and when the beam enters the waveguide, the space-charge potential energy increases. At high current levels, the potential barrier produced by the beam space charge exceeds the beam's kinetic energy, and electrons in the beam are reflected back to the anode. This current level is called the space-charge limiting current. The potential barrier is called a virtual cathode and is formed at the position where the kinetic energy approaches zero. For the case of a mildly relativistic electron beam, an interpolative formula[2] for the space-charge limiting current (I_{scl}) in a cylindrical waveguide that has good experimental agreement is

$$I_{scl} = \frac{17(\gamma^{2/3} - 1)^{3/2}}{1 + 2 \ln r_w/r_b} \quad \text{(in kiloamperes)} \quad ,$$

where γ is the relativistic factor of the electron beam, r_w is the radius of the waveguide, and r_b is the electron beam's outer radius.

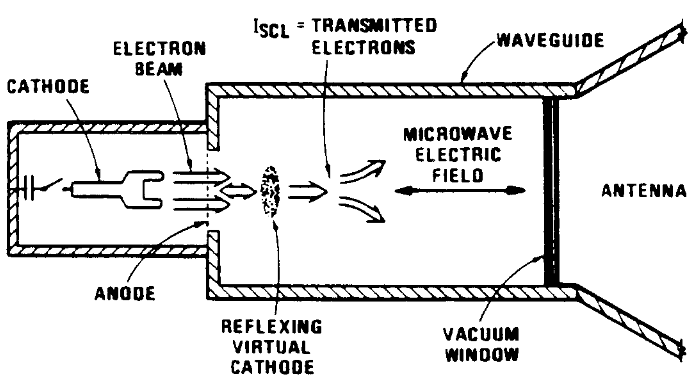

Fig. 1. Typical virtual cathode oscillator source.

Currently there are two models for microwave production. The first is the oscillating virtual cathode in which the virtual cathode oscillates in space and time with a well-defined period.[3,4] This oscillation results in severe longitudinal charge bunching. The oscillation of the virtual cathode excites the longitudinal electric field that drives the transverse magnetic waveguide modes in a cylindrical waveguide. As the ratio of the beam current to the space-charge limiting current increases,[5] the microwave output frequency in an oscillating virtual cathode varies between the plasma frequency ω_p and $\sqrt{2\pi}\ \omega_p$, where

$$\omega_p = \left(\frac{4\pi ne^2}{\gamma m}\right)^{1/2} .$$

In this expression, n is the electron density and m is the electron mass.

The second mechanism for microwave production involves the electrons that are trapped in the potential well between the real cathode and the virtual cathode. The electrons reflexing in this potential well can also generate broadband microwave power at a higher frequency than in the case of the oscillating virtual cathode. The frequency is higher because the individual reflexing electrons can travel at near the speed of light; whereas, the frequency of the virtual cathode oscillations is determined by the plasma frequency ω_p of the electron beam.

The virtual cathode oscillator is not a well-behaved microwave source. It has a broad microwave spectrum with peaks in a variety of waveguide modes. Mainly, two factors contribute to this characteristic. The microwave radiation is generated by a combination of the two processes: the oscillating virtual cathode and the reflexing electrons. Also, frequency chirping occurs during the pulse, caused by diode voltage and current-density variations. Consequently, one has a very unstable free-running oscillator.

A number of researchers have reported microwave generation at the gigawatt level using virtual cathodes formed by high-current relativistic electron beams.[6] Operating frequencies range from 500 MHz to 40 GHz. Efficiencies up to 5% are reported by U.S. researchers and up to 40-50% by the Soviets (Didenko).[7] Didenko has also reported pulsed microwave radiation for half a microsecond at 3 GHz and 500 MW. In spite of these achievements, there has not been much effort toward developing these devices as reliable, efficient, very high power, microwave sources.

The ability of an oscillating virtual cathode to produce very high levels of peak power leads one to consider it as a candidate for an accelerator driver. To become viable in this role, it is essential that the device be made to operate predominately at a single frequency. There should also be some means to control the device's output phase.

Frequency and Phase Locking

It may be feasible to produce a frequency-locked oscillating virtual cathode by surrounding the oscillating virtual cathode with a resonant microwave structure. A microwave cavity resonator has several properties of particular use to us in this application. First, it is frequency selective. The cavity supports a number of well-defined modes of oscillation, and each mode occurs over a very narrow bandwidth. Secondly, microwave energy can be effectively coupled out of a cavity resonator using the same techniques employed for coupling energy into rf accelerating structures.

Examples of microwave generation by passing an electron beam through a resonant structure are the

*Work supported by U.S. Dept. of Energy.

cavity klystron and the magnetron. A series of microwave cavities are used first to bunch the dc electron beam and then to extract the power from it at the microwave frequency. The dynamics of the oscillating virtual cathode is much more complicated and less understood than the previous examples. However, there is no reason to believe that a resonant cavity surrounding the oscillating virtual cathode would not also affect its dynamics. If one can tune the oscillating virtual cathode by varying the beam-current density so that its dominant free-running oscillation frequency is near the passband of a microwave-cavity resonator surrounding the oscillating virtual cathode, then it should be possible to create a strong beam/cavity interaction. Because of this interaction, the cavity field induced by either the oscillating virtual cathode or some other source feeds back on the oscillating virtual cathode, forcing it to oscillate in the desired mode at the cavity resonant frequency f_0. The formation of the virtual cathode is a beam-bunching phenomenon; thus, if one can affect the dynamics of the bunching process, then it should be possible to influence the behavior of the oscillating virtual cathode. Utilizing this feedback interaction, the oscillating virtual cathode and the cavity field should lock together in phase and in frequency, converting beam power to microwave power with improved efficiency. Brandt, et al.,[8] have investigated the effect of feedback on the microwave output of a reflexing electron device. Their simulations added a 100-kV/cm external sinusoidal electric field at 9.8 GHz to the 1-MV/cm field generated by the applied diode voltage. The sinusoidal field increased the microwave energy density at the pump frequency by a factor of 40.

A further refinement to the frequency-locking concept involves exciting the cavity resonator with a microwave signal at the cavity resonant frequency, before injecting the electron beam. The power level of this microwave pump would be a few percent of the power produced by the electron beam. The role of the microwave pump is to build up the microwave field in the cavity so that, when the electron beam enters the cavity, the beam will interact with the existing cavity field. With this technique, the beam should be forced to oscillate at the same frequency as the microwave pump instead of waiting for the virtual cathode oscillation to stochastically build up from noise voltage. The current density of the electron beam would be adjusted by altering the diode geometry to ensure that the free-running frequency of the oscillating virtual cathode would be close enough to the cavity frequency for the beam/cavity interaction to be significant. One then would no longer have a truly free-running oscillator, but instead a device that must interact with a resonant structure that affects the bunching process and, hence, the oscillation frequency.

The concept of injection locking a free-running microwave oscillator to an external signal is one that has been around for some 40 years. An extensive amount of theoretical work on injection locking has been done by persons such as E. E. David,[9] J. C. Slater,[10] and numerous others. David's work has dealt primarily with magnetrons. The work of both indicates that if the coupling between the two sources is strong enough and if their frequencies are close enough together, frequency and phase synchronization (or locking) occurs.

In these microwave oscillators, coherent oscillations spring up from preoscillation noise already present in the system. If an external sinusoidal signal is impressed upon the oscillator, the initial oscillations start from the vector sum of this external signal and the noise voltage. During the rf build-up, the effect of the locking signal is enhanced (over the steady-state case) because the rf voltage due to the virtual cathode is much less than its steady-state value.

Successful experimental work on injection locking magnetrons together has been done by Varian,[11] Raytheon,[12] and P. F. Lewis at English Electric Valve (EEV) Co., Ltd.[13] In the case of Varian and EEV, the locking power in the steady state was 32 to 35 dB below the oscillator output power. With Raytheon's experiment, the locking power required was 26 dB below the output.

Proposed Experiment

Now under construction is an experiment to produce an injection-locked virtual cathode oscillator at 1.3 GHz. The device to be tested will use the cylindrical geometry of Fig. 2. The 1-MeV, 20-kA space-charge-limited electron beam is accelerated into a cylindrical resonator where the TM_{020} transverse magnetic mode is excited. The field pattern for the TM_{020} is shown in Fig. 3.

The fields in the TM_{020} mode have the following form:

$$E_z \propto J_0 \left(\frac{5.520\ r}{a}\right) \text{ , and}$$

$$H_\phi \propto J_0' \left(\frac{5.520\ r}{a}\right) \text{ ,}$$

where J_0 and J_0' are the zero-order Bessel function and its derivative, a is the cavity radius, and r is the radial position. The radial dimension of the cylinder will be selected to place the TM_{020} mode at 1.3 GHz, which results in a cylinder diameter of approximately 40 cm as shown in Fig. 2. The electric field is axial in the z-direction, with maxima at the axis $r = 0$, and at $r = 14$ cm from the central axis, as shown in Fig. 2. The diameter of the electron beam will be chosen to be within the region of the central peak in the electric field shown in Fig. 2. This geometry will result in a strong coupling between the electric field from the oscillating virtual cathode and the cavity TM_{020} mode electric field. Wall currents should be induced by the virtual cathode oscillations that set up the electric and magnetic fields characteristic of the TM_{020} mode.

We will begin experimentation with the microwave cavity in place downstream of the diode. We will optimize the electron-beam diode parameters such as anode-cathode gap spacing and diode voltage to adjust the electron-beam current density so that the microwave radiation peaks in the 1.3-GHz regime. If the presence of the cavity does indeed affect the dynamics

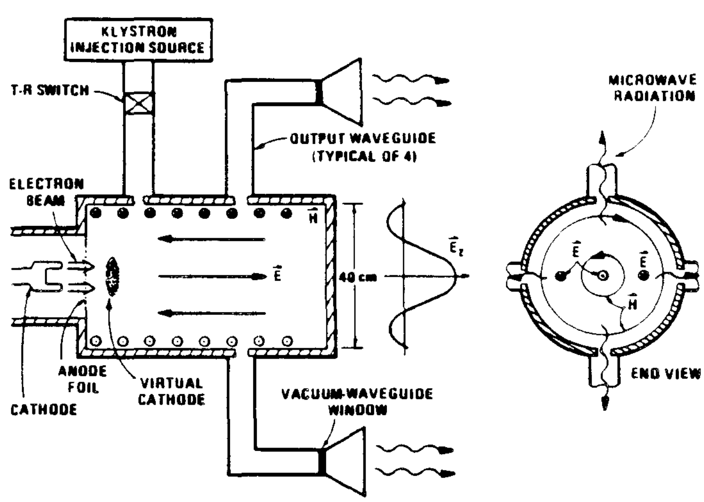

Fig. 2. Cylindrical resonator configuration.

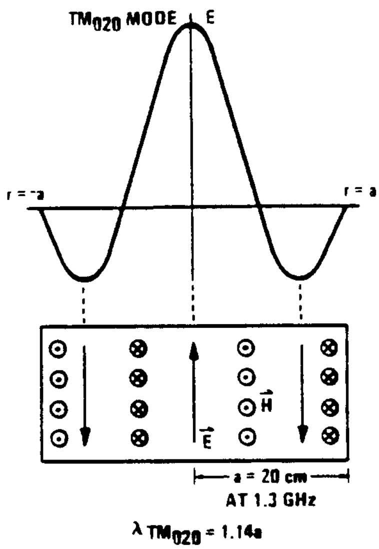

Fig. 3. Electric field distribution in a TM_{020} cavity.

of the virtual cathode oscillations, we should observe an improvement in efficiency and a rise in microwave power output as we tune the oscillating virtual cathode frequency through the cavity resonant frequency.

Having tuned the free-running frequency of the virtual cathode oscillator close to the cavity's 1.3 GHz, we can then apply power from the 1.3-GHz klystron that is used as the injection-signal source. With this configuration, we will be able to see the effect of the cavity resonator on the oscillation frequency of the virtual cathode with and without the microwave injection signal. The use of the external injection signal allows the microwave field in the cavity to be initialized, so that the virtual cathode from its time of formation sees a strong cavity field with which to interact. The klystron would be turned on to pump the cavity before firing the electron beam, which would allow the cavity field to ring up to its steady-state value in a time equal to several e-folding times.

The microwave cavity enhances the effect of the klystron output power by storing the klystron-produced energy in the cavity electromagnetic field over a relatively long period of time. The electric field in our cavity, assuming a Q of 1000, is about 220 kV/cm at 10 MW of klystron output as compared with a field of around 500 kV/cm in the oscillating virtual cathode itself. It must be kept in mind that the rf voltage in the oscillating virtual cathode starts from near zero amplitude in the presence of the 220-kV/cm cavity field. Because our injected signal is comparable in amplitude to the diode field, it seems quite possible that we should be able to injection lock the oscillating virtual cathode with the klystron.

Microwave slot apertures will be used to couple the klystron power to the cavity and to extract power from the device. The coupling occurs through the circumferential magnetic field in the cavity that penetrates the slot and excites the TE_{10} mode in the rectangular waveguide. The short dimension of the slot is parallel to the cavity's center line. The slots will couple to appropriately sized waveguide.

Conclusions

If a virtual cathode source can be phase and frequency locked to a relatively low-power injection signal, and if the problems associated with duty factor and pulse length can be solved, a variety of new possibilities in the microwave area become available to accelerator technology. For example, a single gigawatt-level injection-locked virtual cathode source could replace a large number of klystron sources. To achieve even higher levels of power, several virtual cathode sources could be run coherently in parallel by having all of them frequency and phase locked to a single injection signal.

References

1. L. S. Bogdankevich and A. A. Rukhadze, "Stability of Relativistic Electron Beams in a Plasma and the Problem of Critical Currents," Sov. Phys. Usp. 14, 163 (1971).
2. R. F. Hoeberling and D. Payton, III, "Ion Acceleration in the Evacuated Drift-Tube Geometry," J. Appl. Phys., 5, 48 (1977).
3. C. K. Birdsall and W. B. Bridges, "Space Charge Instabilities in Electron Diodes and Plasma Converters," J. Appl. Phys. 32, 2611 (1961).
4. D. J. Sullivan, Proc. 3rd Int. Topical Conf. on High-Power Electron and Ion-Beam Research and Technology, Novosibirsk, USSR, 1979 (Institute of Nuclear Physics, Novosibirsk, USSR, 1979), Vol. II, 769; D. J. Sullivan, Proc. 4th Int. Topical Conf. on High-Power Electron and Ion-Beam Research and Technology, Palaiseau, France, 1981, edited by H. J. Doudet and J. M. Buzzi, Eds. (Ecole Polytechnique, Palaiseau, France, 1981), Vol. I, 371.
5. M. A. Mostrom, T. J. T. Kwan, and C. M. Snell, "Simulation of Virtual Cathode of a Scattered Electron Beam," Bull. Am. Phys. Soc. 27, 1075 (1982).
6. D. J. Sullivan, "High Power Microwave Generation From a Virtual Cathode Oscillator (VIRCATOR)," IEEE Trans. on Nucl. Sci., 30, (4), 3426 (1983).
7. A. N. Didenko, A. G. Zherlitsyn, A. S. Sulakshin, G. P. Fomenko, V. I. Tsvetkov, and Yu. G. Shtein, "The Generation of High Power Microwave Radiation in a Triode System by a Heavy-Current Beam of Microsecond Duration," Pis'ma Zh. Tekh. Fiz. 9, 1510 (1983).
8. H. E. Brandt, A. Bromborsky, H. B. Bruns, R. A. Kehs, "Microwave Generation in the Reflex Triode," Proc. 2nd Int. Topical Conf. on High-Power Electron and Ion-Beam Research and Technology, Cornell University, Ithaca, New York, 6496(1977).
9. E. E. David, Jr., "RF Phase Control in Pulsed Magnetrons," Proc. of the IRE (Institute of Radio Engineers) 40, 669 (1952).
10. J. C. Slater, Microwave Electronics, (Van Nostrand, New York, 1950), 205-210.
11. "Notes on Phase Locked Magnetrons," Varian Associates Radiation Division, Palo Alto, California, private communication.
12. W. C. Brown, "Microwave Beamed Power Technology Improvement - Final Report," Raytheon Co., Microwave and Power Tube Division, Waltham, Massachusetts 02254, PT-5613, (1980).
13. P. F. Lewis, "An Experiment in the Parallel Operation of High-Power Magnetrons," Microwave Journal, 13, (4), 82, (1970).