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AUTHOR(S): M. V. Fazio, R. F. Hoeberling

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RESONANT CAVITY OPERATION OF A VIRTUAL CATHODE OSCILLATOR (U)*

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

Summary

Gigawatt level virtual cathode sources have been proposed for several applications. These include microwave weapons and drivers for high-energy particle accelerators. Both of these require a microwave source with very high power output that is controllable in frequency and phase. A conventional virtual cathode oscillator will not meet these requirements. The addition of a resonant cavity surrounding the oscillating virtual cathode either alone or pumped with a low-power injection signal, causing it to operate as an amplifier, could greatly influence the performance of this type of source making it more practical for accelerator and weapon applications. The progress on an experiment to test these concepts will be discussed.

Background

Virtual cathode oscillators have been operated over the last few years by many laboratories around the world. These sources have routinely produced microwave power at the gigawatt level.[1] At least one experiment[2] has measured an output in the 10- to 20-GW range at 1.3 GHz. Pulse lengths are generally less than 100 ns with the exception that Didenko in the Soviet Union reports 500 MW at 3 GHz for half a microsecond.[3] There are several serious problems inherent in a conventional virtual cathode oscillator. The device is an unstable free-running oscillator whose frequency can change dramatically during a single pulse. Frequency shifts as large 35% have been observed. The microwave spectrum has peaks in a variety of modes that are usually transverse magnetic in nature. Because of the frequency and phase incoherency of the virtual cathode oscillator, it is impossible to operate several sources in parallel for higher output. Finally, the lack of a stable operating mode makes efficient power extraction and transmission from the source a difficult problem.

Although the virtual cathode oscillator has been used in a few cases as a very high power source for microwave vulnerability testing, its performance must improve dramatically before it can become viable as a microwave power source in the gigawatt class. Virtual cathode sources are being proposed for a variety of applications. These include being used as drivers for linear colliding-beam accelerators[4] for high-energy physics experiments where the required microwave power is in the terawatt regime. Other applications include a variety of microwave weapon concepts.

For the virtual cathode oscillator to be considered as a weaponizable source or as an accelerator driver, it must meet the following requirements. The source must be able to operate reliably for a pulse length of several microseconds. The frequency and, in some applications, the phase should be controllable. Finally, there must be an efficient way of coupling the source power to the load.

For use in a directed-energy weapon, the source must be efficiently coupled to an antenna that radiates the microwave energy into space. Thus an antenna with the required directivity, gain, polarization, and pattern needs to be integrated with the source. To achieve an antenna radiation pattern that has high gain and high radiation efficiency, the microwave source must put its energy into a single, dominant waveguide mode that excites the antenna. The source must also produce the energy coherently, with a dominant polarization, and must operate over a reasonably narrow bandwidth compatible with the transmission and antenna system. These requirements are also true if the load is a resonant, microwave cavity for particle acceleration. In the case where the load is a high-Q accelerator cavity, the cavity may have a bandwidth of only 0.01%, which places even more stringent requirements on the frequency stability of the source than one with an antenna load.

The major obstacles to be overcome in achieving microsecond pulse lengths are diode closure and microwave breakdown. Breakdown can occur in the source, output waveguide power transmission system, across vacuum windows, and in the antenna. Diode closure is a shorting of the anode-cathode gap caused by adsorbed contaminants on the diode surfaces that get vaporized and ionized by the electron beam and then drift across the diode gap. This problem may likely have a solution residing in the process technology expertise of the high-power vacuum-tube industry.

The microwave breakdown problem is indeed a serious one. The maximum power that can be transmitted at 1.3 GHz in L-band waveguide pressurized to 3 atm with the electrophilic agent sulfur hexafluoride is about 1 GW. For a 10-GW source, the electric field is in excess of 1.4 times the Kilpatrick level[5] of 32 MV/m. A source at the 10 GW level may have a difficult time reliably transmitting its power through an output waveguide to an antenna or other load without microwave breakdown occurring. The problem is considerably exacerbated by the vacuum-to-air-transition at the antenna feed point, particularly when the air pressure may be considerably below the value at sea level.

Presented below is a design for a very high power microwave source based on the concept of a frequency-and-phase-locked virtual cathode device that has the possibility of solving several of the above problems. This device would operate in predominantly a single cavity mode resulting in a narrow-frequency bandwidth. Single-mode operation also allows the use of multiple output apertures for coupling power from the source to the load.

Frequency and Phase Locking

It may be feasible to produce a frequency-locked virtual cathode oscillator 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.

The quality factor, or Q, of the resonator is a measure of the ratio of the stored energy to the power dissipated in the cavity per rf cycle and is related to the 3 dB-bandwidth Δf by the expression $Q = f_0/\Delta f$,

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where f_0 is the cavity's resonant frequency in the desired mode of oscillation. Typical microwave resonators have Qs of about 10 000 at 1300 MHz, which imply bandwidths of about 150 kHz. Examples of microwave generation by passing an electron beam through a resonant structure are the 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 are much more complicated and less understood than the previous examples. However, there is reason to believe that a resonant cavity surrounding the oscillating virtual cathode would 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 Fourier components at the cavity resonant frequency of the oscillating virtual cathode or from some other source can feed back on the oscillating virtual cathode, forcing oscillations to build-up in the desired mode at the cavity resonant frequency f_0. The formation of the virtual cathode is a beam-bunching phenomenon; therefore, 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.,[*] have investigated the effect of feedback on the microwave output of the reflex triode. Their simulation 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.

Experiment

An experiment to produce a frequency-and-phase-locked virtual cathode source at 1.3 GHz is in the final stage of assembly. The device to be tested will use the cylindrical geometry of Fig. 1. 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 electric field pattern for the TM_{020} is also shown.

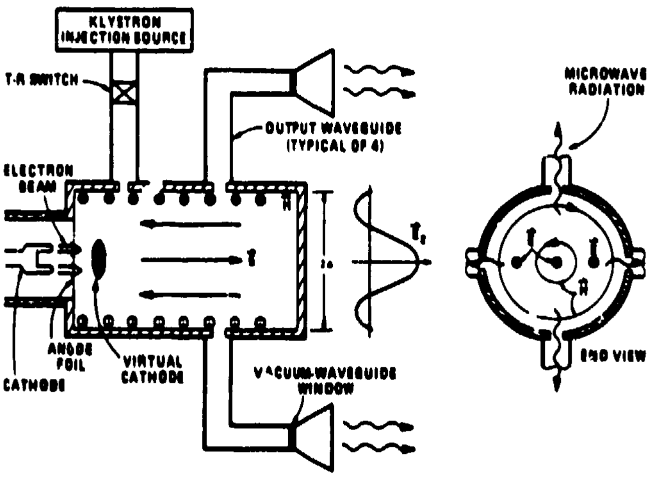

Fig. 1. Cylindrical resonator configuration with klystron injection signal.

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

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

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

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 is selected to place the TM_{020} mode at 1.3 GHz. The electric field is axial in the z-direction, with maxima at the axis r = 0, and at r = 0.7a (Fig. 1). The diameter of the electron beam will be chosen to be within the region of the central peak in the electric field centered at r = 0. This geometry will result in a strong coupling between the electric field from the oscillating virtual cathode and the cavity TM_{020} mode. Wall currents will be induced by the virtual cathode oscillations that set up the electric and magnetic fields characteristic of the TM_{020} mode. The TM_{020} mode resonant frequency depends only on diameter, not cavity length. Operating the cavity at a length longer than a half wavelength should be avoided because higher order modes such as the TM_{011}, TM_{012}, etc., could be excited. Because the TM_{020} mode cavity has more volume than the TM_{010} mode cavity for the same amount of stored energy, the voltage is lower, thereby reducing breakdown problems.

Power extraction from the cavity is done by means of four slot apertures around the circumference that allow the circumferential magnetic field of the TM_{020} cavity mode to couple into the TE_{10} magnetic field in the rectangular L-band waveguide. This magnetic field coupling is graphically illustrated in Fig. 2.

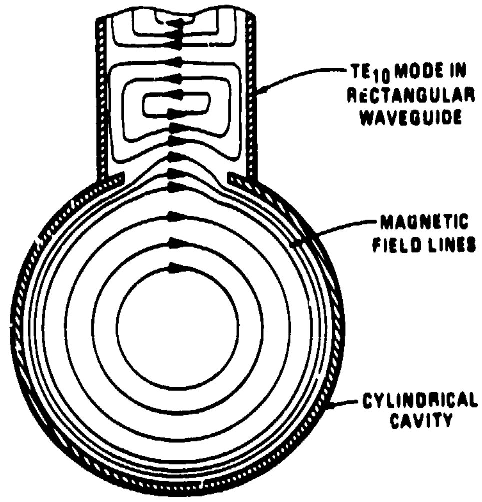

Fig. 2. Aperture coupling from a cavity TM mode to a rectangular waveguide TE mode.

An initial cavity design was done by using the computer code SUPERFISH. This code solves Maxwell's equations for cylindrically symmetric geometries. Our cavity does not possess ideal cylindrical symmetry because of the waveguide and diagnostics penetrations, therefore a cold (low-power) model was built to fine tune the SUPERFISH calculations. Measurements were then made on this cavity to determine the resonant frequencies of the TM_{020} mode and neighboring modes.

A cavity resonator possesses an infinite number of oscillation modes. The mode chart for a cylindrical resonator is shown in Fig. 3. For a given cavity geometry with a diameter D and length L, a vertical line can be drawn at $x = (D/L)^2$. The frequencies of the possible modes that can exist with this geometry are indicated wherever the vertical line crosses the line for each mode. One desires to operate in a mode with an electric field configuration suitable for coupling to the beam and a magnetic field suitable for coupling from the cavity to the output waveguide. Additionally, one would like the neighboring modes to be as far removed as possible from the operating mode so as to eliminate mode hopping and the corresponding frequency instability. The TM_{020} mode meets these requirements when $(D/L)^2$ is approximately 3 or 4. The actual mode spectrum can be shifted considerably from the ideal case in Fig. 3 because of the departure from the cylindrical geometry that is due to output waveguide penetrations, vacuum ports, etc. These asymmetries load the different modes in various ways causing the modes to move up or down in frequency. It is extremely difficult, if not impossible, to predict how far in frequency the various modes will move because of the asymmetries, so there is no substitute for actual mode-spectra measurements.

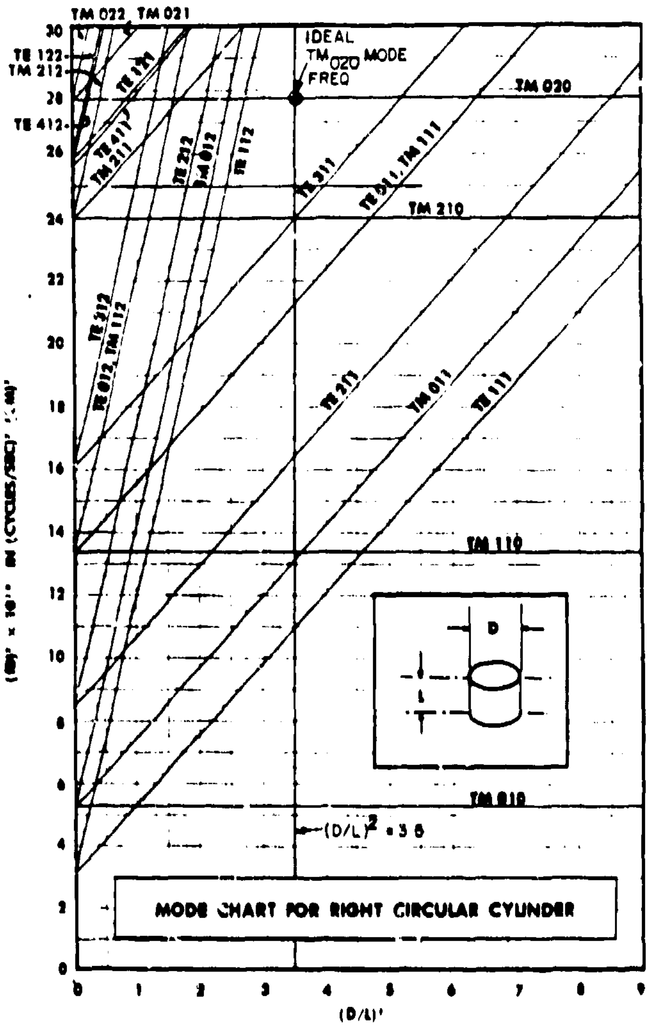

Fig. 3. Mode chart for ideal cylinder (from Saad, Microwave Engineers' Handbook, Vol. 1, p. 181, Artech House, Inc., Dedham, Massachusetts, 1971).

Mode measurements are made by driving the cavity with a swept frequency source through a very undercoupled magnetic loop. Another loop in the cavity is used to sense the power transmitted through the cavity. This transmitted power is zero off-resonance and high on-resonance, providing that the mode being measured has a magnetic field coincident with the orientation of the drive and pick-up loops. The results of the mode measurements on the cold cavity led to the final design of the actual cavity for our experiment.

The mode spectra for the final cavity is shown in Fig. 4. It should be noted that neighboring modes to the TM_{020} are at least 75 MHz away. These measurements were performed before copper plating the stainless steel cavity so the relative amplitudes of the various modes are not relevant. The Qs of the various modes in the copper-plated cavity after final assembly will determine the relative mode amplitudes.

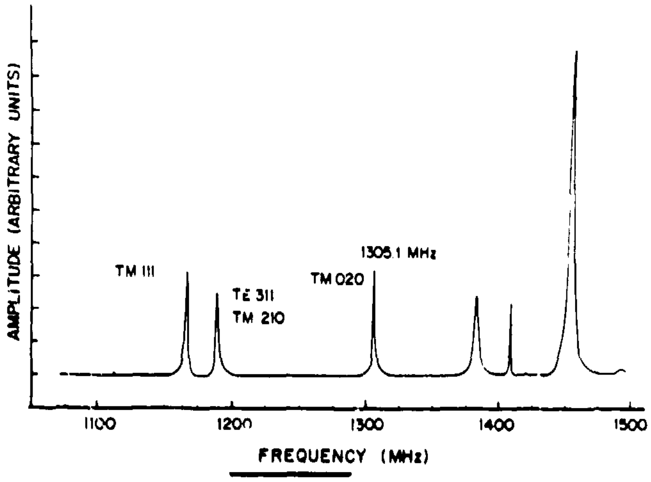

Fig. 4. Measured cavity mode spectra.

A measure of the power transmitted through the cavity during a frequency sweep will reveal where the modes occur in frequency but do not indicate which modes are occurring at those frequencies. To get this information, frequency perturbation measurements must be performed. Slater's Perturbation Theorem[7] relates the change in frequency of a microwave cavity to the volume, shape, material, and position of a perturbing object inserted into the cavity. This theorem can be written as

$$\omega^2 = \omega_0^2 \left[1 + \frac{k \int_{\Delta\tau} (\mu H^2 - \epsilon E^2)\, d\tau}{\int_V (\mu H^2 + \epsilon E^2)\, dV} \right]$$

where $d\tau$ is an element of the volume of the perturbing object and dV is an element of cavity volume. The numerator is an integral over the volume of the perturbing object, and the denominator is twice the average stored energy in the cavity. The perturbed frequency ω is changed from the natural frequency of the cavity ω_0 by an amount that depends on the integral over the perturbation volume, the numerator of the above equation. The quantity k is a constant that depends on the shape of the perturbing volume.

By probing the cavity in many locations with a perturbing object and noting the direction and amplitude of the frequency shift, one can deduce the field pattern and identify the mode at each resonant frequency. This process can, with some modes, be quite straightforward, but with other modes can be very confusing when two modes occur at near the same frequency.

As of this writing, the cavity construction, copper plating, and tuning are complete; final assembly and installation on the beamline is in progress.

In the experiments to be done, electron-beam diode parameters such as anode-cathode gap spacing and diode voltage will be optimized 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 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. Also the spectral output of the source should narrow considerably.

Injection-Locked Virtual Cathode Amplifier

A further refinement to the frequency-locking concept[8] involves exciting the cavity resonator with a microwave pump signal at the cavity resonant frequency before injecting the electron beam into the cavity. The power level of this microwave pump would be a few per cent of the microwave power produced by the electron beam. The role of the microwave pump is to establish the microwave field in the cavity so that, when the electron beam enters the cavity, the beam will interact with the desired 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 on the beam. One then would no longer have a free-running oscillator, but instead an amplifier where the beam's virtual cathode must interact with a resonantly pumped cavity. The output of this virtual cathode device would be locked in frequency and in phase to the injection source that will be a high power klystron as shown in Fig. 1.

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 compared to the electron beam pulse length. 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.

Conclusions

If a virtual cathode source operating as an amplifier can be frequency and phase locked to a relatively low-power injection signal, then some interesting applications become possible. Several virtual cathode sources could be run coherently in parallel by having all of them frequency and phase locked to the same injection signal. This would make possible much higher power phased array sources than a single microwave source could provide. If the bandwidth is narrow enough, these sources could be used as accelerator drivers. Even without injection locking but with the cavity alone to narrow the bandwidth, these sources may be able to efficiently drive a low Q, bandwidth-limited load such as an antenna.

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