Improved Oscillator Phase Locking by Use of a Modulated Electron Beam in a Gyrotron

A. H. McCurdy,[a] C. M. Armstrong, W. M. Bollen,[b] R. K. Parker, and V. L. Granatstein[c]
U. S. Naval Research Laboratory, Washington, D.C. 20375
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A new method of microwave oscillator phase locking, exploiting the extended nature of the gyroklystron configuration, is accomplished by modulation of the electron beam before it reaches the cavity oscillator. The amount of power required to give phase locking in a gyrotron is decreased by more than an order of magnitude from that predicted by Adler's theory. In addition, oscillator priming is observed at drive powers far below all other systems tested to date. These new methods provide the coherence required of rf sources for linear accelerators and may enhance gyrotron performance for fusion heating.

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A continuing need exists for efficient, high-power sources of coherent radiation in the microwave and millimeter wavelength range. The next generation of linear colliders may utilize microwave sources with a higher rf frequency (10–30 GHz), and a higher peak power (~ 100 MW), than previous designs in order to reduce the overall accelerator length.[1] Fusion plasma heating, using electron cyclotron resonance absorption, requires even higher frequencies (>100 GHz), at cw powers in the megawatt range.[2] Gyro devices employing the electron cyclotron-resonance maser (ECRM) instability are particularly attractive as sources in these frequency ranges because they have the potential of providing high average power density and good electronic efficiency.

Gyrotron oscillators,[3,4] using a magnetron injection gun and a resonant cavity, are the furthest advanced of the ECRM devices. Over 60% efficiency in the 100-kW output power range with frequencies below 40 GHz,[5,6] and 36% efficiency with 175 kW at 140 GHz,[7] have been demonstrated in short-pulse gyrotrons. cw performance has been pushed to 100 kW at 140 GHz.[8] For applications where the requirement on phase coherence is strict, such as is the case with high-energy linear accelerators, an amplifier such as the gyroklystron[4,9,10] would be appropriate. Gyroamplifiers, however, have not yet demonstrated the high efficiencies and power output of the oscillators; hence, a method of obtaining phase control over the oscillator is of interest.

For the effort described in this Letter, phase control is achieved by two methods: phase locking and priming. Phase locking is the synchronization in both frequency and phase of a free oscillation by an external signal. Priming is the initiation in phase of a pulsed free oscillation by application of an external signal during the buildup of oscillation. Unlike previous experiments, where phase control was achieved by direct injection of the drive signal into the oscillating cavity, our approach is to control the phase of the oscillator by premodulating the electron beam.[11] Though the possibility is not investigated here, this approach may prove to reduce mode competition in an overmoded oscillator.

These experiments are carried out with a 4.5 GHz, three-cavity gyroklystron configuration with the output cavity operating as a free oscillator (see Fig. 1). A preliminary observation of phase locking had been made with this arrangement.[12] A study of single-cavity gyrotron oscillator response to an external drive shows that there are three qualitatively different regimes of behavior. At low beam currents the device acts as an amplifier. Above the starting oscillation current there is a "soft excitation" regime where free oscillation takes place in the cavity. For beam currents in a confined region between the other two the oscillator exhibits "hard excitation," an autonomous oscillation initiated by the external drive signal. The experiments reported here are all carried out with the output cavity operating in the regime of soft excitation (free oscillation).

The gyroklystron configuration consists of three TE_{101} rectangular cavities whose fields interact with the right-hand circularly polarized beam cyclotron wave at the fundamental electron-cyclotron frequency. The cavities are separated by drift sections which are above cutoff to the generated rf radiation. These drift sections attenuate intercavity power transfer by a factor of 1000. The electron-beam parameters are 6.2 A at 28.5 keV with a perpendicular-to-parallel velocity ratio of about 1.0. A 60-Hz pulse repetition rate is used with a pulse width of 4 μs. The drive signal is applied to cavity No. 1 to begin electron beam modulation via electron-cyclotron reso-

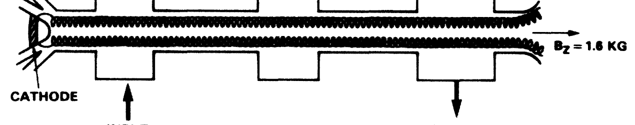

FIG. 1. Schematic of the three-cavity gyroklystron configuration. The first two cavities are 6.06 cm in length while the third is 7.4 cm. The connecting drift spaces are 10.1 cm long.

nance absorption. The beam is further modulated by ballistic bunching in the drift regions and interaction in cavity No. 2. The modulated beam then phases the oscillation in the last cavity. Power is extracted via a waveguide from the side wall of this cavity. The last cavity is made unstable by mechanical tuning of the cavity resonance close to the Doppler-shifted, relativistic, electron-cyclotron frequency. The magnetic field is varied along the axis of the device so that the first cavity absorbs radiation at the drive frequency. Cavity No. 2 is identical to cavity No. 1 in both construction and mechanical tuning.

Phase locking is a feature of self-excited, and hence nonlinear, oscillators which was first quantitatively studied with electron-tube circuits.[13] Adler related the ratio of oscillator power to drive power and the fractional frequency difference between the drive signal and oscillator in a simple way.[14] This relationship was found to be generally applicable to a broad class of oscillators including microwave cavity oscillators[15] and lasers.[16] In a microwave system Adler's equation is written[17] as

$$Q_e(f_d - f_o)(P_o/P_d)^{1/2}/f_0 < 1, \tag{1}$$

where the subscripts "d" and "o" refer to the drive signal and oscillator, respectively, f is frequency, P is power, and Q_e is the external Q of the oscillating cavity. For a given oscillator this equation describes the frequency band over which phase locking can occur at a given drive power. In this experiment $f_o \simeq 4.45$ GHz and $P_o \simeq 1-2$ kW.

It is found, by use of the three-cavity gyroklystron configuration, that locking can be obtained at drive power levels more than an order of magnitude below that predicted by Eq. (1). Adler's equation, though not applicable to a multicavity device, is the benchmark against which our results are compared since it describes the current maximum phase-locking performance of oscillators.

Phase locking is observed experimentally by mixing of the drive signal with a fraction of the output and displaying of the resulting sinusoidal beat signal on an oscilloscope. The frequency of the beat signal corresponds to the frequency difference between the drive and the oscillation in cavity No. 3. The beat signal becomes nonsinusoidal and then vanishes as the oscillator makes the transition to the locked state. Confirmation of locking is made with frequency counters, a spectrum analyzer, a phase discriminator, and crystal-diode measurements of intrapulse output-power variation.

Figure 2(a) shows the phase-locking bandwidth as a function of drive power as calculated from Eq. (1) and measured experimentally for a single-cavity gyrotron oscillator (cavity No. 1). It is found that the phase-locking bandwidth for direct injection of rf into the cavity oscillator follows Adler's theory as long as $P_d/P_o \ll 1$. This result is consistent with a previous experiment and has been substantiated theoretically.[18] The interesting new result, shown in Fig. 2(b), is that phase locking of an oscillation in cavity No. 3 by electron beam modulation in the three-cavity arrangement requires considerably less drive power than predicted by Adler's theory. The difference in power level between the experimental points and the theoretical curve is more than an order of magnitude. This can be understood, in part, as an intensification of beam modulation between the input and output cavities due to the same gain mechanism that operates in the gyroklystron amplifier. Thus the drive power experiences a significant fraction of the gain that a two-cavity gyroklystron amplifier would provide ($\sim$ a factor of 100). Comparison of these results with a more comprehensive theory,[19] in which we take into account the extended nature of the interaction region, will be made in a later work.

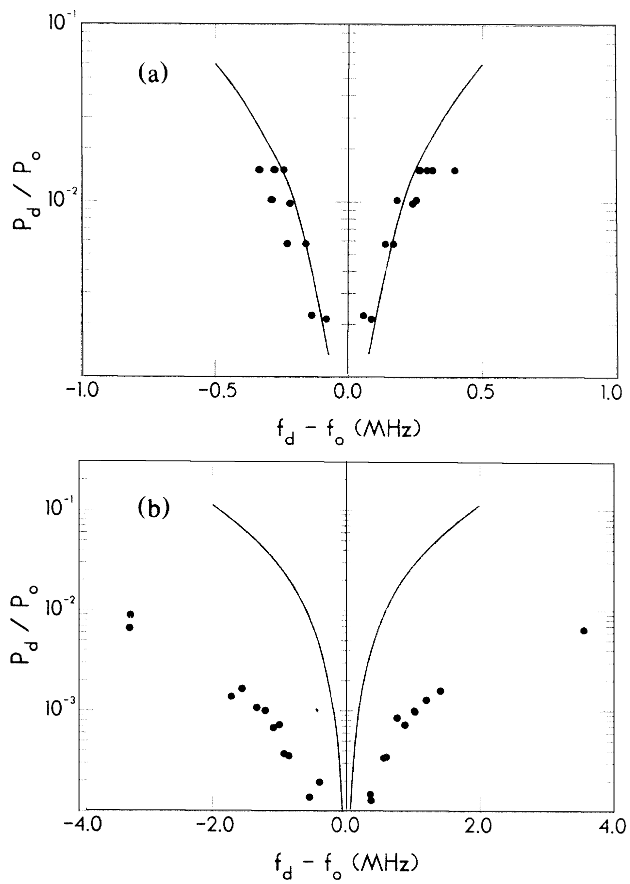

FIG. 2. Phase-locking bandwidths for (a) direct injection of cavity No. 1 with $Q_e = 1100$ and (b) three-cavity configuration with $Q_e = 375$ in cavity No. 3. Note that the locking bandwidth exceeds the theoretical prediction (solid curves) in the multicavity case.

Additional advantages of phase locking via electron beam modulation are that there is a natural separation between the driving components and cavity oscillator, the drive signal is coupled more efficiently to the electron beam, and fluctuations in the gyrotron oscillator amplitude and frequency are reduced. A major problem encountered in direct injection locking is that of obtaining the high-power circulator, or equivalent reciprocal device, to protect the driver from being phase locked by the oscillator. Because of the high degree of isolation between the cavities in our configuration, little oscillator power feeds back into the drive circuit. Along with driver protection, this separation between elements allows more efficient coupling of the drive signal onto the beam. The magnetic field or resonant frequency of the input cavity can now be tuned for optimum absorption of drive power without degrading the performance of the oscillator.

Significant noise reduction is also noted in the phase-locked gyrotron oscillator. The pulse-to-pulse frequency jitter of the oscillation [Fig. 3(a)] is reduced from 18 kHz to a level approaching the 3-kHz driver noise. A frequency discriminator utilizing a mixer-delay-line combination is used to obtain these results. In addition, the pulse-to-pulse jitter in output power is reduced from 4.3% to 0.3% in the center of the locking band. Figure 3(b) shows this power-level fluctuation as a function of frequency difference between the drive and the oscillator. The measurement is made by our taking the standard deviation of the voltage output of a crystal diode over 100 pulses. From Figs. 3(a) and 3(b) it can be seen that both

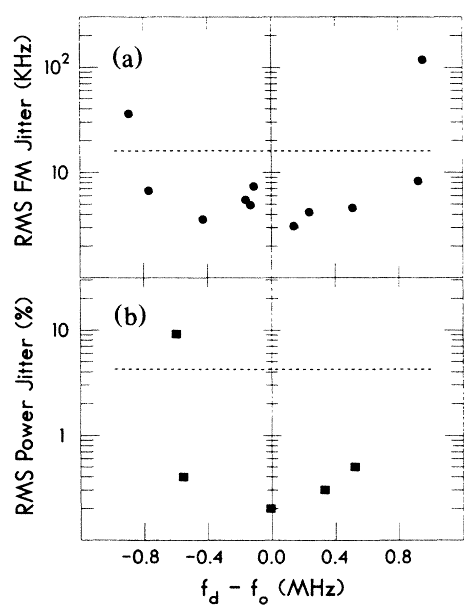

FIG. 3. Noise reduction due to phase locking as drive frequency is varied across the locking band. (a) Amplitude noise ($P_d/P_o = 9.6\times10^{-4}$, locking limits ± 0.6 MHz) and (b) frequency noise ($P_d/P_o = 6.5\times10^{-4}$, locking limits ± 0.9 MHz) both decrease in the locked region. Also shown is the noise from the free-running gyrotron oscillator (dashed lines) and driver (dotted line).

the frequency and amplitude noise become much larger than the free-running values near the edges of the locking frequency band. This observation is consistent with previous phase-locked oscillator experiments and theory.[15] The interline noise (noise between sidebands in the output spectrum) of the gyrotron is considerably reduced by phase locking. This reduction is due to a large decrease in starting-time jitter of the rf pulse, elimination of frequency variation within the pulse (due to voltage droop across the electron gun), and reduction of pulse-to-pulse frequency excursions. The pulse-to-pulse phase jitter in the locked state is measured to be 1.5° in the three-cavity experiment.

Priming is investigated as another method of phase control. Since the priming effect does not control the oscillator frequency, another stabilizing system must be used to compensate for beam fluctuations during the pulse and the poor frequency selectivity of the low Q output cavity. This stabilization can be achieved by a phase-locked feedback loop.[20] Pulse-to-pulse rms phase jitter of less than 2° has been observed on primed magnetrons at drive powers 2 orders of magnitude lower than the oscillator power.[21] However, we observe similar control in priming our three-cavity device at drive power levels 7 orders of magnitude below the output power (see Fig. 4). This increase in priming efficiency can be attributed to both the linear gain the beam modulation experiences during rf oscillation buildup (~power gain of a factor of 1000 in the three-cavity gyroklystron amplifier) and the increased coupling of the drive signal to the beam that can be achieved as a result of the drive cavity-oscillator separation. From Fig. 4 it is clear that the degree of phase control increases as the drive power is increased or as the drive frequency approaches that of the gyrotron free oscillation. Notice that the frequency band

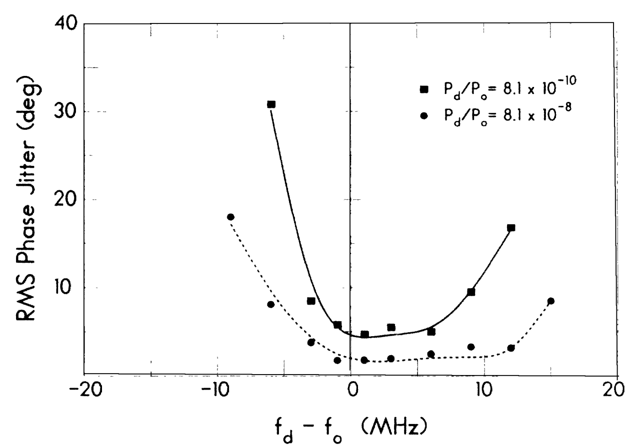

FIG. 4. Reduction in startup phase noise due to priming the pulsed cavity No. 3 gyrotron oscillator, as a function of input drive power and frequency difference between oscillator and driver.

over which significant control is exerted is an order of magnitude larger than in the phase-locked system. The priming measurement is made by mixing of the cw drive and pulsed gyrotron oscillator output in phase quadrature and displaying of the resulting beat signal on an oscilloscope synchronized to the gyrotron. Pulse-to-pulse phase variations are then measured from movement of the zero crossings at the beginning of the pulse on the oscilloscope trace. The use of a primed gyrotron of this type greatly relaxes the drive power requirements in a phased system.

In conclusion, a new method of phase locking of gyrotrons by premodulation of the electron beam produces results which far surpass those of any other locked oscillator system. The power required to lock the oscillator is more than an order of magnitude below that predicted by Adler's theory. In addition, phase control of the gyrotron is obtained via priming at unprecedentedly low drive power levels. This work is expected to have an impact on gyrotron oscillator development and application since phase and frequency control can be obtained with small drive signals.

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[a]Also at Section of Applied Physics, Yale University, New Haven, CT 06520.

[b]Permanent address: Mission Research Corp., Alexandria, VA 22312.

[c]Permanent address: University of Maryland, College Park, MD 20742.

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