standard semirigid coaxial line using nonprecision connectors and interseries adapters. A short, a load, and 1, 3, and 6 dB attenuators were used in conjunction with these delay lines to form transfer standards that were characterized using a calibrated vector network analyzer.

The experimental six-port reflectometer was then calibrated using seven of these transfer standards. A separate set of test devices, differing in reflection coefficient from the calibration standards, was then measured on the six-port reflectometer and on the network analyzer. The test data were compared under the assumption that the network analyzer would exhibit negligible measurement error relative to that of the six-port reflectometer.

The experimental data are shown in Table I, wherein the magnitude of the vector distance between measurements on the two instruments is listed for each test device. The rms radius of the error circles over all the data points is 0.0105. This measure of calibration error is ultimately limited by influences such as uncertainty in the reflection standard parameters, connector repeatability, and measurement system linearity and stability.

V. Conclusions

A method for calibrating the six-port reflectometer with standards of limited quality using the method of minimum-mean-squares has been developed. The solution provided can be implemented in software in a straightforward manner, and a statistical measure of fitting of the derived parameters can be calculated.

Acknowledgment

The authors wish to acknowledge the significant contributions of J. Hornkohl in fabricating and testing the hardware used in this effort.

References

[1] G. F Engen, "Calibration of an arbitrary six-port junction for measurement of active and passive circuit parameters," *IEEE Trans. Instrum. Meas.*, vol. IM-22, pp. 295–299, Dec. 1973.

[2] C A Hoer and K. C. Roe, "Using an arbitrary six-port junction to meausre complex voltage ratios," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-23, pp. 978–984, Dec. 1975

[3] D. Woods, "Analysis and calibration theory of the general 6-port reflectometer employing four amplitude detectors," *Proc. Inst. Elec. Eng.*, vol 126, pp. 221–228, Feb. 1979.

[4] G F. Engen and C A Hoer, "Thru-reflect-line: An improved technique for calibrating the dual six-port automatic network analyzer," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-27, pp. 987–993, Dec. 1979.

[5] P. I. Somlo and J. D. Hunter, "A six-port reflectometer and its complete characterization by convenient calibration procedures," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-30, pp. 186–192, Feb. 1982.

[6] F. M. Ghannouchi and R. G. Bosisio, "A new six-port calibration method using four standards and avoiding singularities," *IEEE Trans. Instrum. Meas.*, vol. IM-36, pp. 1022–1027, Dec. 1987.

[7] J. D. Hunter and P. I Somlo, "An explicit six-port calibration method using five standards," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-33, pp. 69–72, 1985.

[8] C A. Hoer, "Using six-port and eight-port junctions to measure active and passive circuit parameters," NBS Technical Note 673, Sept. 1975.

[9] G F Engen, "A least-squares solution for use in the six-port measurement technique," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-28, pp 1473–1477, 1985

[10] B. A. Herscher and J E. Carroll, "Optimal use of redundant information in multiport reflectometers by statistical methods," *Proc. Inst. Elec. Eng.*, vol. 131, pp. 25–29, 1984.

[11] G. Strang, *Introduction to Applied Mathematics*. Wellesley, MA.: Wellesley-Cambridge Press, 1986, pp. 137–152

Results of Phase and Injection Locking of an Orotron Oscillator

R. W. McMILLAN, SENIOR MEMBER, IEEE,
D. M. GUILLORY, R. G. HAY, D. E. WORTMAN,
H. DROPKIN, SENIOR MEMBER, IEEE, AND
J. M. COTTON, JR., MEMBER, IEEE

***Abstract*—We describe experiments resulting in phase and injection locking of a 60 GHz orotron oscillator in pulsed and CW modes. The measured phase-locked phase noise results obtained in CW mode were −85, −95, and −105 dBc/Hz at 1, 10, and 100 kHz separation from the carrier, respectively. The null depths and asymmetry of the first maxima of the pulsed spectrum for this source were 35 dB and 2 dB (difference between power levels of first maxima), respectively, operating with a pulse width of 15 μs. At 3 μs, these quantities become 25 dB and 1 dB, respectively. The orotron was observed to injection lock in pulsed mode with an input signal 22 dB below the output power level.**

I. Introduction

The orotron is a linear-beam oscillator whose operation is based on the Smith–Purcell effect [1], in which radiation is generated when an electron beam skims the surface of a metallic diffraction grating. Operation of the orotron has been treated elsewhere [2], [3] and will not be described herein, except to say that the orotron may be tuned by varying the cathode-to-grating voltage, which modulates the electron beam velocity, or by varying the mirror spacing, which changes the resonant frequency of the cavity. For phase locking, the phase control signal is fed back to the grating, so that the physical effect of applying a phase correction voltage to the grating is to modulate the beam velocity. The orotron used in the experiments described herein has a grating period of 0.4 mm.

II. Phase-Locking Approaches

Different phase-locking methods were used depending on whether the orotron was operated in short-pulse, long-pulse, or CW mode. The tuning coefficient of the orotron was determined to be 0.2 MHz/V during these measurements, which is a fairly low value, and this lack of gain must be compensated with higher gain elsewhere in the loop. In long-pulse and CW modes a digital phase/frequency detector was used, while in short-pulse mode, a broad-band ac-coupled analog phase lock was used.

The digital phase lock used to lock the orotron in long-pulse and CW modes has been described in [4]. Although the linear circuits [5] give better phase noise performance, digital phase locks have been found to be more nearly immune to circuit variables, such as intermediate frequency (IF) levels and external interference. The approach used was conventional, with part of the orotron power coupled to a harmonic mixer, where it is compared in phase to a stable reference oscillator to generate a

Manuscript received September 12, 1988; revised July 17, 1989. This work was supported by the U.S. Army Harry Diamond Laboratories through Battelle Columbus Laboratories under Contract DAAG29-81-D-9100 (Delivery Order 1932).

R. W. McMillan and J. M. Cotton, Jr., are with the Georgia Tech Research Institute, Georgia Institute of Technology, Atlanta, GA 30332.

D. M. Guillory is with the Hewlett-Packard Company, Boise, ID 83707.

R. G. Hay, D. E. Wortman, and H. Dropkin are with the U.S. Army Harry Diamond Laboratories, 2800 Powder Mill Road, Adelphi, MD 20783-1197.

IEEE Log Number 8930796.

0018-9480/89/1100-1828$01.00

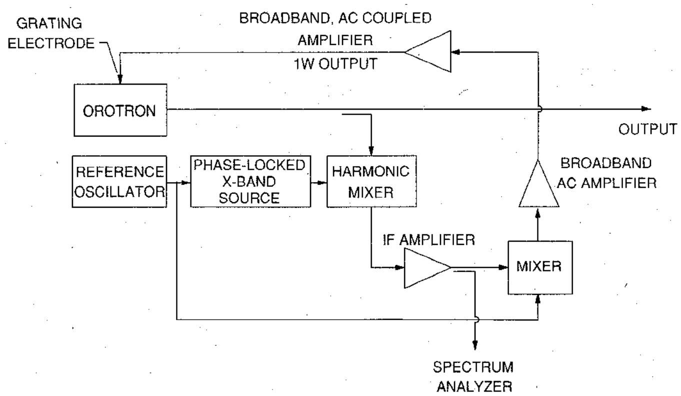

Fig. 1. Block diagram of circuit used to phase lock the orotron at pulse widths down to 2 μs.

phase error signal, which in turn is fed back to the orotron grating.

For phase locking the orotron while operating at short pulse widths (3 μs or less), the circuit of Fig. 1 was used. In this circuit, a double-balanced mixer is used as a phase detector and ac amplifiers are used to couple the phase correction signal to the orotron grating. The low-frequency roll-off of these ac amplifiers was 10 kHz, so that the 3 μs pulse whose amplitude is proportional to phase error, and whose duration corresponds to the orotron pulse width, is coupled to the orotron grating with minimum droop. The upper frequency roll-off of these amplifiers is 300 MHz. Since it is necessary to overcome intrapulse power supply variations with the phase correction voltage, an amplifier capable of at least 1 W of output must be used as a grating driver.

It is possible to lock the orotron in this way without using gain and frequency compensation in the phase-lock loop, provided the high frequency roll-off of the broad-band ac-coupled amplifier is well behaved and occurs at very high frequency. The phase-lock loop is compensated by varying the loop gain with an attenuator, and the acquisition time is a function of this gain and the ac amplifier bandwidth. For the 300 MHz amplifier used for these measurements, this time is several ns, and the spectra shown in the next section seem to indicate that acquisition time is rapid, as indicated by the approximately $\sin^2 x/x^2$ shape.

In locking the orotron at short pulse widths, it was necessary to use a pulse-pedestal mode of operation to minimize turn-on time and ensure the generation of a clean rectangular pulse. In operating in this mode, the orotron beam is pulsed on with a broad pulse in such a way that it is operated just below threshold. The tube is then turned on by applying a short, flat pulse with well-defined rise and fall times to the grating. In this way, the high-voltage beam pulse does not need to have very fast rise and fall times, since the orotron RF pulse shape is determined by the grating pulse.

III. Phase-Locking Results

The orotron oscillator was initially configured to operate in long-pulse mode at a pulse repetition frequency (PRF) of 60 Hz. The phase-lock circuitry was optimized by changing the loop damping and bandwidth, resulting in the near-carrier spectrum shown in Fig. 2, which is a good $\sin^2 x/x^2$ response. The orotron frequency was about 60 GHz, and the bandwidth of the phase-lock loop for these measurements was 1.5 MHz. The correction voltage applied to the orotron grating during phase locking shows

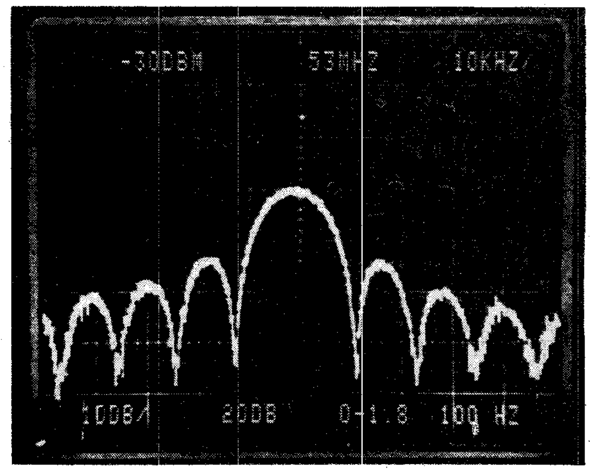

Fig. 2. Near-carrier spectrum of the orotron near 60 GHz measured with a pulse width of 90 μs. The frequency scale is 10 kHz/div, the vertical scale is 10 dB/div, and the bandwidth is 100 Hz. In obtaining this result, the orotron was phase locked using the digital circuit described in the text.

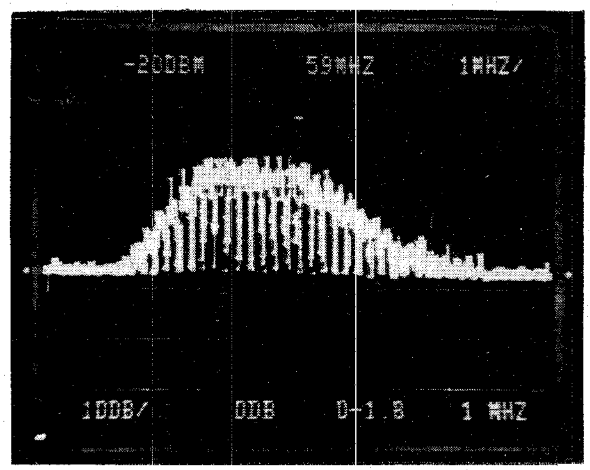

Fig. 3. Spectrum of the unlocked orotron near 60 GHz measured with a frequency scale of 1 MHz/div, a vertical scale of 10 dB/div, and with a bandwidth of 1 MHz.

an overshoot lasting about 3 μs, which is an indication of the capture time of the phase-lock loop. For comparison to the phase-locking results discussed above, Fig. 3 shows the spectrum of the unlocked orotron near 60 GHz. Since this photograph represents an integration of many pulses, the width of the spectrum is not a true indication of open-loop performance, because most of the width of this spectrum is probably contributed by pulse-to-pulse frequency changes. A power supply variation of 25 V peak-to-peak, which is less than 1 percent of the cathode pulse voltage of about 3000 V, will cause this amount of frequency spread, since the tuning coefficient is 0.2 MHz/V. Although it is not possible to estimate the width of the free-running spectrum from Fig. 3, Wortman *et al.* [3] have determined that the free-running spectral width of this device is 0.4 MHz. Comparison of Figs. 2 and 3 gives an indication of the significant improvement in the orotron spectrum attainable by phase locking.

The orotron was next phase locked in short-pulse mode using the pulse-pedestal method of turning on the source. In this mode, the orotron was operated at a PRF of 5 kHz and a pulse width of 3 μs. The near-carrier spectrum of the orotron operated in this way is similar to the long-pulse spectrum, except that the null

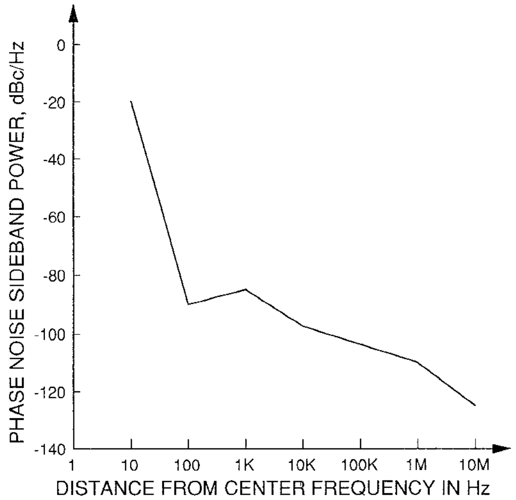

Fig 4. Measured phase noise of the orotron operated in CW mode at 59.725 GHz.

depths are about 25 dB instead of the 35 dB shown in Fig. 2. Since the source was operated at a fairly high *PRF*, it was possible to resolve the *PRF* lines individually on the spectrum analyzer.

The orotron was phase locked at 59.725 GHz in CW mode by using the digital circuit, and its phase noise, shown in Fig. 4, was measured. The phase noise of an oscillator locked to a stable reference is related to the phase noise of the reference by the factor 20 log N, where N is the multiplying factor between the reference frequency and the oscillator output frequency. In locking the orotron in pulsed mode, it does not appear to be possible to relate the orotron phase noise to that of the reference, because the spectral width contributed by the pulse obscures the phase noise. The typical phase noise of the crystal oscillator used as a reference for most of the CW phase-locking experiments reported herein was -130 dBc/Hz at a separation of 1 kHz from the center frequency. In multiplying from 100 MHz to 60 GHz, a factor of 600, the phase noise would be expected to degrade by 56 dB, giving a phase noise of -74 dBc/Hz at 60 GHz. Fig. 4 shows that the orotron phase noise is slightly better than -80 dBc/Hz at 1 kHz, indicating that the crystal reference oscillator is probably better than -130 dBc/Hz. Unfortunately, the crystal oscillator phase noise was not specified at other frequencies.

IV. Injection-Locking Results

Injection-locking measurements were made only in pulsed mode, generally at short pulse widths, using a conventional approach [6]. A reflex klystron oscillator operating at 59.809 GHz was phase locked to a stable cavity oscillator using a digital phase lock similar to that used for locking the orotron. The klystron output was injected into the orotron output through a broad-band isolator with 20 dB isolation, a 6 dB coupler, and an $E-H$ tuner. The orotron was found to behave in much the same way as klystrons [7], laddertrons [8], and other microwave sources when injection locked; namely, it displayed injection-locking gain and frequency pulling. With the klystron frequency adjusted to coincide precisely with the orotron frequency, the orotron was found to injection lock with an output power of 118 mW with an input from the klystron of 0.80 mW, for an injection-locking gain of 22 dB. The null depths for the first minima in this spectrum were 25 dB, which is identical to the nulls obtained for the fast-pulse phase-locking results discussed above. The addition of 20 dB of attenuation in the klystron output reduced the null depths to 13 dB, although there was still significant spectral improvement.

V. Conclusions

This paper describes successful attempts to phase and injection lock an orotron oscillator. Despite a very low tuning coefficient of 0.2 MHz/V, the orotron was found to phase lock easily, with phase noise in the CW mode comparable to other quiet millimeter-wave oscillators, such as klystrons and Gunns. This phase-locking behavior is ascribed to the narrow-band nature of this device, which in turn results from the high-Q optical cavity used as a resonator. Observed frequency variations are largely caused by power supply instability, as described in the text. Although the orotron is observed to be fairly stable when driven by a stable power supply, phase locking is still necessary for a large number of applications, such as Doppler radar, MMW spectroscopy, and to eliminate the effects of temperature drift on the cavity spacing with resultant frequency shifts. The orotron may also be controlled by injection locking. In this mode of operation, it exhibits the general characteristics of injection-locked sources, such as frequency pulling and spectral improvement.

References

[1] S J Smith and E M. Purcell, "Visible light from localized surface charges moving across a grating," *Phys. Rev.*, vol. 92, p. 1069, Nov. 15, 1953.

[2] D. E Wortman, R. P. Leavitt, H. Dropkin, and C. A Morrison, "Generation of millimeter-wave radiation by means of a Smith–Purcell free-electron laser," *Phys. Rev. A.*, vol. 24, no. 2, p 1150, Aug. 1981.

[3] D. E. Wortman, H. Dropkin, and R P. Leavitt, "Millimeter-wave orotron oscillation—Part II: Experiment," *IEEE J. Quantum Electron.*, vol. QE-17, p. 1341, Aug. 1981.

[4] H. M Pickett, "Locking millimeter wavelength klystrons with a digital phase-frequency detector," *Rev Sci Instr.*, vol 48, pp 706–707, June 1977.

[5] P. S. Henry, "Frequency agile millimeter wave phase lock system," *Rev. Sci. Instr.*, vol. 47, pp 1020–1025, Sept 1976.

[6] L. J. Paciorek, "Injection locking of oscillators," *Proc. IEEE*, vol. 53, pp. 1723–1727, Nov 1965

[7] R. Mackey, "Injection locking of klystron oscillators," *IRE Trans. Microwave Theory Tech.*, vol. MTT-10, pp. 228–235, July 1962.

[8] R. G. Strauch, W. T. Smith, and V. E Derr, "Injection locking of a laddertron at 35 Gc/s," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-13, pp. 473–474, July 1965.