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COHERENT TRANSMITTER CONSIDERATIONS UTILIZING INJECTION LOCKED MAGNETRONS

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Abstract

The Radio Frequency (RF) power generation capability of various Ka-band transmitter alternatives are discussed. The coherent magnetron can be a low cost method of producing Ka-band RF power efficiently. Additive FM noise characteristics of commercially available X-band magnetrons were measured and their power combining capability studied. Finally, noise theory for coherent magnetrons is reviewed and an equation to predict FM noise performance is derived.

Introduction

Coherent transmitters have been applied in pulse doppler and Moving Target Indicator (MTI) radars for some time. Recent interest in improving the efficiency, reducing the weight, volume and costs, and extending the shelf life of these transmitter assemblies has prompted the U.S. Navy to study potential solutions to these problems. Ka-band is an area of recent interest and various transmitter alternatives are shown in Figure 1.

This chart shows the current technology options under consideration for potential Ka-band radar systems. The coherent magnetron transmitter scheme offers the lowest cost, volume, and weight assembly theoretically capable of delivering average power levels and bandwidth comparable to that of the CC-TWT (1, 2, 3). The magnetron has been utilized in fuzing systems for decades and has proven to be a rugged RF device with long shelf life capability. A proposed Ka-band coherent magnetron transmitter block diagram may be seen in Figure 2.

The coherent magnetron is a technology option to be considerd for future radar transmitters. The magnetron is normally considered to be a noisy, free running oscillator, so the noise performance of the injection locked magnetron will require special consideration. Ka-band magnetrons are not readily available, so measurements have been made to determine the additive FM noise performance of commercially available X-band injection locked magnetrons. The phase characteristics of these tubes were studied to predict their power combining potential. Finally, this paper concludes with a discussion on the derivation of an equation to predict the FM noise of a coherent magnetron.

Noise Measurement System and Calibration

The measurements were carried out on an X-band noise/phase measurement bridge shown in Figure 3. These particular measurements were carried out at 9.375 KHz Pulse Repetition Frequency (PRF) and 667.0 nsec pulse width because of the fixed capability of the magnetron's built-in high voltage power supply and modulator. The low pass filter shown between the detector and baseband amplifier was designed to break at 5.0 KHz and provide more than 20.0 dB of rejection at the first PRF line. Calibration is performed by placing FM sidebands at an independently measured (high enough level to be accurately measured on a microwave spectrum analyzer, for example) level on the carrier within one leg of the bridge, with frequency or amplitude modulation selectable by appropriate setting of the phase shifter in the calibration path.

Magnetron Noise Measurements

Measurements were carried out on two negative pulsed cathode X-band magnetrons, identified as M-O Valve Model MAG 17, Serial Numbers MRQ-R003 and -R006 each capable of 160.0 watts peak and 1.0 watt average power. Figure 4 shows additive FM noise versus modulation frequency for -R006 from 0.0 to 5.0 KHz from the carrier, with injection locking frequency as a parameter. The injection locked gain was 15.0 dB, and the magnetrons became unlocked 1.0 MHz above and below the extremes shown on Figure 4. In general, the noise was about 80.0 dBc/100.0 Hz below carrier within the injection locking band and rose 10.0 to 15.0 dB near the upper end of the band.

The next set of measurements addressed the dependence of additive FM noise on injection locking gain. At the upper edge of the locking band, tube Serial Number -R006 contributed -69.0 dBc/100.0 Hz at 15.0 dB gain, as shown on Figures 4 and 5. Increasing the RF drive level to decrease the gain to 11.0 dB resulted in a dB per dB linear improvement in the noise, to -73.0 dBc/100.0 Hz. This was the lowest gain that could be achieved, because of the availability of RF drive power.

Measurements of Transient Phase Across the Pulse

Coherent combining of the output power of multiple magnetrons requires not only that they be phase locked to a coherent source, but that any transient phase response associated with the lock-in phenomena be of similar shape and magnitude for each of the I.L.O.'s to be combined. Figure 6 shows this transient for Serial Number -R006, 3.0 MHz above the free running frequency. A measurement gate has been implemented around the pulse in such a manner that

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the transient of interest begins with the negative going trace approximately 700.0 nsec from the left edge of the graticule. Nulling the peak overshoot by changing a phase shifter setting in the measurement (RF) arm of the bridge permitted the determination of the peak-to-peak phase ripple at approximately 40.0 degrees. Figure 7 illustrates the phase transient measured on magnetron Serial Number -R003. This is data at 3.0 MHz above the free running frequency and at 15.0 dB of gain for which the peak-to-peak ripple is 60.0 degrees. Based upon these measurements, one may conclude that the transient phase response for the two injection locked pulsed magnetrons has a well behaved and similar character, near the free running frequency.

FM Noise Theory for Coherent Magnetrons

To obtain pulse to pulse coherence and some locking bandwidth it is necessary to frequency lock the magnetron with an injection signal (5, 6, 7, 8). The free running magnetron oscillator starts each pulse from a signal on the slow wave structure generated by the noisy crossed field beam. This noise on the crossed field beam is broad band with a peak at the cyclotron frequency. Magnetrons tend to operate either above or below this cyclotron resonance, hence we may assume that the noise is essentially broad band with a spectral density of S watts/hertz. The π mode resonance of the slow wave structure acts as a narrow band filter on this noise giving rise to a quasi sine wave at the π mode frequency. The magnitude and phase of this quasi sine wave varies randomly from pulse to pulse thus producing front edge jitter and random starting phase. For a frequency locked magnetron, the oscillation starts from the vectorial addition of this quasi sine wave and the locking signal as seen in Figure 8. Worst case AM occurs when Vn is in phase or 180 degrees out of phase with Vi and maximum FM occurs when Vn is in quadrature with Vi.

From noise theory, an equation may be derived that provides an estimate of the single sideband phase noise, N(SSB), of a coherent magnetron and

$$N(SSB) = 10 \text{ Log } \frac{Q_E^3 \, SNCz}{16D^2 \, |\rho|^2 e^2 f Po} + G \text{ dBc/Hz}$$

where the terms are defined as the following with relation to the MAG 17:

f=frequency ~10.0×10.0^9, e=pulse length=0.67×10.0^{-6} seconds, D=duty factor=0.00625, Q_E=external Q~350, N=number of resonators=12, C=resonator capacitance ~0.1×10.0^{-12} farad, Po=peak output power=160.0 watts, S=spectral noise density~2.0×10.0^{-12} watts/hertz, $|\rho|$=reflection factor~0.14 (9), z=efficiency~0.6 and G=gain in dB. The FM noise for the MAG 17 is estimated to be N(SSB) = -114.5 + G dBc/Hz and for the following gain values, the N(SSB) is calculated to be:

G=20.0 dB N(SSB)=94.5 dBc/Hz
G=15.0 dB N(SSB)=99.5 dBc/Hz.

The above analysis then appears to agree reasonably well with the experimental results given earlier. The extent of the agreement is perhaps fortuitous as the analysis includes many approximations and simplications in particular the dependence of "S" on the tube parameters remains unknown(4).

Conclusion

Measurements of the FM additive noise of two similar X-band magnetrons operating in a low PRF, low duty cycle, injection locked mode have been made along with their transient phase characteristics across the RF pulse length. These measurements show coherent injection locking at gain levels of 11.0 to 19.0 dB, with bandwidths on the order of 5.0 to 10.0 MHz at the 15.0 dB gain level, and additive FM noise on the order of -70.0 dBc/KHz within the injection locking band, flat over deviations from 1.0 to 5.0 KHz. The measured noise rises as much as 10.0 dB near the upper frequency edge of the locking band. The demonstrated bandwidth agreed reasonably well with that predicted from the familiar Adler's equation (7). The similarity of the phase transient curves for the two tubes give credence to claims that such tubes can be coherently combined.
Also, an equation has been derived for calculating N(SSB) for an injection locked magnetron. In conclusion, data has been gathered to support a design approach for a coherent radar transmitter utilizing injection locked magnetrons. Special thanks are extended to Mr. Kent Whitney, Raytheon MSD for conducting the FM noise measurement experiments.

References

(1) Garrigus, W. E., "Phase Noise Performance of Magnetrons", Microwave Journal, July 1977, pp. 59-73.
(2) Devito, P. A., "Some Properties of an Injection Locked Pulsed Magnetron", AFCRL-TR-73-0073, 16 January 1973.
(3) Walker, R. W., "Pulse-to-Pulse Coherence in Magnetrons by Injection Priming", Micronotes, Microwave Associates, Burlington, MA, December 1970.
(4) Vyse, B., "Jitter and the Growth of RF Oscillations in Pulsed Magnetrons", Degree of Doctor of Philosophy Thesis, Edinburgh University, Edinburgh, Scotland, April 1971.
(5) Vyse, Dr. B. Smith, V. H., "The Use of Magnetrons in Coherent Transmitters", Proceedings of the Military Microwave Conference 1982, London, England, October 1982.
(6) Adler, R., "A Study of Locking Phenomena in Oscillators", Proceedings of the IRE and Waves and Electrons, June 1946, pp. 351-357.
(7) Vaughan, J. R. M., "The Injection Locked Voltage Tuneable Magnetron", Microwave Journal, October 1968, pp. 45-47.
(8) Vyse, B., Gissing, J. M., "Spectra of Short Locked Magnetron Pulses", IEEE Transactions on Electron Devices, March 1971, pp. 221-223.
(9) David Jr., E. E., "RF Phase Control in Pulsed Magnetrons", Proceedings IRE, Vol. 40, June 1952, pp. 669-685.

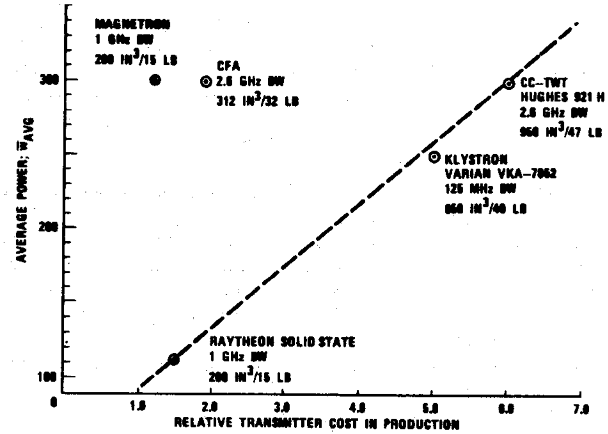
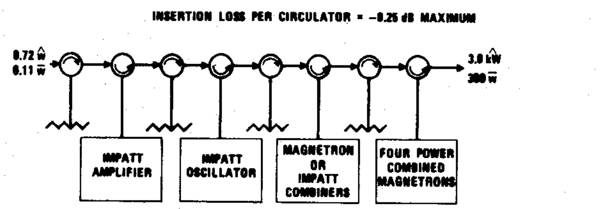


Figure 1. Ka–Band Transmitter Technology Comparisons.



IMPATT AMPLIFIER	IMPATT OSCILLATOR	MAGNETRON OR IMPATT COMBINERS	FOUR POWER COMBINED MAGNETRONS	
0.54	3.4		3366.0	P_{PEAK}/COMBINER; Ŵ
0.10	0.48		336.6	P_{AVG}/COMBINER; W̄
10.0	0.0	15.0	15.0	GAIN; dB
0.8	4.25	106.41	841.5	P_{PEAK}/DEVICE; Ŵ
0.128	0.50	12.65	84.15	P_{AVG}/DEVICE; W̄
10.0	14.0	12.0	10.0	DUTY CYCLE; %

Figure 2. Ka–Band Transmitter Block Diagram.

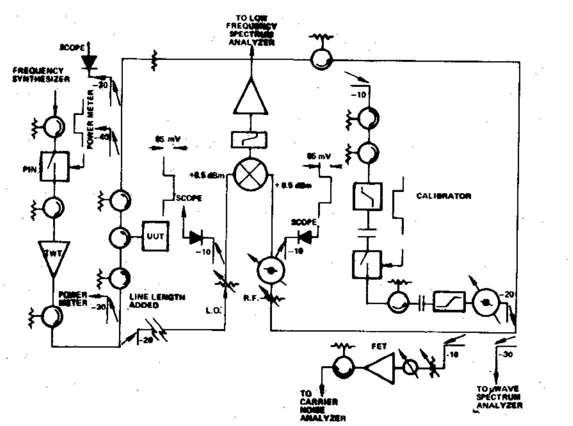


Figure 3. Pulsed Additive FM Noise Measurement System.

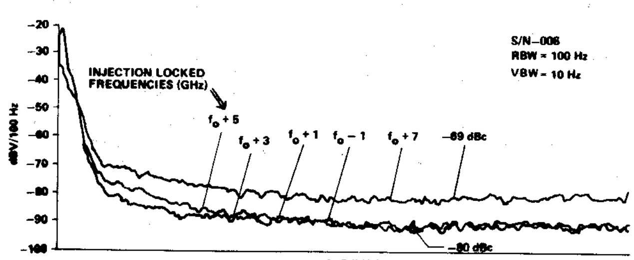


Figure 4. Additive FM Noise vs Deviation Rate.

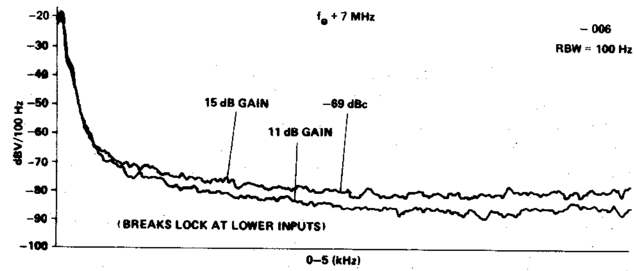


Figure 5. Dependence of Additive FM Noise on Injection Locking Gain at Upper Edge of Injection Locked Band.

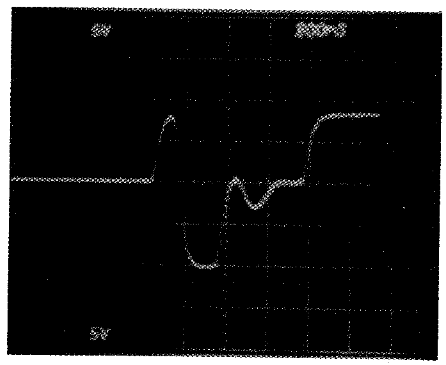


Figure 6. Phase Transients, Magnetron Serial Number –R006 at 15 dB IL Gain, f_o + 3 MHz.

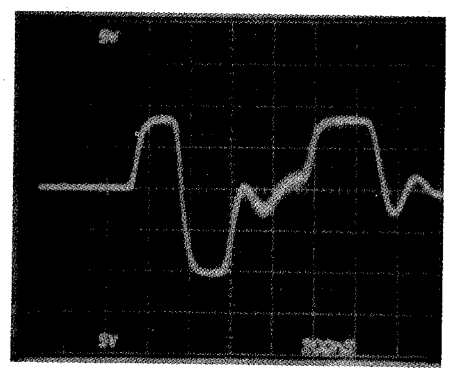


Figure 7. Phase Transients, Magnetron Serial Number –R003 at 15 dB Gain, f_o + 3 MHz.

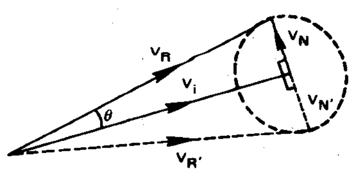


Figure 8. Injected Signal, Noise Signal Vector Addition Relationship.