THE NOISE BEHAVIOR OF AN INJECTION-LOCKED MAGNETRON REFLECTION AMPLIFIER.

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SUMMARY

The noise performance of a modified X-band fixed-frequency magnetron in the fractional kilowatt range is described in this paper. The magnetron was operated in the injection-locked mode via a three-port circulator. The effects of pulse length, pulse repetition frequency and phase-reversal waveforms on the close-in phase and amplitude noise up to 10 KHz from the carrier is described. With 16 db injection-locking gain at 10% duty factor, additive phase noise less than -115 dBc/Hz at 5 KHz offset frequency was measured, regardless of waveform.

INTRODUCTION

The conventional magnetron may be viewed as a short-pulse microwave crossed-field amplifier (CFA) when operated in the injection-locked mode via a three-port circulator (see Figure 1). Since its invention just prior to World War II in l940 [1], the magnetron has been used exclusively as an efficient (>40%), free-running, low duty-factor (<<1%) power oscillator with peak power levels in excess of l megawatts. As such, it has been occassionally used in early Hughes X-band fire-control and related radar applications, where coherence was not required. The magnetron has been historically perceived as an efficient, compact, though "noisy" power source, whose starting RF phase jitter was deemed incompatible with the stringent requirements of coherent pulse-doppler radar.

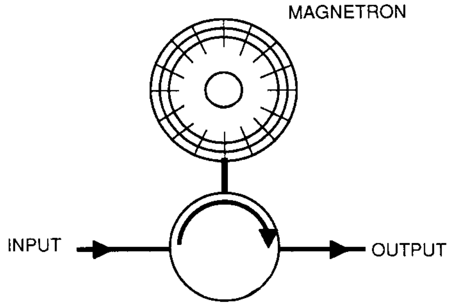

Figure l Injection-locked magnetron reflection amplifier.

Beginning in the early l970's, the starting phenomena of the free-running magnetron was investigated in several studies [2,3,4]. These investigations concluded that the noise might be reduced if the noisy magnetron were primed with or locked to an injected microwave signal of high short term stability. The question of instantaneous frequency range over which an injection-locked oscillator could be used was resolved by Adler [5] and Davis [6], who predicted a small fractional bandwidth (<l%), slowly varying with the external (load) Q of the passive circuit and the injected power level.

The experimental magnetron study reported here is the most recent chapter in this investigation. The goal of our study was to determine the applicability of a commercially available magnetron in the 1 KW power range to pulse-doppler radars. In this preliminary study, answers were primarily sought in the following four areas:

1. Achievable duty factor (D.F.) to permit accurate pulsed noise measurements;
2. Attainable instantaneous bandwidth to accomodate waveform risetimes;
3. Phase and amplitude noise near the carrier;
4. Noise performance with phase reversal waveforms.

Experimental data was obtained from several commercial, X-band, fixed-tuned magnetrons, operating near 9.3GHz with approximately 400 watts peak power output

DUTY FACTOR INCREASE

The low duty factor (D.F. <5%), specified for this magnetron severely limited meaningful evaluation of the magnetron, particularly an accurate noise measurement at any pulse length. Air cooling of the exposed anode, after removal of its protective plastic cover allowed the D.F. to be increased up to 12%, resulting in an anode temperature rise to 170 °C, well below the 200 °C maximum temperature suggested for safe operating temperature. Throughout the tests described in this paper, the magnetron was operated at

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a D.F. of 10%, except for short 12% D.F. intervals at the highest pulse repetition frequencies (PRF). Under these conditions, the magnetron has accumulated many operating hours of stable operation.

BANDWIDTH EXTENSION

Bandwidth can, in principle, be extended substantially by increased coupling to the external circuit load, thereby lowering Q_{ext}. The coupling iris inside the vacuum envelope of the magnetron is fixed. Increased load coupling was achieved with both slide-screw and E-H tuners, the latter being the preferred implementation because of its greater resettability. An instantaneous bandwidth of 80 MHz could be repeatably be obtained, though the 60 MHz setting showed greater stability and a cleaner spectrum. Maximum bandwidth was obtained with a specially-fabricated 3-screw tuner that could be placed closest to the magnetron port. The bandwidth results are summarized in Table I.

Table I Bandwidth results.

Magnetron bandwidth	2 - 6 MHz
With slide-screw tuner	60-80 MHz
With E-H tuner	60-80 MHz
With 3-screw tuner *	120 MHz

* free-running mode

As can be seen, more than one order of magnitude increase in instantaneous bandwidth was realized with relatively simple external matching elements. Note that the 3-screw tuner results were obtained with the magnetron in the free-running mode (not injection-locked). In this case, the magnetron port was terminated in a waveguide load and the frequency determined by the setting of the three screws of the tuner. Under these conditions a tuning range of nearly 1.3% was obtained. It is conjectured that this value may represent the upper limit of instantaneous locking bandwidth possible for this magnetron design.

Unless otherwise noted, the results, to be described in the remainder of the paper, were obtained with the E-H tuner set for a constant bandwidth of 60 MHz.

GAIN-BANDWIDTH BEHAVIOR

The dependence of injection-locking gain (I.L.G.) on instananeous (locking) bandwidth was measured using the larger, cold-circuit bandwidth, as discussed above and at a fixed D.F. of 10%. The bandwidth at each gain setting was then measured by pulling the input signal pulse to the extremes of the locking range. Loss of lock was measured using a spectrum analyzer, that was also monitored to observe and maintain noise- and spurious-free operation.

The results are listed in Table II. For these measurements a 5 µsec 9.3 GHz RF pulse burst was used at a PRF of 20 KHz.

Table II. Magnetron gain-bandwidth behavior.

Drive	I.L.G.	B.W.	Output power	
(dBm)	(dB)	(MHz)	(dBm)	(KW)
+40	17.2	65	+57.2	0.52
+43	14.3	77	+57.3	0.54
+46	11.7	99	+57.7	0.59
+49	8.9	102	+57.9	0.62

It is seen that bandwidth increases with injected power increase, but less rapidly than predicted by reference 1. Output power from the magnetron is approximately constant, keeping in mind that the input signal contributes increasingly to output power at the lower I.L.G. settings.

CLOSE-IN NOISE AND SPECTRA AT EXTENDED BANDWIDTH

The noise performance of the injection-locked magnetron with extended bandwidth, operating at 10% D.F. is described below. The results were obtained with the Hughes Microwave Noise Test Set (MNTS). The MNTS, dedicated to X-band, is unique in the sense that the calibration procedure autmatically accounts for the prevailing duty factor of the device under test.

Additive phase noise within 10KHz from the 9.28 GHz carrier and the corresponding power spectrum are shown in Figure 2, where the ordinates in Figure 2 are 10 dB/vertical division and 1 KHz/horizontal division.

(a) (b)

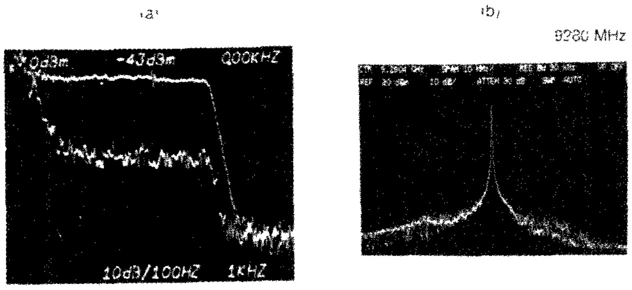

Figure 2 Close-in phase noise (a) and power spectra (b) of injection-locked magnetron 9.28 GHz; locking bandwidth=60 MHz, I.L.G.=16 dB, D./F.=10%, PRF=10 KHz ; the reference line is -80 dBC/Hz.

The -80 dBc/Hz reference line near the top in each figure extends to 8 KHz. Beyond this point, the 8 KHz PRF filter of the MNTS removes objectionably large higher-frequency spectral lines including the first 10 KHz PRF line. Beyond 3 KHz, the phase noise apparently reaches a plateau in each case. Additive phase noise decreases somewhat with increasing carrier frequency (taken at 5 KHz from the carrier) as can be seen from Table III.

Table III. Magnetron phase noise.

Frequency (GHz)	Noise power (dBc/Hz)
9260	-103
9280	-105
9300	-108

The AM noise power density (not shown) was in all cases below the observed phase noise.

THE EFFECT OF INTRA-PULSE MODULATION ON CLOSE-IN NOISE

The ability of the injection-locked magnetron to faithfully follow a rapid phase-reversal waveform with fidelity and without noise degradation is not well established. The spectral density of amplitude and phase noise was, therefore, measured with and without a bi-phase modulated RF pulse burst. The waveform input to the phase modulator consisted of a 5 µsec burst containing five 1 µsec squarewave cycles with 4 nsec rise and fall times.

The magnetron noise behavior under these conditions is shown in Figure 3. System (one-port) AM noise is shown in the top row, while additive PM noise, contributed solely by the magnetron is shown below. Right and left hand columns compare the noise with (left) and without (right) bi-phase modulation. The presence of the 8 KHz PRF low-pass filter is evident by the cutoff characteristic in the right hand portion of each figure. The horizontal and vertical scales are 1 KHz and 10 dB per division, respectively. The -80 dBc/Hz reference trace is seen near the top in each photo. The magnetron appears to process the bi-phase modulation format without noise degradation relative to the simple pulse-burst mode.

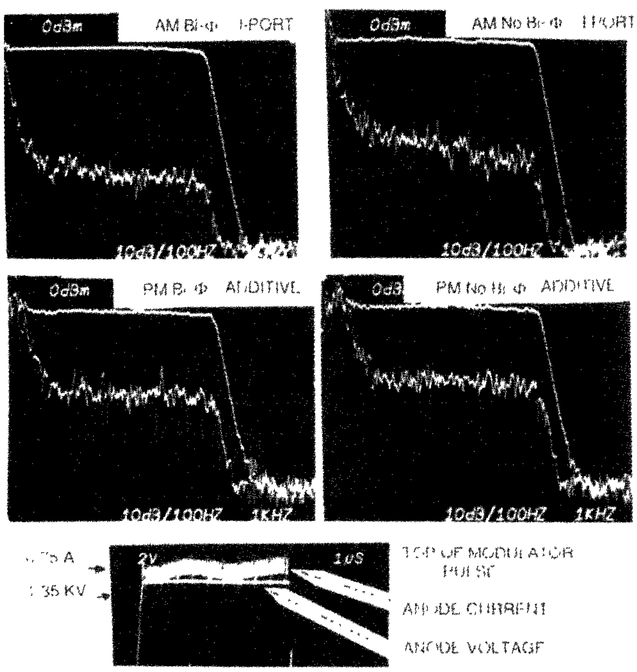

Figure 3 Comparison of close-in noise with bi-phase and pulseburst modulation wave forms; frequency= 9275 MHz, BW=60 MHz, I.L.G.=16dB, pulse length = 5 µsec, PRF = 20 KHz, output power = 0.4 KW

Beyond 2 KHz from the carrier, the noise decreases rather slowly. At 5 KHz from the carrier, the spectral density of phase noise is -105 dBc/Hz, approximately the same for both waveforms. The spectral power density of AM noise is -122 dBc/Hz for the bi-phase signal and -115 dBc/Hz for the pulse burst (without bi-phase modulation) of the same duration. The apparent lower AM noise for bi-phase modulation is somewhat unexpected and at present not understood.

Figure 3 also shows the magnetron anode current and anode voltage pulses. Only the current pulse evidences transition spikes at each phase reversal, of the same magnitude for both advancing and retarding π phase shift. Apparently these current spikes do not affect the near-carrier noise in any measurable way.

The effect of pulse repetition frequency (PRF) on noise at constant pulse length (4.0 µsec) is illustrated in Figure 4. Except for pulse length and PRF, the parameters of Figure III apply here as well. The spectral density of noise power was measured over the allowable PRF range from 8 to 30 KHz, limited by the low average RF power for reliable noise measurements at the low PRF end and limited at the high PRF end by the permissible duty factor (12%) at which the magnetron could reliably perform.

The AM and PM noise measurements, shown in Figure 4 were made in different ways. The AM noise represents a one-port measurement, that includes the total AM system noise, consisting of the pulsed magnetron, the CW output of the TWT driver, and the pulsed AM noise of the gated microwave frequency synthesizer. The PM noise , on the other hand , is a two-port measurement, that represents solely the additive noise that the magnetron contributes.

The AM and PM noise power density show different PRF dependence., that may be related to themeasurement differences discussed above. The AM noise varies approximately as $(PRF)^{-3}$, while the PM noise appears to decrease as $(PRF)^{-1}$. This functional behavior of the AM noise variation is not understood but it may be dominated by the noise characteristics of the input signal. Gating the input to the noise test set, to eliminate the TWT interpulse noise did not affect the AM or PM measurements. The observed PM noise, on the other hand, decreases approximately linearly with PRF, as predicted by [7].

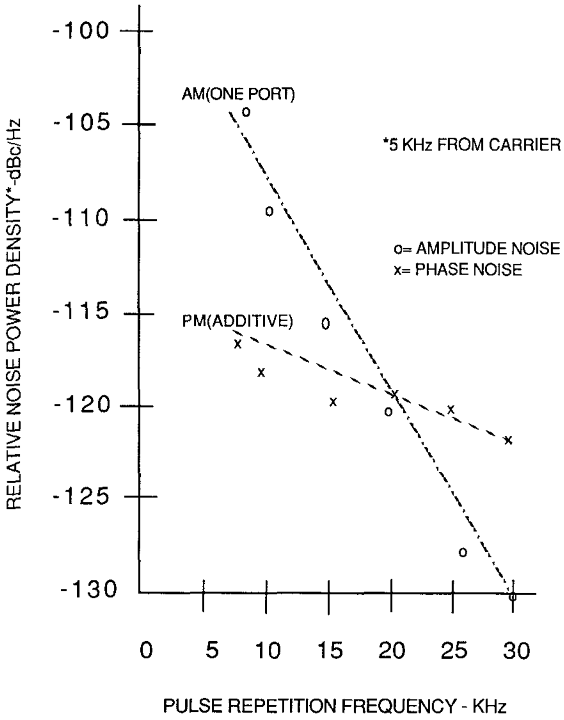

Figure 4 Magnetron close-in noise at constant pulse length; the AM noise is a one-port measurement that includes the magnetron and driver noise sources; the PM noise is additive noise solely contributed by the magnetron; Pulse length=4.0μsec, ILG=16 db, D.F.=12% at 30 KHz, peak power=0.5 KW.

Finally, the video-detected output signal from the magnetron reflection amplifier reproduced the input waveform to the phase modulator quite faithfully, yielding an nearly indistinguishable replica of the 1 μsec squarewave burst.

CONCLUSIONS

The noise performance of the X-band fractional kilowatt injection-locked magnetron, operating as a reflection amplifier, appears to be compatible with moderate coherent radars requirements. At carrier offset frequencies between 3 and 10 KHz, the additive phase noise, contributed by the magnetron, was -115dBc/Hz or lower at pulse lengths between 3 and 10 μsec under the stated conditions. These results were obtained with simple RF pulse bursts as well as with intra-pulse modulation containing rapid phase reversal waveforms. The required locking bandwidth to accommodate these waveforms could be estimated approximately by considering the magnetron as a linear passive resonator.

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