Based upon the driver stage gain of 9 dB and the respective noise figures of both stages, the composite noise figure of the two-stage amplifier is calculated to be 45 dB. The measured noise figure for the two-stage amplifier as plotted in Fig. 5 projects a noise figure of +47 dB at an input drive level of +18 dBm.

V. Conclusions

A strong interdependence exists between the output power, gain, and noise figure of IMPATT amplifiers or injection-locked oscillators (oscillator–amplifiers). An IMPATT-diode oscillator–amplifier exhibits the most desirable output power–noise-figure relationship when the device is operated under minimum injected signal levels. The noise figure of an IMPATT oscillator–amplifier, designed to provide a specified output power level under a given biasing condition, is minimized when the device is matched to provide this output in the free-running mode. It is operated as a high-gain narrow locking band amplifier–oscillator. Increasing the RF load resistance at the diode will reduce the free-running output level and improve the small-signal noise figure. However, this oscillator–amplifier, with lower gain and wider band features under the drive conditions necessary to reestablish the output power of the high-gain oscillator–amplifier, will exhibit a degraded noise figure.

Acknowledgment

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IMPATT-Diode Power Amplifiers for Digital Communication Systems

S. F. PAIK, P. J. TANZI, AND DOUGLAS J. KELLEY

***Abstract*—IMPATT-diode amplifiers with a power output of 1.0 W have been developed for use in an 11-GHz digital radio. Two types of amplifiers, a multistage reflection amplifier and a hybrid amplifier containing an injection-locked oscillator stage, have been evaluated by measuring the bit error rate degradation due to the amplifier. System test data show that the stable amplifier introduces little or no errors while the injection-locked oscillator (ILO) often introduces an error-rate floor.**

I. Introduction

IMPATT-diode amplifiers with power outputs of 1 W or more have been found useful as power amplifiers in microwave communications systems. As the need for high-speed data transmission rises, it is important to establish the capability of the new type of amplifiers to transmit digitally modulated microwave carriers. The purpose of this paper is to present experimental results describing transmission characteristics of IMPATT-diode amplifiers designed for use in an 11-GHz digital radio equipment. The equipment is designed to transmit quadrature phase-shift-keyed (QPSK) [1] carrier modulated at the data rate of 40 Mbit/s.

Two different types of IMPATT-diode amplifiers have been tested for this system: a multistage reflection amplifier [2]–[4] and a hybrid amplifier containing an injection-locked oscillator (ILO) stage [5]–[8]. Both types of amplifiers have a gain of 30 dB at the output power level of 1.0 W. Design considerations and the performance characteristics of the two types of amplifiers are described in Section II.

The most meaningful indicator of the system performance in data transmission is the bit error rate (BER). To assess the "quality" of the amplifiers, the BER degradation introduced by the amplifiers is measured by comparing the system BER with and without the amplifiers in the transmission path. In Section III the experimental results are presented, with a short description of the equipment and test conditions.

II. Amplifiers

The power output requirement for the amplifier is 1.0 W. The input signal to the amplifier is derived from an up-converter whose output level is in the range of 1–2 mW [9], and thus the minimum gain of the amplifier at the saturated output level of 1.0 W is 30 dB. Since the spectral width of the

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modulated carrier is 40 MHz, the minimum instantaneous bandwidth required of the amplifier is of the same magnitude, but the amplifiers should be designed to operate at any assigned frequency within a broad frequency range.

Angle-modulated carriers with little or no AM may be amplified by either a multistage broad-band amplifier operating in the stable mode or a tunable oscillator operating in the injection-phase-locked mode [5]–[8]. The ILO offers the advantages of higher efficiency and economy, while the advantages of the multistage amplifiers are its inherent stability and broad instantaneous bandwidth.

A. Broad-Band Reflection Amplifier

For a 30-dB gain at the saturated power output of 1.0 W, four reflection-amplifier stages are required. At low power levels the gain is limited by the usual gain bandwidth product, while at high power levels it is more a function of the power generating capability of the diode. The amplifier is constructed in a modular form by cascading several integrated single-stage amplifier modules. The driver amplifier module (the first two stages) is constructed in a single ferrite substrate containing three circulating junctions (including input and output isolators), an appropriate transformer section, and a stabilizing network [3], [4]. The diode used in the driver stage is a GaAs diode mounted in a minipill package capable of generating 500 mW at 11 GHz. The driver amplifier module operates linearly with a gain of 10 dB at power output levels of up to 100 mW. The diode is dc biased to 50 V, and draws about 120 mA for a dc power dissipation of 6 W. The power amplifier module (the last two stages) is built in two substrates: one ferrite substrate containing a four-port circulator and an output power detector (for power output monitor), and an alumina substrate for the amplifier section. The diode in the power amplifier module is also a GaAs diode with power ratings of 1.0 W. The dc power input to the diode under normal operating conditions is 9 W (55 V×150 mA). Two power amplifier stages are needed for the last 10 dB of gain. Fig. 1 shows the amplifier package and four amplifier modules cascaded together with appropriate coupling structures designed to reduce leakage and provide an adequate isolation between stages. The amplifier modules, after integration, are mounted in a housing with WR-75 waveguide ports which also contain current regulators for each diode. The driver amplifier module is designed to cover one-half of the 10.7–11.7-GHz band. The power amplifier module (with lower gains) covers the full 1-GHz band. Fig. 2 shows the frequency response of the four-stage amplifiers for the lower half of the band. In Fig. 3, the power output is plotted against the input drive to show that the amplifier is fully saturated at the output level of 1.0 W.

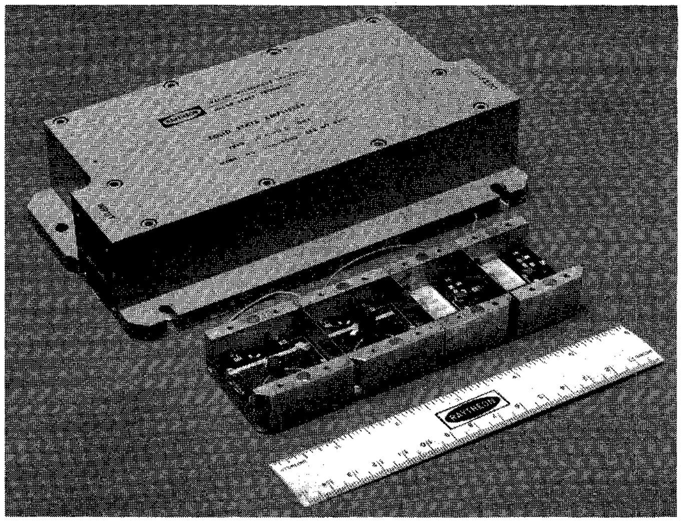

Fig. 1. Four-stage amplifier.

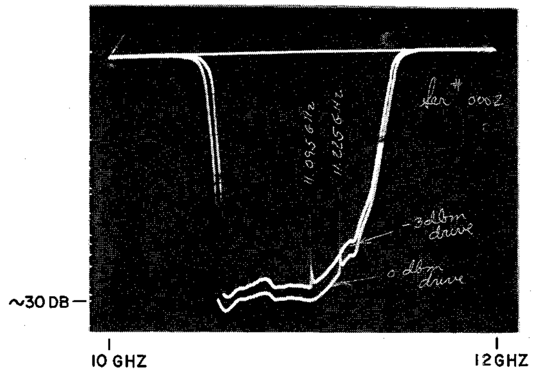

Fig. 2. Frequency response of amplifier. Upper trace is ADA output with −3-dBm drive. Lower trace is with 0-dBm drive. Sweep is 10–12 GHz.

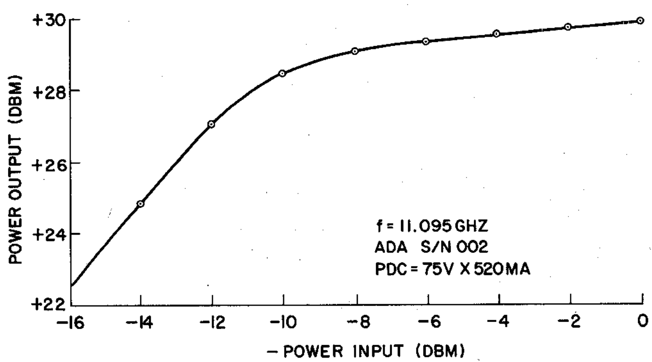

Fig. 3. Power saturation characterization of amplifier.

B. Injection-Locked Oscillator

As an amplifier for QPSK modulated carrier, the most critical characteristic of the ILO is its transient phase response to input phase transitions of ±90 and 180°. The transient response of the output phase to a step-function shift in the input phase is a function of the locking bandwidth and the frequency difference between the oscillator frequency and the input frequency [7], [10], [11]. To reduce the "time constant" of the phase transition, the locking bandwidth should be many times greater than the bandwidth of the modulated carrier [7], [11] (or the data rate), as in the case of FM amplifiers. Unlike FM amplifiers, the free-running frequency of the ILO should be tuned off the carrier frequency, since ILO's do not respond to 180° phase transitions when the locking frequency is equal to the free-running frequency [7], [11]. When used as amplifiers for PSK-modulated carriers, therefore, the ILO's free-running frequency should be set within a relatively narrow "window" in the locking band, the width of the window being dependent again on the magnitude of the locking bandwidth. For the carrier with a 40-MHz modulation bandwidth, a locking range of 200 MHz is considered barely adequate.

The locking range is related to the power gain and the

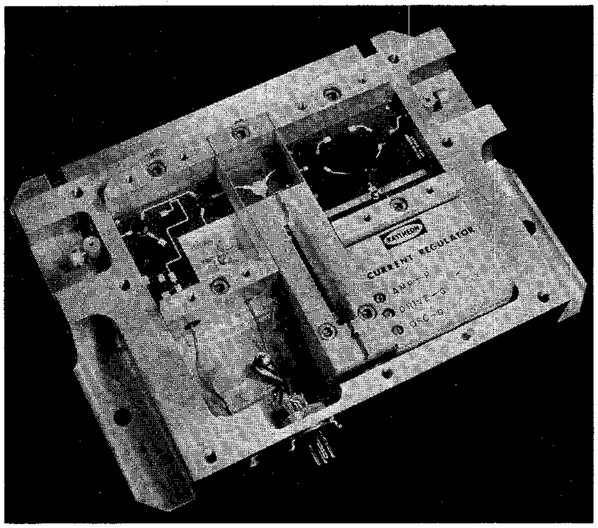

Fig. 4. Three-stage amplifier containing ILO in coaxial circuit.

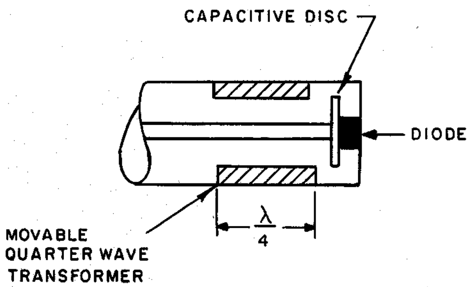

Fig. 5. Coaxial circuit configuration for ILO stage.

external Q of the oscillator by the well-known relation [10], [11]

$$\frac{\Delta f_L}{f_0} = \pm \frac{1}{2Q_{ex}} \sqrt{\frac{P_{in}}{P_{out}}}.$$

To maximize the locking bandwidth with a fixed drive level (and, hence, a fixed gain), the external Q of the oscillator should be made as low as practical; the practical limit being the consideration of the frequency stability. Since the frequency drift of the oscillator is also inversely proportional to the external Q, one practical limit to the gain of ILO's may be established by imposing the condition that the locking bandwidth exceed the drift range under all operating conditions by a considerable margin. The design goal for the ILO gain dictated by this condition is in the range of 13–20 dB [12]. For the 30-dB gain required for the system, therefore, one requires more than one stage of ILO's [6], [8] or a combination of ILO's and reflection amplifier modules.

Fig. 4 shows an internal view of the hybrid amplifier in which two reflection amplifier stages are replaced by an ILO module. The ILO is constructed in the standard 7-mm coaxial circuit. The coaxial design is chosen because it is amenable to easy mechanical tuning. The oscillator circuit configuration, shown in Fig. 5, is a double-tuned circuit [14] in which the capacitive disk is used to shunt-resonate the diode. Tuning is accomplished by moving the quarter-wave transformer with a drive shaft accessible from the outside.

This ILO stage is designed for a gain of 17 dB. The amplifier modules preceding and following the ILO module are the driver and the output amplifier modules described earlier. The diode in the ILO module is identical to the one used in the power amplifier module. The output monitor detector in the power amplifier module serves the function of the out-of-lock monitor as well. The out-of-lock condition is indicated by the presence of an ac signal in the detector output [8].

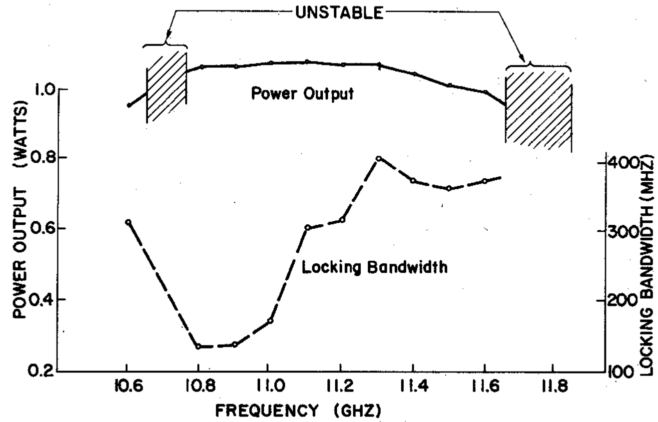

Fig. 6. Power output and locking range of three-stage ILO amplifier.

The power output and the locking range attainable in this three-stage hybrid amplifier are illustrated in Fig. 6. The ILO module is tunable across the whole band (10.7–11.7 GHz), but it is found to be unstable in the absence of a drive signal over certain portions of the band. (It does lock stably, however, to a drive signal over the range of instability.) The locking bandwidth attainable in this unit is determined partly by the frequency response of the driver amplifier module.

III. Bit Error Rate Measurements

The amplifier under test is driven by an up-converter output. The up-converter input is a QPSK modulated 70-MHz IF carrier. The QPSK modulator is illustrated by the block diagram in Fig. 7. The 40-Mbit/s data stream is split into two 20-Mbit/s streams and differentially encoded. Each data stream is used to generate 0–180° phase transitions in a double-balanced mixer. The carrier signal to one mixer is phase shifted by 90° with respect to the other. The orthogonal mixer outputs are added to obtain a QPSK signal. Since there are four phase states, each state representing two bits of information, the phase transitions occur at the rate of 20 MHz.

In digital systems, BER is the most useful indicator of the system performance. In a test setup for BER, the system output is compared bit for bit to an exact replica of the input data. The error indications are accumulated in a counter over a period of time and the BER is determined from the ratio of errors counted to the total number of bits passed in the interval. It is important that the test data stream be representative of the digital traffic or information the system is expected to carry. The system BER performance was measured with a pseudorandom sequence test pattern over one million bits long. The long sequence most closely approximates a system fully loaded with real digital traffic. Tests were also performed with a variety of short patterns (18 b long). Fig. 8(a) and (b) shows the spectra of the RF carrier modulated by the long (10^6) and a short (18 b) data sequences at the rate of 40 Mbit/s.

Fig. 9 shows the block diagram of the test setup. Attenua-

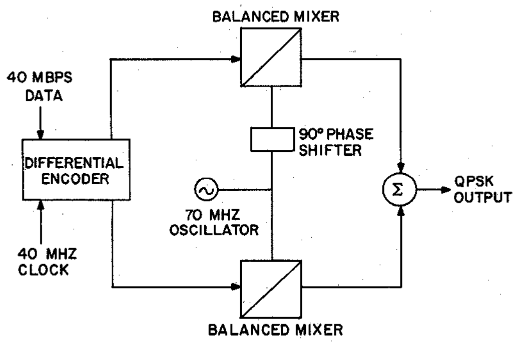

Fig. 7. QPSK modulator.

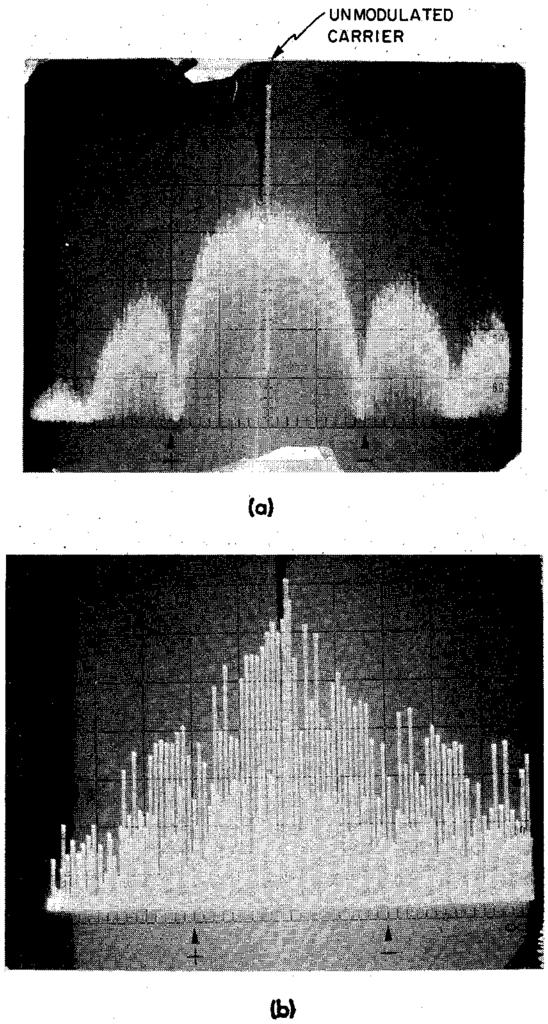

Fig. 8. Spectrum of QPSK modulated carrier; horizontal scale = 10 MHz/div.; vertical scale = 10 dB/div. (a) Long pattern ($2^{20}-1$ b). (b) Short pattern (18 b).

tors were inserted in the transmission path to simulate propagation fades, and the BER was measured as a function of the receiver input level. The system performance was first calibrated without the amplifier. The error counts were taken to determine not only the error thresholds under heavily faded conditions, but to detect the presence of an error floor at relatively high receiver input levels. The long-term error rate tests are performed by accumulating errors over a long period, 24 h, typically. This allows measurements of the error rate down to 10^{-12}.

After the system performance was calibrated without the amplifier, the same tests were repeated with the amplifier inserted in the transmission path. The experimental results are summarized in Figs. 10 and 11. The multistage reflection

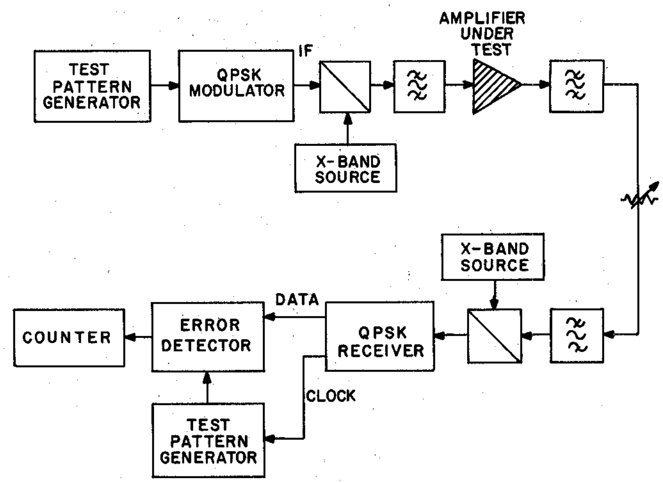

Fig. 9. BER test setup.

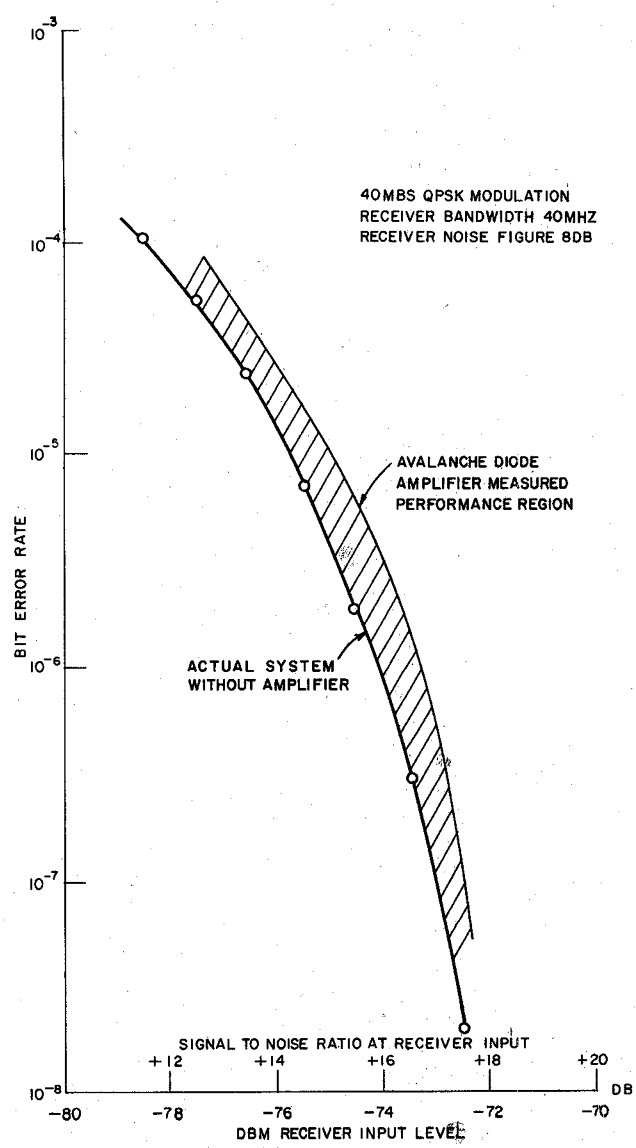

Fig. 10. System BER performance with and without RF amplifiers (ADA) at 11.095 and 11.225 GHz.

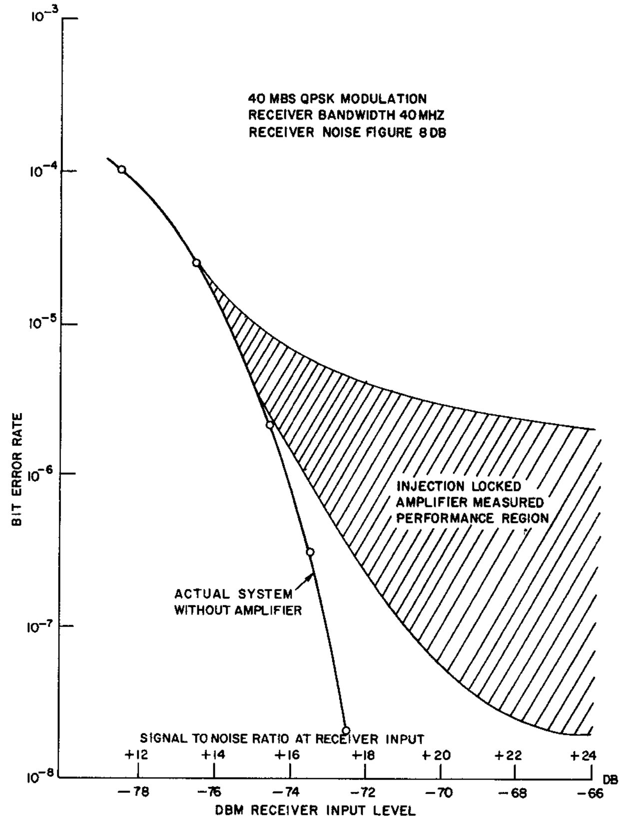

Fig. 11. System BER performance with and without RF amplifiers (ILO) at 11.095 and 11.225 GHz.

amplifier introduced little or no BER degradation under all test conditions. Only when the amplifier exhibited instabilities (often, of the kind induced under large-signal conditions [15]) within the 40-MHz band were errors measured in the system that were directly attributable to the amplifier.

With the ILO, a series of tests were run with the free-running frequency tuned to several different spots off the carrier frequency. Short-term tests showed that there is indeed a window in the tuning range of the oscillator for which the error curve did not deviate far from the system calibration. Long-term tests showed, however, that ILO's introduced an error floor. The experimental results are well scattered within the shaded area in Fig. 11, depending on the free-running frequency and also the digital test pattern. Long-term tests at high receiver levels over long periods (24–168 h) always showed a large count of errors. The observed BER degradation introduced by the ILO cannot be totally accounted for by the existing theories of ILO. Two probable causes of error are: 1) the amplitude modulation of the carrier that inevitably accompanies 180° phase shifts; and 2) long-term drifts of the free-running frequency of the oscillator. The measured BER variations could not be related to the FM noise characteristics of the amplifiers. The FM noise figure [16] of the reflection amplifiers was in the range of 30–35 dB, while the ILO displayed a much higher (45–50 dB) noise figure. Identical experiments using lower noise ILO's (30–35 dB attained with a Gunn-diode driver [8]), however, showed results similar to the ones presented in Fig. 11. In fact, exact causes of the BER floor introduced by the ILO could not be related to any parameter of the ILO that could be measured in short-term laboratory experiments.

IV. Conclusions

A multistage reflection amplifier and a hybrid amplifier containing an ILO have been tested for their suitability as power amplifiers for QPSK modulated carriers. System test results show that the stable amplifier introduces little or no system degradation while the ILO consistently introduced an error-rate floor over long periods. Both types of amplifiers were tested in the same setup under the same set of experimental conditions. System test results presented above were obtained over a long period (six months) both in the laboratory and in the field.

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