OPTICAL INJECTION LOCKING OF FET OSCILLATORS USING FIBER OPTICS

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ABSTRACT

We discuss the effects of multimode fiber-optic coupling on optical injection-locked GaAs MESFET oscillators. Locking frequency range data are presented and the effects of laser mode locking and fiber modal microphony discussed. The effects of FET photodetection efficiency as a function of modulation frequency are identified together with means for locking range enhancement.

INTRODUCTION

Optical locking of GaAs FET oscillators at microwave frequencies has been investigated as a means of feeding an active phased antenna array with coherent local oscillator signals or high-speed clock signals. For the function to be useful, locking ranges of at least tens of MHz should be achievable with optical power injection levels of a few microwatts. The work reported here sets out to verify experimentally earlier predictions of achievable locking range (1), and the departures from ideal behavior resulting from multimode fiber-optic distribution of the optical locking signal. A secondary objective has been to explore means to enhance optical injection locking range and experimentally verify its frequency dependance. Locking ranges up to 5 MHz have been demonstrated at S-band using fiber-optic distribution, but there is evidence that locking range may be limited by FET photodetection efficiency as locking frequency increases.

DISCUSSION

1. Experimental Configuration

The experimental configuration is shown schematically in figure 1. A microwave modulatable laser source (Ortel model LDS 10-PMF) employs a feedback stabilized current drive referenced to a monitor photodiode embodied in the laser package to achieve stable optical power emission at selectable levels. Microwave modulated 830 nanometer laser light traverses a graded index multimode optical fiber and is launched into coupling optics which concentrate the energy upon an elliptical zone coincident with the π gate region of an S-band GaAs FET oscillator. Figure 1 also indicates the relative dimensions of the GaAs FET gate region and illumination zone employed in the experiment. The coupling optics project a demagnified image of the 50 micron diameter fiber exit aperture in the X and Y axis focal planes which are separated along the Z axis because of the single (X) axis divergence introduced by the cylindrical lens. The effect is to produce an elliptical illumination zone in the Y axis focal plane with the major axis aligned along the X axis. In the absence of an optical input, the GaAs FET oscillator bias settings produce a pinch-off condition which prevents oscillation. When a CW optical input is applied to the GaAs FET gate region, free running oscillation is established tunable as a function of optical intensity; and when microwave modulation is applied to the laser via a bias tee, the oscillator may be phase locked to the signal generator over a limited tuning range observable on the spectrum analyzer display.

The GaAs FET oscillator operating at ~3 GHz employs a common drain circuit to take advantage of the large drain to gate capacitance C_{GD} as a feedback path. The negative resistance results from this feedback coupled with an AC shorted stub which appears inductive at the gate while permitting dc gate bias adjustment. The oscillator gate stub and source matching networks are deposited on an alumina substrate bisected by a gold-plated copper ground rib on which the GaAs FET is soldered.

2. Optical Footprint Characterization

The optical power density incident upon the GaAs FET gate region is critical in determining the number of hole-electron pairs generated at microwave rates in the FET depletion zone, hence, the oscillator locking characteristics. Although the gate region may be located in approximately the correct focal plane by adjusting for maximum drain current with the laser unmodulated, it was found that this did not provide adequate three axis positioning sensitivity under modulated conditions. Operating the GaAs FET as a photodetector (gate stub disconnected to prevent oscillation) in conjunction with the microwave modulated laser has permitted optimum positioning of the gate region within the footprint and measurement of footprint dimensions. Thus, the detected microwave power at the GaAs FET output was maximized by position and gate bias adjustments, followed by translations to measure the ellipse minor axis width at the -6 dB

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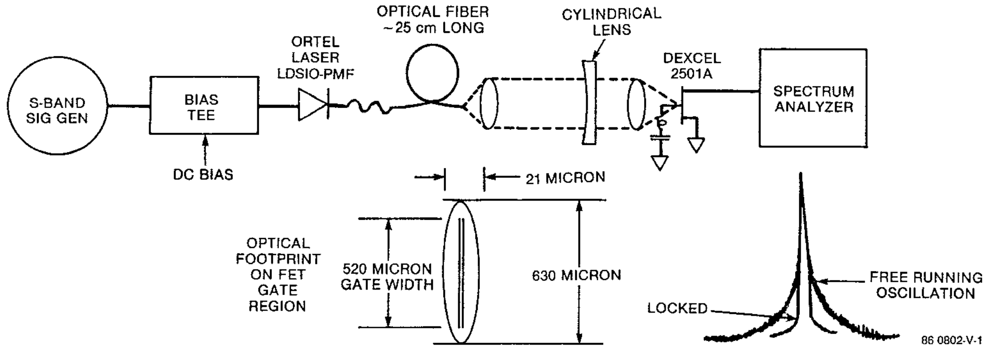

Figure 1. Experimental Configuration

detected power points. The measured width fell in the 15-18 micron range, which is in fair agreement with the 21 micron dimensions theoretically predicted from the coupling optics design. The observed minor axis dimension measured in terms of detected microwave power was ~30% of that obtained on a DC basis assuming that FET drain current is proportional to incident optical power density. The major axis dimension is far less critical as it extends well beyond the 520 micron gate width; nevertheless there is good agreement between predicted and measured values.

3. Depth of Modulation Investigations

Because oscillator locking range is directly related to optical depth of modulation (DOM) it has been important to verify experimentally the DOM achieved as a function of modulation frequency using a commercial wideband photodetector (Ortel PD050-PM) of known responsiveness at 830nm wavelength. The data so acquired is shown in figure 2 for an average laser current of ~ 1.5 times the threshold current, but the magnitude of the relaxation resonance peak is a function of the specific laser structure in use, and the fraction of energy reflected back into the laser cavity from the external optical "load". The benchmark DOM in figure 2 corresponds to the value calculated from the modulating signal power by means of the expression

$$DOM = \frac{P_{L(p-p)} \times 100\%}{P_{L\,(AV)} + P_{L\,(p-p)/2}}$$

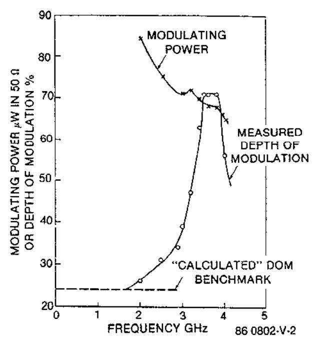

Figure 2. Modulating Power and Modulation Depth as a Function of Frequency

where $P_{L(p-p)}$ = peak laser output power excursion during the modulation cycle, and

$P_{L(AV)}$ = average (unmodulated) laser output power.

For the specific laser used in the experiment:

$$P_{L\,(p-p)} = .735\sqrt{\frac{P_{MOD}}{50}}$$

where P_{MOD} = power level of modulating microwave signal (watts) in a 50 ohm terminating resistor built into laser. The constant 0.735 derives from a conversion factor of $2\sqrt{2}$ multiplied by the laser differential quantum efficiency of 0.26 mW/mA. Thus, for P_{MOD} = 84 µW and $P_L(AV)$ = 3.5 mW the calculated DOM is 24%, which agrees well with the photodetector measured value of 26% at 2 GHz shown in figure 2. The DOM measurements shown in this figure were obtained using the configuration of figure 3 under conditions of tight optical coupling, but without the use of index matching fluid between the mating fibers. In this configuration, it was assumed that optical reflections from the fiber interface and photodetector are comparable with those seen by the laser when feeding the coupling optics. The DOM values at spot frequencies plotted in figure 2 were calculated from measurements of detector DC photocurrent and peak-to-peak microwave photocurrent using the known detector responsivity at 830 nm wavelength. Optical energy reflected back into the laser cavity not only affects the data of figure 2, it also produces fine structure variations in DOM resulting from active mode locking.(2) Typical behavior is shown in figures 4A and B which differ only in that the laser modulation frequency has been shifted ~10 MHz. The ripple spacings in figure 4A(~65 MHz) correspond to reflection from the photodetector after traversing 175 cm of fiber. It was observed that the ripple amplitude typically produces a 3-5 dB variation in detected microwave carrier power, which in turn will influence oscillator locking range. Unfortunately, the fraction of reflected optical energy coupled into the laser cavity is very subject to modal microphony resulting in an elevated and

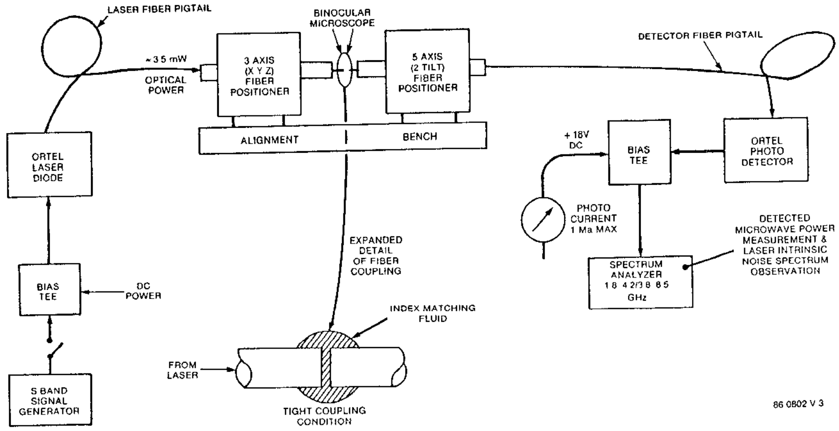

Figure 3. Technique for DOM Measurement and Observation of Laser Instrinsic Noise Spectrum

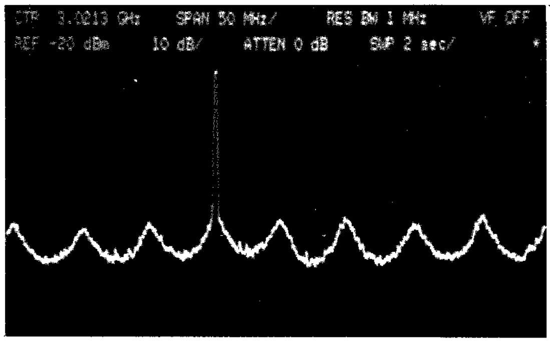

Figure 4A. Spectrum Analyzer Display of Detected Microwave Carrier and Intrinsic Laser Noise. Modulating Drive Power ~ 0 dBm at 2960 MHz, Ripple Spacing ~ 65 MHz

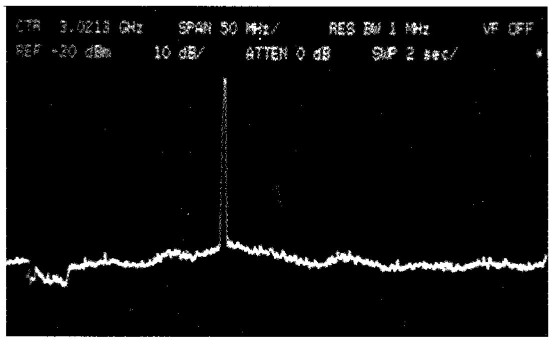

Figure 4B. As Above Except Modulation Frequency Is 2970 MHz

unstable intrinsic noise spectrum and fine structure ripple phenomenon. These effects can also produce FM sidebands surrounding the detected microwave carrier, and are perhaps the greatest drawbacks stemming from the use of multimode fiber signal distribution.

4. Operation as an Injection Locked Oscillator

Conventional microwave injection locking tests at about 3 GHz showed free running oscillator Q's from 7–11 for various bias conditions. Similar results were obtained when operating the FET gate biased up to 2 volts beyond pinchoff, but with CW light of a few mW sufficient to cause drain currents up to I_{DSS}. Biasing the gate more negative quenched the oscillation.

Figure 5 shows drain current versus V_{GS} for optical injection locking with > 70% DOM* and laser power 3.5 mW. At V_{SD} = -6V and I_{DS} < 40 mA, locking range Δf was generally less than 1 MHz; significant Δf occurred only for $I_{DS} \geq$ 45 mA. The same effect was noted for lower laser power levels with V_{SD} = -5V.

A plausible rationale for the steep rise of I_{DS} versus V_{GS} is that at pinchoff with optical modulation the oscillator runs class B or C, depending on V_{GS}. With the onset of optical modulation, the oscillation will build up to a saturation value limited by the CW optical input. Similar I_{DS} - V_{GS} curves were observed for the oscillating FET biased to near pinch-off with no light. The I_{DS} - V_{GS} slope with no oscillation approximates one-third that with oscillation build up as figure 5 shows. Locking range dependence upon FET operating point and laser power are shown in figure 6. Maximum values of Δf increase with optical power, and vary with V_{DS} roughly as:

$$\Delta f_{PK} \text{ (MHz)} = 11.7 - 13\, V_{DS}$$

for laser power of 3.5 mW.

Injection locking was obtained with free running frequencies between 2.6 and 3 GHz. To ascertain frequency dependence, we operated the FET as an AC photodetector by removing the wire bond between the gate and the shunt inductor to ground. AC detected output versus V_{GS} is shown in figure 7 for 2 GHz and 0.25 GHz, using 64% DOM. Both spectrum analyzer and I_{DS} data are shown.

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* The data was taken with a constant calculated optical DOM of 70%, but actual DOM is expected to be ~100% due to relaxation frequency resonance.

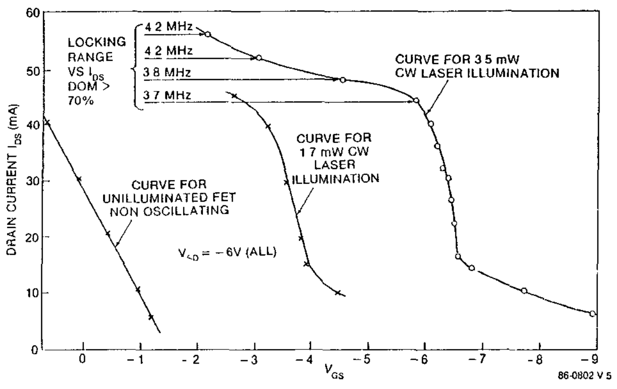

Figure 5. GaAs FET Oscillator I_{DS}/V_{GS} curves and Locking Behavior

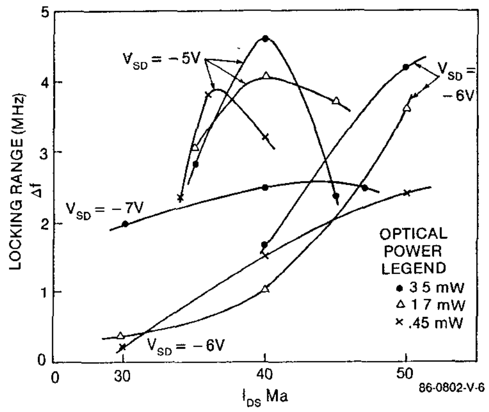

Figure 6. Locking Range vs I_{DS} for Three Optical Power Levels

5. Discussion

Experiment showed that light impingent on the entire active area of the pinched-off FET set the value of I_{DS}, but S-band locking range Δf may be due to depletion zone photocurrent or to photovoltaic modulation made frequency dependent by the low pass filter in the gate bias tee.(3,4) Spectrum analyzer measurements of detected microwave power at 3 GHz (for 3.5 mW of modulated optical power incident) imply an A.C. photocurrent typically 0.1% of I_{DSS}, and thus an expected Δf range of a few MHz. If locking gain is taken to be 20 $\log_{10}$ (FET oscillator I_{DS}/optically induced S-band drain current), then Δf is consistent with Adler's equation for an oscillator Q ~10. Maximum Δf for constant optical power always occurred at relatively large values of I_{DS} and decreased for V_{DS} > 5V. This corresponds to the region of maximum g_M determined from static I_{DS} - V_{DS} data. It does not explain quantitatively the observed steep reduction in Δf with reduced CW light induced I_{DS}. It may be that at low I_{DS} the oscillator saturation is due to optically generated current whereas at ~ I_{DSS} saturation is due to I_{DS} clipping resulting from forward biasing of the gate - source junction during the RF cycle. Reduced Δf when optically generated $I_{DS}>I_{DSS}$ is thought to be due to such clipping. Also there will be a smaller depleted zone in which GHz range photocurrents can be generated. To obtain significantly greater locking range, the density of optically induced carriers in the depletion region must be increased by one to two orders of magnitude. This can only be achieved by improved focussing and/or increased optically accessible depletion zone area. Optical fiber induced mode locking can cause 3-5 dB variations in Δf, and although the use of multimode fibers does not seriously degrade the optical footprint on the FET, the effects of modal microphony may cause MHz level FM spectral broadening.

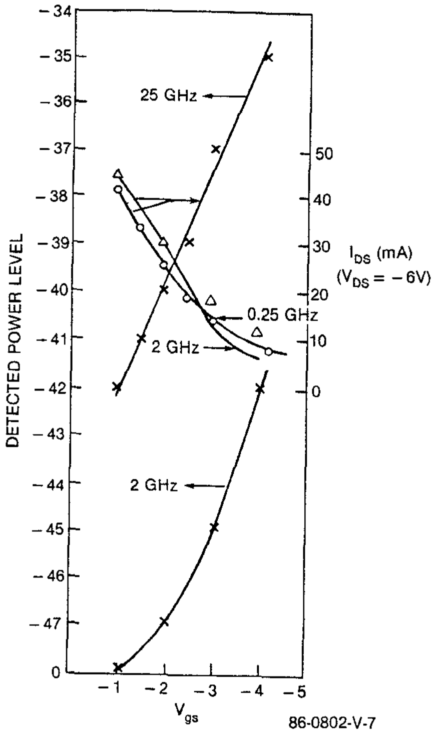

Figure 7. FET As an AC Photodetector

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