Simulation of Optically Injection-Locked Microwave Oscillators Using a Novel SPICE Model

DAVID WARREN, J. MICHAEL GOLIO, MEMBER, IEEE, AND EARNEST JOHNSON

***Abstract* —Optical injection locking of GaAs FET microwave oscillators has been examined experimentally as well as by using two different optical interaction models. A novel first-order interaction model which utilizes a standard version of SPICE has been developed which produces predictions of injection locking range in excellent agreement with measured results.**

I. Introduction

Optical injection locking of GaAs FET oscillators has been investigated by several researchers [1]–[3], [6]. Physically derived mathematical models which describe the effects of photons interacting with the FET channel have been developed [4]–[6] and show good correlation with measured dc and small-signal characteristics. Simulating the large-signal performance of an optically injection-locked oscillator, however, involves modeling the large-signal optical effects of the FET as well as the external circuitry surrounding the FET. A method for simulating optically injection-locked oscillators using SPICE is presented. An additional SPICE circuit for observing small locking ranges has also been developed. These tools allow the oscillator designer to optimize the injection locking performance by analyzing various circuit topologies and dc bias levels.

II. Optical Model Implementation

There are two optical effects that can be expected to influence the optical injection locking of a GaAs FET. The first and most widely published effect is produced by optically injected holes in the active region migrating to a position under the gate. This increases the positive charge concentration of the depletion region and therefore reduces its volume. This in turn allows more current to flow in the undepleted channel from the drain to the source. The effect just described will be referred to as the photovoltaic effect. This effect makes the FET act as if the pinch-off potential had been increased. The gate-to-channel junction causes the effective voltage produced by light to follow the equation [4], [5]

$$V_{\text{light}} = (kT/q) * \ln(I_p/I_{\text{ave}}) + V_{\text{off}}. \quad (1)$$

The term V_{off} in (1) is an offset voltage that is produced by the average value of light intensity illuminating the channel. The offset voltage can easily be measured experimentally using a FET like the one used in the oscillator circuit. The term I_p/I_{ave} represents the modulation of the light beam, where I_p is the peak value of the modulation and I_{ave} is the average value of the light beam. This equation describes the nonlinear conversion of injected light power to an effective gate voltage. The photovoltaic effect can be modeled as shown in Fig. 1, where V_{light} is implemented as a series gate voltage on the FET. The standard SPICE diode model has the flexibility to describe the logarithmic portion of (1) for a given optical modulation.

The method described above is based on dc analysis of the semiconductor device. Measurements by several researchers, however, indicate that measured dc transconductance and output impedance of GaAs MESFET's are significantly different from the same characteristics when measured at a frequency greater than a few hundred kilohertz [7], [8]. Our own measurements of FET oscillator performance under optical stimulation indicate that there is a fast, high-frequency effect which occurs nearly instantaneously and a second dc effect which occurs over a length of time on the order of seconds. These effects are observed when monitoring the oscillator output spectrum while the unilluminated FET is exposed suddenly to an illuminating source.

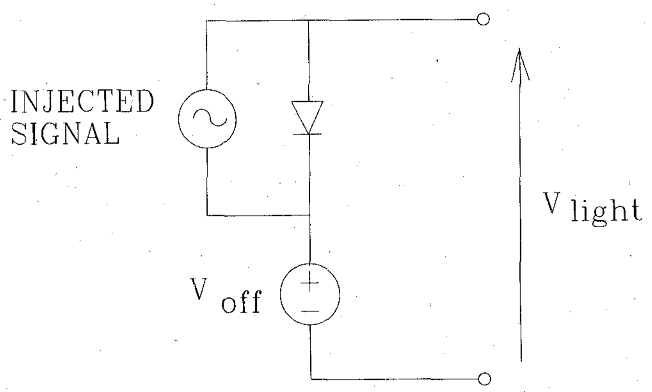

Fig. 1. Photovoltaic effect implementation on SPICE.

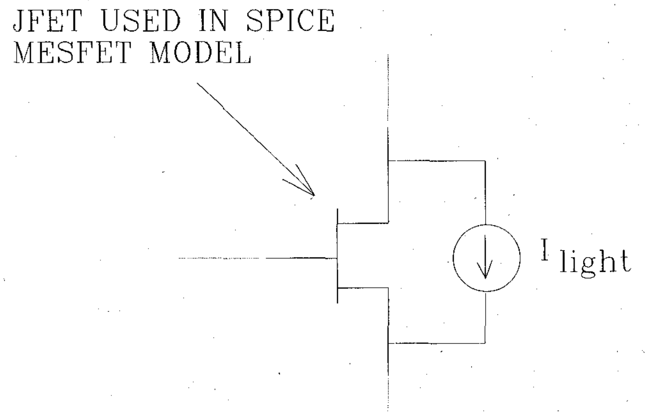

Fig. 2. High-frequency effect SPICE model.

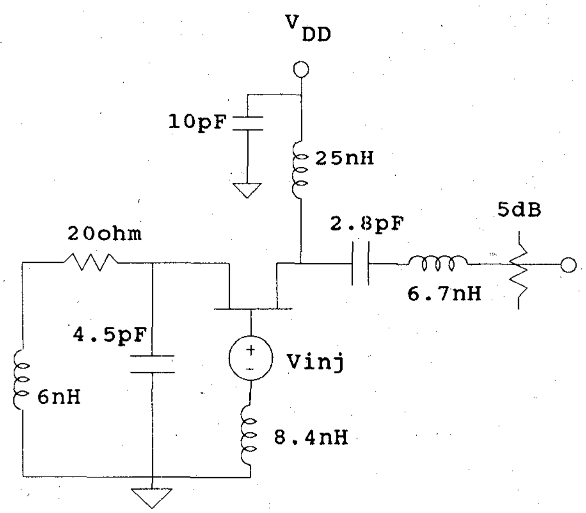

Fig. 3. Schematic of 2 GHz oscillator with the injected signal on the gate.

Manuscript received January 29, 1988; revised May 25, 1988.
The authors are with Motorola Inc., Government Electronics Group, Chandler, AZ 85248-2899.
IEEE Log Number 8823255.

0018-9480/88/1100-1535$01.00 ©1988 IEEE

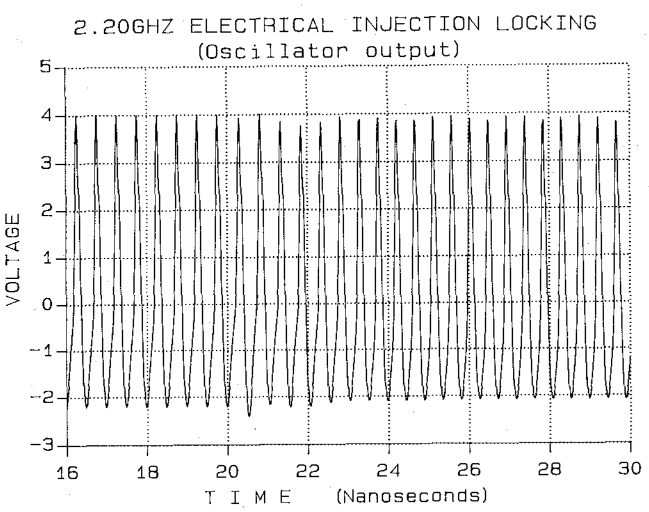

Fig. 4. Transient analysis with injected signal of 2.2 GHz.

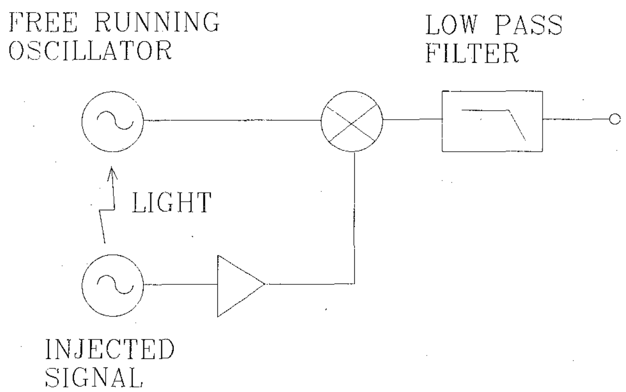

Fig. 5. Circuit used to determine a locked condition.

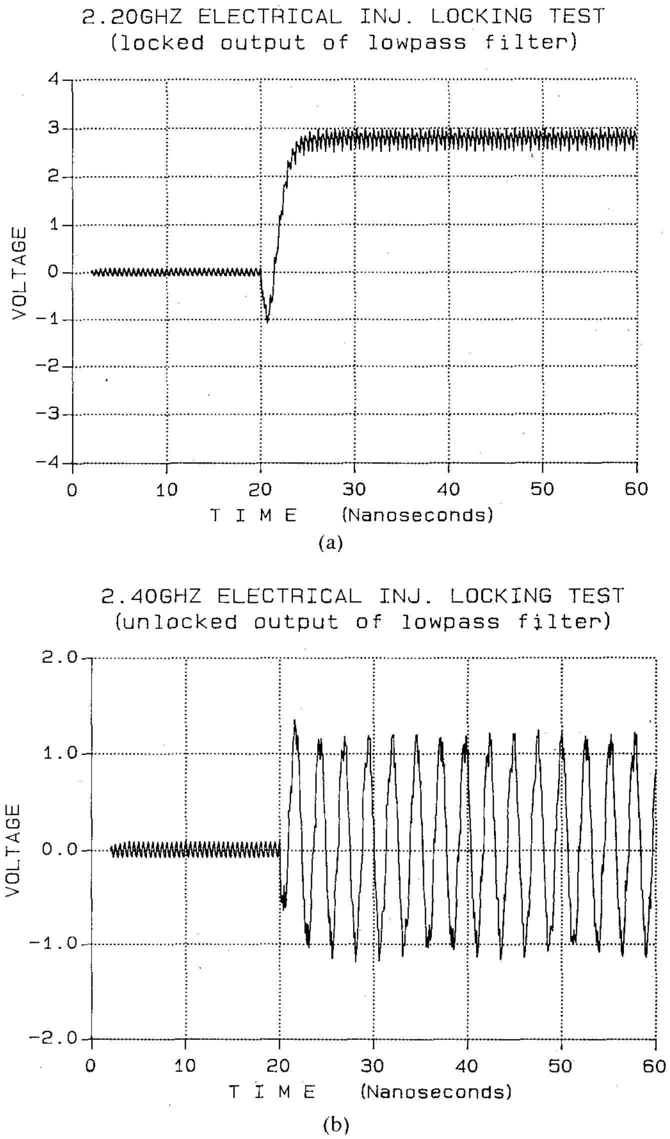

Fig. 6. (a) Locked and (b) unlocked outputs of the low-pass filter.

When such a shift in illumination condition occurs, the oscillation frequency is observed to shift significantly instantaneously (high-frequency effect). After this initial shift occurs, the oscillator frequency begins to slowly move back toward the direction of the unilluminated frequency until a steady-state value is reached (dc effect). This second shift occurs on the order of seconds and constitutes about 5 to 10 percent of the observed total instantaneous frequency shift. For the optical injection locking application, where incident light is being modulated at GHz rates, high-frequency interactions can be more critical to overall performance than the dc effect. Since the primary nonlinearities describing transient MESFET characteristics are the transconductance and output conductance, we have chosen to model these high-frequency effects using an ideal current source placed in parallel with the transconductance and output conductance elements in the equivalent circuit of the FET. The value of current injected by this current source is assumed to be linearly related to the incident light on the FET. This first-order approximation can be written as

$$I_{\text{light}} = I_{\text{off}} + M * I_{\text{off}} * \sin\left(w_{\text{inj}} * t\right) \tag{2}$$

where I_{off} is the experimentally measured shift in I_{ds}, M is the modulation, and w_{inj} is the injected radian frequency. The SPICE implementation of this model is shown in Fig. 2. The parameters required to describe the MESFET model were obtained by considering RF (as opposed to dc) characterization data. The high-frequency optical current source described by (2) was then placed internal to the drain and source parasitic resistances.

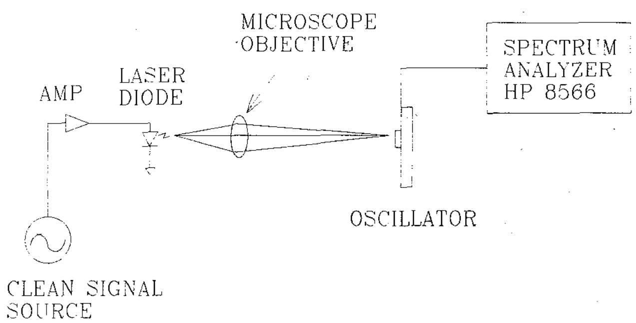

Fig. 7. Diagram of laboratory setup for injection locking experiment.

III. SPICE Modeling of the Injection-Locked Oscillator

The simulation of microwave GaAs FET oscillators using SPICE has resulted in very good predictions of the operating frequency and output power (providing that an accurate large-

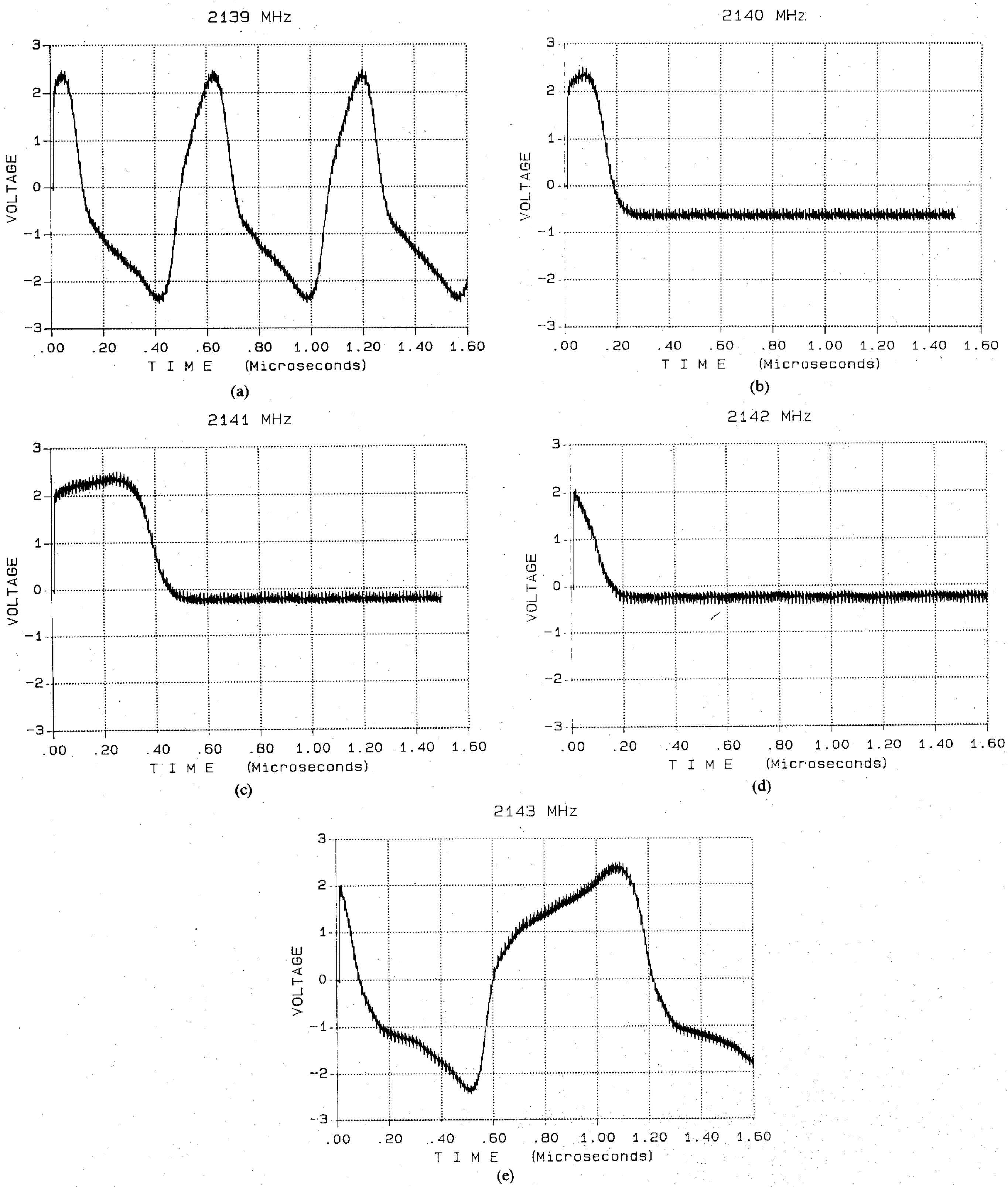

Fig. 8. Spice simulations of optical injection locking using the high-frequency model. Plots are shown for (a) 2139 MHz, (b) 2140 MHz, (c) 2141 MHz, (d) 2142 MHz, and (e) 2143 MHz.

signal FET model is available) and has been a valuable tool for oscillator designers. It should be noted that the GaAs FET model used in our simulation utilized a standard empirical SPICE JFET model surrounded by external components to approximate the nonlinear GaAs FET characteristics. Extending this simulation technique to incorporate the process of injection locking requires the introduction of a clean fixed-frequency signal into the oscillator network. For purely electrical injection locking this external signal can be represented by an ideal voltage source placed in series with the FET gate circuitry. A 2 GHz oscillator schematic is shown in Fig. 3 along with the injected signal modification. Large-signal modulation of the injected signal produces a very wide locking range. Fig. 4 shows the results of a transient analysis with an injected frequency of 2.2 GHz; the injected signal was turned on at time $t = 20$ ns. For large injected signals the corresponding large locking range allows frequency changes to be observed directly from the oscillator's output. But for optical injection locking, the injected signal power is small and the locking ranges are of the order of several MHz. Changes of a few MHz in a 2 GHz output frequency cannot be detected in a plot such as shown in Fig. 4. To overcome this problem a method for determining whether the oscillator output is phase locked to the injected signal has been developed.

Fig. 5 shows the circuitry used to determine whether the output is operating in a locked condition. The oscillator output signal is multipled by the injected signal (the injected signal has been increased in amplitude so that it has approximately the same amplitude as the oscillator output). The resultant of this multiplication is then filtered using a low-pass network. The pole of the low-pass circuit is set at approximately 1/2 of the oscillator frequency. This allows only the difference frequency between the oscillator and the injected signal to pass through the filter. A small amount of the high-frequency component leaks through, but the filter is designed so that the rise time will be small. The multiplier was realized by using an ideal dependent voltage source which is a polynomial function of order two. The two variables are the oscillator output voltage and the injected signal voltage. The constants of the polynomial are set to give an ideal multiplication of the two signals with equal amplitude on each. If the oscillator is locked to the injected signal then the output signal from the filter will settle to some constant dc level. If the oscillator is not locked, however, then the filter output signal will be periodic at the beat frequency. This circuit is included in the SPICE simulation so that by examining the output signal of the low-pass filter it is easily determined whether or not the oscillator is operating in a locked condition. The resolution in determining locking range using this method is limited only by the length of the transient analysis. Utilizing the power of an IBM mainframe computer, locking ranges have been determined within 1 MHz with a 1.5 μs analysis time. Fig. 6 shows the output of the filter for both locked and unlocked conditions using electrical injection locking.

IV. Comparison to Measured Data

A 2 GHz hybrid oscillator was built and experimentally injection locked using a modulated laser source with approximately 1 percent modulation (the actual modulation could be anywhere from 0.5 to 2 percent). A block diagram of the experimental setup is shown in Fig. 7. With the unmodulated beam focused on the FET, the drain-to-source current changed by 10 mA. Examining the oscillator output on an HP 8566 spectrum analyzer the locking range was easily determined. The modulated beam produced a locking range of 4.5 MHz. Using the photovoltaic model in the SPICE simulation with $I_p/I_{\text{ave}} = 0.01$, no locking range was observed (with a 1 MHz resolution in determining locking range). The high-frequency model with $M = 0.01$ predicted a locking range of $3+/-1$ MHz. The resultant plots of the simulation are shown in Fig. 8, where the circuit is analyzed in 1 MHz steps across the locking range. Simulations were also run at modulation percentages of 10 and 20. Fig. 9 is a comparison of the SPICE predictions in locking range to the well know Adler locking equation [9], [10]. Very good agreement is shown at the higher modulation percentages. A slight offset, however, is shown for the 1 percent case. Detailed analysis has revealed that the 1 MHz offset in the SPICE prediction at 1 percent modulation is primarily due to an asymmetrical locking range with respect to the free-running frequency. Adler's theory predicts an equal amount of pulling range on each side of the free-running frequency, whereas the SPICE predictions show a small amount of asymmetry. The uneven pulling on SPICE is a small effect and shows up only when trying to predict small locking ranges. The SPICE model also tracks well with other aspects of Adler's locking equation. Adler has shown that the phase difference between the oscillator output and the injected signal must be between $-90°$ and $+90°$ if the oscillator is operating in a locked condition. Many simulations have been run using our model and in all cases the edges of the locking ranges were at $-90°$ and $+90°$ (the phase difference is easily determined from the filter output plots).

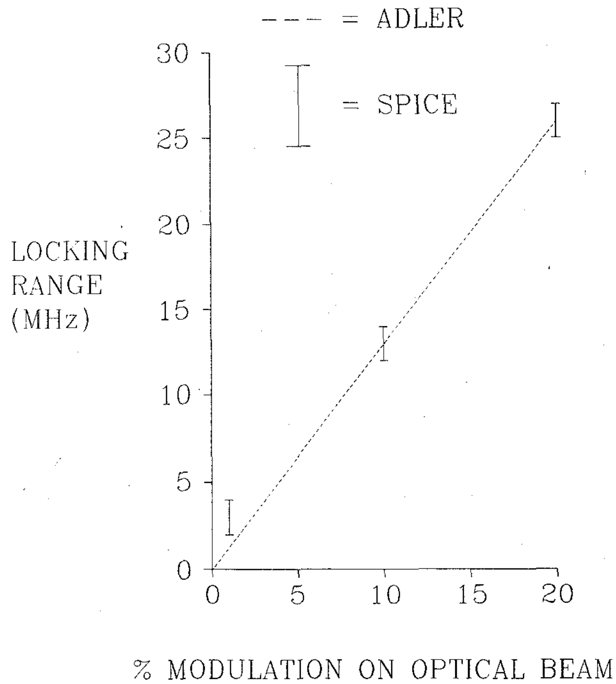

Fig. 9. Comparison of SPICE predictions to Adler's locking theory.

V. Conclusions

The simple high-frequency model described in this paper has shown great promise in its ability to predict optically injection-locked oscillator performance. Ongoing research with this model has indicated that the higher modulation percentages also track well with measured data. This indicates that the simple linear high-frequency model can predict optical locking performance within the range of experimental uncertainty. Also, it appears that the photovoltaic model does not describe the dominant transient optical effect which determines oscillator injection locking behavior.

Modeling of injection-locked oscillators using SPICE has not been previously reported and has now been shown to be a powerful tool. Future research should refine the simple optical model described in this paper and accelerate the process of incorporating optically injection-locked oscillators into actual systems. Using these techniques the designer can now predict the injected signal and oscillator parameters that are necessary to ensure reliable performance.

References

[1] A. A. Salles and J. R. Forrest, "Initial observations of optical injection locking of GaAs metal semiconductor field effect transistor oscillators," *Appl. Phys. Lett.*, vol. 38, no. 5, pp. 392–394, Mar. 1981.

[2] D. C. Buck and M. A. Cross, "Optical injection locking of FET oscillators using fiber optics," in *IEEE MTT-S Dig.*, 1986, pp. 611–614

[3] H. W. Yen and M. K. Barnaski, "Optical injection locking and switching of transistor oscillators," *Appl. Phys. Lett.*, vol. 32, no. 3, pp. 182–184, Feb. 1978.

[4] R. N. Simmons and K. B. Bhasin, "Analysis of optically controlled microwave/millimeter wave device structures," in *IEEE MTT-S Dig.*, 1986, pp. 551–554.

[5] J. L. Gautier *et. al*, "Optical effects on the static and dynamic characteristics of a GaAs MESFET," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-33, pp. 819–822, Sept 1985.

[6] A. A. A. DeSalles, "Optical control of GaAs MESFETS," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-31, pp. 812–820, Oct. 1983.

[7] L. E. Larson, "An improved GaAs MESFET equivalent circuit model for analog integrated circuit applications," *IEEE J. Solid-State Circuits*, vol. SC-22, pp. 567–574, Aug. 1987.

[8] M. A. Smith and T. S. Howard, "RF nonlinear device characterization yields improved accuracy," in *IEEE MTT-S Dig.*, 1986, pp. 381–384.

[9] R. Adler, "A study of locking phenomena in oscillators," *Proc. IRE*, pp. 351–357, June 1946.

[10] K. Kurokawa, "Injection locking of microwave solid-state oscillators," *Proc. IEEE*, vol. 61, pp. 1386–1410, Oct. 1973.