Comparison of Indirect Optical Injection-Locking Techniques of Multiple X-Band Oscillators

AFSHIN S. DARYOUSH, STUDENT MEMBER, IEEE, PETER R. HERCZFELD,
ZYGMOND TURSKI, SENIOR MEMBER, IEEE,
AND PRADEEP K. WAHI, SENIOR MEMBER, IEEE

Abstract —**Experimental results of indirect optical injection-locking of two X-band FET oscillators are presented. An S-band master source is used to synchronize both oscillators simultaneously, with 18-MHz locking range using the fiber-optic link nonlinearity. The source of the optical link nonlinearity is traced to the laser diode by interferometric measurement. Both the laser diode and the FET oscillator nonlinearities can be exploited to achieve frequency multiplication of the master oscillator signal. The merits of these different methods are evaluated based on the locking range and the FM noise level of the injection-locked oscillator.**

I. Introduction

FUTURE tactical planes are being designed with greater electronic warfare capabilities and independence from electronically intelligent systems. For example, an instantaneous frequency measurement (IFM) system is presently being investigated where the sensor listens for illumination at four quadrants of the plane, in frequency bands of 2–18 GHz, and then engages in active/passive jamming. Such a system requires stability of local oscillators over 110°C (−45 to 65°C) to achieve IFM within 1-MHz accuracy. Injection-locked FET oscillators are preferred over expensive oven-controlled oscillators, or dielectric resonator oscillators. The synchronizing signals are distributed from a common master source to the independent and spatially distributed local oscillators for injection-locking. Conventional coaxial cables may be used to distribute the control signals, but they are undesirable, because of their large size, weight, and high loss (10 dB/100 ft at 1 GHz); hence, fiber-optic distribution networks are considered as a viable alternative [1], [2]. The advantages of fiber-optic links are light weight, small size, low loss, broad bandwidth, immunity to interference (EMI, EMP), and high electrical isolation.

The fiber-optic distribution links are composed of high-speed semiconductor lasers, optical couplers, fiber-optic distribution networks, and high-speed photodetectors. The bandwidth of the state-of-the-art commercial electrooptic components (lasers and photodetectors) are limited to 10 GHz; therefore, new schemes are sought to extend the bandwidth of the synchronizing fiber-optic link to the higher microwave frequencies. A possible approach to overcome this gap is to exploit the inherent nonlinearities of fiber-optic link (i.e., optoelectronic components) and FET oscillator, to generate harmonics, thereby extending the effective synchronizing link's bandwidth.

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A. S. Daryoush and P. R. Herczfeld are with the Department of Electrical and Computer Engineering, Drexel University, Philadelphia, PA 19104.
Z. Turski and P. Wahi are with LORAL-ATL, Lanham, MD 20706.
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The present work has three main objectives. The first is to report on the simultaneous indirect optical injection locking of two independent free-running X-band microwave oscillators over a significant (several MHz) locking range. By indirect optical injection-locking [3], we mean that the modulated optical signal is first demodulated by a high-speed photodiode and then electrically injected to the FET oscillator, versus direct illumination of the active region of the FET [4]–[6]. The second objective is to determine the source of nonlinearity in the high-speed optical link; the third is to investigate and evaluate various methods of achieving subharmonic injection-locking, which extends the effective bandwidth of the optical link. In these experiments, both the fiber-optic link and the FET oscillator nonlinearities are exploited to achieve frequency multiplication. More explicitly, the relationship between the master oscillator frequency, f_{master} and the slave oscillator f_{slave} is expressed as

$$f_{\text{slave}} = m_{\text{laser}} * m_{\text{fet}} * f_{\text{master}} + \delta f \tag{1}$$

where m_{laser} and m_{fet} are the frequency multiplication factors of the laser diode and the FET, respectively, and δf is the frequency detuning. These experiments demonstrate methods by which practical optical synchronization of oscillators can be extended to K-band and above. The performance of the subharmonic injection-locked oscillator is compared in terms of locking range and FM noise for a matrix of different m_{laser} and m_{fet} values.

II. Indirect Optical Injection-Locking

The first set of experiments described pertains to indirect optical injection-locking of two FET oscillators.

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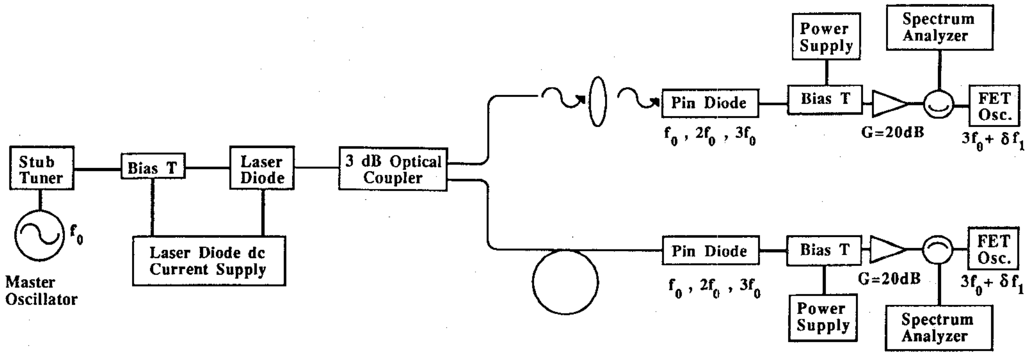
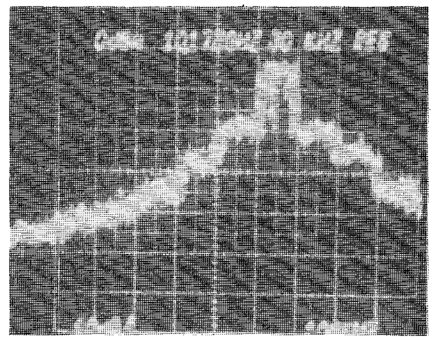


Fig. 1. Experimental setup for indirect optical injection locking of two X-band FET oscillators. The wiggly arrows indicate optical waves in the free-space optical focusing system.

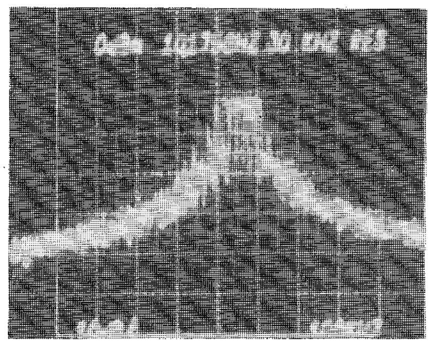
A. Experimental Setup

The experimental arrangement is shown in Fig. 1, depicting two independent free-running slave oscillators that are synchronized to a master oscillator via a fiber-optic link. The optical link consists of commercially available components, high-speed semiconductor laser and detectors, and a fiber-optic power splitter. For the optical source, a buried heterojunction (BH) AlGaAs injection laser with a short cavity is used. The laser diode, manufactured by Ortel Corp. (LDS10-PFM), is a packaged device with an SMA connector for RF input, and has a multimode fiber-optic pigtail output. The signal from the master oscillator is injected to the laser through a bias tee circuit, directly modulating the laser drive current and hence the optical output. The laser diode is broad-band matched to a standard 50-Ω system by a series 47-Ω chip resistor. The laser optical output power is 10 mW at 830 nm and has a 3-dB small-signal bandwidth of 5 GHz, for a driving current level corresponding to 80 percent of its maximum output power. The laser output is coupled to a multimode fiber (50/125 μm), with a 70-percent coupling efficiency. The laser's fiber-optic output is fused to a commercial 3-dB optical coupler (Canstar, PC3-C-50), which has a 10-percent insertion loss. The optical power splits by 47 percent and 43 percent, in two arms of the optical fiber. The light from each arm is coupled to high-speed AlGaAs pin heterostructure photodetectors.

The optical output from the first arm is focused onto an Ortel PD025-OM pin photodiode, using a 0.25-pitch selfoc lens and a laser diode focusing lens (Melles Griot 06GLC001). This detector has a responsivity of 0.45 A/W at 840 nm and 10-dB bandwidth of 15 GHz at 20 V reverse bias voltage. The second arm of the coupler is butt-coupled to a fiber pigtailed version of the same pin photodetector, which has a responsivity of 0.35 A/W at 840 nm. Both detectors are packaged with SMA output connectors. The dc optical efficiency in the first arm is calculated to be 43 percent, with the second arm at 32 percent. The demodulated RF signals are amplified using 20-dB-gain broad-band (8–18 GHz) LNA's made by Narda, and are electrically injected to the free-running oscillators through X-band circulators.



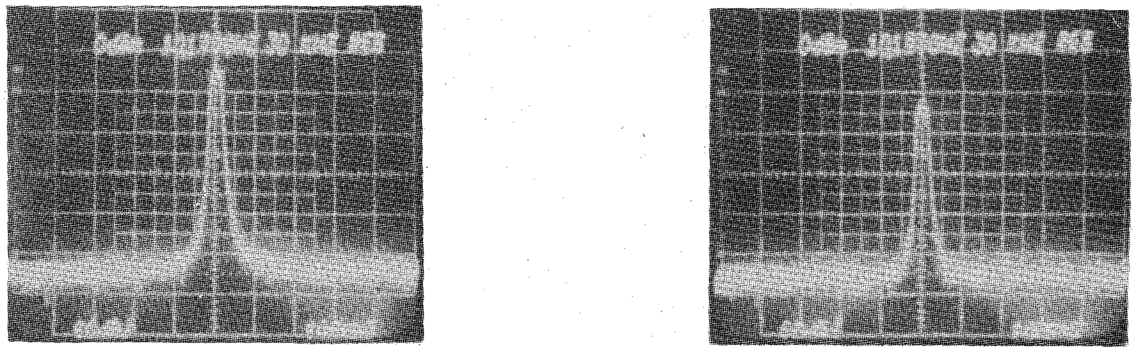
(a)



(b)

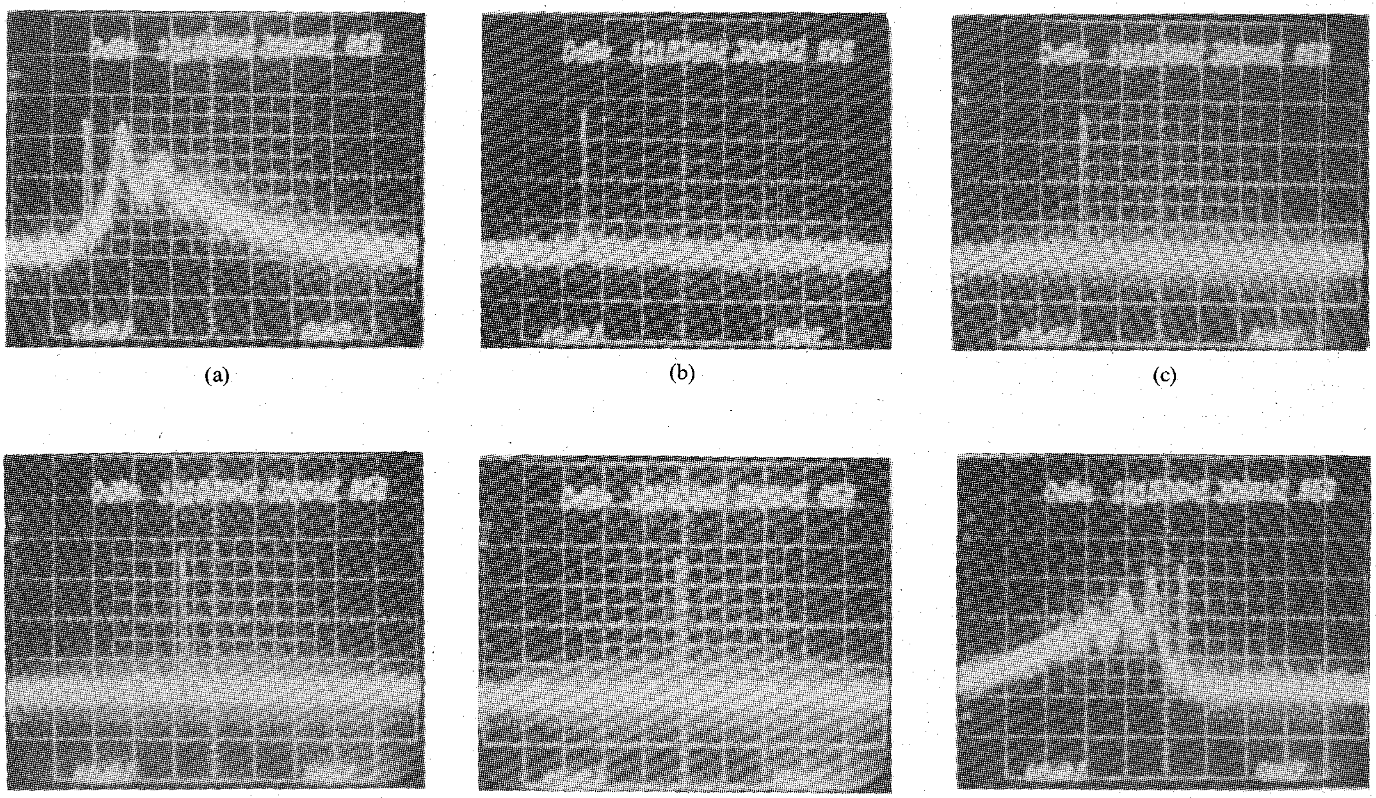
Fig. 2. Spectrum of two free-running FET oscillators. Vertical scale is 10 dB/div, with 100 kHz/div in horizontal scale. (a) Oscillator #1, $P_o = 7$ dBm. (b) Oscillator #2, $P_o = 2$ dBm.

The X-band free-running oscillators are designed and fabricated using low-noise FET's (NEC71083). A reverse channel configuration is used by applying a negative drain to source bias voltage ($v_{ds} < 0$). An open-circuited stub in the gate circuit is utilized to tune the oscillator. The oscillators are biased for 7 and 2 dBm output power, respectively. The external Q of the free-running oscillators is determined by direct electrical injection-locking, and is found to be 60. The spectra of the free-running oscillators prior to indirect optical injection-locking are shown in Fig. 2. The lack of synchronization and high FM noise are evident. The frequency drift of the free-running oscillators



(a) (b)

Fig. 3. Spectrum of two X-band slave oscillators synchronized to the S-band master source. Vertical scale is 10 dB/div, with 100 kHz/div in horizontal scale. (a) Oscillator #1. (b) Oscillator #2.



(a) (b) (c)

(d) (e) (f)

Fig. 4. Master–Slave pulling range of the oscillator #2 for six 1-MHz steps of master source. Horizontal scale is 5 MHz/div and center frequency is 10.183 GHz. (a) 3.390 GHz (beginning of locking with sidebands). (b) 3.391 GHz (locked). (c) 3.392 GHz (locked). (d) 3.394 GHz (locked). (e) 3.395 GHz (locked). (f) 3.396 GHz (end of locking with sidebands).

over a temperature range of -45 to 65°C is measured to be 20 MHz. The goal of the optical injection-locking is to maintain synchronization of the free-running oscillators over this temperature range, and to reduce their FM noise.

B. Experimental Results

The laser diode is modulated at 3.393 GHz by an 8-dBm signal from a synthesized source. The fundamental signal, as well as higher harmonics, is demodulated by the two high-speed photodetectors. In particular, the third harmonic signal (10.179 GHz) is matched to the broadband LNA by a double stub tuner and the amplified signal is electrically injected to the free-running oscillator. Both free-running oscillators are simultaneously locked to the master source.

The injection-locked spectrum of the free-running oscillators is shown in Fig. 3. It depicts synchronization of the two slave oscillators at 10.179 GHz to the third harmonic

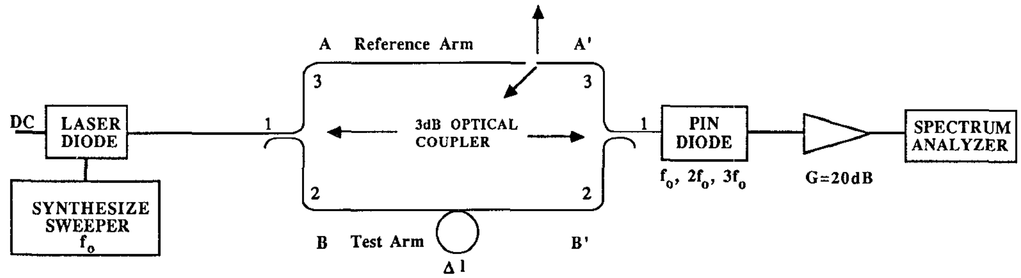


Fig. 5. Optical/microwave interferometric setup for the high-speed fiber-optic link nonlinearity assessment. The arrows in the reference arm indicate the two-dimensional micropositioner to balance the power in both arms of the interferometer.

of the master source, accompanied by a significant reduction in the FM noise. The injection-locking process for the 2-dBm oscillator is depicted in Fig. 4. A locking range in excess of 18 MHz is achieved for both oscillators. The system FM noise degradation of the master oscillator signal due to the optical link and the broad-band amplifier setup is measured to be 14 dB, where 9 dB is due to the third harmonic generation technique ($20\log N$), 2 dB is attributed to the fiber-optic link, and 3 dB is due to AM to PM conversion in the broad-band LNA.

III. Source of Nonlinearity in the High-Speed Fiber-Optic Link

In the synchronization of X-band oscillators, the nonlinearities of the fiber-optic link are exploited to achieve an improved locking range at frequencies above the laser diode's relaxation oscillation frequency (5 GHz). Therefore, the main question arises: what is the source of nonlinearity in a high-speed fiber-optic link and how could it be optimized? This question is critical, since if the source of harmonic generation can be identified and optimized to increase detected signal levels at frequencies above the laser bandwidth, then optical injection-locking at millimeter-wave frequencies [7] may be achieved. The source of nonlinearity in the fiber-optic link can be attributed to both the high-speed laser diode and the photodetector. For example, it is reported that the signal harmonic content and the third-order intermodulation distortion alarmingly increases for modulation depths larger than 70 percent [8]. On the other hand, high-speed photodetectors are employed as a mixers (a nonlinear device) in optical heterodyning experiments [9].

To resolve this question, an experiment is performed to determine the origin of the nonlinearity in the high-speed fiber-optic link. Since detection and subsequent processing of harmonic signals in the electrical domain provide no information about the source of harmonics in the fiber-optic link, the experimentation must be realized in the optical domain. An interferometric experiment, described below, is used to assess the origin of nonlinearity.

A. Experimental Setup

The experimental setup is shown in Fig. 5. The AlGaAs BH semiconductor laser is directly modulated by a microwave sweeper. The optical output of the laser diode is split using a 1:1 fiber-optic coupler from Canstar. The coupling from port 1 to 2 is 45 percent, and 43 percent from port 1 to 3. The optical insertion loss is 12 percent. The modulated light in the reference arm of the interferometer ($A-A'$) is butt-coupled to a fiber-optic power combiner. A three-port optical coupler is used in place of a polarization-sensitive power combiner, with a 3-dB optical power loss. It couples 47 percent of the power from port 1 to 2 and 37 percent from port 1 to 3 with an optical insertion loss of 16 percent. The test arm of the interferometer ($B-B'$) is delayed by $\Delta\tau$, using a short length of fiber (Δl), and then spliced to port 2 of the power combiner coupler. The modulated optical powers in the reference and test arms of the interferometer are balanced by adjusting the coupling at the butt-coupled joint in the reference arm. This is necessary due to the dissimilar coupling coefficients of the couplers. The modulated optical output is detected by the high-speed GaAs photodiode and the fundamental and harmonic signals are displayed on a spectrum analyzer.

B. Theory of Operation

The optical signals in each arm of the interferometer can be expressed in terms of the dc and the modulating ac optical powers. The total optical signals after power combing are expressed as

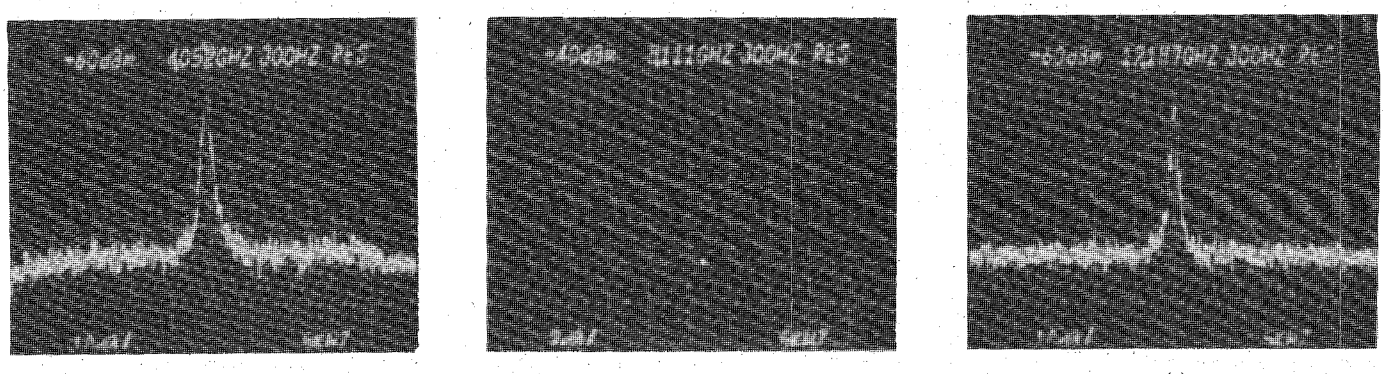
$$P(t) = p(f)\,\mathrm{Re}\{\exp[i2\pi f(t_o + t)] + \exp[i2\pi f(t_o + t + \Delta t)]\} + 2P_o$$

where

t_o = time delay corresponding to the shortest fiber,
$p(f)$ = modulated optical power at frequency f,
P_o = average optical power in each arm,
$\Delta\tau$ = time delay in the test arm with respect to the reference arm = $(\Delta l / v_g)$.

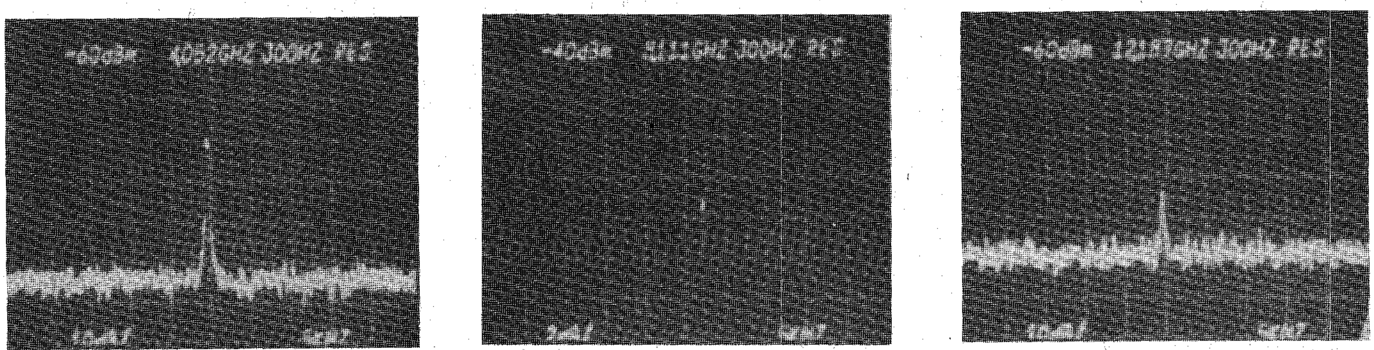
Here, v_g is the group velocity of light in the fiber, and Re{ } represents the real part of the complex optical field. Simple factorization and use of trigonometric identities result in

$$P(t) = 2p(f)\cos(\pi f \Delta\tau)\cos[2\pi f(t + t_o + \Delta\tau/2)] + 2P_o.$$



(a) (b) (c)

Fig. 6. Spectrum analyzer display of the detected signals in the interferometric experiment, with the reference arm disconnected. (a) The fundamental signal at 4.05 GHz (vertical scale is 10 dB/div). (b) The second harmonic at 8.10 GHz (vertical scale is 2 dB/div). (c) The third harmonic at 12.15 GHz (vertical scale is 10 dB/div).



(a) (b) (c)

Fig. 7. Spectrum analyzer display of the detected signals in the interferometric experiment, with the reference arm connected and the optical powers balanced. (a) The fundamental signal at 4.05 GHz with a 20-dB power reduction w.r.t. Fig. 6(a) (vertical scale is 10 dB/div). (b) The second harmonic at 8.10 GHz with a 3-dB power increase w.r.t. Fig. 6(b) (vertical scale 2 dB/div). (c) The third harmonic at 12.15 GHz with a 20-dB reduction of power w.r.t. Fig. 6(c) (vertical scale is 10 dB/div).

The first null of this expression is observed at frequency $f = (2\,\Delta\tau)^{-1}$, and in general, nulls are observed at frequencies where the product of $\pi f \Delta\tau$ is an odd multiple of $\pi/2$.

If the time delay $\Delta\tau$ in the test arm is related to the modulation frequency f_o by $\Delta\tau = (2f_o)^{-1}$, the modulated signal in the test arm is 180° out of phase with the reference arm, and the modulated optical component at f_o is canceled. This cancellation corresponds to the first null in the interferometer ($\pi f \Delta\tau = \pi/2$), and the modulating frequency is not observed on the spectrum analyzer. Furthermore, for the same time delay $\Delta\tau$, and frequencies corresponding to the second and third harmonics of the modulating frequency f_o, phase differences of 2π and 3π are produced. Due to these phase differences for frequencies of $2f_o$ and $3f_o$, the detected signal at $2f_o$ has twice the power in each arm of the interferometer ($\pi f \Delta\tau = \pi$), while the second null is observed at $3f_o(\pi f \Delta\tau = 3\pi/2)$. In general, for any odd multiples of f_o, the modulated signals in the interferometer arms add destructively (out of phase), and for even multiples of f_o, they add constructively (in phase). The time delay $\Delta\tau$ in the test arm, is adjusted such that the first null is observed at 4.05 GHz.

C. Experimental Results

The laser diode is modulated at 4.05 GHz under large-signal operation ($P_{\text{in}} = 8$ dBm). When the reference arm is disconnected, the harmonics at 8.1 GHz and 12.15 GHz are observed on the spectrum analyzer, as shown in Fig. 6. However, when the reference arm is connected and power in both arms is balanced, the detected power for fundamental and third harmonic is reduced by 20 dB, while a 3-dB power increase is observed for the second harmonic, as shown in Fig. 7. Since, under large-signal modulation (above 70 percent) of laser diodes, the bandwidth reduces to 0.6 f_r [10], the laser's nonlinearity was also examined at frequencies below relaxation oscillation frequency. When the laser diode was modulated at 2.025 GHz, the second harmonic at 4.05 GHz was nulled using the same interferometer. This cancellation conclusively indicates that the laser diode is the main source of nonlinearity. A large-sig-

TABLE I
LOCKING RANGE AND FM NOISE LEVEL OF THE INDIRECT OPTICALLY INJECTION-LOCKED X-BAND FET OSCILLATOR WITH A 2-dBM OUTPUT POWER, USING LASER DIODE MULTIPLICATION m_{laser}

Master osc. freq. (GHz)	m laser	Locking range (MHz)	FM noise at 100KHz offset (dBc/Hz)	FM noise at 1KHz offset (dBc/Hz)
10.174	1	≈9	-78	-45
5.087	2	≈6	-75	-42
3.391	3	19	-72	-38
2.543	4	32	-70	-35

TABLE II
LOCKING RANGE AND FM NOISE LEVEL OF THE INDIRECT OPTICALLY INJECTION-LOCKED X-BAND FET OSCILLATOR WITH A 2-dBm OUTPUT POWER, USING FET MULTIPLICATION FACTOR m_{fet}

Master osc. freq. (GHz)	m fet	Locking range (MHz)	FM noise at 100KHz offset (dBc/Hz)	FM noise at 1KHz offset (dBc/Hz)
10.174	1	≈9	-78	-45
5.087	2	≈1	-74	-37
3.391	3	≈3	-72	-36
2.543	4	6	-71	-35

nal analysis of the laser diode [11] has shown that the harmonic contents are enhanced at frequencies in proximity of the large-signal relaxation frequency, which is dependent on the optical modulation depth.

IV. COMPARISON OF LASER AND FET NONLINEAR BEHAVIOR FOR FREQUENCY MULTIPLICATION

The purpose of this experimentation is to compare the relative merits of the laser and FET nonlinearity for indirect optical injection-locking. The experimental setup is similar to the one described earlier for indirect injection locking except that experimentation is carried out for the 2-dBm FET oscillator. The laser is operated under large-signal and is modulated by an 8-dBm signal from the master oscillator at approximate frequencies of f_{slave}, $f_{\text{slave}}/2$, $f_{\text{slave}}/3$ and $f_{\text{slave}}/4$. In the first set of experiments, the harmonics generated by the laser are utilized to injection-lock at the fundamental frequency (i.e., $m_{\text{laser}}=1$, 2, 3, and 4, $m_{\text{fet}}=1$). The demodulated optical signal at X-band is amplified using a 20-dB, 8–18-GHz amplifier, and the amplified signal is then injected into the FET oscillator. The characteristics of the injection-locked slave oscillator are listed in Table I. The locking range is optimum at 2.543 GHz and 3.391 GHz, corresponding to the modulating frequencies in the proximity of the laser self-resonance where the harmonics are substantial [11]. The enhanced harmonic yields a significant locking gain, providing for a large locking range, as high as 32 MHz. However, at the frequencies above the laser resonance, the harmonic levels are not significant, resulting in a reduced locking range. This condition is manifested at 5.087 GHz, where a locking range of only 6 MHz was achieved. For the fundamental injection-locking, when the modulating frequency is close to the slave oscillator frequency, viz. 10.174 GHz, a moderate locking range of 9 MHz is obtained. This result does not compare favorably with the subharmonic modulation at $f_{\text{slave}}/3$ and $f_{\text{slave}}/4$. This can be explained by the rapid (40 dB/decade) rolloff at frequencies above the laser's bandwidth and by the parasitic losses.

In the second set of measurements, the laser driving conditions remained the same as in the previous set of measurements, but the 8–18-GHz amplifier was replaced at the 2–6-GHz amplifier with a 20-dB gain, and the X-band circulator was replaced by a C-band one. The harmonics generated by the laser diode are filtered out by the 2–6-GHz amplifier, which attenuates the higher harmonics; thus, the nonlinear performance of the FET oscillator can be investigated. In these experiments, the FET is responsible for the frequency multiplication, i.e., $m_{\text{fet}}=1$, 2, 3, and 4. The results of locking range and FM noise performance measurements using the FET nonlinear contribution are summarized in Table II. The maximum locking range in this experiment is 9 MHz, which corresponds to locking at the fundamental. The locking range at 5.087 GHz, $m_{\text{fet}}=2$, is the lowest, which is attributed to the laser response rolloff at the frequencies above the relaxation oscillation, and a lower locking gain due to the subharmonic injection-locking process. However, the locking range for the frequencies close to the large-signal resonance is more substantial ($m_{\text{fet}}=3,4$), because the laser resonance enhances the detected signal signified by a higher locking gain.

These experiments demonstrate that the laser nonlinearity can substantially improve the locking range. The nonlinear contribution of the FET in the injection-locking process is not as pronounced as that of the laser diode. However, the nonlinearity of the laser diode and the active device can be simultaneously exploited, as has been demonstrated in the case of the IMPATT oscillator [7]. The locking ranges achieved for fundamental and subharmonic injection locking are different, and are dictated by the characteristics of the device [11].

V. DISCUSSION

The feasibility of the subharmonic indirect optical injection-locking of the two X-band oscillators is demonstrated using an S-band master source, where a locking range in excess of 18 MHz is achieved. The advantages of the indirect over direct optical injection-locking are the availability of commercial components, and higher available locking gain due to the efficient detection of synchronizing signal by the pin diode and subsequent amplification of the control signal before injection-locking.

The 14-dB FM noise degradation of the master oscillator in the indirect optical injection-locking system is related to the optical link and the broad-band amplifier characteristics. The optical link noise degradation is dominated by the light scattering within the coherent length of the laser, which may be decreased by reducing the optical mismatch and using optical isolators. A narrow-band amplifier, in place of the broad-band one used in these experiments, would reduce its noise contribution by minimizing AM-to-PM conversion.

Frequency multiplication by both the laser diode and the FET is also demonstrated. The source of the optical link nonlinearity is traced to the laser diode by the interferometric measurement. The interferometric technique performs like a notch filter operating in the optical domain and has applications in instantaneous frequency measurements (IFM). The large-signal modulation of laser diodes increases the harmonics content, which is attenuated at rates slower than 40 dB/decade above relaxation frequency. Therefore, large-signal modulation of lasers extends the effective bandwidth of the optical link.

Comparison between the laser diode nonlinear contribution versus the FET with locking range as the figure of merit indicates that it is more desirable to utilize the multiplication by the laser than by the FET. The use of laser diode nonlinearity provides substantial harmonics levels, which results in a larger locking gain than the subharmonic injection-locking achieved in the active device. Further work to extend synchronization of the FET oscillators to 20 GHz with a substantial locking range, reduction in the system FM noise degradation, and a power budget calculation is currently pursued.

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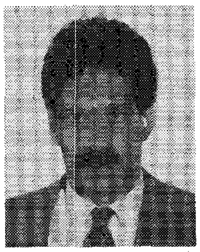
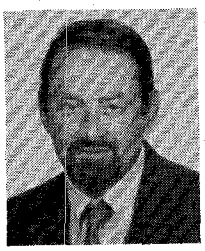


Afshin S. Daryoush (S'84) was born in Tehran, Iran, in 1957. He received the B.S. degree in electrical engineering from Case Western Reserve University, Cleveland, OH, in 1981. He received the M.S. degree in 1984 and the Ph.D. degree in 1986 from Drexel University, Philadelphia, PA, also in electrical engineering.

From 1983 until June 1986, he was a Research Assistant in the Microwaves and Electro-optics Laboratory, Department of Electrical and Computer Engineering, Drexel University, performing research under RCA, Loral, and NADC grants. Since June 1986, he has been on the staff of Drexel University as Associate Research Engineer, conducting research in the area of optically controlled microwave devices and subsystems, high-speed fiber-optic links, and system studies of large-aperture, phased-array antennas.

Dr. Daryoush has authored or coauthored over 30 technical publications in the area of light interaction with passive and active microwave devices, circuits, and systems. He has two U.S. patents pending in the area of optically controlled microwave circuits. He is a member of Sigma Xi.



Peter R. Herczfeld was born in Budapest, Hungary, in 1936. He is a U.S. citizen. He received the B.S. degree in physics from Colorado State University in 1961. In 1963, he received the M.S. degree in physics and, in 1967, the Ph.D. degree in electrical engineering, both from the University of Minnesota.

Since 1967, he has been on the faculty of Drexel University, where he is a Professor of Electrical and Computer Engineering.

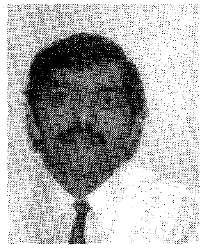
He has published over 70 papers in solid-state electronics, microwaves, solar energy, and biomedical engineering. He served as project director and principal investigator for 21 projects sponsored by DOD, NSF, NASA, DOE, and private industry. Dr. Herczfeld has taught 20 different courses at the graduate and undergraduate level and has lectured extensively in this country and in ten

foreign countries. He coordinates the microwave and electrooptics program at Drexel.

Dr. Herczfeld is a member of APS, SPIE, and the International Solar Society.

Zygmond Turski (S'73–M'74–SM'86) received the B.S. and M.S. degrees in electrical engineering from Drexel University in 1972 and 1974, respectively.

In 1973, he joined RCA Laboratories, NJ, where he worked in the areas of microwave acoustics and microwave circuits involving MESFET's. He joined General Microwave Corporation, NY, in 1976, as a Senior Engineer and worked in the area of microwave control components. In 1978, he joined Amecom Division of Litton Industries, MD, initially as a Section Manager and later as a Department Manager for Advanced Technology. Since 1982, he has been General Manager and Vice President of Loral Advanced Technology Laboratories, MD. The areas of his professional interest include microwaves, optics, and acoustooptics.



Pradeep K. Wahi (S'75–M'82–SM'84) was awarded the B. Tech and M. Tech degrees in electrical engineering from the Indian Institute of Technology, Kanpur, in 1972 and 1976, respectively, and the M.S. degree from the State University of New York at Stony Brook in 1978.

He has worked on the development of microwave integrated circuits and subassemblies, fiber optics, and magnetostatic wave devices for electronic warfare and communication systems. His current research efforts are focused on the insertion of optics technology in microwave systems and the optical control of microwave devices. Mr. Wahi is the author of over 20 technical papers in the fields of MIC, MSW, and fiber optics and is an author/contributor to three books. Since 1982, he has been working as Scientist/Chief Engineer at Loral Advanced Technology Laboratory. Prior to this, he worked for the Advanced Center for Electronic Systems in India, Litton Industries, and the General Instrument Corporation.