# Optical Synchronization of Millimeter-Wave Oscillators for Distributed Architectures

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*(Invited Paper)*

*Abstract* —Future generations of communication and surveillance platforms will be based on large-aperture phased array antennas composed of many active-MMIC-based transmit/receive modules. This paper concerns the phase and frequency coherency of these modules. A review of various methods of phase and frequency synchronization of active modules is presented, and particular emphasis is placed on the synchronization of oscillators through the use of an indirect subharmonic optical injection locking technique. In this approach, the nonlinear behavior of both large-signal modulated laser diodes and solid-state oscillators is exploited to extend the bandwidth of the synchronizing link to the millimeter-wave frequency range. Experimental results of the phase and frequency coherency of two 21.5 GHz FET oscillators are also reported here. Optimum performance has been achieved at a subharmonic factor of 1/4, with a locking range of 84 MHz and a phase noise degradation of only 14 dB. The phase coherency measurement of two injection-locked oscillators points to a phase shift, which is introduced as a result of the frequency detuning between the slave and master oscillator signals. A scheme to correct for this phase error is also presented.

## I. Introduction

With recent advances in low-cost fabrication techniques for solid-state electronic circuits and high-speed parallel signal processing capabilities, complex surveillance and communication systems can now be designed according to the concept of distributed sensors. The active and passive sensors utilize coherent integration methods for signal processing, which demand a phase and frequency coherency in these distributed microwave systems.

For example, in the case of future high-data-rate satellite communication systems, large-aperture phased array antennas are designed with as many as of $10^3$–$10^5$ active-MMIC-based millimeter-wave transmit/receive (T/R) modules. These modules must be phase and frequency synchronized so that a coherent radiating/receiving beam can be constructed. Because of the complexity of feed networks at millimeter-wave frequencies, fiber-optic links are employed to distribute reference signals, amplitude and phase control information, and data/communication signals. Optical distribution of the modulated millimeter-wave frequency carrier demands ultra-high-speed fiber-optic links; however, because of the performance limitations of electro-optic components, millimeter-wave modulation of light is not feasible at present. Therefore, if the fiber optical feed network is to satisfy the stringent system performance requirements, the conventional system architectures should be modified to address the bandwidth inadequacy of the fiber-optic links.

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The most viable system architecture at millimeter-wave frequencies, satisfying bandwidth and dynamic range requirements, is *T/R level data mixing* [1], shown in Fig. 1. In this approach the communication and reference signals are distributed using separate fiber-optic links to the T/R (or subarray) modules for mixing, as opposed to the commonly used *CPU level data mixing*, where communication signals are up-converted at the CPU prior to the optical distribution. In the T/R level data mixing approach, however, a number of local oscillators (LO's), collocated with the active modules and dedicated to each T/R module (or subarray), are synchronized to the same frequency reference, which in turn can be used to up-convert or down-convert the information.

The major advantage of the T/R level data mixing architecture lies in the separation of the ultra-high-speed fiber-optic link, dedicated to distribution of millimeter-wave carrier signal at a single frequency, from the high-speed fiber-optic link, which is used for distribution of communication signals with bandwidths up to a few gigahertz. As result of this separation, the frequency reference link is designed for maximum bandwidth, whereas the data fiber-optic link is optimized for lowest loss and highest dynamic range [1].

Development of low-loss, high-dynamic-range fiber-optic links, which is quite realizable, is discussed in detail elsewhere [2]. On the other hand, distribution of carrier frequency signals extending well into millimeter-wave frequencies (particularly of 60 and 94 GHz) using state-of-the-art fiber-optic links presents a challenge that requires more attention. The goal of this paper is i) to review various methods of establishing a coherent carrier frequency up to the millimeter wave, with particular emphasis on the subharmonic indirect optical injection locking technique; ii) to present experimental results that support the viability of subharmonic indirect optical injection locking by evaluating coherency of the two 21.5 GHz free-run-

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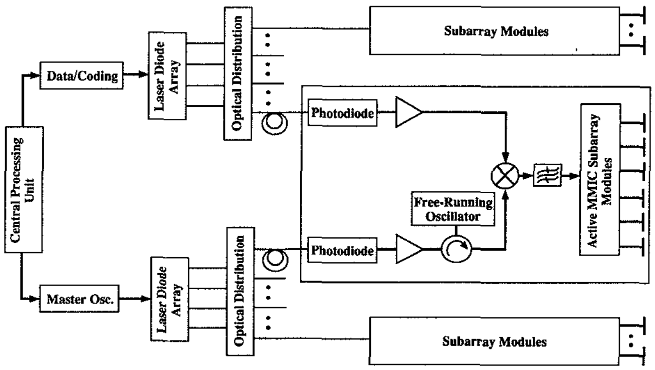



Fig. 1. Conceptual representation of T/R level data mixing based on the subharmonic indirect optical injection locking of distributed antenna structure and distribution of data signals. The bandwidth limitation of the fiber-optic link requires exploitation of both laser and oscillator nonlinearities. To address synchronization of a large number of modules, microwave distribution, laser diode arrays, and optical distribution networks should be used.

ning FET oscillators synchronized to the same frequency reference; and finally iii) to discuss those emerging concepts that bear on the optical synchronization of millimeter-wave oscillators.

## II. Background

### A. Millimeter-Wave Modulated Laser Light

The generation of modulated light up to millimeter-wave frequencies is necessary for the distribution of millimeter-wave carrier signals. A number of methods have been shown to generate millimeter-wave optical modulated signals. Among them, only the heterodyning technique has demonstrated millimeter-wave modulation. In this approach, the outputs of two stabilized lasers are heterodyned and low-pass filtered by a photodetector; the detected signal is related to the frequency difference between the two lasers and can be adjusted to operate at microwave or millimeter-wave frequencies. In fact, the high temperature sensitivity of the laser wavelength (for semiconductor lasers $\approx 0.6$ nm/°C) can be used to sweep into millimeter-wave frequencies, but this dependence also restricts the practical application of this scheme to a few specialized cases. Another disadvantage of this technique is that any optical frequency jitter of the lasers is directly translated to the FM noise of the heterodyned electrical signal. Nevertheless, reference signals up to 100 GHz have already been reported using this novel technique [3]–[5].

Alternatives to the heterodyning scheme are the direct modulation of a laser diode or the use of external modulators. The external modulators take advantage of optical wave interaction with the electrical, magnetic, or acoustic waves throughout the electro-optic, magneto-optic, or acousto-optic property of the guided wave material respectively. Even though magneto-optic modulators hold great promise for attaining very high speeds, the highest speeds of external modulators reported to date are in Mach–Zehnder electro-optic modulators. Using $Ti:LiNbO_3$ Mach–Zehnder traveling wave modulators, an electro-optic modulation bandwidth up to 17 GHz [6] has been reported. The bandwidth limitations of traveling wave modulators are primarily a result of the velocity mismatch between electrical and optical waves and are not affected by the electro-optic response, which is in the picosecond range. Recently, traveling wave Mach–Zehnder modulators with bandwidths up to 40 GHz have been reported [7], where velocity matching is obtained by introducing a 180° coded phase reversal of biasing electrodes. The disadvantages of the external electro-optic modulators at present are high optical insertion loss, size, and, for coded velocity matched modulators, phase distortion.

On the other hand, direct modulation of short cavity laser diodes at room temperature has been reported up to 20 GHz [8], [9], where parasitic roll-off was reduced by minimizing the substrate capacitance and operating lasers at high bias currents. But while the high-speed laser diode operation is achieved at high bias current in the small active region, this operating condition reduces laser reliability. On the other hand, multi-quantum-well laser diodes [10] enjoy high differential quantum efficiency, leading to ultrahigh relaxation oscillation without high bias currents. Nevertheless, Su [11] has predicted that the damping factor caused by gain compression would inherently limit the bandwidth of laser diodes to a level well below their relaxation oscillation frequency. Therefore, it is not predicted that low-cost fabrication of laser diodes with bandwidths in excess of 20 GHz will be feasible in the near future. Furthermore, because lasers exhibit chirping at fast modulation rates, the usable bandwidth of a directly modulated laser diode will also be limited. Therefore, new methods to generate ultra-high-speed modulated light need to be developed.

### B. Coherency of Local Oscillators

In the T/R level data mixing system architecture, stabilized microwave or millimeter-wave local oscillators are used to up-convert the data signal to the carrier frequency or down-convert the modulated RF to the IF frequency. The viability of this architecture depends on highly stable local oscillators. Numerous methods to generate highly stabilized single-frequency microwave and millimeter-wave signals exist [12] and full discussion of this important subject, within the context of this paper, is practically impossible. Historically, direct and indirect synthesis techniques have been employed to produce a microwave carrier from a frequency reference. Optical synchronization of distributed independent oscillators to the same frequency reference, in principle, can be implemented by synthesis of the frequency reference at the CPU or the T/R modules.

*1) Phase Locked Loop (PLL):* The essence of this method is better known in control engineering than microwave circuits. Gardner gives a suitable introduction to this subject [13]. In this approach the frequency reference is used to synthesize coherent carriers at each T/R module. In the optically synchronized oscillators, a frequency reference at low frequency (typically about 100 MHz) is distributed through a fiber-optic link and used to generate comb lines; after filtering, only one of these comb lines is used to phase lock a voltage controlled oscillator (VCO). For example, a fiber-optic link was employed to distribute a 100 MHz frequency reference to phase lock 14.15 GHz dielectric stabilized oscillators in the antenna mounted electronics of distributed antenna structures [14]. The advantage of this technique is that the carrier signal is synthesized from lower frequencies, replacing ultra-high-speed fiber-optic links with links of much lower bandwidth and higher efficiency.

Nevertheless, because each LO requires a comb line generator composed of amplifiers and a step recovery diode operating in large-signal domain, thermal dissipation and overall efficiency limit the applicability of this approach to higher frequencies. Even though in the PLL approach the average phase error can be reduced to zero by having a large dc amplification gain, because of instantaneous phase differences between the frequency reference and VCO, stemming from the VCO's frequency instability, spurious signals manifested by low-frequency FM noise will be present in the stabilized LO. The low-frequency noise is reduced by increasing the locking range as seen in the second-order PLL [13]; however the penalty is a longer settling time.

*2) Optical Injection Locking:* In this approach fiber-optic links distribute the synthesized carrier signal to each module, which is then used to injection lock a local oscillator. Injection locking, or forced oscillation of an oscillator to follow characteristics of a master oscillator, is a well-known phenomenon in nonlinear oscillators [15], [16]; hence, only relevant issues in optical injection locking will be reviewed. In this approach, the master oscillator signal directly or externally modulates the laser diode output light, and the modulated light is then distributed to the modules for injection locking of the LO. Two methods can be used for injection locking, viz. direct and indirect. In direct optical injection locking, the modulated light is injected into the active region of the solid-state device used in the local oscillator, as demonstrated for TRAPATT [17], BJT [18], IMPATT [19], MESFET [20], and HEMT [5].

Although this technique is very elegant, it suffers from poor optical coupling efficiency of the modulated light to the sensitive region of the device, resulting in a limited locking range and poor close-in carrier FM noise level. The alternative approach is indirect optical injection locking (cf. Fig. 1), where the modulated light is first detected by a high-speed photodiode and, after amplification, is electrically injected into the LO [21]. The advantages of this technique are greater coupling efficiency and higher master oscillator signal power before injection locking, resulting in a higher locking range and a better close-in carrier phase noise. Furthermore, because the master signal can be amplified before injection to the LO, the nonlinear characteristics of the oscillator can be exploited and synchronization can be observed at parametrically related frequencies of the slave oscillator's frequency. More specifically, frequency entrainment can be observed at those injected frequencies that are subharmonically related to the free-running oscillation frequency of the slave local oscillator. Therefore, the bandwidth of the fiber-optic link necessary for distribution of the frequency reference can be much lower than the slave oscillator's frequency, as demonstrated in the case of a 38.9 GHz IMPATT oscillator [22]. In this experiment, the nonlinearities of both the laser diode and the IMPATT diode were exploited to achieve the frequency multiplication necessary for synchronization of the millimeter-wave oscillator. For subharmonic injection locking, the relationship between the master oscillator frequency, $f_{\text{master}}$ ($=3.3$ GHz), and the slave oscillator, $f_{\text{slave}}$ ($=38.9$ GHz), can be expressed more explicitly as

$$f_{\text{slave}} = m_{\text{laser}} \times m_{\text{Osc.}} \times f_{\text{master}} + \delta f \tag{1}$$

where $m_{\text{laser}}$ ($=4$) and $m_{\text{Osc.}}$ ($=3$) are the frequency multiplication factors of the laser diode and the oscillator, respectively, and $\delta f$ is the frequency detuning. The laser nonlinearity demonstrates a desirable feature by which practical optical synchronization of oscillators can be extended to *Ka*-band and above.

### C. Nonlinear Characteristics of Laser Diodes

One way to overcome the bandwidth limitations of laser diodes and extend the effective synchronizing fiber-optic link is to exploit the inherent nonlinearities of semiconductor laser diodes. In fact, a study comparing the characteristics of an optically injection locked oscillator in terms of locking range and FM noise for various multiplication factors of $m_{\text{laser}}$ and $m_{\text{Osc.}}$ indicated that nonlinearity of the laser diode is more significant and should be exploited [23]. A study of the dynamic behavior of a large-signal direct modulated laser diode demonstrated that at modulating frequencies close to the large signal relaxation oscillation results in a strong nonlinear behavior, leading to high harmonic levels [23], [24]. The harmonics generated at these frequencies are at a much higher level than those achieved by fundamental modulation at the same harmonic frequency. The generated harmonics of the frequency reference can then be used to injection-lock millimeter-wave free-running oscillators subharmonically. The time evolution of photon density, $P(t)$, for a large-signal modulated laser diode at an angular frequency $\omega$ can be expressed as [24]

$$P(t) = \frac{P_0}{I_0(a)}\left[I_0(a) + 2\sum_{k=1}^{\infty} I_k(a)\cos k(\omega t + \theta)\right]$$

where $I_k(a)$ is the modified Bessel function of the first kind and order $k$, and $P_0$ is the average photon density. The parameter $a$ corresponds to the exponential amplitude of the photon density. The amplitude $a$ is related to laser physical parameters and the current modulation

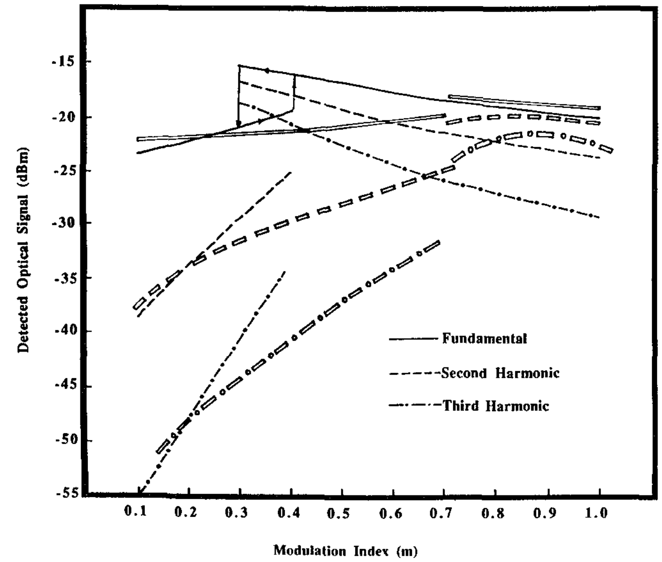



Fig. 2. Comparison of the detected harmonics as a function of current modulation index for symmetric——— and asymmetric ▭▭▭ laser diodes modulated by a 0 dBm signal at 5 GHz.

index of the laser [25]:

$$m = a\sqrt{\left\{\left(\frac{\omega^2}{\omega_0^2}\right) - \phi(a)\right\}^2 + \omega^2\tau_p^2\left\{\left[\frac{1}{\omega_0^2\tau_p\tau_s}\right]+1\right\}^2}$$

where $\omega_0^2 = \alpha P_0/\tau_p$ is the small-signal relaxation oscillation frequency, $P_0$ is the time-averaged photon density, $\alpha$ is the differential optical gain, and $\tau_s$ and $\tau_p$ are electron and photon lifetimes respectively. The current modulation index is defined as $m = \{I_{RF}/(I_b - I_{th})\}$, where $I_{RF}$ corresponds to the RF current passing through the laser diode's junction for bias and threshold currents of $I_b$ and $I_{th}$ respectively. Finally, the term $\phi(a) = 2I_1(a)/aI_0(a)$. This expression can be used to evaluate the harmonic content of different laser diode structures, such as *symmetric* and *asymmetric*, in terms of $\tau_s$ and $\tau_p$ and operating conditions [26] as well as the device structure.

The degree of nonlinear behavior is predominantly affected by the ratio of $\tau_s$ to $\tau_p$; these two physical parameters are influenced by the Fabry–Perot facet coating for the given laser diode geometry and structure. In particular, lasers with back facet reflective coating (asymmetric) have a shorter electron lifetime and a longer photon lifetime than the uncoated laser diodes (symmetric). This degree of control can enhance or suppress the harmonic generation in the laser diode. A theoretical comparison of harmonic content of symmetric and asymmetric buried heterojunction (BH) laser diodes for an RF input current of 6 mA (0 dBm input power to 50 Ω system) at a modulating frequency of 5 GHz is rendered in Fig. 2 for various modulation indices. This graph predicts that higher harmonic content will be observed for symmetric laser diodes close to the relaxation oscillation frequency than asymmetric laser even though the asymmetric laser provides higher output power from the front facet.

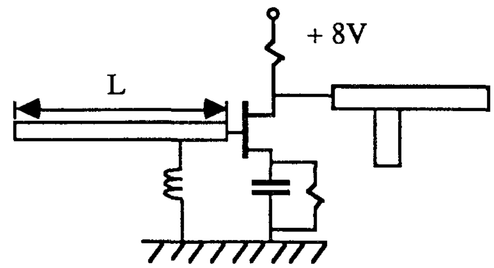



Fig. 3. Simplified layout of the 21.5 GHz FET oscillators.

## III. Phase and Frequency Coherency Experiments

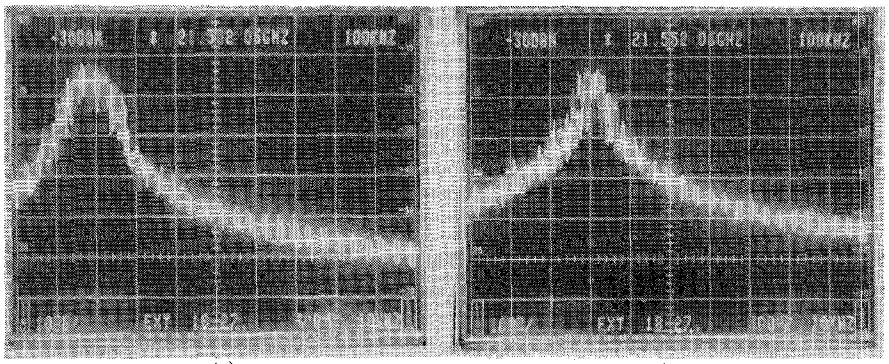
The concept of large-signal modulation of laser diodes and its applicability in indirect subharmonic optical injection locking are well illustrated by the following case. Two oscillators operating at 21.5 GHz were designed and fabricated using low-noise 0.5 $\mu$m GaAs MESFET's from Avantek. The FET oscillators, realized on alumina substrates in a hybrid form, were self-biased at 50% of $I_{dss}$ using a chip voltage regulator of 8 V. The biasing conditions were $V_{ds} = 4$ V and $V_{gs} = -1$ V for $I_{ds} = 45$ mA. The $I_{ds}$ was adjusted with the bias resistance in the source as shown in Fig. 3. By using the transistor model and microwave CAD program, the value of the series feedback capacitance was determined to optimize the negative resistance around the desired frequency of 21.5 GHz.

A microstrip open-circuited stub in the gate was adjusted to satisfy the oscillation frequency at 21.5 GHz. A matching stub on the drain was used primarily to maximize the output power. The output power of 10 mW was measured at 21.55 GHz. The power spectrum of the free-running oscillators is shown in Fig. 4. A good pushing factor of 100 kHz/V was obtained for the oscillator due to the stable dc biasing provided by the voltage regulator. The external $Q$ of the free-running oscillators was determined by direct electrical injection locking and was calculated to be 205 using Adler's locking range equation [27].

### A. Frequency Coherency Experiments

*1) Experimental Setup:* In the experimental setup shown in Fig. 5, two 21.5 GHz FET oscillators are optically synchronized to a reference source. A high-speed BH GaAlAs laser diode, manufactured by the Ortel Corporation, is used in this experiment as an optical source. The fiber pigtailed laser diode package emits light at 810 nm and has an output power of 4.5 mW out of the fiber end. The laser diode has a threshold current of 17 mA and is biased by an optical power monitored power supply to maintain constant output power. The 3 dB bandwidth of the laser diode is 9.3 GHz at a biasing level corresponding to 90% of maximum output power. The laser diode is modulated under the large-signal domain at $f_0$ by a synthesized source through a bias tee.

The modulated light output is coupled to a 3 dB optical coupler from Canstar with coupling coefficient of 47% and 43%. Light in the first arm of the coupler is colli-



(a) (b)

Fig. 4. Spectrum of the free-running oscillators at 21.5 GHz: (a) oscillator #1, (b) oscillator #2 (horizontal scale of 100 kHz/div., vertical scale of 10 dB/div., and resolution filter of 10 kHz).

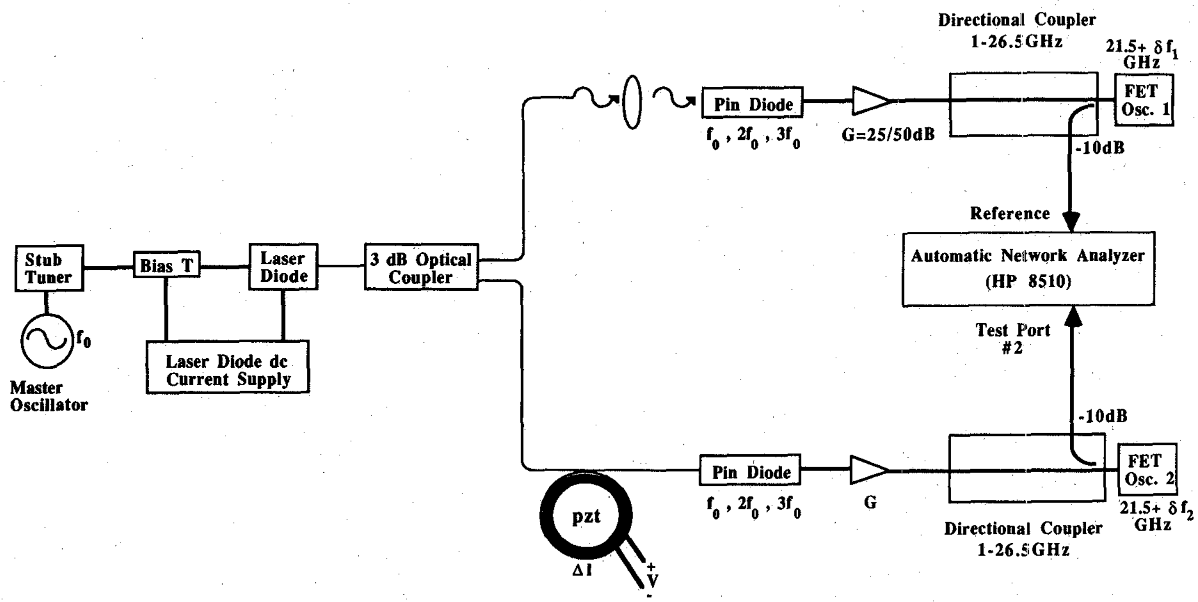
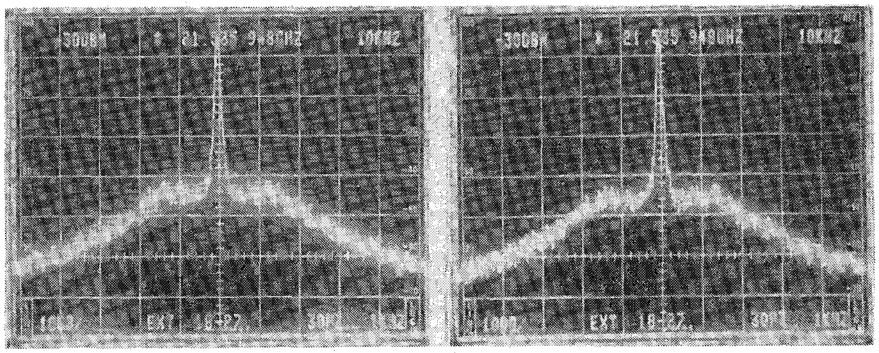



Fig. 5. Experimental setup for frequency synchronization of the two FET oscillators. Thin lines corresponds to optical fibers and the thicker lines refer to the electrical connections. The pzt ring is used for examining the phase coherency of the injection locked two oscillators. For frequency observation the network analyzer is replaced by a spectrum analyzer.

mated using a 0.25 pitch graded index lens and is focused on a high-speed p-i-n photodiode by a short-focal-length lens from Melles Griot. The output from the second arm of the coupler is spliced to 100 m of graded index multimode fiber, which is wrapped around a piezoelectric (pzt) crystal 150 times.

The light is then detected by a high-speed pigtailed p-i-n photodiode. The p-i-n photodiodes, manufactured by Ortel, have 3 dB bandwidths of 14 GHz. The responsivities of photodiodes are 0.45 mA/mW and 0.35 mA/mW at 840 nm for 20 V reverse biasing respectively. The detected fundamental and harmonics (i.e., $f_0, 2f_0, 3f_0$) of the master source are amplified in both arms by broad-band (6–12 GHz) amplifiers from Avantek. Amplification gain stages of either 25 or 50 dB can be introduced using two ac coupled amplifiers. The amplified signals are then injected to the free running FET oscillators at 21.5 GHz through broad-band (1–26.5 GHz) directional couplers from Krytar in place of circulators. The output of the injection locked oscillators is monitored on a spectrum analyzer using external mixers.

*2) Experimental Results:* In the injection locking of two slave oscillators, nonlinear multiplications in laser diode and FET were exploited. More specifically, when the BH laser diode was large-signal modulated by an 8 dBm signal from a synthesized master source at frequencies of *S*-, *C*-, and *X*-bands, the harmonics were generated in the laser diode [23], [24]. In particular, the signal at 10.764 GHz was filtered out and amplified by the cascaded amplifier stage. The amplified signal was then subharmonically injected to the 21.5 GHz FET oscillators. Therefore, a multiplication factor of 2 was attained in the FET, and, based on the modulating frequency employed, multiplication factors of 3, 2, and 1 were obtained in the laser. More explicitly from the master oscillator point of view, injection locking occurred at subharmonics of 1/6, 1/4, and 1/2 respectively (i.e., 3.588 GHz$\times 3 \times 2 = 21.528$ GHz, 5.382 GHz$\times 2 \times 2 = 21.528$ GHz, $10.764 \times 1 \times 2 =$



(a) (b)

Fig. 6. Spectrum of the 21.5 GHz FET oscillators synchronized to the master oscillator signal of 5.383 GHz: (a) oscillator #1, (b) oscillator #2 (vertical scale of 10 dB/div., horizontal scale of 10 kHz/div., and resolution filter of 1 kHz).

21.528 GHz). The spectrum of the free-running FET oscillators after injection locking by the 5.382 GHz signal from the master oscillator is shown in Fig. 6, where not only synchronization is achieved but also the close-in carrier phase noise is substantially reduced.

Similar results were also achieved for subharmonic factors of 1/6 and 1/2. The characteristics of the injection locked oscillators in terms of figures of merit, such as locking range and FM noise degradation of the master source, were studied. The performances of the injection locked oscillator #1 for subharmonic factors of 1/6, 1/4, and 1/2 are compared in Table I, where a gain of 25 dB was used. In these experiments the laser diode dc biasing was adjusted at each modulating frequency to optimize the attainable locking range for a constant 8 dBm input RF power (i.e., current modulation index was adjusted for best results). These results indicate that the best performance in terms of locking range and close-in carrier noise is at a subharmonic factor of 1/4.

Next the optimum locking range for a 50 dB amplification gain was measured. For a subharmonic of 1/2 (i.e., modulating frequency of 10.764 GHz) a locking range of 12 MHz was attained. However, for the modulating frequency of 5.389 GHz (subharmonic of 1/4), a larger locking range was achieved, as shown in Figs. 7 and 8 for oscillators #1 and #2 respectively. Similar results were also obtained for a subharmonic factor of 1/6; however the performance was inferior to the subharmonic factor of 1/4. Since the best results were achieved at 5.389 GHz, all the other characterizations were made for the subharmonic factor of 1/4. Next, the FM noise levels of the two oscillators were compared for the subharmonic factor of 1/4 at the midband of locking range, indicating very similar characteristics. In addition, the FM noise of injection locked oscillator #1 was compared at the midband to the end of locking range, revealing that the usable range of the injection locked oscillator is narrower than the locking range. These results are summarized in Table II.

### B. Phase Coherency Experiments

*1) Experimental Setup:* The approach to measuring the phase coherency of the two injection locked oscillators is to compare the phase of one with that of the other on a HP8510A network analyzer's test set. The experimental setup is similar to the one used for frequency coherency measurement (cf. Fig. 5), except that the spectrum analyzer is replaced by the network analyzer. The output of oscillator #1 is fed to the reference port of the test set and the signal from oscillator #2 is provided to port 2 of the test set. When the oscillators are locked, superheterodyne detection provides the phase difference between the reference (oscillator #1) with respect to the test signal (oscillator #2). For examination of the phase coherency of the injection locked oscillators, the pzt ring is utilized as a variable phase shifter. The pzt crystal has a diameter of 9.6 cm and the radial strain factor, $\Delta C/C$, is $10^{-2}$ ppm/V, where $C$ is the circumference of the ring. The capacitive breakdown voltage of the pzt crystal is calculated to be as high as 4 kV. A high-voltage dc supply provides the biasing voltage for expansion of the pzt ring, hence causing the fiber to stretch. This expansion introduces a variable time delay (i.e., phase shift) for the phase of the reference signal [28]. The phase shifting by the piezoelectric stretcher follows the simple relation

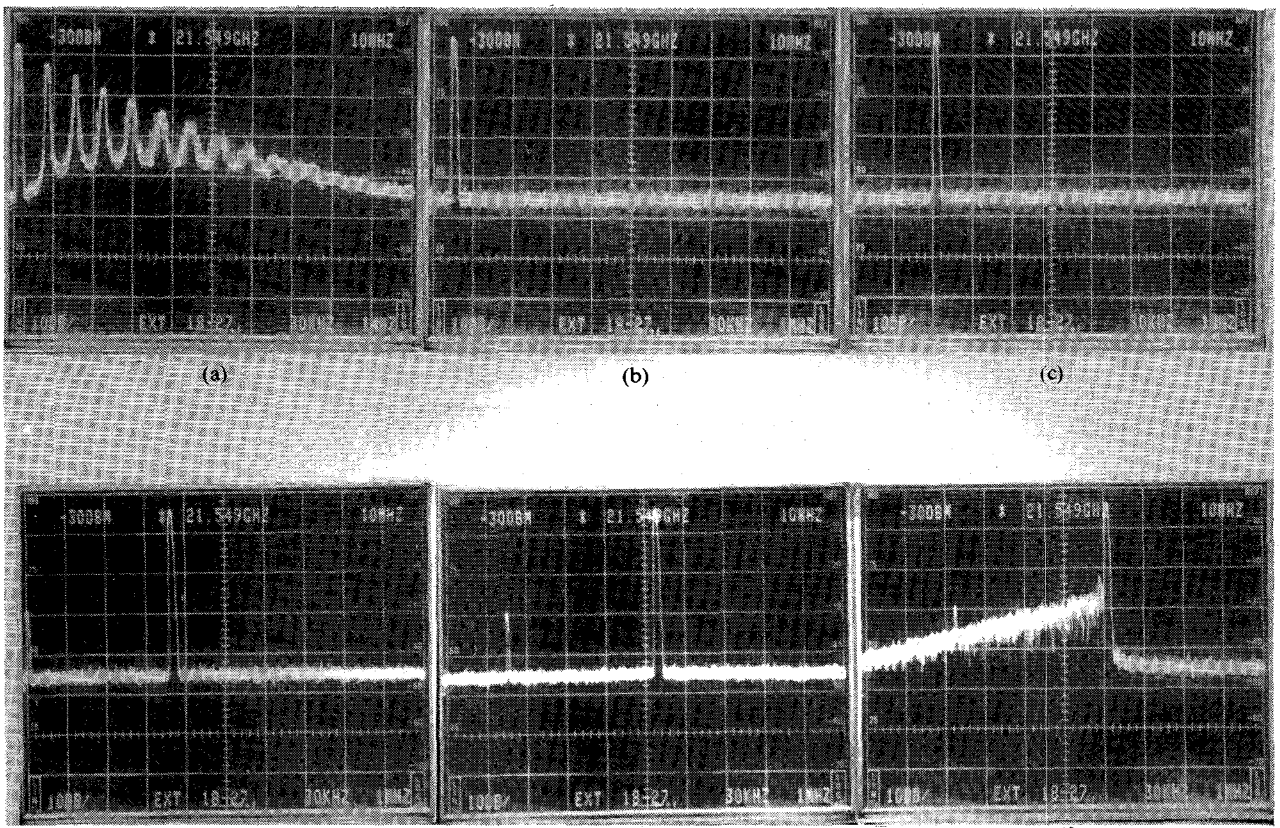
$$\Delta\Phi = 2\pi(\Delta l/\lambda_g) = 2N\pi^2 D * 10^{-5} * V/\lambda_g$$

where $\Delta\Phi$ is the phase shift in radians, $\Delta l$ is the stretching introduced in the fiber, $\lambda_g$ is the guide wavelength of the microwave modulating envelope of the optical carrier,

TABLE I
COMPARISON OF LOCKING RANGE AND FM NOISE DEGRADATION OF THE OSCILLATOR #1 FOR THREE DIFFERENT SUBHARMONIC FACTORS OF 1/6, 1/4, AND 1/2

| Modulating Freq. $f_o$ (GHz) | Biasing Current $I_b$ (mA) | Locking Range $\Delta f$ (KHz) | FM Noise Degradation at 1KHz Offset (dB) |
|---|---|---|---|
| 3.593 | 22 | ≈800 | ≈13 |
| 5.389 | 32 | 1600 | ≈12 |
| 10.779 | 42 | ≈400 | ≈4 |

The RF input power to the laser diode is kept constant at 8 dBm for all frequencies, while the laser dc bias is adjusted for maximum pulling range. The FM noise degradation is measured with respect to the master oscillator signal at the modulating frequencies of 3.588, 5.382, and 10.764 GHz.



(a) (b) (c) (d) (e) (f)

Fig. 7. Master–slave pulling range of the FET oscillator #1 for 15 steps of 1 MHz/step, corresponding to a locking range of 60 MHz (horizontal scale of 10 MHz/div. and vertical scale of 10 dB/div.): (a) 5.375 GHz (beginning of locking range), (b) 5.376 GHz (locked), (c) 5.380 GHz (locked), (d) 5.384 GHz (locked), (e) 5.388 GHz (locked), and (f) 5.390 GHz (end of locking range).

$N$ is the number of turns, $D$ is the diameter of the pzt ring, and $V$ is the dc applied voltage in kV. With this variable phase shifting scheme, a phase shift is introduced in the synchronizing signal which is monitored as a phase shift between oscillator #1 and oscillator #2 on the network analyzer. The phase difference arising from any frequency detuning between the free-running oscillators is also measured using the same measurement technique.

*2) Experimental Results:* First the concept of phase shifting in the optical path by stretching the optical fiber using the pzt crystal was investigated. For no bias voltage applied to the pzt, the phase difference between the two injection locked oscillators, which is primarily due to electrical path length difference between the reference and the test path, was calibrated out using the port extension feature of the HP8510A network analyzer. Fig. 9 shows that analog phase shifts of up to 40° can be introduced to the test signal for a 3.8 kV dc voltage applied to the pzt crystal. The phase shifts introduced by the pzt crystal are linear functions of the dc biasing voltage.

The phase difference was always repeatable as long as the oscillators were kept at the same temperature. However as the temperature of oscillator #2 was lowered (by spraying Freon), a fixed phase shift was measured, as shown in Fig. 10. The result of this simple measurement indicates that the injection locked oscillators experience a temperature-dependent phase offset, which would lead to phase incoherency between the two injection locked oscillators. This phase error was first predicted by Adler [27] and should be corrected for in the phased array scenario.

## IV. Discussion

Two FET oscillators at 21.5 GHz were fabricated on alumina substrate by the use of hybrid techniques with a very low pushing factor. These free-running oscillators were subharmonically synchronized to a synthesized reference signal through a fiber-optic link. A locking range of 84 MHz was achieved for a subharmonic factor of 1/4 with respect to the master source. Multiplication factors of 6, 4, and 2 were attained by using laser diode and FET nonlinearities. The performance of the injection locked oscillators was evaluated from locking range and FM noise degradation figures of merit, and subharmonic locking using the factor 1/4 was preferred to 1/6 and 1/2, as a result of a compromise between FM noise degradation and locking range. A more efficient use of frequency reference power can be made by minimizing the insertion loss of the synchronizing fiber-optic link [2]. The design of narrow-band reactively matched optical transmitter and receiver modules is being actively pursued to synchronize a larger number of oscillators.

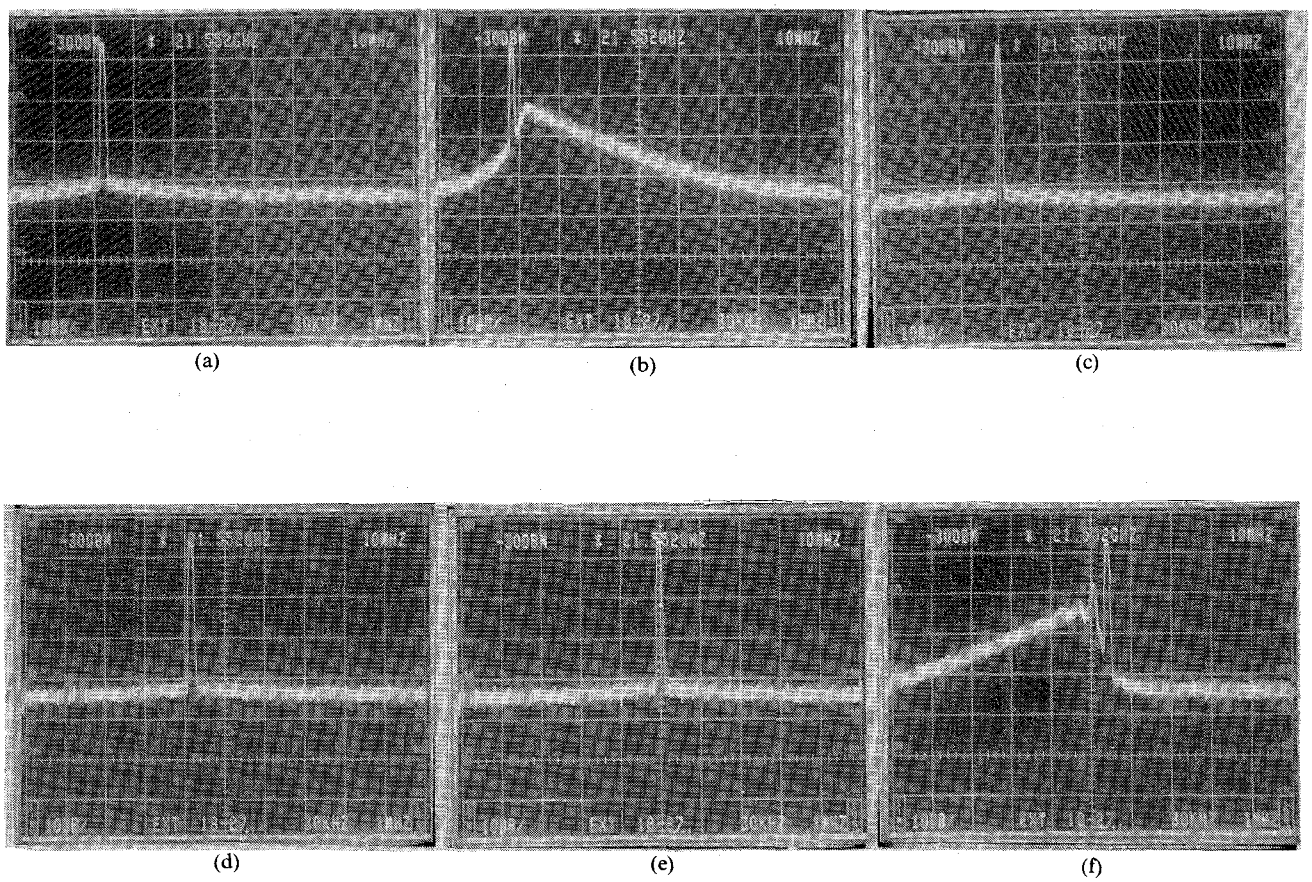


Fig. 8. Master–slave pulling range of the FET oscillator #2 for nine steps of 1 MHz/step, corresponding to a locking range of 36 MHz (horizontal scale of 10 MHz/div. and vertical scale of 10 dB/div.): (a) 5.380 GHz (beginning of locking range), (b) 5.381 GHz (locked), (c) 5.383 GHz (locked), (d) 5.386 GHz (locked), (e) 5.388 GHz (locked), and (f) 5.389 GHz (end of locking range).

TABLE II
FM NOISE MEASUREMENT OF THE INJECTION LOCKED 21.5 GHz FET OSCILLATORS AT DIFFERENT CARRIER OFFSET FREQUENCIES: COMPARISON OF THE FM NOISE LEVEL OF OSCILLATOR #1 AT THE FREQUENCY CORRESPONDING TO THE MIDBAND LOCKING RANGE (5.383 GHz) AND THE EDGE OF GETTING OUT OF LOCK (5.390 GHz).

| | FM Noise Level (Offset Carrier) | 100 Hz (dBc/Hz) | 300 Hz (dBc/Hz) | 600 Hz (dBc/Hz) | 900 Hz (dBc/Hz) | 1.2kHz (dBc/Hz) |
|---|---|---|---|---|---|---|
| Osc. #1 | Master Osc. Freq. (5.382GHz) | -38 | -38 | -40 | -50 | -52 |
| Osc. #2 | Master Osc. Freq. (5.382GHz) | -37 | -39 | -40 | -48 | -51 |
| Osc. # 1 | Master Osc. Freq. (5.383GHz) | -37 | -42 | -39 | -47 | -54 |
| | Master Osc. Freq. (5.390GHz) | -19 | -26 | -24 | -28 | -34 |

This paper also presents results of a phase coherency examination of the optically injection locked oscillators. Initial results indicate that the phase of the injection locked oscillators does not remain coherent and that their phase is dependent on the frequency difference of the master and free running oscillators. In the context of large-aperture antennas with distributed LO's injection locked to a frequency reference, if the active antenna aperture experiences temperature gradients, then the free-running oscillation frequency of the local oscillators would be shifted, resulting in a phase difference between the injection locked oscillators. This phase difference would result in an inaccurate difference between the injection locked oscillators. This phase difference would result in inaccurate phase shifting for an individual radiating element, distorting the radiating beam. Approaches such as injection locked phase locked loops [29] or optical phase lock loops [30] are therefore recommended to ensure both frequency and phase coherency of the distributed oscillators. The former scheme [29] not only will correct for any phase error introduced due to a temperature gradient across the active aperture, but also is suitable for introducing analog phase shifts in the range of $\pm 90°$. This approach could reduce the size of MMIC-based real-time-delay phase shifters, as presently designed for beam steering, by performing some of the phase shifts.

When the phase errors of the injection locked oscillators are corrected for, then because of low AM to PM conversion and high AM compression [31], injection locking is the preferred method of synchronization over direct amplification of the carrier signal. Furthermore, by exploiting both the oscillator nonlinearity and the laser diode, synchronization can be extended well above the

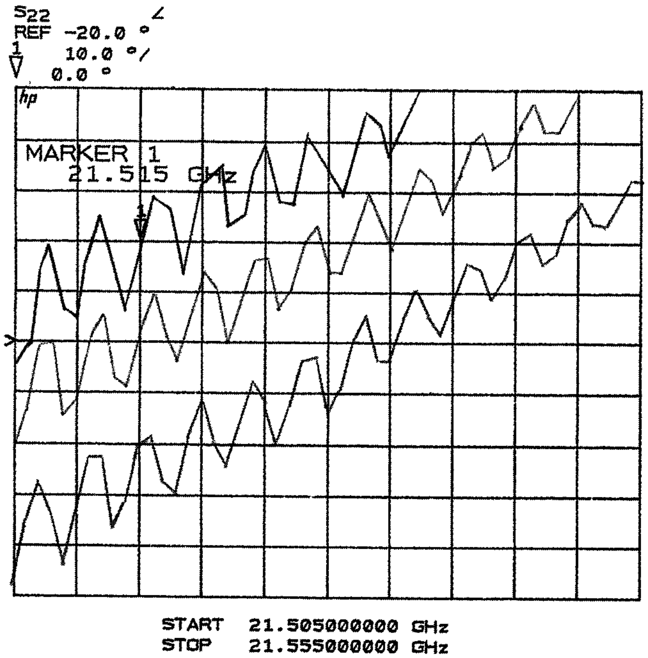



Fig. 9. Phase difference between the two subharmonic indirect optically injection locked oscillators as a function frequency for three bias voltages to the pzt crystal (vertical scale of 10/div., reference level of −20, and start frequency of 21.505 GHz and stop frequency of 21.555 GHz): zero bias (*red*), bias voltage of 2 kV (*green*), bias voltage of 3.8 kV (*blue*).

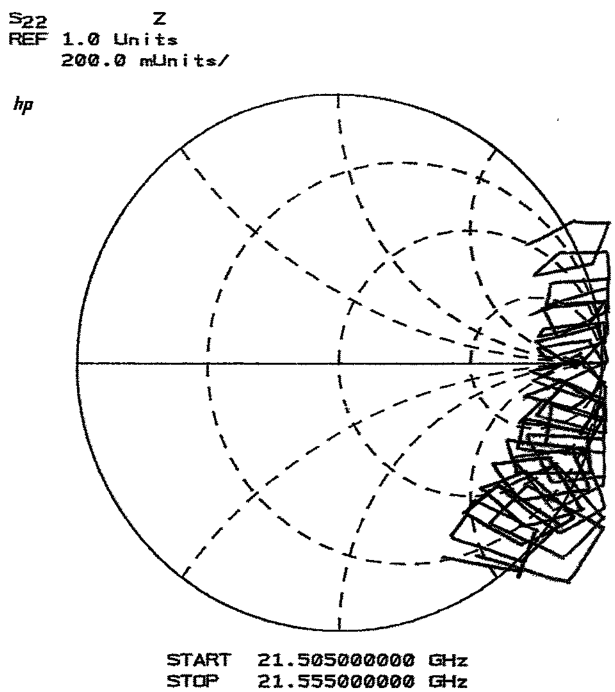



Fig. 10. Standard Smith chart plot of the two injection locked oscillators. Oscillators are at the same temperature (*red*); temperature of oscillator #2 is lowered with Freon spray (*blue*).

bandwidth of electro-optic devices, as was previously reported (cf. [22]). For synchronization of oscillators at frequencies above 40 GHz (such as 60 and 94 GHz), other methods of injection locking, such as sideband [32] or idler [33] techniques, should be investigated. Both techniques are currently under investigation.

The nonlinear characteristics of laser diodes are very useful in multiplying the lower frequencies up to the millimeter-wave frequency references. The nonlinearity of laser diodes is strongly dependent on the strength of the relaxation oscillation frequency. Furthermore, the laser nonlinear behavior in the presense of optical feedback can be used to generate ultra-high-frequency modulation, as was recently demonstrated up to 40 GHz by Tucker *et al.* [34]. In summary, this paper, along with previously reported work, points to three subtle issues that should be considered in selecting laser diodes to be used in optically controlled phased array antennas:

- Large-signal modulation of lasers is an important technique to generate harmonics for optical synchronization of oscillators at frequencies above 10 GHz.
- Nonlinear characteristic of laser diodes is optimum at frequencies which are close to the large-signal relaxation oscillation frequency, and this nonlinearity is highly dependent on the amplitude of relaxation oscillation frequency. The amplitude of the relaxation oscillation frequency for asymmetric laser diodes is less than that of symmetric ones. Therefore, for distribution of frequency reference, symmetric lasers are preferred.
- The asymmetric laser diodes with reflective coating are more suitable for data transmission, where linearity is of great interest. Furthermore, since the high reflectivity at the back facet causes the photon to travel twice in the Fabry–Perot cavity, asymmetric lasers have lower relative intensity noise than symmetric lasers. Therefore, the asymmetric lasers are more suitable for data transmission.

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