Broad-Band ($\geq$20 GHz) Laser-Diode-Based Optoelectronic Microwave Phase Shifter

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***Abstract*— We demonstrate a new type of broad-band microwave phase shifter with superior performance at frequencies up to 20 GHz. This is implemented by simply adding an offset voltage prior to the loop filter (LF) in a laser-diode-based digital optoelectronic phase-locked loop (OEPLL). Accurate control of the phase of microwave signals with a continuously tunable range exceeding 640° ($\sim$3.6π) is achieved. The phase fluctuation and long-term drift of any desired phase shift are as small as $\pm$0.4° and 0.08°, respectively, at 20 GHz. The relative phase instability can be maintained within 0.09° while operating in a phase-shift-keying (PSK) scheme. We also demonstrate accurate control of relative phase difference between dual phase-locked microwave sources using the phase shifter. Our results indicate potential application of this broad-band optoelectronic phase shifter in a phased-array antenna system.**

***Index Terms*—Microwave, optoelectronic, phase shifter.**

I. Introduction

THE phase shifter is a key microwave component which has been extensively employed in various systems for communication, instrumentation, and measurement at microwave frequencies [1]. For certain special applications such as the phased-array antenna system, an ideal phase shifter for an individual microwave oscillator should simultaneously meet several requirements. These include higher power-handling capability, broad-band and frequency-independent operation, accurate and continuous phase control, etc. Most phase shifters developed earlier were of the mechanical type. These consist of either a set of microwave waveguides with various lengths or a certain kind of transmission structure with tunable length [2]. In 1960, the emergence of the ferrite and electronic phase shifters lead to a new era of phase-shifting technology [3]. The waveguide-type phase-shifting devices can now accurately control the required phase shift via the true-time-delay technique. However, these are usually frequency-dependent, narrow-band (only 5%–10% of the central frequency), and bulky. With the advent of monolithic-microwave integrated-circuit technology, the aforementioned disadvantages have been largely overcome. This trend led to the development of hybrid or fully monolithic phase-shifting modules. Nonetheless, phase-shifting elements based on semiconductor devices such as field-effect transistors [4], and Schottky or p-i-n diodes [5] suffer from relatively high insertion loss while operating at higher microwave or millimeter-wave frequencies.

Recently, optical distribution of narrow-band microwave or millimeter-wave clock signals has attracted much attention due to its many advantages, e.g., compatibility to fiber-optic networks, electromagnetic immunity, ultrahigh operating bandwidth with ultra-low distortion, etc. Furthermore, the optical control of microwave or millimeter-wave components has also been accomplished by using a medium whose properties (such as dielectric constant or conductivity) at microwave frequencies can be dynamically controlled by optical illumination. Based on these advanced concepts, several optical [6]–[8] and optoelectronic [9]–[11] phase-shifting schemes have been demonstrated at frequency up to several gigahertz. For example, optical implementations of true-time-delay phase shifts by using fiber-optic delay [6] or a variable opto-mechanical delay line [8] have been demonstrated. Lately, optoelectronic phase shifting at 7 GHz has also been reported by controlling the dc bias-current of an RF-modulated laser diode [11]. Recently, we have successfully developed a laser-diode-based optoelectronic phase-locked loop (OEPLL) for phase-tracking free-running microwave signals beyond 20 GHz [12]. It is well known that a phase-locked voltage-controlled oscillator (VCO) in the phase-locked loop (PLL) can generate a relatively pure and narrow-band microwave signal with ultrahigh phase stability. Thus, the OEPLL technique can further allow phase tracking of the microwave oscillator to a set of optically distributed clock signals generated from a gain-switched laser diode (GSLD) [13]. The overall operating bandwidth of the OEPLL has shown to be well beyond the 3-dB bandwidth of harmonics of the GSLD pulses.

In this paper, we further extend the OEPLL technology to demonstrate a novel broad-band optoelectronic microwave phase shifter with its operational frequency beyond 20 GHz. Highly accurate phase shift was achieved from such an OEPLL-based phase shifter (OEPLL-PS). Characteristics such as the maximum phase-shifting range, linearity, insertion loss, and long-term phase stability of the OEPLL-PS were investigated. Submicrometer-second response as well as ultra-low phase-shift error under phase-shift keying (PSK) operation were realized. Furthermore, we also demonstrate precision control of relative phase change between two optoelectronic microwave sources using the phase shifters. This suggests

Manuscript received September 12, 1997.

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Publisher Item Identifier S 0018-9480(98)07246-9.

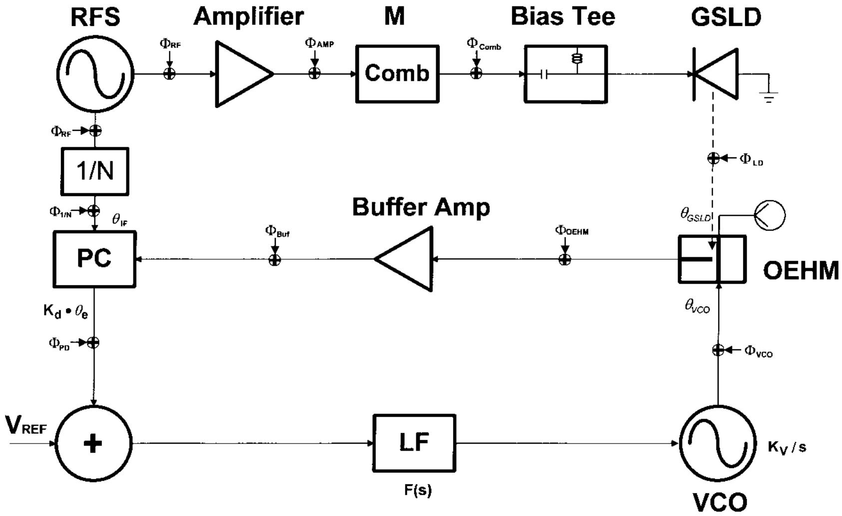


Fig. 1. The configuration and equivalent noise model of the OEPLL-PS. RFS: radio-wave frequency synthesizer. LF: loop filter. PC: phase comparater.

that the current technique is potentially useful in phased-array antenna systems.

II. System Analysis

The configuration of the OEPLL-PS is schematically shown in Fig. 1. The basic principle can be explained by deducing the phase change of the VCO from the equivalent noise model of the OEPLL. By using nodal analysis, we can express the effect of phase shift and phase noise on the desired phase of the output from VCO as

$$\begin{aligned}\theta_e &= \theta_{\mathrm{IF}} - [(\theta_{\mathrm{VCO}} - \theta_{\mathrm{GSLD}}) + \Phi_{\mathrm{OEHM}} + \Phi_{\mathrm{Buf}}]\\ \theta_{\mathrm{IF}} &= \left[\frac{\Phi_{\mathrm{RF}}}{N} + \Phi_{1/N}\right]\\ \theta_{\mathrm{GSLD}} &= M\Phi_{\mathrm{RF}} + M\Phi_{\mathrm{AMP}} + \Phi_{\mathrm{Comb}} + \Phi_{\mathrm{LD}}\\ \theta_{\mathrm{VCO}} &= [\theta_e K_d + N_s(\Phi_1) - V_{\mathrm{REF}}]F(s)K_v/s + \Phi_{\mathrm{VCO}} \qquad (1)\end{aligned}$$

where θ_e is the phase difference of the input signal and the reference at the phase detector, θ_{IF} is the phase of the intermediate frequency (IF) reference signal derived from the RF synthesizer through the divider, θ_{VCO} is the phase of the VCO in the OEPLL under closed-loop condition, and θ_{GSLD} is the phase of the optical clock signal from the GSLD. The phase noise of each component in the OEPLL is denoted by Φ's with corresponding subindexes. In addition, $F(s)$ is the S-domain transfer function of the second-order active loop filter (LF), and K_d and K_v are the gain constants of the phase detector and the VCO, respectively.

In (1), we have assumed that an offset voltage V_{REF} is added prior to the LF. By substituting θ_{IF}, θ_{VCO}, and θ_{GSLD} into θ_e, we can rewrite the phase change θ_{VCO} of the output signal from the VCO phase locked to the clock signal as follows:

$$\begin{aligned}\theta_{\mathrm{VCO}} &\approx \left[M\Phi_{\mathrm{RF}} + \Phi_{\mathrm{SYSTEM}} - \frac{V_{\mathrm{REF}}}{K_D}\right]\frac{K_dF(s)K_v/s}{1+K_dF(s)K_v/s}\\ &\quad + \frac{\Phi_{\mathrm{VCO}}}{1+K_dF(s)K_v/s}\\ &\approx \Phi_{\mathrm{PLL}} - V_{\mathrm{REF}}\,\frac{F(s)K_v/s}{1+K_dF(s)K_v/s}\\ &\equiv \Phi_{\mathrm{PLL}} + \Delta\theta_{\mathrm{VCO}} \qquad (2)\end{aligned}$$

where $\Delta\theta_{\mathrm{VCO}}$ is the phase shift of the VCO caused by the V_{REF}. Equation (2) represents the effect of the offset voltage V_{REF} prior to the LF on the phase change of the microwave signal from the VCO. Owning to a relatively large loop gain in the OEPLL passband, we can make the following approximation:

$$\frac{F(s)K_v/s}{1+K_dF(s)K_v/s} \approx 1/K_d. \qquad (3)$$

As a result, the phase shift of the microwave signals from OEPLL-controlled VCO $\Delta\theta_{\mathrm{VCO}}$ is linearly proportional to the offset voltage V_{REF} as follows:

$$\Delta\theta_{\mathrm{VCO}} = V_{\mathrm{REF}}\,\frac{F(s)K_V/s}{1+K_dF(s)K_V/s} \approx V_{\mathrm{REF}}/K_d \equiv R_dV_{\mathrm{REF}}. \qquad (4)$$

That is, the phase change of the microwave signal can be controlled by simply varying V_{REF} without the use of high-frequency circuit components. The parameter $R_d \approx K_d^{-1}$ with a unit of degree/volt, represents the phase sensitivity of the OEPLL-PS system. In typical PLL systems, it is mandatory to choose a phase detector with a larger phase-gain constant K_d. This, however, will lead to a smaller phase sensitivity. As a result, the maximum phase-shifting range is reduced. Thus, an optimal design of the phase-comparing circuit for achieving larger phase sensitivity without degradation of the phase-comparing ability (against the selection rule of the phase sensitivity) is needed for such systems.

III. Experimental Method

The block diagram of our experimental apparatus is also shown in Fig. 1. It is similar to the OEPLL system reported previously [13]. A GSLD ($\lambda = 0.8$ μm) driven by the radio-wave frequency synthesizer (RFS) HP8657A operated in the continuous wave (CW) mode was used to generate ≈40 ps pulses at $f_o \approx 500$ MHz. The pulse train functioned as the optical clock. The VCO was a broad-band synthesized sweeper (HP83620A) operated in the dc–FM mode. A photoconductive switch with a 30-μm gap in a microstrip line fabricated on a

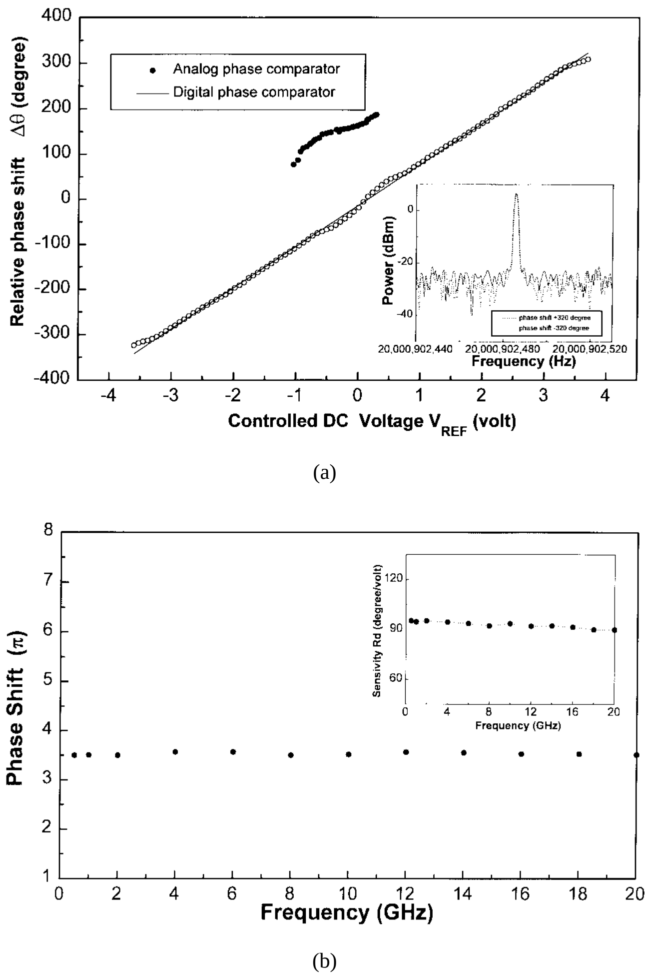


Fig. 2. (a) Phase shift versus controlled voltage of the 20-GHz microwave signal from the VCO by using APC- or DPC-based OEPLL-PS. The spectrum of a phase-locked VCO phase-shifted at +320 and −320° is shown into the inset. (b) The maximum phase-tuning range and the phase sensitivity of the OEPLL-PS as a function of operating frequency.

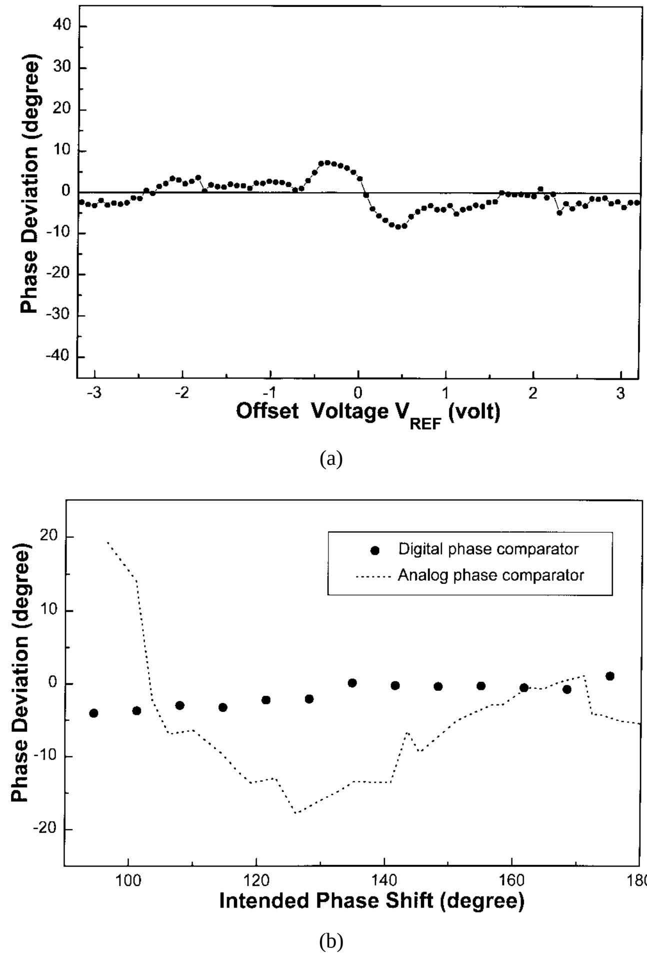


Fig. 3. (a) The linearity of the digital-phase-detector-based OEPLL-PS. (b) The deviation of the real phase shift from the linear phase change of the analog-phase-detector-based (dashed line) and digital-phase-detector-based (solid dot) OEPLL-PS.

semi-insulating (SI) GaAs substrate served as the optoelectronic harmonic mixer (OEHM) [14]. It was employed for intermixing the microwave signal and harmonics of the laser pulse train to generate an IF signal. The IF signal was amplified by a 50-dB low-noise amplifier and converted to a digital signal by a voltage comparator (National Semiconductor, LM319). The phase of the digitized IF signal was compared with that of the IF reference clock using a digital phase detector (PC Motorola MC4044). The IF reference clock signal was derived from the RFS through a divider ($1/N$). The error signal $V_d = K_d\theta_e + V_{\rm REF}$ was then fed to the VCO through an active LF. The phase of the VCO can, therefore, be shifted to a desired value by varying $V_{\rm REF}$. The OEPLL allows stable optoelectronic phase locking of the VCO at frequencies $f_m = Nf_o \pm f_{\rm IF}$ beyond 20 GHz to the 40–50-ps optical pulse trains from GSLD. The single-sideband (SSB) phase noise of the VCO phase locked to the RFS ($f_m = 500$ MHz) at 1-kHz offset is as low as −75 dBc/Hz. Note that the corresponding SSB phase noise of the RFS is approximately −90 dBc/Hz. Further improvement of the performance on the SSB phase-noise figure can be achieved by simply using an RFS with better noise figure (e.g., an HP8662A with a specification of −125 dBc/Hz or less).

IV. Results and Discussions

We have studied the performance of the OEPLL-PS at frequencies up to 20 GHz. For characterization of the phase change of the microwave signal from the phase-locked VCO, we used high-speed oscillators and spectrum analyzers or the frequency down-conversion technique [11]. In this paper's subsequent sections, the maximum phase-shifting range, linearity, ultrawide-band, and frequency-independent operation, as well as the extremely high phase stability of the OEPLL-PS, are described.

A. Phase-Shifting Range

The phase of the VCO operating at 500 MHz can be tuned from −320° to 320° as the offset voltage was adjusted from −3.6 to 3.6 V. This is shown in Fig. 2(a). The maximum phase-shifting range and phase sensitivity are 640° ($\sim \pm 1.8\pi$) and ≈92°/V, respectively. Except for $|V_{\rm REF}| \leq 0.5$ V, the phase shift is nearly a linear function of $V_{\rm REF}$. The nonlinearity is mainly due to the finite rising time of the digital signals to

TABLE I
PERFORMANCE OF OEPLL-PS AND CONVENTIONAL PHASE SHIFTERS

Type	f_o (GHz)	$\Delta\theta_{shift}$	$\Delta\theta_{error\ (rms)}$	$\Delta\theta_{rms}$	η_{loss} (dB)	Broadband	Ref.
Waveguide (true time delay)	40	<20°	±2°	-	1.3	no (12%)	2
Ferrite	2 to 40		±5%	-		no	3
Digital FET	18-40	180°, 90°, 45° 3 Bit	±10°	-	9.5±2.5	no	4
Electronic PLL	1.5	468°	±2.6°	0.8°		yes	15
Analog varactor	6-18	360±17°		-	2.7±1.3	no	9
Fiber Optic (true time delay)	2-18	100°	5°	-		no	6
Optoelectronic	60	360°		0.1°	~40	no	8
Our Work	0.08-20	>600°	±3.27°	<±0.39°	<3	yes	

be phase compared in the digital phase comparator (DPC). The phase-shifting range of our OEPLL-PS has been measured at 2-GHz intervals and found to be frequency-independent up to 18 GHz, as shown in Fig. 2(b). At 20 GHz, the phase-shifting range narrows down to 600° ($\sim \pm 1.67\pi$). This corresponds to the tuning of reference voltage from −3.2 to 3.2 V. Beyond this range, the OEPLL-PS tends to unlock, causing the phase of the microwave signal to fluctuate. The slight reduction in the phase-shifting range at 20 GHz is primarily attributed to the following factors: the increasing conversion loss (defined as power ratio of IF to RF signal) of the OEHM from −39 dB at 500 MHz to 80 dB at 20 GHz, and the degradation of SSB phase noise of the phase-locked microwave signal from −75 dBc/Hz at 500 MHz up to −35 dBc/Hz at 20 GHz. As a result, the signal-to-noise ratio (SNR) of the OEPLL-PS is reduced. If the power of the GSLD or the bandwidth of the OEHM can be increased, the operation bandwidth of the OEPLL-PS can be further improved. A nearly "constant" phase and frequency-independent (from 500 MHz to 20 GHz) gain $K_d \approx 0.62$ V/rad was calculated from the measurement data [see inset of Fig. 2(b)].

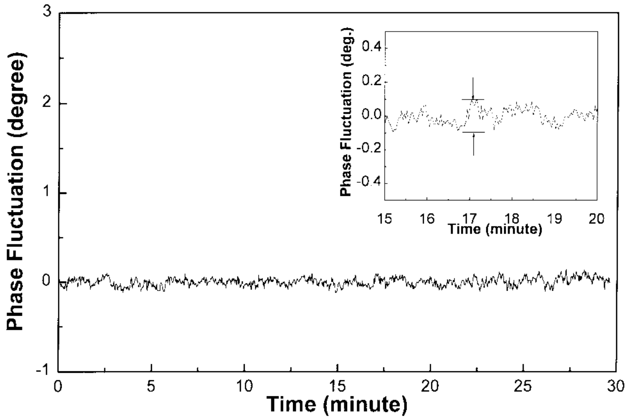
We have studied and compared the performance of using a DPC instead of an analog phase comparator (APC) in the OEPLL-PS system. We found that the phase-gain constant of the OEPLL-PS with an APC (EXAR, XR-2208) is about 0.89 V/rad. This corresponds to a phase sensitivity of only 64°/V, which is lower than using a DPC. The higher phase gain of an APC compared to the DPC in the OEPLL-PS is beneficial, as the phase error signal is larger during phase detection. On the other hand, it requires a larger tuning voltage V_{REF} for a desired phase change. In addition, we have also observed a narrower phase-shifting range of less than 120° for the APC-based OEPLL-PS, as shown in Fig 2(a). This is due to the nonlinear phase gain of the APC, which is proportional to both the amplitude and the cosine of phase difference of the input signals.

B. Linearity

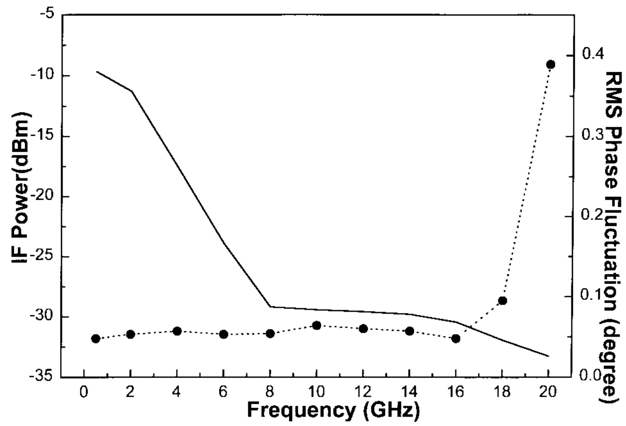
The phase comparing function of a conventional mixer-based (or multiplier-based) APC is basically a frequency-multiplication process. As a result, the error voltage output from an APC is a cosine function of the phase difference between the signals to be compared. Such a nonlinear transfer function is an intrinsic disadvantage of the APC-based OEPLL-PS. By using a DPC in the OEPLL-PS, the linearity of phase shift as a function of control voltage can be improved. This is shown in Fig. 3(a). We also measured and compared the phase deviation as a function of the intended phase shift for the APC- and DPC-based OEPLL-PS's. The phase nonlinearity of a DPC-based system for a desired phase change is less than ±1%, as shown in Fig. 3(b). The accuracy of the reference voltage was about ±0.01 V. Further reduction of the phase deviation can be achieved by using a more accurate and stable dc voltage source. In comparison, the APC-based system exhibits a larger phase error with its maximum value of up to ±20°. Clearly, linearity of the DPC-based OEPLL-PS is much superior compared with the APC-based system. Our results are comparable with other types of phase-shifting schemes reported in the literature (see Table I).

C. Phase-Shift Stability and Phase-Shift Keying Measurements

The short-term phase fluctuation (10 s) and long-term phase drift (30 min) of the OEPLL-PS were evaluated by monitoring the IF signal using a lock-in amplifier. At 500 MHz, the



(a)



(b)

Fig. 4. (a) The overall phase fluctuation and long-turn phase drift of the OEPLL-PS operated at 500 MHz. (b) The rms phase fluctuation as a function of operating frequency.

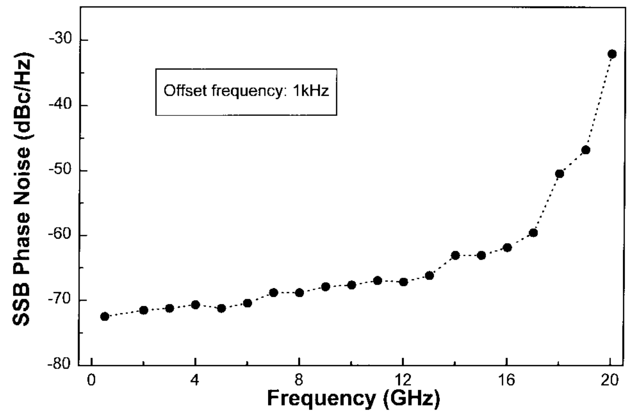


Fig. 5. The SSB phase noise of microwave signal output from a phase-locked VCO as a function of frequency.

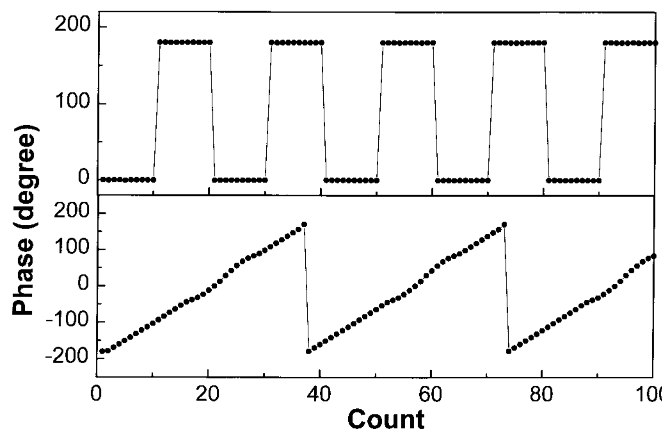


Fig. 6. The program-controlled low-frequency PSK (top trace) and continuously phase-tuning (bottom trace) test of the OEPLL-PS.

root-mean-square (rms) phase fluctuation and phase drift of the phase-shifted microwave signal were less than 0.05° and ~0.08°, respectively, as shown in Fig. 4(a). The maximum phase fluctuation is only 0.1°. Similar phase stability with a rms phase fluctuation of less than 0.1° (maximum: 0.15°) and minimal phase drift (0.08° or less) was achieved for operating frequencies up to 18 GHz [see Fig. 4(b)]. However, at 20 GHz, the phase stability degraded with a rms fluctuation of 0.39° (the maximum is 0.55°). This can be understood by the fact that the phase fluctuation of the phase-locked signal tends to increase linearly with the microwave frequency due to higher SSB phase noise at higher frequencies (see Fig. 5). In addition, a dramatic increase in amplitude fluctuation at microwave frequencies higher than 18 GHz worsen SNR of the down-converted IF signal from the OEHM, which in turn degrades the noise-suppressing ability of the OEPLL system, due to excessive amplification of noise associated with the IF signal. Based on the experimental results, we conclude that the power and the SNR of the IF signal prior to the phase comparator should be at least larger than −35 dBm and 10 : 1, respectively.

We also conducted a PSK experiment to verify the phase-tracking capability of the OEPLL-PS during phase-hopping operation. It allows us to estimate the switching response of the OEPLL-PS. This is performed by introducing a digital clock ($V_{pp} = 3.2$ V) from the analog/digital (A/D) output of the lock-in amplifier as a offset voltage source. After switching, the phase fluctuation was as low as ±0.09°. This is shown in Fig. 6. The highest phase-modulation frequency tested was approximately 1–2 kHz. This means the phase-hopping time constant (or switching time) of the OEPLL-PS is from 500 μs to 1 ms. This is more than sufficient for most applications. Our results also compare well with previously reported data using true-time-delay electronic PLL or photonic approaches (see Table I).

D. Relative Phase-Shift Between Two Phase-Locked VCO's

We have also demonstrated the feasibility of adjustable phase shift between two phase-locked VCO's using two OEPLL-PS's. The schematic diagram is shown in Fig. 7. In this experiment, the optical clock generated from the GSLD was delivered to the individual OEPLL-PS module by using a 50/50 beam splitter. Two independent $V_{\rm REF}$ sources were used to control the phase shift of each OEPLL-PS. All of the microwave coaxial cables used in the experiment were approximately of equal length. The microwave signals from the two phase-locked VCO's both operated at 500 MHz

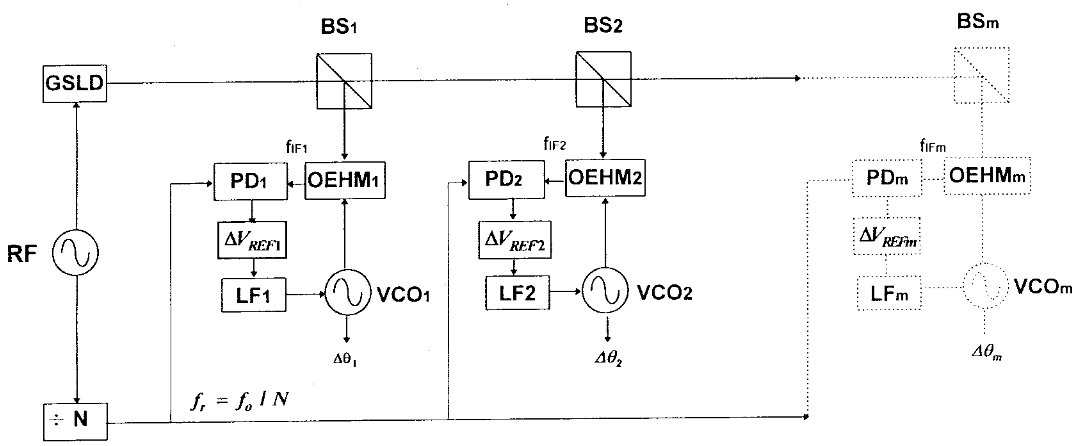
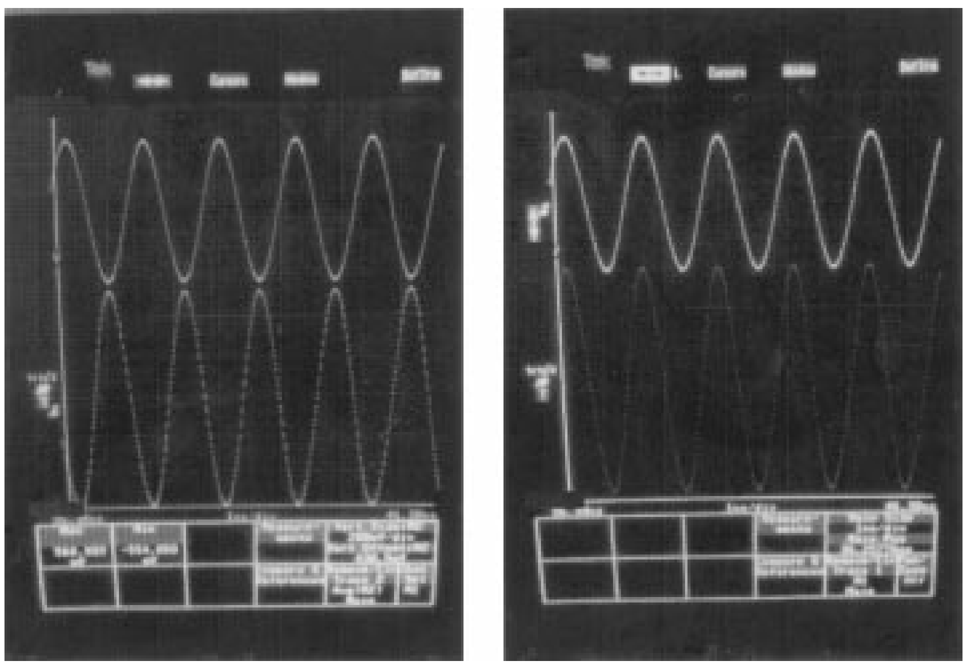


Fig. 7. Schematic diagram of microwave phase shifters based on optoelectronically phase-locked dual or multiple VCO's.



(a) (b)

Fig. 8. Relative phase shift of (a) 0° and (b) 180° between microwave signals output from two phase-locked VCO's at a frequency of 500 MHz.

were monitored by using a sampling oscilloscope (Tektronics, CSA830), which is shown in Fig. 8(a). By tuning $V_{\rm REF}$ of one OEPLL-PS from 0 to ~1.9 V, a relative phase difference of 180° between the two phase-locked VCO's was observed, as depicted in Fig. 8(b). The maximum phase change between two phase-locked VCO's via the adjustment of the reference voltage $V_{\rm REF}$ prior to LF in one of the OEPLL-PS's is shown in Fig. 9. By using an HP 8560E spectrum analyzer with resolution bandwidth of 1 Hz, the central frequency of microwave signals from the phase-locked VCO was monitored to be invariable during the phase-tuning procedures. This is illustrated in the inset of Fig. 9. In the present scheme, we have obtained a maximum phase-shifting range of approximately 640° between two microwave signals, while the phase of one of the phase-locked VCO's was maintained at a desired value.

E. Comparison with Other Phase Shifters

To compare our OEPLL-PS system with other phase shifters, we list the typical performance for different types of phase shifters reported in Table I. Key parameters such as the maximum operating frequency (f_o), maximum phase-shifting range ($\Delta\theta_{\rm max}$), phase error ($\Delta\theta_{\rm error}$) deviated from the intended phase change, rms phase fluctuation ($\Delta\theta_{\rm rms}$), and insertion loss ($\eta_{\rm loss}$) are shown [1]–[11], [15], [16]. The true-time-delay microwave-waveguide-type or electronic phase-shifting schemes exhibit relatively low phase error and/or insertion loss. Unfortunately, they are not broad-band devices, and thus require a complete set of waveguides with desired phase shift for a given frequency. In comparison, a fiber-optic-type true-time-delay system was reported [6].

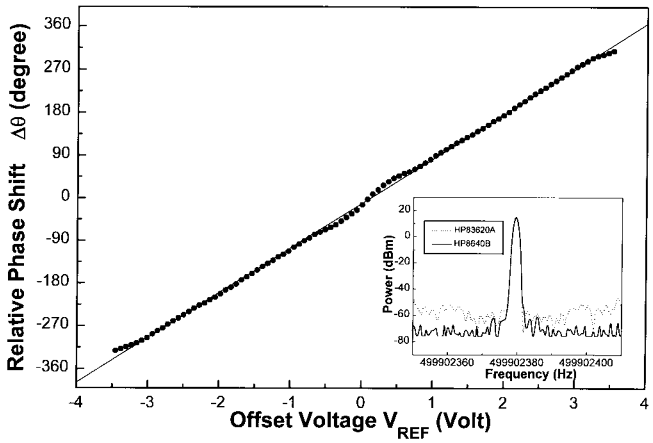


Fig. 9. The relative phase shift between dual phase-locked VCO's as a function of offset dc voltage. The spectra of the VCO's during the phase-shifting experiment are shown in the inset.

In this system, the phase shifter was achieved by using a wavelength-tunable laser diode in combination with dispersive fiber-optic links. However, residue frequency-dependent phase shift was present. On the other hand, the OEPLL-PS exhibits much larger operation bandwidth and phase-shifting range, which is frequency-independent. Thus, the instantaneous bandwidth is smaller than that all-electronic phase shifter. Nonetheless, the switching time of the OEPLL-PS can be as short as 1 ms or less (see Section IV-C). The bandwidth of the OEPLL-PS is, therefore, sufficient to meet the demand of a phased-array antenna or radar system [1]. As compared with the fiber-optic or optoelectronic phase shifters, the OEPLL-PS exhibits minimal insertion loss (less than 0.1 dB at 20 GHz) of microwave signal. Furthermore, no additional optical or waveguide-typed delay line are required by using the OEPLL-PS. In comparison with conventional electronic PLL-type phase shifters, [15], [16] the repetition frequency of the GSLD, which serves as the optical clock for the OEPLL-PS, can be easily tuned to phase lock broad-band microwave signals. By using a frequency-translated phase-locking technique, none of the microwave integrated circuits, except a photoconductive OEHM, are needed, and only lower frequency IF phase detector and related electronic devices are required. Furthermore, broad-band operation of this system beyond the 3-dB frequency bandwidth of GSLD and photoconductive mixer can be easily achieved via amplification of the IF signals instead of microwave signals.

V. Conclusion

In summary, we have developed a novel optoelectronic phase shifter for operation at microwave frequency up to 20 GHz. By simply adding a dc-offset voltage prior to the LF in a laser-diode-based digital OEPLL, the accurate control of the phase of microwave signal with ultrawide phase-tuning range exceeding 640° ($\sim 3.6\pi$) was achieved. Extreme linear response of the actual phase shift, which deviated from the intended phase change within ±3.3°, has also been demonstrated. Ultrahigh stability with rms phase fluctuation and long-term phase drift at any phase shift of less than ±0.4° and 0.08°, respectively, at 20 GHz was realized. The switching time of the phase change while operating in a PSK scheme can be less than 1 ms. As an application, we have also demonstrated the control of relative phase difference between dual phase-locked microwave sources. These results suggest a potential application of the OEPLL-PS in a phased-array antenna system.

The merits of the present approach are: 1) intrinsic compatibility with fiber-optic distribution networks; 2) shifting the phase of microwave signals using low-frequency electronic circuits; 3) ultra-wide bandwidth up to terahertz is feasible with the development of shorter laser pulses and faster photoconductive switches; and 4) the GSLD-based OEPLL system is compact, compatible with fiber-optic networks, and has an ultra-wide optoelectronic phase-tracking bandwidth. Such an OEPLL-PS can be used for remote frequency-independent control of relative phase difference among individual microwave sources in phased-array antenna. As laser diodes generating ultrashort pulses become available, the extension of this technique to higher microwave and millimeter waves should be straightforward.

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