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Phase-locked-loop-based delay-line-free picosecond electro-optic sampling system

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A delay-line-free, high-speed electro-optic sampling (EOS) system is proposed by employing a delay-time-controlled ultrafast laser diode as the optical probe. Versatile optoelectronic delay-time controllers (ODTCs) based on modified voltage-controlled phase-locked-loop phase-shifting technologies are designed for the laser. The integration of the ODTC circuit and the pulsed laser diode has replaced the traditional optomechanical delay-line module used in the conventional EOS system. This design essentially prevents sampling distortion from misalignment of the probe beam, and overcomes the difficulty in sampling free-running high-speed transients. The maximum tuning range, error, scanning speed, tuning responsivity, and resolution of the ODTC are 3.9π (700°), <5% deviation, 25–2405 ns/s, 0.557 ps/mV, and ~1 ps, respectively. Free-running wave forms from the analog, digital, and pulsed microwave signals are sampled and compared with those measured by the commercial apparatus.
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I. INTRODUCTION

The high-speed sampling oscilloscope is an extensively used system that enables picosecond resolution for high-speed measurements of repetitive electrical transients. It originates from the development of sampling techniques since the 1950s, however, its use is limited below 10 ps owing to the slow evolution of fast step-recovery diodes. From the beginning of the 1980s, approaches have successively emerged to improve the sampling resolution.[1] Josephson junction sampling was primarily demonstrated by using a superconducting switch as an electronic sampling gate, which although it has been refined to achieve a temporal resolution of 2 ps, it is still restricted in practical applications due to its requirement of a low-temperature environment. Later, photoconductive sampling (PCS) geometry was demonstrated with subpicosecond temporal resolution, microvolt sensitivity, and a larger dynamic range. A photoconductive switch made on semiconducting materials with an ultrashort carrier lifetime is employed as an ultrafast sampling gate in the PCS system. Picosecond optical pulses are then introduced to trigger the switch for wave-form sampling. Although such a technique exploits jitter-free synchronization in favor of the optical triggering scheme, it still suffers from the limited sampling resolution that is determined by the device geometry and the material parameters of the sampling gate. In addition, the photoconductive gates must be either integrated with the device under test (DUT) or fabricated as an external probe tip.[2] Electro-optic sampling (EOS) is the latest technique developed, which is unique among the proposed sampling systems due to its all-optical configuration. It relies only on electric field coupling between the optical sampling gate [i.e., an electro-optic (EO) crystal] and the DUT. Hence, it does not remove real charge from the DUT to the sampling gate. The electric field of the DUT results in a change in the birefringence properties of the EO crystal and a rotation of optical polarization. By placing the EO crystal between crossed polarizers, the intensity of the transmitted (or reflected) optical probe beam thus linearly changes as a function of the electric field strength. With the fast evolution of ultrafast laser technology, an EOS system with subpicosecond sampling resolution has previously been demonstrated.[3]

Figure 1 illustrates a typical setup of conventional EOS systems, in which the laser pulse train is divided into pump and probe beams. The pump beam repetitively impulses the DUT, while the probe beam synchronously samples the field-induced birefringence caused by the transient response of the DUT in the EO medium. The pump beam is modulated at a frequency far below the laser repetition rate to facilitate lock-in detection. Alternatively, an electrical pulse generated by an ultrafast optoelectronic switch or a comb generator is used to drive the electrical devices that cannot be optically triggered. The probe beam is passed through an optomechanic delay line (OMDL) to provide a true-time delay with respect to the measured DUT signal.[4] A variable compensator is added between the crossed polarizers to optically offset the static birefringence of the EO medium for linear operation at 50% transmission. The intensity of the reflected probe beam is measured by a low-speed photodiode to obtain the average response via the integration of pulse trains in the modulating duration. A lock-in amplifier (LIA) is used to measure the amplitude of the modulated intensity, which yields a dc output voltage that is proportional to the amplitude of the sampled electrical signal. The LIA facilitates the detection of DUT signals with microvolt sensitivity. The out-

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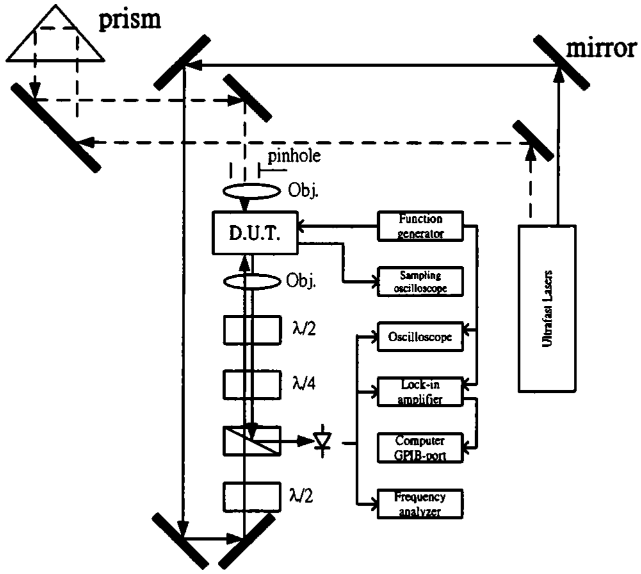

FIG. 1. Block diagram of the conventional synchronous-frequency electro-optic sampling system.

put signal is either plotted as a function of the delay time or real time displayed on an oscilloscope. This results in an equivalent time representation of the impulse response of the DUT.

Alternatively, unsynchronized sampling based on an instantaneous scanning of the relative delay time between the DUT signal and optical probe beam has also been demonstrated.[5,6] This is implemented by slightly offsetting their corresponding repetition frequencies, thereby a repetitive scanning can be obtained after a number of periods. The schematic diagram of the real-time EOS system is depicted in Fig. 2. The merit is that a ''real-time'' reconstruction of the high-speed DUT signal can be made on an oscilloscope with a very low sampling rate and frequency bandwidth. Such an offset-frequency sampling technique essentially eliminates the need of the OMDL, which causes the difficulty in precise alignment of the optical beam, the measuring inaccuracy due to misalignment, and the limited scanning speed. However, such a system still suffers from the limitation in millivolt sensitivity of oscilloscopes to date.

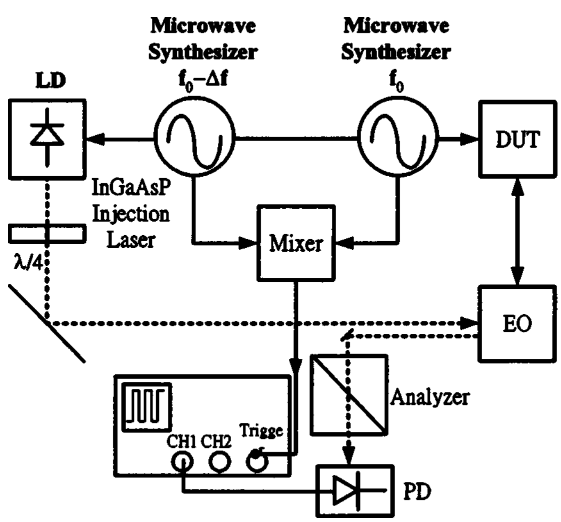

FIG. 2. Block diagram of the real-time nonsynchronous-frequency (or offset-frequency) electro-optic sampling system using a low-frequency-replica technique.

Subsequently, a delay-time-tunable picosecond Nd:YAG laser has been proposed by employing the phase-shifting technology[7] to amend the aforementioned problems in a conventional EOS system. However, the nonlinear transfer function (delay time versus tuning voltage) of the analog phase shifter used in the laser inevitably leads to a larger sampling distortion during EOS measurement. Therefore, an EOS system with a better sensitivity by use of lock-in detection, and a linear and quasi-instantaneous scanning measurement without the use of the OMDL module is of great interest. Recently, a linear phase shifter based on digital phase-locked-loop (PLL) technology has been developed.[8] The improvement on the operating bandwidth of the PLL-based phase shifter (hereafter referred as the PLL PS) has also been achieved by employing the optoelectronic frequency-downconverting technique.[9] By adding a photoconductive switch as the optoelectronic harmonic mixer (OEHM) in the PLL, the operating frequency can extend to 20 GHz or higher (currently limited by the measuring system). In this work, we employ the PLL PS as an optoelectronic delay-time controller (ODTC) to replace the OMDL in a conventional EOS system, which eliminates the drawbacks of the OMDL such as low scanning rate and alignment-induced sampling distortion. Versatile configurations of PLL-PS-based ODTC circuits suitable for modifying the EOS system are introduced. The performances of the ODTC, including maximum tuning range, linearity, scanning speed, and resolution are determined. By using the different EOS systems proposed in this work, the wave-form sampling of a free-running sinusoidal microwave signal, a digital signal output from a frequency divider (or prescaler), and an electrical pulse generated by the comb generator are demonstrated.

II. SYSTEM CONFIGURATION

A. Design of the PLL PS

The design principle of a PLL PS is based on the modification of a conventional frequency-translated PLL into a frequency-discriminated and phase-tunable delay-locked loop. To achieve frequency discrimination between local clock and free-running DUT signals, several kinds of PLL configurations have been designed for different frequency-tracking schemes, as shown in Fig. 3. For example, two kinds of PLLs for achieving nonoffset frequency synchronization are shown in Figs. 3(a) and 3(b). In each configuration, the frequency of the voltage-controlled oscillator (VCO) is directly frequency synchronized to that of a rf clock. The drawback of the scheme plotted in Fig. 3(a) is the need for high-frequency phase-frequency detectors (PFDs) when operating at high repetition rates. Note that the highest frequency bandwidth of commercially available PFDs is approximately 2.7 GHz. The latter scheme shown in Fig. 3(b) is a possible solution that employs the frequency-translation technique by use of frequency dividers. This design essentially takes the advantage of recent advances of the frequency prescalers or dividers (FDs) with a reported bandwidth of up to 20 GHz. In contrast, Figs. 3(c) and 3(d) illustrate the block diagrams of mixer-based offset-frequency-discriminated PLLs that are designed for operating at a bandwidth of larger than 20 GHz. In Fig. 3(c), two microwave frequency synthesizers are phase locked at an offset-frequency condition. The offset frequency is set by the frequency-divided rf clock, that is, $f_{\mathrm{rf}}-f_{\mathrm{VCO}}=\Delta f=f_{\mathrm{rf}}/N$. For the wave-form sampling of highly repetitive transients, a PLL scheme proposed in Fig. 3(d) is more suitable than that in Fig. 3(c). The main difference between Figs. 3(c) and 3(d) is that the latter one benefits from locking of signals with higher repetition frequencies using a low-frequency VCO. This is attributed to both the higher optoelectronic harmonic generation of the fundamental frequency via a gain-switched laser diode (GSLD), and the higher operating bandwidth of the OEHM as compared to the microwave mixer. The pulse train generated from the GSLD consists of a set of superposed harmonic frequency components, which mixes with the rf clock to generate an intermediate frequency (IF) in the OEHM. In addition, to facilitate the capability of high-frequency synchronized operation for the EOS, the latter scheme can further be modified by use of a pair of VCOs to individually drive the DUT and a pulsed laser source for sampling. However, it makes the EOS system complicated, expensive, and bulky.

The basic principle of the PLL PS can be explained by analyzing the phase change of the VCO from the equivalent noise model.[9] With nodal analysis, we can express the effect of dc reference voltage (V_{REF}) on the phase shift and the delay time of the output signal from the VCO as

$$\begin{aligned}\theta_{\mathrm{VCO}} &\approx \Phi_{\mathrm{PLL}}-V_{\mathrm{REF}}\frac{F(s)K_0/s}{1+K_dF(s)K_0/s}\approx\Phi_{\mathrm{PLL}}-V_{\mathrm{REF}}/K_d\\ &\equiv\Phi_{\mathrm{PLL}}-R_dV_{\mathrm{REF}}\\ &\equiv\Phi_{\mathrm{PLL}}+\Delta\theta_{\mathrm{VCO}},\\ \Delta t &= \frac{\Delta\theta_{\mathrm{VCO}}}{2\pi}\,\frac{1}{f_{\mathrm{rep}}}\\ &= \frac{1}{2\pi f_{\mathrm{rep}}}\cdot V_{\mathrm{REF}}\frac{F(s)K_0/s}{1+K_dF(s)K_0/s}\\ &\cong\frac{V_{\mathrm{REF}}/K_d}{2\pi f_{\mathrm{rep}}},\end{aligned}$$

where ϕ_{PLL} is the phase noise induced by the PLL, $F(s)$ is the transfer function of the second-order active loop filter (LF) in the PLL, K_0 is the VCO gain, K_d is the gain of the PFD, $R_d\approx 1/K_d$ (degree/volt) is the phase sensitivity of the PLL PS, θ_{VCO} is the phase of the VCO, f_{rep} is the repetition frequency of the synchronous signal, and $\Delta\theta_{\mathrm{VCO}}$ is the phase shift of the VCO caused by the tuning of V_{REF}. This approximation sustains only at the PLL passband region due to its relatively large loop gain. It is seen that the phase change of the microwave signals from the PLL-controlled VCO ($\Delta\theta_{\mathrm{VCO}}$) is approximately in linear proportion to V_{REF}. The phase retardation of the microwave signal can, therefore, be linearly and continuously controlled by varying V_{REF} instead

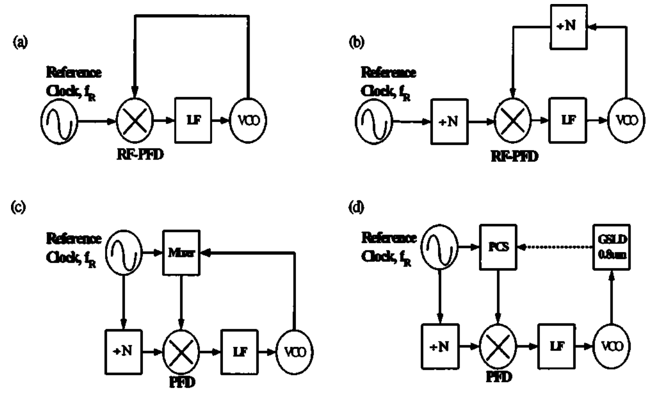

FIG. 3. Different configurations of electron- or optoelectronic-typed phase-locked loops designed for delay-time control of laser pulses. GSLD: gain-switched laser diode; LF: loop filter; PCS: photoconductive switch; PFD: phase/frequency detector; PS: power splitter; rf PFD: radio-frequency phase/frequency detector; and VCO: voltage-controlled oscillator.

of using any high-frequency components. 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 smaller phase sensitivity and a reduced phase-shifting range for our application.

B. PLL-PS-based EOS systems

Early EOS systems sampled the wave form generated from a DUT by simply using two individual microwave/optical clocks with identical or locked time bases. Today, most of the discrete electronic or microwave/millimeter-wave modules are commonly integrated with individual monolithic frequency sources. This leads to a difficulty in using the conventional frequency-synchronization technique. Owing to such a special requirement, the recently proposed EOS system should also emphasize its design for wave-form sampling of unknown or free-running DUT signals at higher repetition rates. The experimental setup of the proposed delay-line-free EOS system by using ODTC with two offset-frequency PLL PSs, is shown in Fig. 4.[10] VCO1 and VCO2 with identical frequencies are individually phase locked to the reference clock. VCO1 is used to drive the GSLD for

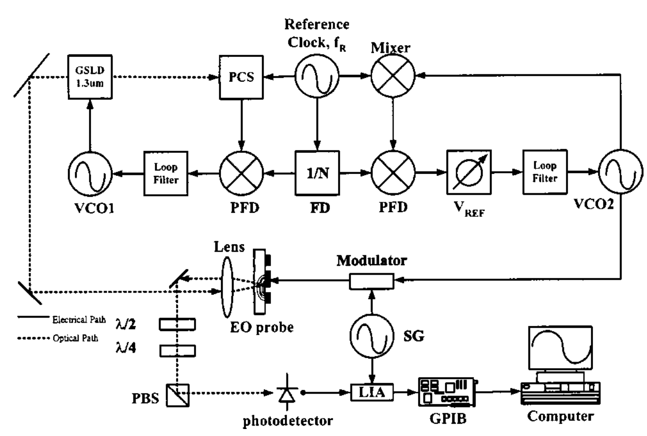

FIG. 4. Novel delay-line-free equivalent-time electro-optic sampling system using delay-time-controlled laser diode source. PCS: photoconductive switch; GSLD: gain-switched laser diode; VCO: voltage-controlled oscillator; PD: phase detector; PS: power splitter; and SG: signal generator.

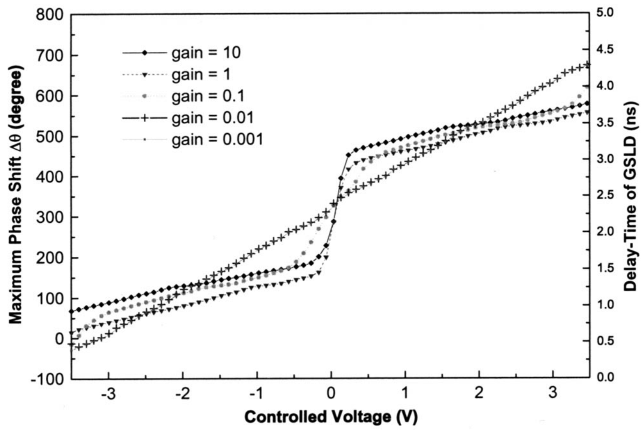

FIG. 5. Phase shift of the PLL PS as well as the delay time of the ODTC-controlled GSLD pulse train plotted as a function of controlled voltage under different gain constants of the filter in the PLL PS.

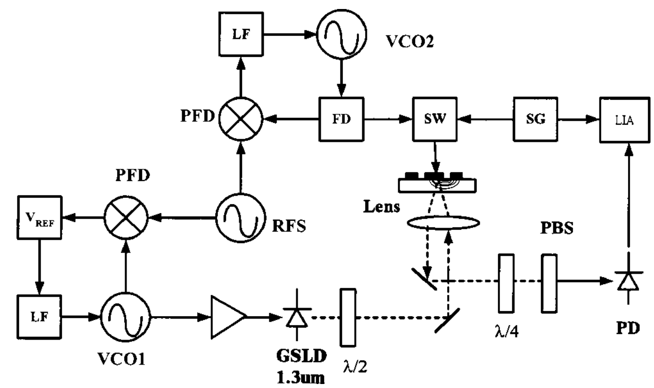

FIG. 7. Schematic diagram or two PLL-based EOS system. GSLD: gain-switched laser diode; LF: loop filter; PCS: photoconductive switch; PFD: phase/frequency detector; PS: power splitter; rf PFD: ratio-frequency phase/frequency detector; VCO: voltage-controlled oscillator; RFS: reference frequency signal; DUT: device-under-test; PBS: polarization beam splitter; PD: photodetector; LIA: lock-in amplifier; SW: electrical switch; and SG: signal generator.

generating the optical pulse train, and VCO2 is used to drive the DUT. The DUT signal is further modulated by an IF synthesizer to facilitate lock-in detection. The phase of the signal output from VCO2 can be linearly and continuously changed with respect to VCO1 via the tuning of the PLL PS controlled by V_{REF}. Since it is also possible to add the voltage-tuning circuit into the ODTC used with VCO1, the phase of the signal output from VCO1 as well as the delay time of the optical probe pulse can be adjusted alternatively.[10,11] The circuit parameters of the ODTC are carefully adjusted to obtain a linear transfer function of the phase shift versus V_{REF}. The effect of the gain of the loop filter in the PLL on the maximum phase shifting range and linearity is illustrated in Fig. 5. In addition, the phase-tuning gain of the ODTC is set as 100°/V. This corresponds to a delay-time responsivity of 0.557 ns/V. The minimum tuning step that can be monitored by a commercial digital sampling oscilloscope is already smaller than 5 ps (at a voltage tuning step <10 mV). Theoretically, the maximum phase shift of the ODTC can be up to 720°, which corresponds to a variation in the delay time of up to 2 periods. The corresponding phase noise spectrum of the GSLD controlled by the ODTC is shown in Fig. 6. In the aforementioned configurations, the use of two frequency-translated PLLs is mandatory since the frequency synchronization between the electronic/optoelectronic DUT signal and the optical probe beam must remain. This preserves the high-sensitivity feature of the EOS system that uses the lock-in detection technique.

On the other hand, the aforementioned EOS system can also be simplified to facilitate the characterization of free-running microwave signals from electronic devices or integrated circuits (ICs) with internal time bases or oscillators. To meet this demand, two modified ODTCs based on all-electrical frequency-translated PLLs, as shown in Fig. 3(c), are employed to control the frequency and delay time of the GSLD source in the EOS system, as shown in Fig. 7. In comparison with the original design, this approach is more compact and easier to be set up since the optoelectronic harmonic mixing module has been replaced by a microwave mixer.

Owing to the recent advances of high-operation-bandwidth FDs, a state-of-the art EOS configuration for real-time measurement without the use of the frequency down-conversion technique can be achieved, as shown in Fig. 8. The dash-line box in Fig. 8 functions as an arbitrary frequency-divided clock. The ODTC-controlled GSLD pulse-train can be frequency locked to the frequency-divided

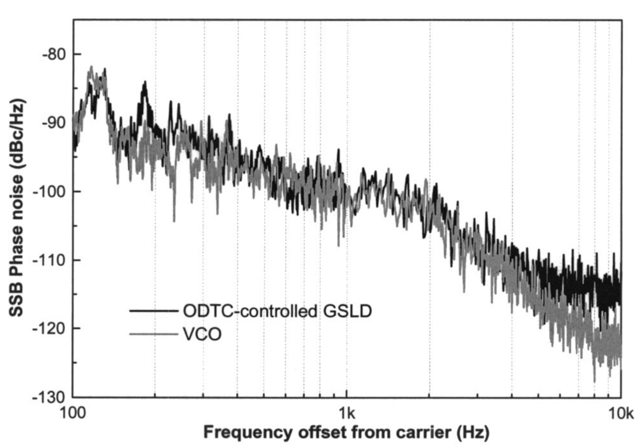

FIG. 6. Single-sided band phase noise spectra of the VCO in PLL-PS-based ODTC and ODTC-controlled GSLD pulses.

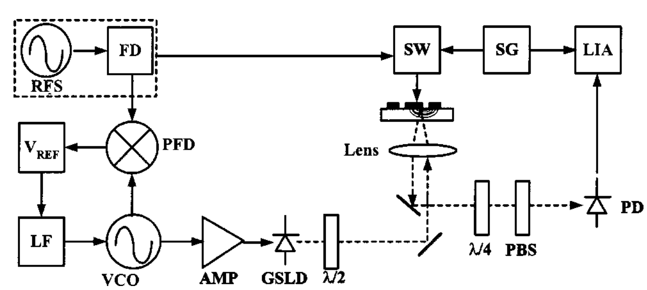

FIG. 8. Schematic diagram of one PLL-PS-based EOS system. GSLD: gain-switched laser diode; LF: loop filter; PCS: photoconductive switch; PFD: phase/frequency detector; FD: frequency divider; PS: power splitter; rf PFD: ratio-frequency phase/frequency detector; VCO: voltage-controlled oscillator; RFS: reference frequency signal; DUT: device-under-test; PBS: polarization beam splitter; PD: photodetector; LIA: lock-in amplifier; SW: electrical switch; and SG: signal generator.

TABLE I. Comparisons in performances of ODTC- and OMDL-based EOS systems.

	Conventional	Ours
Tuning range	$2\pi\left[\frac{2L}{c}/\frac{1}{f_{\mathrm{rep}}}\right]$	3.9π (theoretically, 4π)
Tuning resolution	6.6 fs	~1 ps (<0.2 ps)
Jitter/phase noise	1.23 ps/−115 dBc/Hz at 1 kHz	1.7 ps/−105 dBc/Hz at 1 kHz
Tuning rate	270–3330 ns/s	25–3405 ns/s
Tuning linearity	<1%	<5%

clock of free-running microwave or millimeter-wave signals by use of high-speed FDs. The relative delay time between the microwave and the GSLD pulse-train signals can thus be controlled since there is a linear relationship between the phase of the frequency-divided clock and the microwave signal. Such a design has greatly extended the frequency-discriminating capability of the EOS system with simple circuitry, which is very promising for application in the IC testing industry.

III. SYSTEM PERFORMANCE AND SAMPLING RESULTS

Based on the equivalent-time-sampling theory, the phase change is required to be larger than at least 2π for scanning a one-period wave form of a repetitive DUT signal. It is seen from the experimental results that the tuning range of the delay-time-free EOS system can be up to 1.95 periods (nearly 3.9π) of the DUT, which is beyond the requirement of the sampling theory and has already exceeded the records of similar systems.[6] On the other hand, the tuning resolution of the ODTC is mainly affected by the pulse width of the GSLD, the stability of the phase-tuning circuit, and the timing jitter of the DUT. The GSLD is simultaneously dc biased at the near-threshold condition and driven by an electrical pulse at the desired frequency to generate optical pulses with a full width at half maximum (FWHM) of 15 ps. The short-term stability of the voltage regulator in the ODTC that provides V_{REF} is relevant to the overall timing jitter of the pulse trains as well as the sampling resolution of the EOS system. To improve the sampling resolution, a smaller optical pulse width via the pulse compression technique, a PLL technique with suppressed timing jitter, and a high-precision voltage regulator with stabilized temperature control, are necessary. As a result, the timing jitter of the ODTC-controlled laser diode is reduced to be 1 ps or less, which also depends on the phase noise performance of the reference source to be frequency tracked. The overall performances of the conventional and proposed systems are compared in Table I.

The minimum settling time of the ODTC for each step of desired temporal delay of the laser pulse train is 0.1 ms, which is strictly limited by the pull-in and lock-in speed of the PLL-PS-based ODTC. The scanning time for one period of the DUT signal using the ODTC can be expressed as

$$t_p=[v_t f_{\mathrm{rept}}\Delta\tau]^{-1},$$

where t_p is the periodical scanning time of the ODTC, v_t is the point-to-point scanning speed, f_{rept} is the repetition frequency of the optical pulse train from the GSLD, and $\Delta\tau$ is the minimum tuning step (i.e., the sampling resolution). For example, a periodical scanning time required for the ODTC operated at a repetition frequency of 500 MHz with 1 ps resolution is calculated to be 0.2 s if the scanning speed is 1000 points/s. The scanning speed of the ODTC is relatively comparable with that of the conventional OMDL module. However, the scanning time of the ODTC-based EOS system depends further on the output bandwidth and the integral time of the lock-in amplifier (which cannot exceed 0.6–1 kHz), the executing speed of the controlling program, and the interface between the lock-in amplifier and the computer. This result in an actual tuning speed of 200 points/s or less. Further improvement by use of a high-speed PLL with a shorter pull-in and lock-in time of 1 μs or less can be achieved at the possible cost of unexpected phase noise and timing jitter. The minimum tuning step (i.e., the sampling resolution) of the ODTC-based EOS system is about 0.15–0.2 ps, which is limited by the amplitude noise of the voltage power supply ($\Delta V_{\mathrm{rms}}\cong 0.25$ mV) for the ODTC circuit. The temporal resolution of the current apparatus is inversely proportional to the repetition rate of the DUT signal. Although the resolution of the ODTC is slightly lower than that of a conventional OMDL-based true-time-delay module ($\tau_{\min}=2\Delta 1_{\min}/C\approx 0.0067$ ps with $\Delta 1_{\min}=1$ μm), such a resolution under a relatively high sampling rate (as compared to that of the OMDL) is sufficient for most of the picosecond wave-form measurements in the IC testing industry. Thus, the tradeoff between scanning speed and sampling resolution can be made for practical applications.

By using the ODTC-controlled GSLD as the optical source for the EOS system, different kinds of repetitive DUT signals generated from free-running microwave sources and modules such as the frequency synthesizer, frequency prescaler, and electrical pulse-forming module, are sampled. First, a frequency-synthesized sinusoidal signal at 500 MHz is measured to determine the linearity and sensitivity of the proposed EOS system. The time-resolved wave forms of the DUT signals sampled by a digital sampling oscilloscope (DSO) and the delay-line-free EOS system are shown in Fig. 9 for comparison. The EOS wave form matches perfectly with the DSO wave form except slight deviations caused by the nonlinear response in the delay-time tuning function of the ODTC-controlled GSLD. The wave-form-measurement distortion of the delay-line-free EOS system plotted as a function of delay time is, therefore, compared with the phase-tuning error of the ODTC as a function of tuning volt-

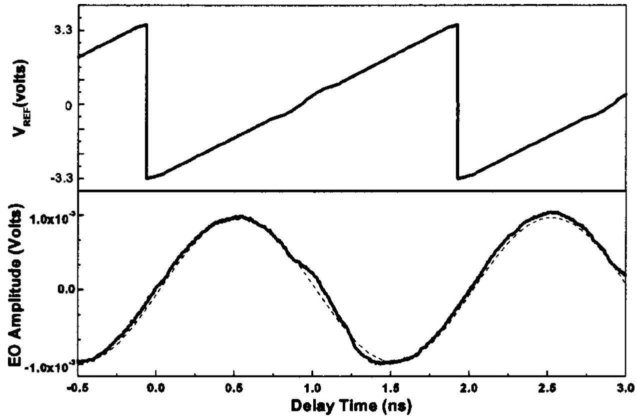

FIG. 9. Wave form of a microwave signal at frequency of 500 MHz generated from phase-locked VCO2 sampled by using the ODTC-based EOS (solid line) and commercial DSO (dashed line).

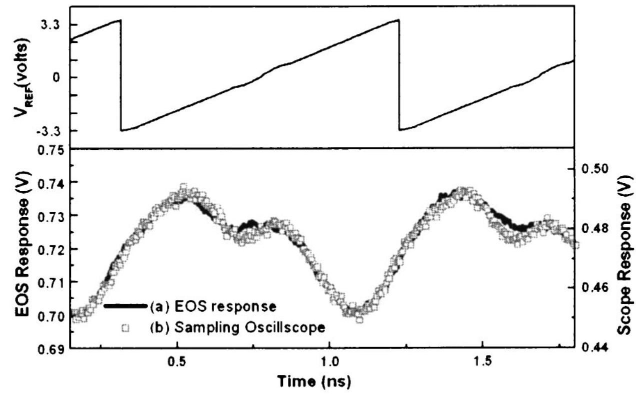

FIG. 11. Wave forms of a digital signal at frequency of 500 MHZ generated from prescaler sampled by using the ODTC-based EOS (solid line) and commercial DSO.

age and is shown in Fig. 10. It is found that the sampling deviation can be controlled within 5% or less, which corroborates the phase tuning error of the ODTC (Ref. 9) with a maximum value of 8°. This is mainly caused by the finite bandwidth of the PFD, which leads to tuning nonlinearity of the ODTC while operated at the nearly zero-delay region. We have previously mentioned that a further improvement in reducing the sampling deviation relies on the use of an ultraprecise voltage regulator under temperature-controlled condition and high-speed PFD with shorter rise/fall time in the ODTC module. In addition, the amplitude fluctuation of the voltage power supply of the ODTC should also be minimized since that will cause timing jitter in the ODTC-controlled pulse train. On the other hand, the detection sensitivity of the proposed delay-line-free EOS system is about 1 mV/$\sqrt{\text{Hz}}$, which is comparable with that of the conventional OMDL-based EOS system.

A frequency-prescaled positive-ECL signal (with a divisor of 2 or 4) driven by the free-running frequency synthesizer at 1 GHz was also characterized. Figure 11 presents the nearly identical positive-ECL wave form at 500 MHz measured by either system. It is worth noting that the wave forms measured by the sampling oscilloscope are probably distorted since the ECL signal has to be first offset by using a microwave bias *T* and then attenuated by at least 10 dB in order to prevent damage of the high-speed sampler in the DSO. Finally, we have also demonstrated the wave-form measurement of a high-speed electrical pulse-train output from a homemade comb generator using a step recovery diode (SRD). The EOS wave forms of the SRD with a FWHM of 52 ps sampled by EOS and DSO are shown in Fig. 11. It is found that the SRD wave form sampled by the DSO exhibits more detailed features, which is mainly attributed to the higher sampling bandwidth of DSO up to 50 GHz (equivalent to a temporal resolution of about 7–9 ps). In comparison, the EOS wave form of the SRD pulses reveals less featured shapes. This deficiency is more significant as the temporal response of the DUT becomes shorter due to the finite bandwidth of a GSLD-based EOS technique. The temporal resolution of the proposed delay-line-free EOS system is similar to the conventional GSLD-based EOS one. In principle, the time resolution of EOS is decided by statistically independent parameters such as the pulse width of probe beam, the absolute and relative timing jitter of the optical pulse and electrical signal, and the optical/electrical interaction times, which can collectively be described as

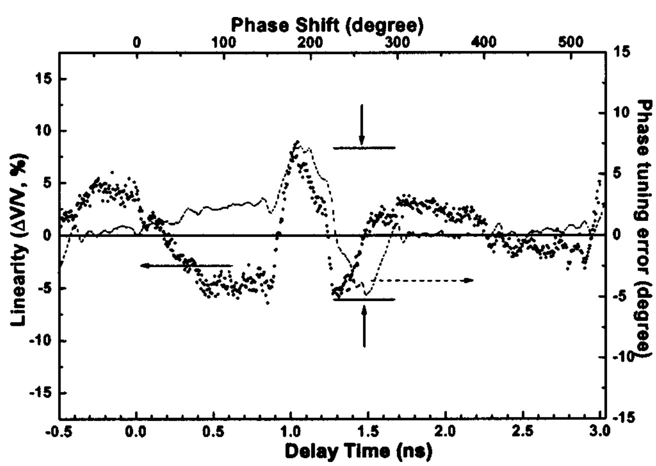

FIG. 10. Measured distortion of the modified EOS system and the phase-tuning error of the ODTC plotted as a function of delay time (as well as phase shift).

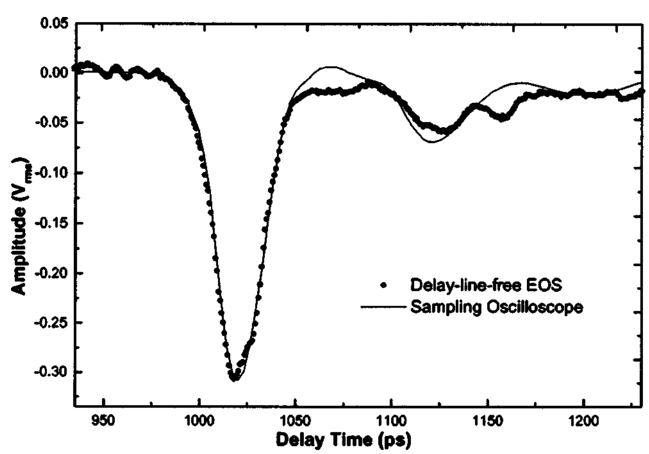

FIG. 12. Wave form of the signal output from a step recovery diode sampled by ODTC-based EOS. Inset plots the same wave form monitored by the DSO.

$$\tau_{\text{total}} = \sqrt{\tau_{\text{pw}}^2 + \tau_j^2 + \tau_{\text{ito}}^2 + \tau_{\text{ite}}^2},$$

where τ_{total} is the overall response time of the EOS, τ_{pw} is the FWHM of the optical probe pulse from GSLD, τ_j is the timing jitter from GSLD pulses and DUT signals, τ_{ito} is the optical interaction time required for the probe beam passing through the EO medium, and τ_{ite} is the electrical interaction time of the DUT signal within the spot (cross section) of optical pulses. The optical and electrical interaction times for reflective-type EOS scheme can be expressed as

$$\tau_{\text{ito}} = \frac{2n_0 H}{c},$$

$$\tau_{\text{ite}} = \frac{W_0}{c}\sqrt{2 \ln 2 \varepsilon_{\text{eff}}},$$

where c is the speed of light in vacuum, n_0 is the refractive index of the GaAs, H is the substrate thickness, W_0 is the minimum spot size of probe beam, and ε_{eff} is the effective dielectric constant of GaAs. In our experiment, the residual timing jitter of about 1.7 ps is mainly contributed by the GSLD pulses since it has been synchronized to the DUT signal. The calculated optical and electrical interaction times were 9.6 ps and 23 fs, respectively. Therefore, the calculated temporal resolution of the current EOS system is approximately 26.8 ps. We conclude that the proposed delay-line-free EOS system would be more practical in noninvasive and *in situ* wafer tests than the DSO, however, a less-distorted determination of the frequency-prescaled wave forms relies on the development of improved ODTC-controlled lasers with ultrashort pulse widths. Nonetheless, the delay-line-free EOS has shown to exhibit superior performances such as a maximum phase shift of up to 700° (corresponding to a delay time of about 3.9 ns and nearly 1.95 periods of a 500 MHz signal), a tuning responsivity of 0.557 ps/mV with sampling error of $<5\%$, and a comparable scanning speed ranging from 25 to 2405 ns/s with highest resolution ~ 1 ps. The compact design of the delay-line-free EOS system without the need of a conventional optomechanical delay line (OMDL) makes this system very promising. Due to the increased requirement of *in situ* and noninvasive wafer characterization, a delay-line-free EOS system without the need of a conventional optomechanical delay line makes it more promising for the very large-scale integrated makes industry. The design and construction of an extremely compact and real-time EOS system using an ODTC-controlled ultrashort pulsed laser diode or fiber laser source has been demonstrated.

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