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Free-running waveform characterization using a delay-time tunable laser based delay-line-free electro-optic sampling oscilloscope

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Abstract

We develop a delay-line-free and frequency traceable electro-optic sampling oscilloscope by use of a digital phase-locked loop phase shifter (PLL-PS) controlled delay-time-tunable gain-switched laser diode (GSLD). The home-made voltage-controllable PLL-PS exhibits a linear transfer function with ultra-wide phase shifting range of $\pm 350°$ and tuning error of $< \pm 5\%$, which benefits the advantages of frequency tracking to free-running signals with suppressed timing-jitter. The maximum delay-time of PLL-PS controlled GSLD is up to 1.95 periods by changing the controlling voltage (V_{REF}) from -3.5 to 3.5 V, which corresponds to 3.9 ns at repetition frequency of 500 MHz. The tuning responsivity and resolution are about 0.56 ns/V and $0.15 \sim 0.2$ ps, respectively. The maximum delay-time switching bandwidth of 100 Hz is determined under the control of a saw-tooth modulated V_{REF} function. The waveform sampling of microwave PECL signals generated from a free-running digital frequency divider is performed with acceptable measuring deviation.

Keywords: Electro-optic sampling; Phase-locked loop; Phase-shifter; Delay-time tunable; Laser

1. Introduction

Electro-optic sampling (EOS) technique has emerged since late of 1970s [1] as a non-contact and non-invasive optical probing tool for high-speed signal diagnostics. The merits of sub-pico-second temporal [2] and micro-meter spatial resolutions [3] have particularly made the EOS system very promising for versatile applications such as on-wafer IC nodal testing and field sensing, etc. Remarkably, the state-of-the-art external EOS geometry with THz measuring bandwidth and $mV/\sqrt{Hz}$ signal sensitivity has been reported.[3] To meet the demand of real-time and on-line waveform characterization of the on-wafer ICs, different clock-extracting or frequency-discriminating schemes have been proposed for the EOS system, which are generally distinguished as

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frequency-synchronous sampling and frequency-asynchronous sampling (or so-called low-frequency replica) types. For synchronous EOS scheme, the clock frequency of the optical probe pulse in EOS system is either identical or synchronized to that of the device under test (DUT). A pair of synchronized frequency sources or a laser-probe-pulse triggered electrical transient was previously employed to achieve the purpose. However, those approaches are not practical for DUT with independent or free-running clock, the introduction of phase-locked loop for frequency synchronization is thus required in this case. In addition, either an electrical phase-shifting or an optical path-length tunable unit (usually an opto-mechanic delay-line module, hereafter referred as OMDL) is required to adjust the relative delay-time of the optical probe pulse-train with respect to the time-base of signal output from DUT. The OMDL is constructed by using a right-angle prism (or retro-reflector) on translating stages, which makes the EOS system bulky for nanosecond delay-time tuning since a large scanning length is required. In addition, a precise and time-consuming alignment is necessary to prevent the degradation of the parallelism between the incident probe beam and the surface normal of the prism, since which inevitably leads to the transverse shift of the sampling point as well as the sampling distortion during the delay-line tuning process. Furthermore, the OMDL-based EOS is usually not a real-time system since that the upper limit of the scanning speed of an actuator-controlled translating stage used in the OMDL module is about 0.5 mm/s, which corresponds to a maximum scanning rate for the OMDL of 3.3 ps/s. This seriously lengthens the periodical sampling time of up to half a minute for DUT signal with GHz repetition rate. Using a piezoelectric transducer controlled delay line can efficiently improve the scanning rate, however, at the cost of reduced scanning range.

The frequency-asynchronous EOS is generally a real-time scheme based on either the low-frequency replica [4–7] or the single-shot [8,9] technique. For example, Valdmanis and Mourou [8] have demonstrated an electro-optic waveform mapping technology with resolution and sensitivity of 2 ps and $100\text{mV}/\sqrt{\text{Hz}}$, respectively, by using continuous-wave laser, traveling-wave modulator, and streak-camera. Alternatively, the time dilation between the sampling pulse-train and the DUT signal can also be achieved by copying and delaying the waveform in a fiber-based passive pulse replicator [9]. Later on, Weingarten et al. proposed the most popular delay-line-free EOS system by slightly offsetting the repetition rate of laser pulse-train and DUT signal with two synchronized microwave synthesizers. IN this approach, the repetition rate of the probe pulse (f_P) slightly offsets by a small amount of Δf (from 1 Hz to 1 kHz in general) from that of the DUT signal (f_{DUT}). This results in an automatic delay of $\Delta t = n \cdot \Delta f/(f_P \cdot f_{DUT})$ between the probe pulse the DUT signal in nth period. After $n = f_P/\Delta f$ periods, the probe pulse finishes the sampling of one-period waveform within a duration of $t_0 = 1/\Delta f$. Although such an alignment-free technique benefits advantage of real-time waveform monitoring on oscilloscope, however, its application is still limited due to the bad sensitivity of the oscilloscope (1 mV/div). The use of lock-in detection technique may greatly improve the sensitivity, but also gives rise to an unexpected waveform distortion owing to the finite output bandwidth of the commercial lock-in amplifier.

Obviously, the OMDL-free, real-time and high-speed EOS system with a frequency traceable and delay-time tunable laser source is an alternative approach. Previously, a delay-time tunable, actively mode-locked Nd:YAG laser has successfully demonstrated by integrating the mode-locker with an electrical phase shifter [10]. Such a laser with inherent phase-tuning function is a very promising optical source for the delay-line-free EOS system, however, the delay-time of the laser controlled by an analog phase shifter exhibits a nonlinear transfer function with small phase-tuning range. To overcome this disadvantage, we have reported a voltage-controlled, phase-locked loop phase shifter (PLL-PS) with ultra-wide and linear transfer function [11]. The frequency of the voltage-controlled oscillator (VCO) in the PLL can be synchronized to that of the free-running microwave clock, but the relative phase deviation between these two signals can be arbitrary adjusted via a voltage tuning circuit in the digital PLL. Later on, such technique has been employed to build versatile PLL-PS controlled, delay-time tunable ultrafast lasers [12–14]. By using a delay-time tunable gain-switched laser diode (GSLD) as an example, we demonstrate frequency traceable and delay-line-free EOS oscilloscope for real-time waveform characterization of free-running positive-emitter-couple leveled (PECL) signals from a microwave frequency divider (FD) at different operating conditions are discussed.

2. Experimental

The block diagram of a frequency traceable and delay-line-free EOS oscilloscope is shown in Fig. 1, which consists of frequency synchronization, delay-time controlling, GSLD pulsing, and electro-optic sampling functions. Previously, we have employed the optoelectronic harmonic mixing (or frequency translating) technique to extend the operating bandwidth of PLL-PS up to 20 GHz.[11] For EOS application, the entire circuitry becomes more complicated since two sets of the offset-frequency PLL-PS modules are required for frequency synchronization between DUT signal and laser pulse-train. Therefore, only one of a modified PLL-PS is designed for the proposed scheme to concurrently control the frequency and the phase between the DUT signal and the GSLD pulse-train with repetition rate of 1 GHz. The simplification is due to the fast evolution of microwave

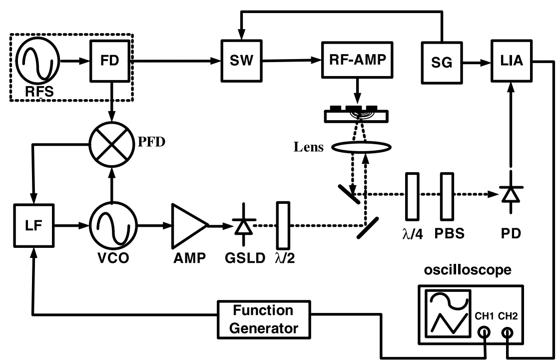

Fig. 1. The schematic diagram of a delay-line-free EOS system with a PLL-PS controlled delay-line-tunable GSLD source.

phase-frequency detectors (PFDs) and frequency dividers (FDs) with their operating bandwidth of greater than 1 and 10 GHz, respectively. The modified PLL-PS consists of a microwave digital PFD (Motorola, MC12140) to replace the individual frequency dividers, optoelectronic harmonic mixer, and D/A converter in previous circuitry. A microwave FD (Motorola, MC12019) with the divisor of 2 driven by a free-running radio-frequency synthesizer (RFS, HP8648A, $f_c = 1$ GHz) is employed as the DUT in our experiment. The microwave signal generated from the voltage controlled oscillator (VCO, simulated by HP8640B in DC-FM mode) is forced to frequency-synchronized with the DUT signal via the PLL-PS circuit. The phase of the frequency-divided signal is compared with that of the VCO signal in the PFD, which results in a an error voltage ($V_{err} = k_d \theta_e$) due to the phase deviation between DUT and VCO signals. The error voltage then feedbacks to the VCO after passing through a second ordered active loop filter. This leads to frequency synchronization of VCO with respect to DUT signal eventually. Subsequently, the VCO is further amplified to gain-switch the laser diode (GSLD, $\lambda = 1.3$ μm as the probe beam in the EOS system). A clipping diode is added to avoid the reverse breakdown of the GSLD. The GSLD is DC biased at near threshold and driven sinusoidally to generate optical pulses. In contrast to OMDL-based EOS approach, we have previously shown that by adding a DC voltage-tuning circuit or saw-tooth signal (from an IF frequency generator) prior to the loop filter, the phase of the microwave signal from VCO as well as the delay-time of the optical pulse-train from GSLD can be linearly and continuously changed as a function of the controlling voltage (V_{REF}) [11]. Such implementation concurrently rules out the alignment problem in the OMDL-based delay-time controller, and overcomes the nonlinearity and small tuning range of conventional analog phase shifters. For EOS probing and lock-in detection, the DUT signal is further on-off keying by an ultra-wideband electronic switch, and is send into a planar microwave transmission line made on 350 μm-thick S.I. GaAs substrate that acts as a reflect-mode EO sampler. The entire waveform of the DUT signal can thus be equivalent-time sampled and monitored on the oscilloscope by linearly scanning the relative delay-time of the optical pulse-train via the saw-tooth modulation of V_{REF}.

3. Results and discussions

As a result, the optical pulse-trains of GSLD controlled at different V_{REF}s are monitored by a commercial digital sampling oscilloscope (DSO) and shown in Fig. 2. By setting V_{REF} as −1 V, the GSLD pulse-train is delayed by about 0.6 ns. As the V_{REF} increases to 2.9 V, the pulse-train is leading by 2.6 ns as compared to the original one. A wide delay-time tuning for the GSLD pulse-train of greater than 1 period can easily be achieved (see Fig. 3). The maximum delay-time switching bandwidth can be up to 100 Hz under a saw-tooth modulated control of V_{REF} function. By changing V_{REF} within a range of ±3.5 V, the maximum delay-time tuning range of the GSLD pulse-train is up to 1.95 periods, which equals to 3.9 ns for a DUT signal with repetition frequency of 500 MHz. This corresponds to a tuning responsivity of about 0.28 period/V (or 0.56 ns/V at repetition rate of 1 GHz). This is attributed to the ultra-wide phase shifting range (~700°) of the PLL-PS integrated with GSLD [11]. The sampling resolution of the PLL-PS controlled GSLD is about 0.15 ~ 0.2 ps, which is limited by the root-mean-square amplitude noise ($\Delta V_{rms} \sim 0.5$ mV) of

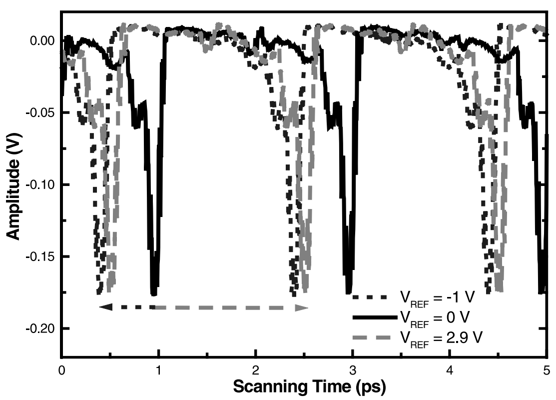

Fig. 2. The time-delayed GSLD pulse-train monitored by commercial digital sampling oscilloscope at different V_{REF}s.

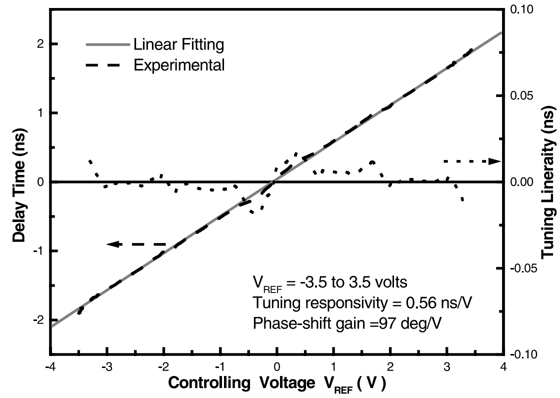

Fig. 3. The delay-time (experimental: dashed line, fitted: solid line) and tuning linearity (dotted line) of the GSLD pulse-train as a function of controlling voltage.

the power supply for the PLL-PS circuitry. To date, the maximum phase change of the PLL-PS has already approached the operating limitation of the digital phase/frequency detector with its maximum phase detecting range of $\Delta\theta_{max} = 4\pi$ (or 2 periods). According to the equivalent-time sampling theory, a phase change of at least 2π (or 1 period) for waveform sampling of a repetitive signal is required. Significantly, the delay-time tuning performance of the PLL-PS controlled GSLD system is far beyond this demand. The required periodical scanning time of the PLL-PS can be described as $t_p = [V_t \cdot f_{rept} \cdot \Delta\tau]^{-1}$, where t_p denotes the periodical scanning time of the DEPS, V_t denotes the point-to-point scanning rate, f_{rept} is the repetition frequency of the optical pulse-train from the GSLD, and $\Delta\tau$ is the sampling resolution. Subsequently, the pulsewidth, phase-noise density, and relative timing jitter of the GSLD pulses under the control of PLL-PS are characterized. The pulse shapes of GSLD at different driving currents measured by DSO are shown in Fig. 4. Although the threshold current of GSLD is 12 mA (operated at continues-wave mode), the pulsewidth of GSLD is found to greatly decrease from 90 ps at threshold to 18 ps at far below threshold (~5 mA) condition. The single-sided-band (SSB) phase-noise density spectra of the PLL-PS controlled VCO and GSLD signals at repetition frequency of 500 MHz are compared in Fig. 5. Note that the corresponding SSB phase noise of the free-running RFS

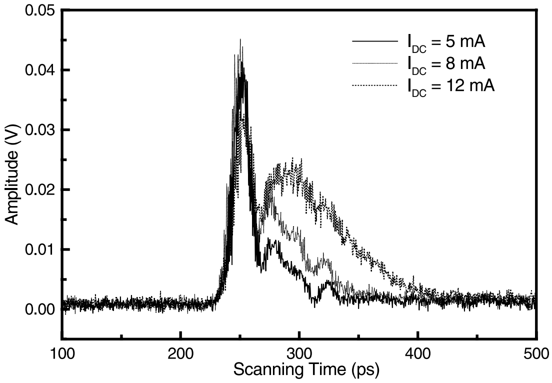

Fig. 4. The PLL-PS controlled GSLD pulse shapes at different DC-biased currents of GSLD.

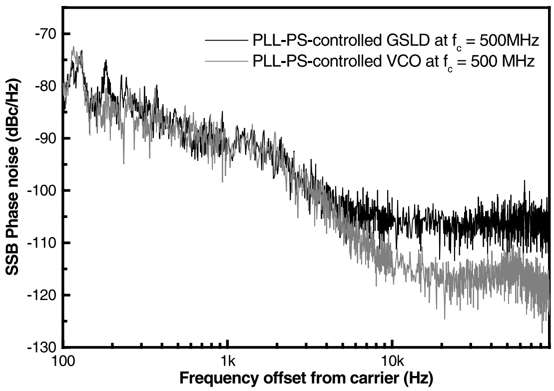

Fig. 5. The SSB phase-noise spectra of the PLL-PS controlled VCO signal (gray line) and GSLD pulses (black line) measured at offset frequencies.

is approximately −100 dB/Hz at offset frequency of 1 kHz. Even in the worst case, the SSB phase noise of the PLL-PS controlled VCO at the offset frequency of 1 kHz can still be smaller than −90 dB/Hz. The GSLD only introduces additional phase noise at offset frequency of higher than 10 kHz, which is mainly attributed to the uncorrelated excess laser noise such as the spontaneous emission and the shot noise of GSLD itself. By subtracting the measured SSB phase-noise spectra of the GSLD pulses measured at the fundamental and the 10th harmonic, the relative timing jitter of the PLL-PS controlled GSLD pulse-train frequency-tracked to the DUT signal is calculated and shown in Fig. 6. The timing jitter of GSLD is found to

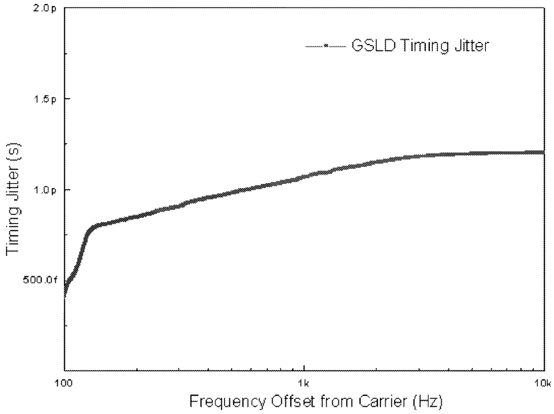

Fig. 6. The relative timing jitter of the GSLD pulse with respect to the free-running frequency synthesizer.

saturate at 1.2 ps as the offset frequency is higher than 1 kHz. The measurement indicates that the further improvement on the SSB phase noise of this system relies on frequency-tracking to an ultra-low phase-noise RFS, and the use of low-noise active components for the PLL-PS circuitry.

To characterize the accuracy of the PLL-PS controlled EOS system, the waveform sampling of a repetitive sinusoidal signal generated from a free-running RFS was previously performed [15]. The sampled waveform almost matches with the signal measured by commercial DSO except some deviation of less than 5% at small V_{REF}s due to the finite rising time of the PFD that leads to a slightly nonlinear transfer function of PLL-PS within the region. In this work, we employ the proposed delay-line-free EOS oscilloscope for simultaneously frequency-tracking and waveform-sampling of a free-running microwave digital PECL signal generated from a microwave FD with divisor of 2. Prior to the experiment, the waveforms of the PECL signal frequency-divided from 1 GHz to 500 MHz by FD at different input levels are characterized by DSO (see Fig. 7). The output responses measured by using our system and commercial DSO are compared in Fig. 8. The overall measuring deviation of the PLL-PS controlled EOS system is less than ±5%. It is found that the DSO sampled waveform posses a more significant damping behavior, such a discrepancy could be attributed to the combining effect of the tuning

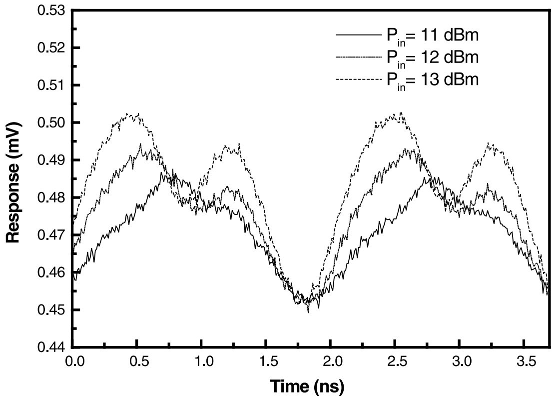

Fig. 7. The output waveforms of a microwave frequency divider operated at different input levels.

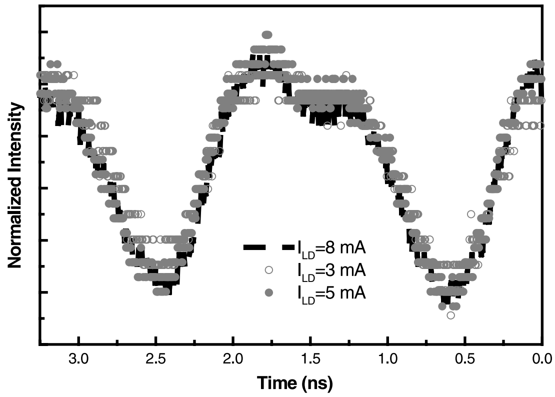

Fig. 9. The PECL signal sampled by the delay-line-free EOS oscilloscope with degraded GSLD pulses at DC-biased levels of far below threshold condition.

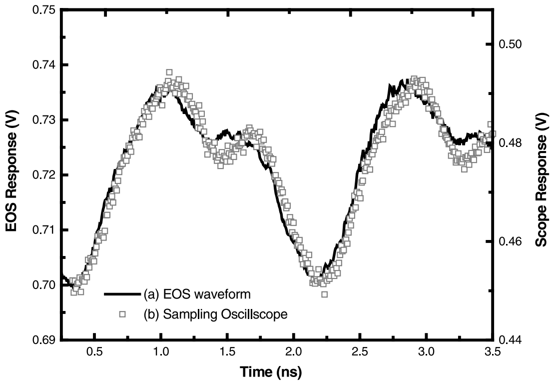

Fig. 8. The waveforms of PECL signals output from free-running microwave frequency divider sampled by the proposed delay-line-free EOS oscilloscope (solid line) and commercial DSO (hollow squared line).

nonlinearity of the PLL-PS, the finite frequency response of the EO sampler with larger thickness, and the limited pulsewidth of the GSLD source, etc. Nonetheless, the possible influence of the DC-blocking circuit that connected with DSO sampler for DC-damage protection should not be ruled out. Moreover, the measuring distortion caused by the degradation of GSLD peak power is also discussed. As the DC-biased current decreases from 8 to 3 mA, the output peak power of GSLD dramatically reduces from 4 mW to below 1 mW. The PECL waveforms sampled by the degraded pulse-train from GSLD biased at far below threshold conditions are shown in Fig. 9. It is seen that there are no significant distortion among the measured waveforms except a small degradation on the signal-to-noise ratio due to the decreasing power of the optical pulse at low-biased conditions. These results have proved the comparable sensitivity and accuracy of the proposed delay-line-free EOS oscilloscope based on PLL-PS technique. Note that there could be an inconceivable deviation between the EOS measured and DSO monitored waveforms for the PLL-PS operating beyond limit (-3.5 V $< V_{REF} <$ 3.5 V). Nonetheless, this is not a necessary procedure since the entire delay-time tuning range of the PLL-PS controlled GSLD pulse-train has already exceeded one period.

In comparison with other OMDL-based or non-OMDL approaches, it is worthy noting that the proposed EOS system with PLL-PS controlled GSLD is definitely a more simplified, flexible, and compact module for industry applications, which is also a completely non-offset-frequency (or frequency synchronous) phase-locking technique as compared to our previous demonstrations [11,12]. The proposed scheme benefits the advantages from directly discriminating the frequency and shifting the phase between free-running DUT signal and the GSLD clock with the digital-PFD based PLL-PS technology. The delay-time tuning range and linearity of the proposed digital PLL-PS has already exceeded the records of a similar analog system [10]. Although the sampling resolution of the PLL-PS based system is less comparable with that of a OMDL-based one (can be as small as 6.7 fs), which still exhibits the niche of alignment-free setup with faster delay-time scanning rate for on-line IC testing. For example, the tuning of the PLL-PS controlled GSLD can be as fast as 100 point/s with point-to-point delay-time resolution of 0.15 ps at repetition rate of 1 GHz (corresponding to a delay-time scanning rate of 15 ps/s), which is far larger than the conventional EOS system using OMDL module (with maximum delay-time scanning rate of 3.3 ps/s). The operational bandwidth of PLL-PS is limited by the loop filter (with $f_{3dB} \leqslant 100$ Hz, corresponding to a switching time constant of ~10 ms). Further improvement on the scanning rate of the system is achievable at the cost of larger timing jitter. On the other hand, the offset-frequency (or low-frequency-replica) EOS system although has shown its intriguing merits of such as real-time revelation of waveform and free of alignment-based measuring distortion, still exhibits a relatively low detecting sensitivity of 2–20 $\mathrm{mV}/\sqrt{\mathrm{Hz}}$ [16] (has been improved to 0.5–1 $\mathrm{mV}/\sqrt{\mathrm{Hz}}$ [17,18] by use of lock-in technique) as compared to that of the non-offset-frequency EOS (about 22–70 $\mu\mathrm{V}/\sqrt{\mathrm{Hz}}$).[19] The dynamic range of the low-frequency-replica system is further limited by the sensitivity of general oscilloscope (1 mV/div) while performing time-domain waveform revelations. On the contrary, the PLL-PS controlled EOS oscilloscope is generally based on modified non-offset-frequency technique, which remains the performance of ultra-high sensitivity since a lock-in amplifier instead of an oscilloscope is employed. Such system is free of any true-time-delay unit and dual-frequency synthesizers, which thus rules out the drawbacks of such as the bulky arrangement for long-range scanning process in OMDL-based schemes, and the relatively low sensitivity and dynamic range in the low-frequency-replica EOS systems. In addition, this system further benefits the advantages of frequency tracking to free-running signals with suppressed relative timing-jitter. Although the sampling resolution of the PLL-PS controlled GSLD is still frequency dependent and is less comparable to the conventional approaches at lower repetition rates, we conclude that the proposed system is more compatible with the on-line IC testing industry for synchronous characterization of the waveforms from the free-running or unknown circuits/nodes. In spite of the finite frequency-extension capability owing to the slow evolution on the operating bandwidth of microwave digital PFD, the promising application of the proposed delay-line-free EOS oscilloscope in on-line and on-wafer free-running IC testing is straightforward.

4. Conclusion

In this section, we have developed a delay-line-free and frequency traceable EOS system by use of a digital PLL-PS controlled delay-time-tunable GSLD source. The home-made voltage-controllable PLL-PS exhibits a linear transfer function with ultra-wide phase shifting range of ±350°. By changing the controlling voltage from −3.5 to 3.5 V, the maximum pulse delay-time tuning can be up to 1.95 periods, with a tuning responsivity and deviation of about 0.28 period/V (or 0.56 ns/V at repetition of 1 GHz) and <5%, respectively. The sampling resolution and rate of the PLL-PS controlled GSLD are about 0.15–0.2 ps and ~100 Hz, respectively. The measuring deviation between the proposed EOS scheme and commercial DSO on the waveform sampling of microwave PECL signals generated from a free-running digital frequency dividers is less small. The present technique has overcome several disadvantages of the conventional OMDL-based EOS system, such as the align-dependent sampling distortion, the aligning complexity, and the bulky arrangement, etc. A potential application of the proposed delay-line-free EOS oscilloscope in on-line and on-wafer free-running IC testing is straightforward.

Acknowledgements

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