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Generalized Linear Optical Sampling Technique Realized by Using Non-Pulse Electro-Optic Frequency Comb Sampling Source

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ABSTRACT We propose a novel generalized linear optical sampling (GLOS) technique realized by using an electro-optic frequency comb (EOFC) as the sampling signal. GLOS technique is demonstrated as a bandwidth compression process in frequency domain instead of gating effect in time domain. An EOFC without the limitation to be ultra-short pulse serves as sampling signal is pre-measured. In experiments, the waveforms are sampled by an EOFC with agile repetition rates and bandwidths. After a demodulation process with pre-measured information, the original signal under test in both intensity and phase fields can be recovered. The results obtained from the proposed method are consistent with those from traditional linear optical sampling technique. Besides, with a high average mode power, EOFC-based GLOS technique realizes more than 10 dB SNR improvement and has ability to detect weak signal with a power of −47.3 dBm. Our demonstration opens the way for cost-effective comb sources to be used in optical sampling fields.

INDEX TERMS Linear optical sampling, electro-optic frequency comb, repetition rate agility, SNR improvement.

I. INTRODUCTION

With the development of next generation high-capacity optical communication networks, the bandwidth and data rate of the optical communication signals with advanced modulation formats are respectively beyond 100 GHz and 1 Tb/s [1], [2], which poses high requirement on large-bandwidth optical signal monitoring system. Besides, the development of optical performance monitoring system, Lidar, microwave photonics, ultra-fast optics and optical signal processing also demands the characterization of the large-bandwidth ultra-fast signal with high time resolution and high signal-to-noise ratio (SNR) [3]–[5]. However, restricted to the limited bandwidth of the photodetector (PD) and sampling-and-hold circuit, the most common method of direct-detection with conventional electronics becomes very expensive or even impossible. Although the bandwidth and sampling rate of the state-of-art commercial oscilloscope have reached up to 65 GHz and 160 GS/s, the vertical resolution is only 8-bit and the phase-insensitive all-electronic diagnostics are limited to intensity measurements.

The optical sampling technique uses ultra-short optical pulses as functions of gating effect to characterize the repetitive temporal waveforms or eye diagrams with dramatically high time resolution and large bandwidth, which are not possibly realized by conventional methods [6], [7]. Essentially, optical sampling technique is an equivalent sampling method, which means only low-bandwidth PDs and analog-to-digital converters (ADCs) are required for the signal acquisition. Without the need of nonlinear interaction [8], the linear optical sampling (LOS) technique offers the possibility of surpassing nonlinear optical sampling techniques [9], [10] in sensitivity. For waveform measurement in both intensity and phase, LOS technique has been widely adopted to monitor high-symbol-rate modulation signals, such as optical time division multiplexed (OTDM) signals, differential phase-shift key (DPSK) signals, complex optical modulation signals and wavelength-division multiplexing (WDM) signals [11]–[19]. Besides, LOS technique is also applied for impulse response measurement [20], [21].

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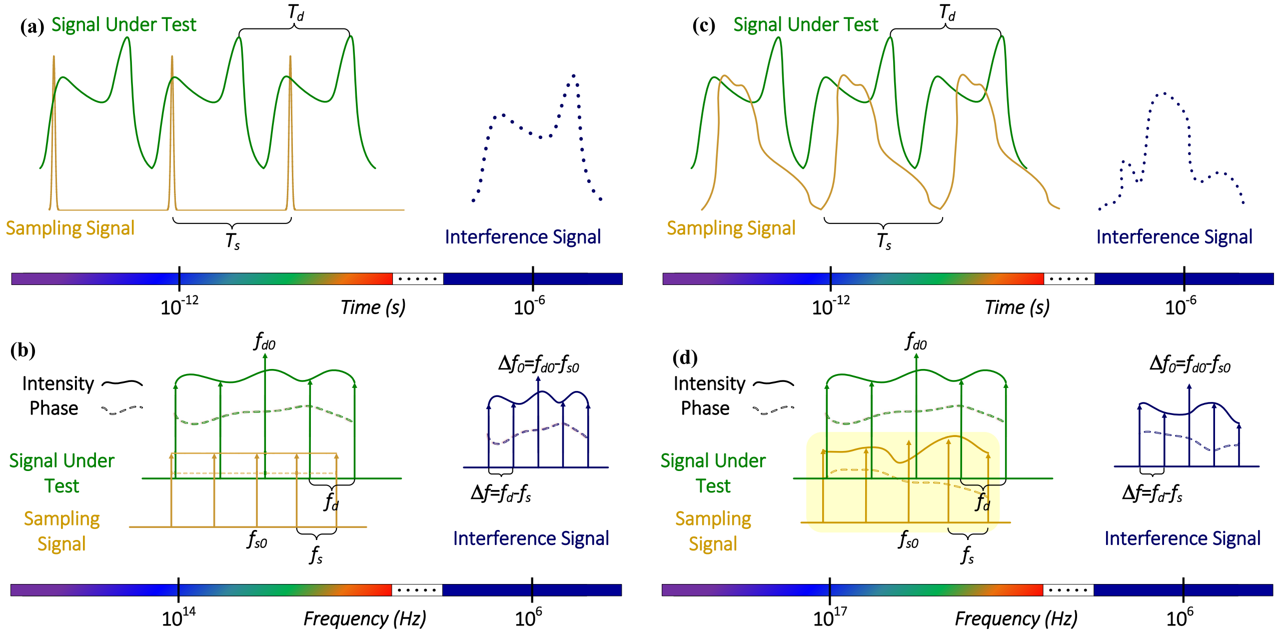

FIGURE 1. Schematic of traditional LOS technique in (a) time domain and (b) frequency domain; Schematic of GLOS technique in (c) time domain and (d) frequency domain.

LOS technique based on the gating effect of ultra-short pulses implies that the sampling results are determined by pulse sources directly [22], [23]. A costly mode-locked laser (MLL) with a rigid repetition rate is needed to provide high-quality transform-limited pulse. Recently, some other comb sources have been proposed to be used in fields of spectroscopy, optical synthesis and imaging, such us electro-optic frequency comb (EOFC) [24]–[27], gain-switch frequency comb [28] and microresonator frequency comb [29], [30]. These outputs in time domain are difficult to be shaped to transform-limited pulses. The time domain theory of LOS restricts the employment of the cost-effective comb sources to high-performance LOS, which limits the practical implementation. Besides, high-peak-power sampling pulse generated by MLL has relatively low average power and the power of one comb-line is only several μW. The average power is hard to be amplified without distortion and even needs to be reduced for the protection of PD, which limits the ability for weak signal detection and restricts the system signal-to-noise ratio (SNR).

In this paper, we propose a novel generalized LOS (GLOS) technique with non-pulse sampling signal, based on the comprehension in frequency domain as a bandwidth compression process. Instead of gating effect, an EOFC with a temporal repetitive waveform serves as a media of a one-to-one mapping process in frequency domain. This media with uneven spectrum causes distortion of the interference result, which is compensated in a post-demodulation process. The compensation signal is derived from the pre-measured information of the sampling signal by using traditional LOS technique with an MLL. Since the sampling process is a linearly reversible process, the signal under test (SUT) in both intensity and phase fields are recovered after demodulation. The sampling source in experiments is an EOFC generated by electro-optic modulation, which may be extended to more comb-like sources. The EOFC has an adjustable repetition rate from 1 GHz to 18 GHz, and covers over 500 GHz bandwidth at most. We measure both intensity and phase profiles of the different signals under test (SUTs), which demonstrates the performance and agility of this sampling source. Besides, we prove that the SNR can be improved with EOFC sampling source due to its high average power of comb lines, and therefore GLOS technique has the capability for weak signal detection with a power of −47.3 dBm.

II. PRINCIPLE OF MEASUREMENT

The schematics of the traditional LOS technique using sampling pulse and the proposed GLOS technique using nonpulse sampling signal are shown in Fig. 1.

Traditional LOS technique for waveform measurement is commonly described in time domain as shown in Fig. 1(a). The periods of the sampling signal and the SUT have a slight difference $\Delta T = T_s - T_d$, which is also suitable for optical communication signal characterization or optical performance monitoring when the bit length of the pseudo-random Binary sequence signal is fixed. This difference ΔT causes a small time interval between any two adjacent periods, which is also the equivalent sampling interval. The sampling signal scans the SUT during $K = T_d/\Delta T$ periods to complete one-round sampling event, corresponding to a time stretch factor of $K = T_d/\Delta T = T_s/\Delta T - 1$ in time domain. Then the large-bandwidth SUT is reconstructed with K times measurement time. Detailed explanation of traditional LOS process in time domain has been discussed in Ref. [12]–[15]. Here, we mainly focus on the explanation in frequency domain.

In frequency domain, the electric fields of sampling signal can be expressed as

$$E_s(t) = e^{j2\pi f_{s0}t}\sum_{l}\widetilde{A}_s(lf_s)e^{j2\pi lf_s t} \tag{1}$$

where f_{s0} is the carrier frequency, $f_s = 1/T_s$ is repetition rate, $\widetilde{A}_s(lf_s)$ are complex coefficients of corresponding frequency components, and l is the frequency index. When the sampling signal is a transform-limited pulse train, $\widetilde{A}_s(lf_s)$ can be regarded as a constant as shown in Fig. 1(b).

The repetitive SUT can be expressed as

$$E_d(t) = e^{j2\pi f_{d0}t}\sum_{k}\widetilde{A}_d(kf_d)e^{j2\pi kf_d t} \tag{2}$$

where f_{d0} is the carrier frequency, $f_d = 1/T_d$ is repetition rate, $\widetilde{A}_d(kf_d)$ are complex coefficients, and k is the frequency index. Similarly, the repetition rates also have a slight difference $\Delta f = f_d - f_s = \Delta T/T_d T_s$. This frequency relation can guarantee that each frequency component of the SUT has the unique corresponding frequency component from the sampling signal.

Then, considering the effective detection bandwidth of $f_s/2$, the interference result between the SUT and the sampling signal can be expressed as

$$\begin{aligned} E_i(t) &= E_s^*(t)E_d(t) \\ &= e^{j2\pi\Delta f_0 t}\sum_{k,l}\widetilde{A}_d(kf_d)\widetilde{A}_s^*(lf_s)e^{j2\pi(kf_d - lf_s)t} \\ &= e^{j2\pi\Delta f_0 t}\sum_{m}\widetilde{A}_d(mf_d)\widetilde{A}_s^*(mf_s)e^{j2\pi m\Delta ft} \end{aligned} \tag{3}$$

where $\Delta f_0 = f_{d0} - f_{s0}$ and $\Delta f = f_d - f_s$ can be respectively regarded as the carrier frequency and the repetition rate of the interference signal. After the interference process which is illustrated in Fig. 1(b) and (d), the center frequency is down-converted to radio frequency (RF) Δf_0 via the heterodyne detection. Other frequency components are down-converted to different RF frequencies with evenly spaced line spacing Δf. This process is a one-to-one mapping of the SUT, yielding a compression factor in repetition frequency of $K = f_s/\Delta f = f_d/\Delta f - 1$. For a certain SUT, the spectrum bandwidth is also compressed with same factor, which equals to the stretch factor of the temporal waveform. This analysis in frequency domain is essentially identical with multi-heterodyne detection or dual-comb spectroscopy [31]–[33].

As shown in Fig. 1(a) and 1(b), using the transform-limited pulse as the sampling source is a special condition that the interference signal is directly a recovery of SUT in time domain. For a generalized condition, a nonpulse waveform with same repetition rate f_s serve as the sampling signal. Compared with a transform-limited pulse, this sampling signal has a distorted spectrum with uneven intensity and disordered phase. As a result, the temporal interference signal cannot be directly regarded as the recovery of SUT. However, in frequency domain, the interference signal is still a one-to-one mapping process of the SUT with bandwidth-compression as shown in Fig. 1(d). Represented by complex coefficients $\sum\widetilde{A}_s^*(mf_s)$ in Eq. (3), the distortion introduced by this sampling signal may be compensated since the sampling process is linear and reversible. These coefficients are derived from the local sampling signal, which may be measured in advance. The obtained compensation array $\sum 1/\widetilde{A}_s^*(mf_s)$ as a precondition will be used for demodulation process.

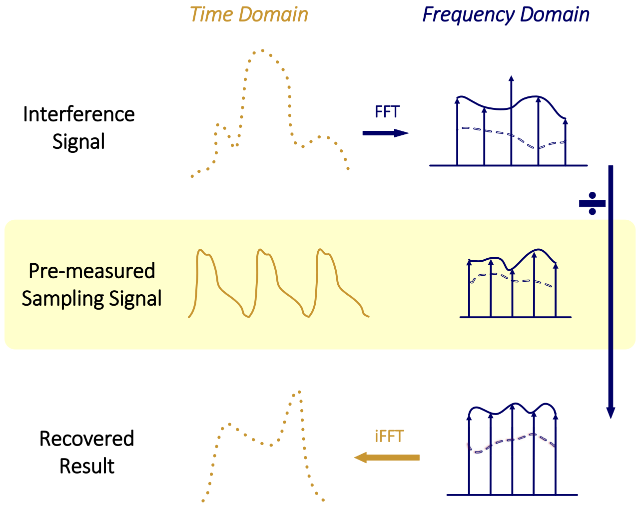

FIGURE 2. **Schematic of demodulation process for GLOS technique in time domain and frequency domain.**

As shown in Fig. 2, the exact demodulation process is an all-digital process after the acquisition and digitization of the interference signal. The complex coefficients $\sum_m \widetilde{A}_d(mf_d)\widetilde{A}_s^*(mf_s)$ of the interference result may be extracted from the discrete RF frequency of the Fourier transformation. This linear array is aligned with the compensation array centered at the carrier frequency. By multiplying with the compensation array, the demodulated spectrum of the SUT is restored without any distortions. Then the recovery of the original SUT in time domain is obtained by an inverse Fourier transformation. The intensity profile may be extracted by taking the envelope of the temporal waveform. In coherent measurement, the carrier frequency may be accurately calculated and the extracted phase of the temporal waveform need to be used for subtracting the phase of carrier frequency to obtain the phase information. A certain waveform or flat spectrum is not required for the sampling signal. However, a missed line or a line with quite low power is not acceptable, which may lose information for demodulation. This demand is easily met by most of comb-like sources.

III. EXPERIMENTAL SETUPS AND RESULTS

A. SAMPLING SIGNAL GENERATION AND PRELIMINARY CHARACTERIZATION

In this part, we generate an EOFC with agile repetition rates to be used for the GLOS experiments and characterize it for obtaining the compensation array for demodulation. The local light of the SUT may be used as the seed laser of the sampling signal generation, and the merit is that same seed laser guarantees the mutual coherence between the sampling signal and SUT, which eliminates the phase noise especially for phase detection.

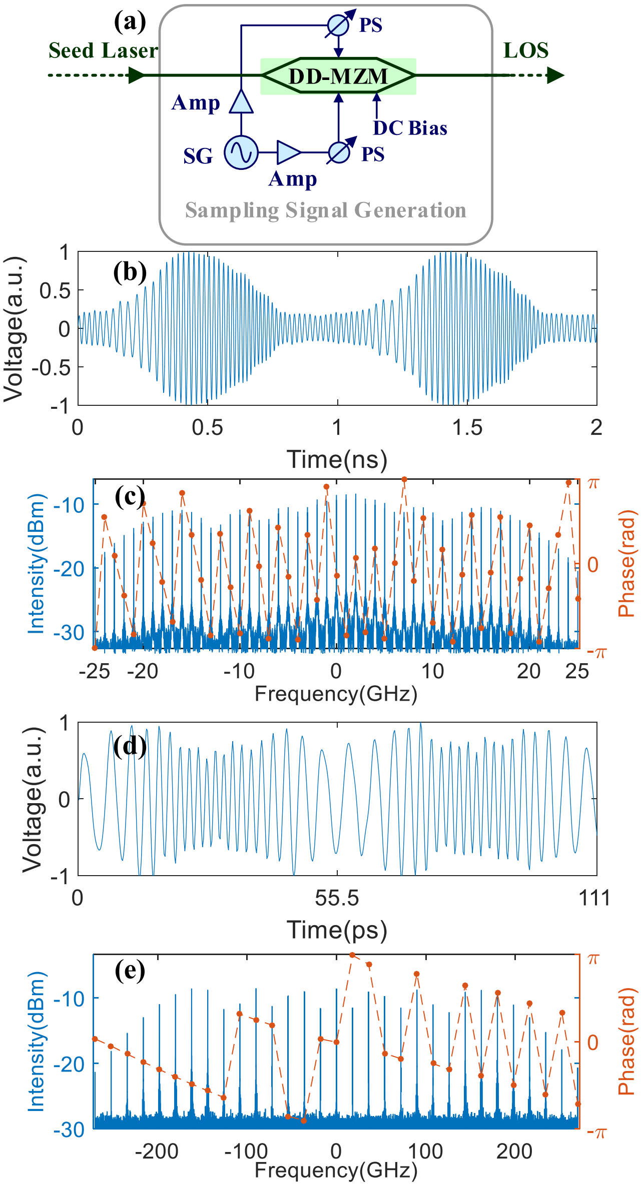

FIGURE 3. **(a) The experimental setup of sampling signal generation. SG: microwave signal generation; Amp: electrical amplifier; PS: phase shifter; DD-MZM: dual-drive Mach-Zehnder modulator. (b), (c) Waveform and spectrum of EOFC as sampling signal with 1 GHz repetition rate measured by traditional LOS technique; (d), (e) Waveform and spectrum of EOFC with 18 GHz repetition rate.**

As shown in Fig. 3(a), a dual-drive Mach-Zehnder modulator (DD-MZM, Fujistu FTM7937) with a low half-wave voltage (1.5 V at 25 GHz) is used to generate an EOFC [24]. The sinusoidal electrically-driven signal is generated by a microwave signal generator (SG) and separated to two branches, which are then highly amplified to 3 W in parallel by two RF amplifiers. Driven by high power RF signal, several high-order sidebands are generated. The phase shifters (PSs) are used to adjust the flatness of overall shape of multi-sidebands. The generated EOFC with a repetition rate of 1 GHz is measured by traditional LOS technique using an MLL (Menlo, FS-250), in which an auxiliary interferometer is used to recover the mutual coherence [12]. For EOFC characterization, the output pulse of the MLL is filtered by optical filter with 0.8 nm bandwidth, corresponding to the pulsewidth of 4.4 ps. The temporal waveform is shown in Fig. 3(b) with an equivalent sampling rate of 500 GS/s. The 50 GHz optical spectra in intensity and phase are obtained by digital FFT of the waveform as depicted in Fig. 3(c), which covers 25 GHz bandwidth quantified in single-sided spectrum.

The line-spacing of EOFCs have a wide adjustable range, and therefore it is an effective way to increase the line-spacing for enlarging the EOFC bandwidth. The sinusoidal electrical signal of 18 GHz (limited by the RF amplifier bandwidth) is generated and amplified to drive the DD-MZM. The EOFC with 18 GHz line-spacing is also characterized by the MLL with its pulses filtered with 8 nm bandwidth and having 440 fs pulsewidth. The temporal waveform with 9 TS/s and the spectra with more than 550 GHz optical bandwidth are shown in Fig. 3(d) and 3(e).

Since the efficiency of amplifier and the response of modulator depend on the frequency of driven signal, the maximum index of sidebands for 18-GHz EOFC is only 15 and that for 1-GHz EOFC is 25. Obviously, the waveforms of two EOFCs are not standard pulse-shapes and the spectra are not flat. Two EOFCs with different parameters will be used as the sampling signals for the following two GLOS experiments and these pre-measured information will be used for demodulation. The slow temperature drift of DD-MZM may influence the stability of the EOFCs, which can be maintained in several hours in experiments. A modulator bias controller may be introduced for long-term stability.

B. GLOS TECHNIQUE WITH EOFC AS SAMPLING SOURCE

As shown in Fig. 4(a), we implement the GLOS technique using the EOFC mentioned above as sampling source. The SUT is also generated by electro-optic modulation. An arbitrary waveform generator (AWG, Keysight M8195A) with a sampling rate of 64 GS/s is used to generate the electrical signal, which drives a Mach-Zehnder modulator (MZM) to generate the SUT. The seed laser is a continuous-wave fiber laser (FL, NKT Adjustik E15) centered at 1550 nm with 50 mW output power. An acousto-optic modulator (AOM) introduces 80 MHz frequency shift of the sampling-signal branch, which determines the down-converted carrier to be $\Delta f_0 = 80$ MHz. This frequency shift avoids the overlapping between the positive and negative sidebands, which can also be realized by an optical 90° hybrid. The interference signal between the sampling signal and the SUT is detected by a 400 MHz balanced photodetector (BPD) and then digitized by a 14-bit ADC (National Instruments 5171R) at a sampling rate of 250 MS/s.

Firstly, the AWG generates an electrical signal with a repetition rate of 1 GHz and a bandwidth of 20 GHz. After the double-sideband modulation, the optical SUT with 40 GHz bandwidth is generated. The EOFC with 1 GHz repetition

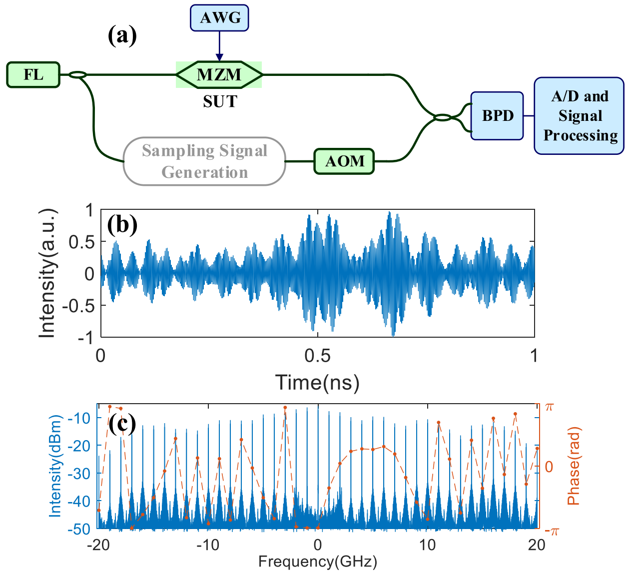

FIGURE 4. **(a) The experimental setup of the GLOS technique. FL: continuous-wave fiber laser; AOM: acousto-optic modulator; MZM: Mach-Zehnder modulator; AWG: arbitrary waveform generator; BPD: balanced photodetector. (b), The temporal waveform and (c) the spectrum of raw results sampled by EOFC.**

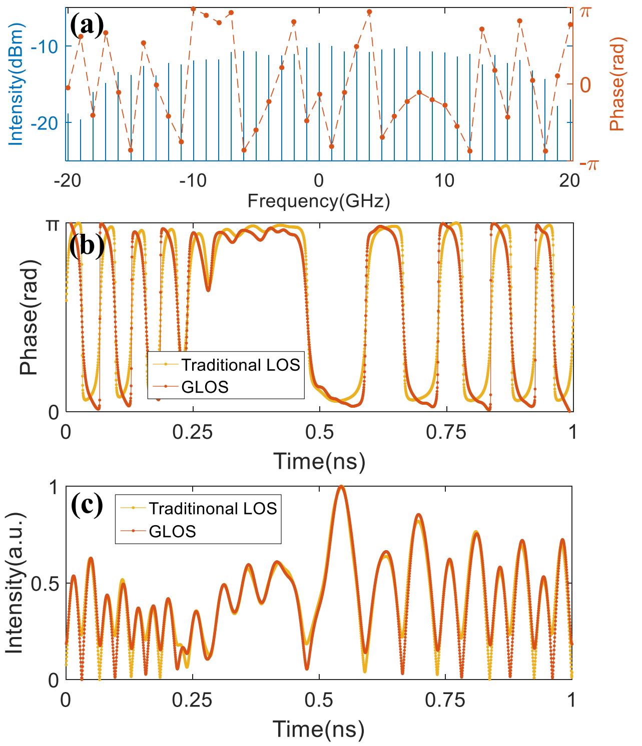

FIGURE 5. **(a) The spectrum of demodulated results with 1 GHz repetition rate. (b) The intensity and (c) the phase profiles measured by GLOS technique and LOS technique.**

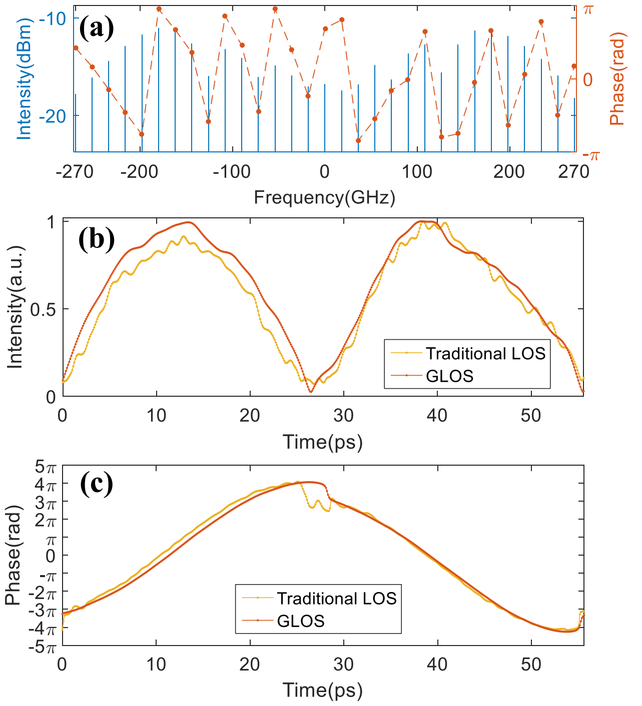

FIGURE 6. **(a) The spectrum of demodulated results with 18 GHz repetition rate and 558 GHz bandwidth. (b), (c) The intensity and phase profiles measured by GLOS technique and LOS technique.**

rate serves as the sampling signal with a frequency detuning Δf of 500 kHz. The compression factor is $K = 2000$, and the bandwidth is compressed to 20 MHz in RF domain. The digitized result of interference signal with 250 MS/s sampling rate is shown in Fig. 4(b), which is digitally filtered to remove the out-of-band noise. The equivalent sampling rate is 0.5 TS/s. The spectra obtained by digital Fourier transformation are depicted in Fig. 4(c).

To process these finite points following the demodulation methods described in Section II, we recover the spectrum of the original SUT, as shown in Fig. 5(a). Then we can recover the waveform in both intensity and phase fields. We also measure this waveform with the MLL described in Section III. *A* by using traditional LOS technique with the same equivalent sampling rate of 0.5 TS/s. For comparison, Fig. 5(b) and 5(c) respectively show the intensity and phase profiles by using traditional LOS technique and GLOS technique together in one period, where the intensity waveform is normalized. The averaged relative errors are calculated to be 0.0583 for intensity and 0.11π for phase. The measurement result of the proposed GLOS method is consistent with the result of LOS technique in both intensity and phase, which prove the effectiveness of this method.

To further increase the measurement bandwidth, we use the EOFC with 18 GHz repetition rate as the sampling signal and the effective measurement bandwidth is over 500 GHz. Correspondingly, the SUT is changed to be 18 GHz repetition rate and 558 GHz bandwidth, which is generated by electro-optic modulation with similar setup for EOFC generation. The frequency detuning Δf is 0.5 MHz corresponding to a compression factor of 36000. The interference result is detected with the same BPD and ADC, and the equivalent sampling rate is 9 TS/s. The experimental results are also demodulated as the method mentioned above by digital processing. The spectra after demodulation are shown in Fig.6(a) with total 558 GHz bandwidth. The temporal waveforms in one period (55.5 ps) of intensity and phase are shown in Fig. 6(b) and

6(c), which are respectively measured by the proposed technique and traditional LOS technique with same equivalent sampling rate. The averaged relative errors are calculated to be 0.078 for intensity and 0.22 π for phase. These results are also consistent, and the observable difference in SNR will be discussed in Section III. C.

Further expansion of the measured bandwidth for EOFC sampling source may be realized by cascading multi-modulator or nonlinear spectrum broadening method. These two methods multiply the EOFC bandwidth but relatively introduce more instability, which may be solved by using temperature stabilization techniques.

C. SNR IMPROVEMENT AND WEAK SIGNAL DETECTION

MLL outputs transform-limited pulse with large bandwidth and high stability, which makes it the significant tool of optical sampling. Since the sampling source with arbitrary waveform still needs the pre-characterization of an MLL, the intuitive performance is hard to surpass the traditional LOS technique. However, the power of each mode for MLL is commonly limited and hard to be amplified. In contrast, the power of each comb line for EOFC is higher and has the potential to be amplified, which means that this method has the capability to improve SNR and to realize weak signal detection.

We set up the experiments with the same configuration in Section III. B with 1 GHz repetition rate. The average power of MLL output with filtered 0.8 nm bandwidth is measured to be -2.65 dBm, corresponding to an average power of 4.6 μW each comb line. The average power of EOFC sampling source without amplification is -5 dBm, and the average power of each comb line is calculated to be about 63.2 μW. We measure and calculate the average SNR in frequency domain in an average time of 400 μs, when the average power of SUT is -18.5 dBm. As shown in Table. 1, the average SNR of GLOS technique is 10 dB larger than that of traditional LOS technique. In time domain, the order of white noise in digitization is about 1 mV, and we define the minimum power of SUT to obtain the same signal voltage as minimum detection power (MDP). We measure the MDPs of LOS and GLOS techniques respectively. As shown in Table. 1, the GLOS technique has more than 15 dB superior for weak signal monitoring, due to the SNR improvement and intrinsic mutual coherence between SUT and the sampling signal.

TABLE 1. **The SNR (when the power of SUT is −18.5 dBm) and MDP (minimum detection power) of traditional LOS technique and GLOS technique.**

	SNR(dB)	MDP(dBm)
Traditional LOS	24.82	-31.9
GLOS	35.39	-47.3

Besides, compared with MLL, the EOFC has agile repetition rates from hundreds of MHz to tens of GHz, which means the proposed GLOS technique may be suitable for more practical operation situation. Without the need of additional structure to recover the mutual coherence between the MLL and SUT, such as auxiliary interferometer, GLOS technique has low system complexity compared with traditional LOS technique.

IV. CONCLUSION

In this paper, we propose a GLOS technique, where an EOFC with non-pulse waveform serves as the sampling source. The EOFC has adjustable repetition rate and covers over 500 GHz bandwidth at most. The sampling signal need to be characterized in advance to obtain the necessary information for demodulation in GLOS measurement. We measure two SUTs with 40 GHz bandwidth (1 GHz repetition rate) and 558 GHz bandwidth (18 GHz repetition rate) respectively. The comparison between the demodulated results and traditional LOS results validate the effectiveness of the proposed method. Compared with traditional LOS, GLOS with EOFC sampling signal can improve the SNR and detect weak signal, thanks to the high line power. Besides, GLOS technique with EOFC offers intrinsic mutual coherence and agile repetition rate, which reduces the system complexity and improve the practicality. The results show that GLOS technique is effective for large-bandwidth signal monitoring just by using low-speed PD and ADC. Without the restriction on pulsed sampling sources, a practical sampling scheme of GLOS with EOFC sampling source will find its prospect in many applications with high cost-effectiveness.

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