Absolute time delay measurement of stimulated Brillouin scattering based all-optical pulse compression

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Abstract—**A novel scheme to determine the absolute time delay of an unknown signal in a stimulated Brillouin scattering based all-optical pulse compression system is demonstrated. Optical pulse train with high repetition rate is utilized as the probe lightwave to interact the counter-propagating pump lightwave modulated by the microwave signal to be processed. The finite optical fiber length brings in insufficient interactions between pump lightwave and probe pulses. The absolute time delay of the unknown microwave signal is determined by the pulse-compressed results that are carried by these probe pulse trains. The absolute time delay is experimentally demonstrated and is theoretically analyzed. The maximum experimental error is about 7 ns for a linearly frequency modulated pulse with 1 GHz sweep range.**

Keywords—absolute time delay; pulse compression; stimulated Brillouin scattering

I. INTRODUCTION

The pulse compression processing raised in 1960s is an important technique for radar systems [1]. Mature pulse compression systems are implemented by electronic devices, which has the advantages of high resolution and good flexibility. However, pure electronic systems is difficult to deal with the microwave signals with high frequency and broad bandwidth due to the bandwidth limitation of the electronic devices [2]. In the last decade, the developing microwave photonic techniques [3, 4] have encouraged many photonic-assisted techniques to break through the bandwidth limitation in signal processing [5-9]. On the other hand, most of the pulse compression systems are realized in a digital way and the matched filtering is often implemented after sampling and quantization of the received signal. Meanwhile, these digital processing systems gradually face challenges for the analog-to-digital convertor (ADC) bandwidth, digital storage, and processing ability. Although the photonic ADCs [10-12] have settled down the bandwidth problem, the demands for the digital signal processing modules remain unsolved and the analogue pulse compression technique becomes one of the promising solutions.

In our previous work [13], we have demonstrated the all-optical pulse compression technique based on the stimulated Brillouin scattering (SBS) in optical fibers. The stimulated acoustic wave is able to inherit the amplitude and frequency information of the pump or probe lightwave. Conditions of time inverse and amplitude conjunction for matched filtering processing are naturally satisfied during the SBS interaction. The pulse compression result of the modulated microwave signal is contained in the so-called Brillouin gain component of the probe lightwave. However, one vital problem remains to be solved before this technique is utilized in a practical radar system is the detection of the absolute time delay. The problem is that this proposed SBS based all-optical pulse compression scheme just obtains the self-correlation of the modulated microwave signal. The absolute time delay information is lost after SBS interaction.

In this paper, we demonstrate a novel scheme to measure the absolute time delay of the microwave signal in an SBS based pulse compression system. Compared to the original structure, the short pulse probe lightwave is replaced by a pulse train with a relatively high repetition rate. Under this condition, insufficient interaction occurs for the first several probe pulses that encounter the pump lightwave modulated by the microwave signal. The Brillouin gains (i.e. the pulse compression results) for these probe pulses are generated by different parts of the modulated pump lightwave, which is related to the relative time of the modulated pump lightwave launched into the fiber. After simple signal processing, the absolute time delay can be estimated from these pulse compression results. We experimentally demonstrate the measurement for a linearly frequency modulated (LFM) pulse with 1 GHz sweep range. The experimental data coincides with the theoretical analysis and the maximum detection error is about 7 ns.

II. PRINCIPLE

Similar to the structure in [13], the pump lightwave is modulated by the broadband microwave signal with duration D whereas the counter propagating probe lightwave is a short pulse train with the repetition rate of T_p instead of a single pulse. In this scheme, the absolute time delay d of an unknown microwave signal is determined by two aspects. Assuming that the k-th pulse is the first one to interact with the unknown

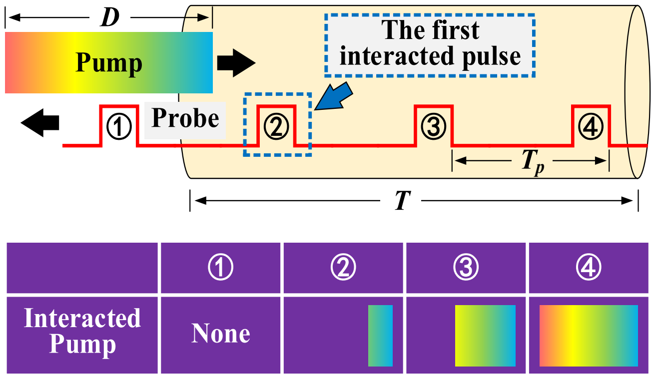

Fig. 1. The illustration of the insufficient SBS interaction between the pump signal and probe pulse train.

microwave signal, a preliminary coarse estimation of d can be decided as $kT_p+T < d < (k+1)T_p+T$, where T is the time that the light needs to travel through the SBS interaction fiber.

The precise estimation of d is implemented with the help of the insufficient interaction between pump lightwave and some probe pulses. The so-called insufficient interaction is illustrated in Fig. 1. When the modulated pump lightwave is launched into the SBS interaction fiber, the nearest probe pulse (the second pulse from left to right in Fig. 1) is the first pulse to interact with the pump lightwave. If the condition that $T_p < D$ is satisfied, this pulse has no chance to meet the entire pump lightwave and insufficient SBS interaction occurs. Moreover, if T_p is high enough, there will be several pulses that experience this kind of insufficient SBS interaction. Consequently, the pulse compression results carried by these probe pulses can be processed by different parts of the microwave signal.

The percentage of the actually interacted pump lightwave P_{k+l} ($P_n = 0$ or $P_n = 1$ means none or entire pump lightwave interact with the n-th probe pulse, respectively) for the k+l pulse can be deduced as follow,

$$P_{k+l} = \frac{(k+l)T_p + T - d}{D}, l = 0,1,\cdots,\left\lfloor \frac{D}{T_p} \right\rfloor \qquad (1)$$

where $\lfloor x \rfloor$ means the biggest integer less than x.

In this way, by calculating the P_{k+l}, the d of the microwave signal can be determined by,

$$d = (k+l)T_p - P_{k+l}D + T, l = 0,1,\cdots,\left\lfloor \frac{D}{T_p} \right\rfloor \qquad (2)$$

III. EXPERIMENTAL DETAIL

Proof-of-concept experiment is carried out to measure an LFM pulse signal. The experimental setup is depicted in Fig. 2. The lightwave generated by a 1550 nm distributed-feedback laser (DFB-LD, NEL NLK1C6DAAA) is divided into two branches by a 1:1 coupler. The upper branch is shaped by a pulse train via an electro-optic modulator (EOM, Eospace AX-6K5-10-PFU-PFUP-R4) as the probe lightwave, and the lower branch is modulated by the LFM pulse through a single sideband modulator (SSBM) as the pump lightwave. The polarization controllers (PC1 and PC2) are used to optimize the lightwave polarization before modulators. Erbium-doped fiber amplifiers (EDFA1 and EDFA2) are utilized to compensate and control the optic power that launched into the fiber. PC3 and PC4 are used to maximize the SBS gain. The modulated pump and probe lightwaves are injected into the fiber from two ends. The amplified probe lightwave goes through a circulator and a photo-detector (PD) converts its optical power into the electrical voltage. The data is captured by an oscilloscope (OSC, Tektronix DSA70804).

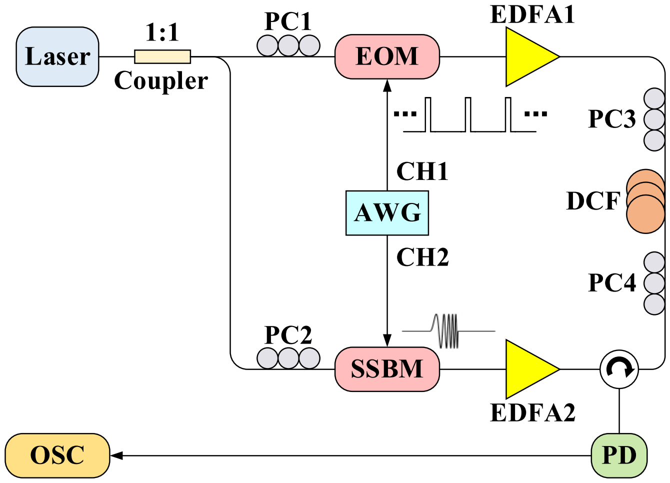

Fig. 2. Experimental setup for the measurement of the absolute time delay in an SBS-based all-optical pulse compression system. PC: polarization controller. EOM: electro-optic modulator. SSBM: single sideband modulator. EDFA: erbium-doped fiber amplifier. DCF: dispersion compensation fiber. PD: photo-detector. OSC: oscilloscope.

The fiber used for SBS interaction is a 2 km dispersion compensation fiber (DCF) and T = 13.405 μs is measured in advance. The D of the LFM pulse is 2.048 μs and its frequency sweeps from 9.672 GHz to 10.672 GHz, where 9.672 GHz is the Brillouin frequency shift of the DCF. The T_p of the probe pulse train is set to be 128 ns (which means the first 16 pulses could experience the insufficient SBS interaction) and the pulse width is 500 ps. Both the LFM pulse and probe pulse train are generated by a two-channel arbitrary waveform generator (AWG, Keysight M8195A) with 25 GHz analog bandwidth. The optical powers of pump and probe lightwaves that enter the DCF are 17 dBm and 15 dBm, respectively.

Figure 3 shows the measurement result for an LFM pulse with d = 16.745 μs. For convenience, we focus on the time delay $d' = d - T$, which means d' = 3.340 μs for this LFM pulse. The received signal is given in Fig. 3(a). The 26th pulse is found as the first pulse to interact with the LFM signal, which proves the coarse estimation $26\times T_p < d' < 27\times T_p$. The 16 pulses that experience the insufficient interaction is marked in Fig. 3(a). It should be mentioned that the pump lightwave reflected by the DCF is also received but it doesn't affect the measurement result. As the same to the work in [13], the probe gain is obtained by an on-off and power subtraction process. Figure 3(b) gives the pulse compression results for these 16

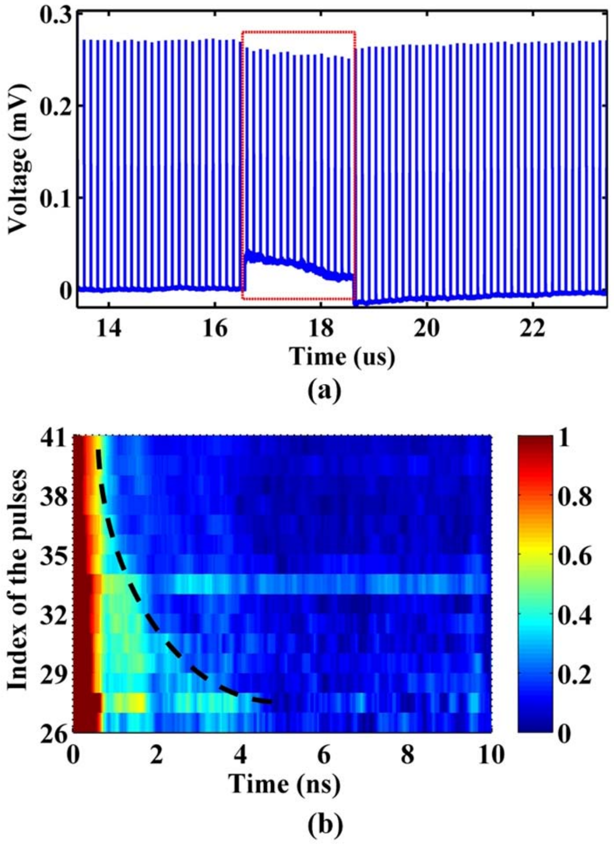

Fig. 3. The experimental result for an LFM pulse. (a) The received probe pulse train after SBS interaction. The marked 16 pulses are the first 16 to interact with the LFM pulse and experience the insufficient SBS interaction. (b) The net Brillouin gain for these 16 pulses.

pulses. As it is shown in the black dashed line, the width of the mainlobe τ from each pulse is shorter than the previous pulse. This is because the former pulse interacts with less part of the LFM signal, which can be considered as an LFM signal with smaller bandwidth B and thus the τ becomes larger.

According to Eq. (2) and the τ-B relationship for the LFM pulse, the d' of the LFM signal can be determined as,

$$d' = (k+l)T_p - \frac{D}{\tau_{k+l}B}, l = 0,1,\cdots,15 \qquad (3)$$

where B is the bandwidth of the original LFM pulse. In the proof-of-concept experiment, B = 1 GHz.

Despite the information is enough to calculate the time delay d' for single n-τ_n pair, measurement resolution can be improved by the parameter fitting. Figure 4 shows the calculated n-τ_n data and the fitting results for measurement. Three experiments are carried out with the time delay d' = 3.340 μs, 3.590 μs, and 3.890 μs. The corresponding n-τ_n data are given in different symbols. It should be mentioned that for the first two pulses, the theoretical τ is larger than 10 ns, which is around the phonon lifetime of the DCF. According to the analysis in [13], the compression results for these pulses is

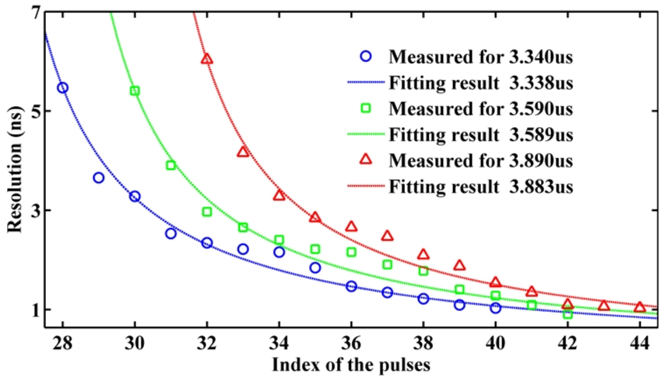

Fig. 4. The measured n-τ_n data and corresponding fitting results with d' = 3.340 μs, 3.590 μs, and 3.890 μs, respectively. The estimation for time delays are 3.338 μs, 3.589 μs, and 3.883 μs, respectively.

seriously distorted. Thus the determination of τ for these pulses is meaningless and we just show the other pulses' data. Using Eq. (3), the fitting curves for these data are also given in dashed lines and the fitting for d' are 3.338 μs, 3.589 μs, and 3.883 μs, respectively. The estimation results are close to the ideal values and the maximum error is about 7 ns.

IV. CONCLUSION

We have demonstrated a novel scheme to measure the absolute time delay of an unknown microwave signal processed in an SBS based pulse compression system. Through using the probe pulse train with high repetition rate, the absolute time delay information of the signal can be reconstructed due to the insufficient SBS interaction. Measurement for an LFM pulse with 1 GHz bandwidth has been implemented. The experimental data fits well with the theoretical analysis and the measured error is less than 7 ns. It should be pointed out that, since the principle for this scheme is general, the practical waveform is not limited to the LFM pulse.

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