



# Accurate measurement of time delay of broadband microwave signal via high-repetition-rate pulse train probing SBS based all-optical pulse compression

XIN LONG, WEIWEN ZOU,\* YI JI, AND JIANPING CHEN

State Key Laboratory of Advanced Optical Communication Systems and Networks, Department of Electronic Engineering, Shanghai Jiao Tong University, Shanghai, 200240, China

\*wzou@sjtu.edu.cn

**Abstract:** We demonstrate a novel scheme to determine the absolute time delay of an unknown signal in an all-optical pulse compression system based on stimulated Brillouin scattering (SBS). Optical pulse train with high repetition rate is utilized as the probe lightwave and unknown broadband microwave signal is modulated on the pump lightwave. The pump and probe lightwaves interact along an optical fiber via SBS. The finite optical fiber length and high pulse repetition rate of probe signal make SBS insufficient since the first several probe pulses meet a part of the entire pump signal. The absolute time delay of the unknown microwave signal is determined through the amplitude variations of the pulse compression results, which are intrinsically carried by the probe pulses suffering insufficient SBS gain. The measurement of the absolute time delay is theoretically analyzed and is experimentally demonstrated. The maximum experimental error is about 7 ns for a linearly frequency-modulated pulse with 1 GHz sweep range at the center frequency of 10 GHz.

© 2017 Optical Society of America under the terms of the [OSA Open Access Publishing Agreement](#)

**OCIS codes:** (070.1170) Analog optical signal processing; (190.0190) Nonlinear optics; (290.5900) Scattering, stimulated Brillouin.

## References and links

1. C. E. Cook, "Pulse compression-key to more efficient radar transmission," in *Proceedings of the Institute of Radio Engineers* (IEEE, 1960), pp. 310–316.
2. S. Pan and J. Yao, "Photonics-based broadband microwave measurement," *J. Lightwave Technol.* **35**(16), 3498–3513 (2017).
3. J. Yao, "Microwave photonics," *J. Lightwave Technol.* **27**(3), 314–335 (2009).
4. J. Capmany and D. Novak, "Microwave photonics combines two worlds," *Nat. Photonics* **1**(6), 319–330 (2007).
5. P. Ghelfi, F. Laghezza, F. Scotti, G. Serafino, A. Capria, S. Pinna, D. Onori, C. Porzi, M. Scaffardi, A. Malacarne, V. Vercesi, E. Lazzeri, F. Berizzi, and A. Bogoni, "A fully photonics-based coherent radar system," *Nature* **507**(7492), 341–345 (2014).
6. H. Zhang, W. Zou, and J. Chen, "Generation of a widely tunable linearly chirped microwave waveform based on spectral filtering and unbalanced dispersion," *Opt. Lett.* **40**(6), 1085–1088 (2015).
7. W. Zou, S. Yang, X. Long, and J. Chen, "Optical pulse compression reflectometry: proposal and proof-of-concept experiment," *Opt. Express* **23**(1), 512–522 (2015).
8. J. Zhang and J. Yao, "Time-stretched sampling of a fast microwave waveform based on the repetitive use of a linearly chirped fiber Bragg grating in a dispersive loop," *Optica* **1**(2), 64–69 (2014).
9. D. Marpaung, B. Morrison, M. Pagani, R. Pant, D.-Y. Choi, B. L. Davies, S. J. Madden, and B. J. Eggleton, "Low-power, chip-based stimulated Brillouin scattering microwave photonic filter with ultrahigh selectivity," *Optica* **2**(2), 76–83 (2015).
10. G. C. Valley, "Photonic analog-to-digital converters," *Opt. Express* **15**(5), 1955–1982 (2007).
11. A. Khilo, S. J. Spector, M. E. Grein, A. H. Nejadmalayeri, C. W. Holzwarth, M. Y. Sander, M. S. Dahlem, M. Y. Peng, M. W. Geis, N. A. DiLello, J. U. Yoon, A. Motamedi, J. S. Orcutt, J. P. Wang, C. M. Sorace-Agaskar, M. A. Popović, J. Sun, G. R. Zhou, H. Byun, J. Chen, J. L. Hoyt, H. I. Smith, R. J. Ram, M. Perrott, T. M. Lyszczarz, E. P. Ippen, and F. X. Kärtner, "Photonic ADC: overcoming the bottleneck of electronic jitter," *Opt. Express* **20**(4), 4454–4469 (2012).
12. G. Yang, W. Zou, L. Yu, K. Wu, and J. Chen, "Compensation of multi-channel mismatches in high-speed high-resolution photonic analog-to-digital converter," *Opt. Express* **24**(21), 24061–24074 (2016).
13. X. Long, W. Zou, and J. Chen, "All-optical pulse compression of broadband microwave signal based on stimulated Brillouin scattering," *Opt. Express* **24**(5), 5162–5171 (2016).

14. Y. Ji, W. Zou, X. Long, and J. Chen, "Signal-to-noise ratio enhancement of stimulated Brillouin scattering based pulse compression of an ultrabroad microwave signal by use of a dispersion compensation fiber," *Opt. Lett.* **42**(15), 2980–2983 (2017).
15. H. Jiang, D. Marpaung, M. Pagani, K. Vu, D. Choi, S. J. Madden, L. Yan, and B. J. Eggleton, "Wide-range, high-precision multiple microwave frequency measurement using a chip-based photonic Brillouin filter," *Optica* **3**(1), 30–34 (2016).
16. X. Long, W. Zou, and J. Chen, "Broadband instantaneous frequency measurement based on stimulated Brillouin scattering," *Opt. Express* **25**(3), 2206–2214 (2017).
17. W. Zou, Z. He, and K. Hotate, "Demonstration of Brillouin distributed discrimination of strain and temperature using a polarization-maintaining optical fiber," *IEEE Photonics Technol. Lett.* **22**(8), 526–528 (2010).
18. D. P. Zhou, W. Li, L. Chen, and X. Bao, "Distributed temperature and strain discrimination with stimulated Brillouin scattering and Rayleigh backscatter in an optical fiber," *Sensors (Basel)* **13**(2), 1836–1845 (2013).
19. Y. Mizuno, N. Hayashi, H. Fukuda, K. Y. Song, and K. Nakamura, "Ultrahigh-speed distributed Brillouin reflectometry," *Light Sci. Appl.* **5**(12), e16184 (2016).
20. N. Levanon and E. Mozeson, *Radar Signals* (John Wiley & Sons, 2004).
21. R. W. Boyd, *Nonlinear Optics* (Academic, 2003).

## 1. 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 with the advantages of high frequency resolution and good flexibility in digital processing. However, pure electronic systems is difficult to deal with the microwave signals with high frequency and broad bandwidth due to the limited bandwidth 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 and the required matched filtering are implemented in the digital domain after sampling and quantization of the received signal. Meanwhile, these digital processing systems gradually face challenges for the analog-to-digital convertor (ADC), 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.

An all-optical pulse compression technique based on the stimulated Brillouin scattering (SBS) in optical fibers was recently proposed [13]. The stimulated acoustic wave inherits the amplitude and phase information of the pump or probe lightwave. Conditions of time inverse and amplitude conjunction for the matched filtering of the pulse compression technique are naturally satisfied during the SBS interaction. The pulse compression of the modulated microwave signal is contained in the Brillouin gain carried by the probe lightwave. By using an optical fiber with high Brillouin gain coefficient, the bandwidth of the microwave signal to be processed can reach up to 5 GHz [14]. As the matched filtering processing is employed in the analogue domain, the sampling rate and ADC bandwidth for detection or data recording could be effectively reduced.

However, there is one vital problem to be solved before this technique are utilized in a practical radar system, that is, the determination of the microwave signal's absolute time delay. The essential problem is that the SBS based all-optical pulse compression scheme [13] implements the self-correlation of the pump wave that is modulated by the broadband microwave signal. No matter when the microwave signal modulated pump lightwave is launched into the optical fiber, the received probe pulse is always the same result as long as the SBS interaction is sufficient. The absolute time delay of the microwave signal is lost.

In this paper, we demonstrate a novel scheme to measure the absolute time delay of the microwave signal in the SBS based pulse compression system. In the previous scheme [13, 14], the probe lightwave was a single pulse. In this novel scheme, the probe lightwave is replaced by a pulse train with a relatively high repetition rate (the repetition rate, typically tens of MHz, is more than the reciprocal of the duration of the signal to be measured). Under this condition, insufficient SBS 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) carried by these probe pulses are generated by different portions of the modulated pump lightwave, which is intrinsically decided by the relative time of the modulated pump lightwave launched into the fiber. After signal processing, the absolute time delay can be estimated by the amplitude variations from these pulse compression results. We experimentally demonstrate the measurement of a linearly frequency-modulated (LFM) pulse with 1 GHz sweep range at 10 GHz. The experimental result is in a good agreement with the theoretical analysis and the maximum detection error is 7 ns.

## 2. Principle

Similar to the structure in [13], the pump lightwave is modulated by the broadband microwave signal with duration  $D$ . However, the counter-propagating probe lightwave is a short pulse train with the repetition rate of  $T_p$  instead of a single pulse. If a probe pulse meets the modulated pump lightwave in the fiber, the pump lightwave will be compressed in the probe gain and then detected.

In this scheme, the absolute time delay  $\Delta t$  of an unknown microwave signal is defined by the time difference between the moment when the 0th probe pulse is launched into the fiber and the moment when this unknown signal is received. Assuming that the  $k$ -th probe pulse is the first one to interact with the unknown microwave signal (i.e. the first probe pulse obtains Brillouin gain), a preliminary coarse estimation of  $\Delta t$  can be decided as  $(k-1)T_p + T < \Delta t < kT_p + T$ , where  $T$  is the time-of-flight of any pulse travelling through the entire fiber. It can be seen that the resolution of this estimation is  $T_p$ . Therefore, one simple aspect to improve the resolution is to set a shorter  $T_p$  of the probe pulse train. However, a shorter  $T_p$  usually means less Brillouin gain differences among the adjacent pulses and it is more difficult to find this “first” pulse.

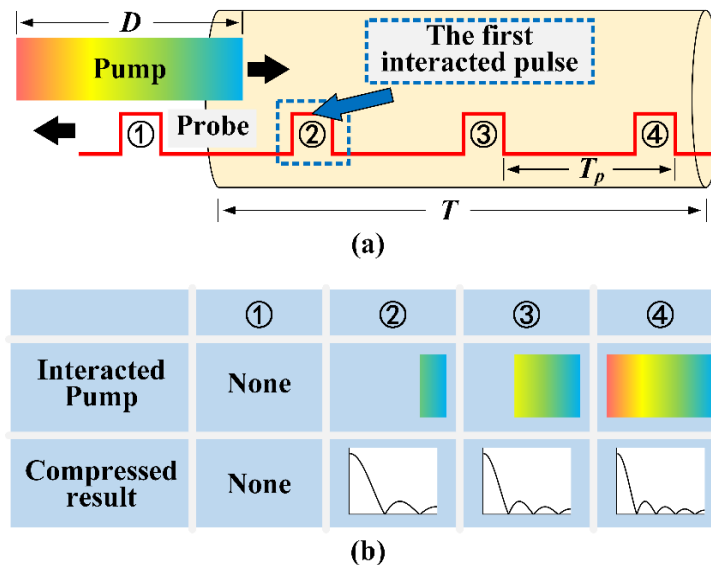


Fig. 1. (a) Insufficient SBS interaction between the pump lightwave and probe pulse train. (b) The first several pulses meet different portions of the modulated pump lightwave. The pulse compressed results are different from each other.

For the so-far Brillouin based signal processing schemes [13–16], the insufficient interaction was not preferred. The optical fiber should be long enough and the pump and probe lightwaves cannot be launched at any time. It needs to be ensured that both pump and

probe lightwaves can meet and interact completely with each other in the fiber. However, in the scheme demonstrated in this study, the insufficient SBS interaction between pump and probe lightwaves are newly utilized to obtain the precise estimation of  $\Delta t$ . Note that the insufficient or localized SBS interaction was well employed in the SBS based distributed sensing techniques [17–19]. The so-called insufficient interaction is illustrated in Fig. 1. When the modulated pump lightwave is launched into the fiber, the nearest probe pulse, i.e. the second pulse from left in Fig. 1(a), is the first pulse to interact with the pump lightwave. If the condition that  $T_p < D$  is satisfied, this pulse definitely 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 can experience this kind of insufficient SBS interaction. As it is shown in Fig. 1(b), for these pulses, they meet different portions of the pump lightwave. Consequently, the pulse compression results carried by these probe pulses would be different from each other, which is correspondingly decided by the absolute time delay of the modulated pump lightwave.

Figure 2 gives two examples of the SBS interaction. The specific portions of the interacted pump lightwaves are marked with black squares for different probe pulses. Suppose the  $k$ -th pulse is the first probe pulse that meets and interacts with the front part of the pump lightwave. Due to the high  $T_p$ , there are still several probe pulses that experience the insufficient SBS interactions and more and more portions of the pump lightwave will be compressed. If the optical fiber is long enough ( $T > D$ ), there will be some probe pulses that interact with the entire pump lightwaves [see the index of  $k + 4$  and  $k + 5$  in Fig. 2(a)]. Otherwise ( $T < D$ ), all interactions are insufficient [see Fig. 2(b)]. It should be pointed out that, the last (several) probe pulses suffer the same situation of the insufficient SBS gain, which can be also used for the estimation of the absolute time. Without loss of generality, we only discuss the case of the first several probe pulses in this study.

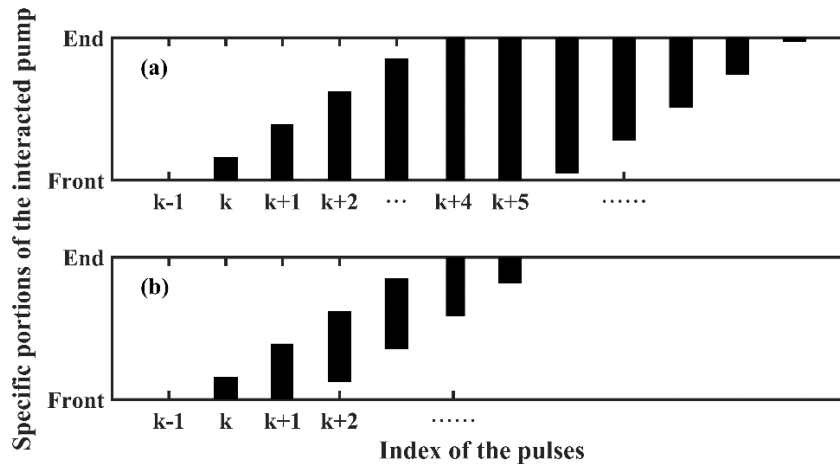


Fig. 2. Illustration of the pump-probe overlap in the fiber. The black squares represent the portions of the interacted pump lightwaves. (a) The fiber length is long enough ( $T > D$ ) and several SBS sufficient interactions occur. (b) The fiber length is relatively short ( $T < D$ ) and all SBS interactions are insufficient.

The portions  $P$  of the interacted pump lightwaves for each probe pulse is dependent on  $\Delta t$ , where  $P_n = 0$  or  $P_n = 1$  means none or entire pump lightwave interact with the  $n$ -th probe pulse, respectively. For the purposes of this manuscript, it is illustrative to consider the portion  $P$  for the first group of probe pulses that experience insufficient interaction [e.g., the pulses  $k, k + 1, \dots, k + 3$  in Fig. 2(a)]. For a long length fiber, the interacting portion of this subset of probe pulses is given by,

$$P_{k+l} = \frac{(k+l)T_p + T - \Delta t}{D} \quad (1)$$

where  $\lfloor x \rfloor$  means the biggest integer less than  $x$ . The index  $k$  satisfies  $(k-1)T_p + T < \Delta t < kT_p + T$  as mentioned above and  $l$  denotes an integer within the following range:

$$l = 0, 1, \dots, \left\lfloor \frac{D}{T_p} \right\rfloor - 1 \quad (2)$$

Equation (1) shows that the portion  $P$  for each probe pulse increases by a fixed step of  $D/T_p$ . By determining the portion  $P$ , the  $\Delta t$  of the microwave signal can be precisely estimated by,

$$\Delta t = (k+l)T_p + T - P_{k+l}D \quad (3)$$

As illustrated in Fig. 1(b), the pulse compression results from different portions of the microwave signal are usually different from each other. And thus the portions  $P$  can be uniquely determined by the obtained pulse compression results from these insufficient interacted probe pulses. However, it should be pointed out that, the difficulty and accuracy of the determination is dependent on the waveform of the microwave signal to be processed. Two types of waveforms (i.e. LFM pulse and frequency Costas coded pulse) [20] are characterized in this study. They correspond to two different cases, where any part of this signal does or doesn't remain the same/similar variation patterns of their instantaneous frequency. Figure 3 depicts the simulation results of SBS based pulse compression from different portions of the microwave signal for two waveforms. Both pulses are set as 1 GHz bandwidth at the center frequency of 10 GHz and 1.6  $\mu$ s duration and the length of the Costas code is 40. All portions begin from the head of the microwave signal. The duration of the probe pulse is 500 ps and the phonon lifetime is 10 ns.

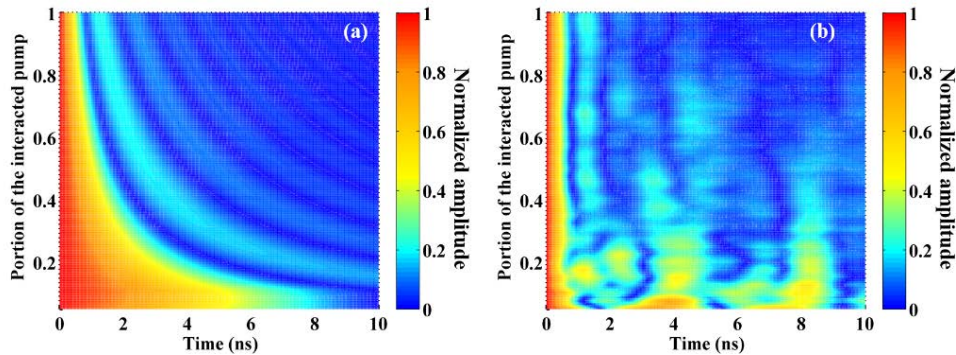


Fig. 3. Simulation results of SBS based pulse compression for different portions of two microwave waveforms. (a) LFM pulse and (b) frequency Costas coded pulse.

LFM pulse is such a waveform that any part of it is still an LFM pulse with the same frequency slope but different bandwidth and duration (proportional to the portion  $P$ ). The determination for this type of signal is easier because all pulse compression results from different portions share the same waveform type with different mainlobe's width. Thus the determination of  $P$  is realized through the determination of the mainlobe's width. As it is shown in Fig. 3(a), the pulse compression results are all *sinc* function and the compressed pulse narrows with the increase of the portions  $P$ . On the other hand, the frequency Costas coded pulse is a more complex waveform due to the strict definitions. A Costas code is in principle designed to suppress the sidelobe of its pulse compression and to avoid the range-Doppler coupling problem [20]. According to its definition, a Costas code cannot be created

through another code with shorter length, which means that one part of this code is no longer a Costas code. As a result, unlike the LFM pulse's case, the pulse compression results from different portions of the frequency Costas coded pulse is irregular [see Fig. 3(b)] and the determination of the portion  $P$  cannot be simplified as an estimation of the mainlobe's width.

### 3. Experimental results

The proof-of-concept experiment is carried out to measure an LFM pulse signal with different absolute time delay. The experimental setup is depicted in Fig. 4. 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. The lower branch is modulated by the LFM pulse through a single sideband modulator (SSBM), which is served 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 optical power 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 average optical powers of pump and probe lightwaves that enter the DCF are 17 dBm and 15 dBm, respectively. 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).

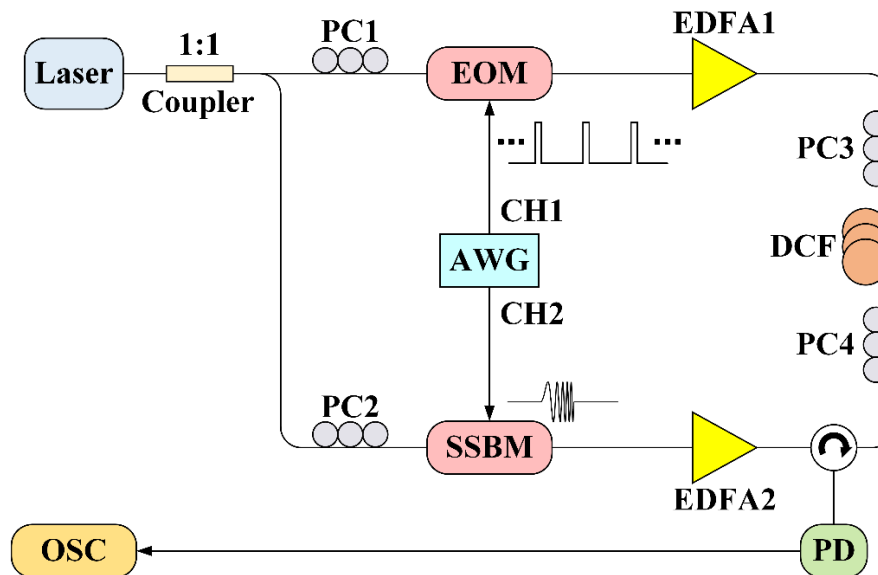


Fig. 4. Experimental setup of an SBS-based all-optical pulse compression system to measure the absolute time delay of a broadband microwave signal. PC: polarization controller. EOM: electro-optic modulator. SSBM: single sideband modulator. EDFA: erbium-doped fiber amplifier. DCF: dispersion compensation fiber. PD: photo-detector. OSC: oscilloscope.

For a better SNR of the pulse compression results, a dispersion compensation fiber (DCF) is used instead of standard single mode fiber as proved by work in [14]. The DCF used for SBS interaction is 2 km and  $T = 13.405 \mu\text{s}$  is measured in advance. The  $D$  of the LFM pulse is set to be about  $2.048 \mu\text{s}$  and its frequency sweeps from 9.672 GHz to 10.672 GHz, where 9.672 GHz is the Brillouin frequency shift of the DCF.  $T_p$  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 microwave signal and probe pulse train are generated by a

two-channel arbitrary waveform generator (AWG, Keysight M8195A) with 25 GHz analog bandwidth. The time difference  $\Delta t$  between the generations of the LFM pulse and probe pulse are set to different values so as to simulate absolute time delays. It is equivalent to the situation that both LFM pulse and the 0th probe pulse are generated at the same time and then the LFM pulse is received by our system after absolute time delay of  $\Delta t$  due to the target reflection (such as echoes). Note that the simultaneous generation for radar signal and the 0th probe pulse is not necessary. Knowing the relative time between the launching of the radar signal and the probe pulse train is enough.

Figure 5 shows the measured result for an LFM pulse with  $\Delta t = 16.745 \mu\text{s}$ . For convenience, we focus on the time delay  $\Delta t' = \Delta t - T$ , which means  $\Delta t' = 3.340 \mu\text{s}$  for this case. The received signal is given in Fig. 5(a). The 27th pulse is found as the first pulse to interact with the LFM pulse, which provides the coarse estimation of  $26 \times T_p < d' < 27 \times T_p$ . The 16 pulses that experience the insufficient interaction is marked in Fig. 5(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 its frequency is about 10 GHz away from the probe lightwave, which is out of the bandwidth of the OSC we used. Similar to the work in [13], the probe gain is obtained by a subtraction process between the power-on and -off of the pump lightwave. Figure 5(b) presents the pulse compression results for these 16 pulses. As shown in the black dashed line, the width of the mainlobes is shorter than the previous pulse, which is in a good agreement with the trend illustrated in Fig. 3(a).

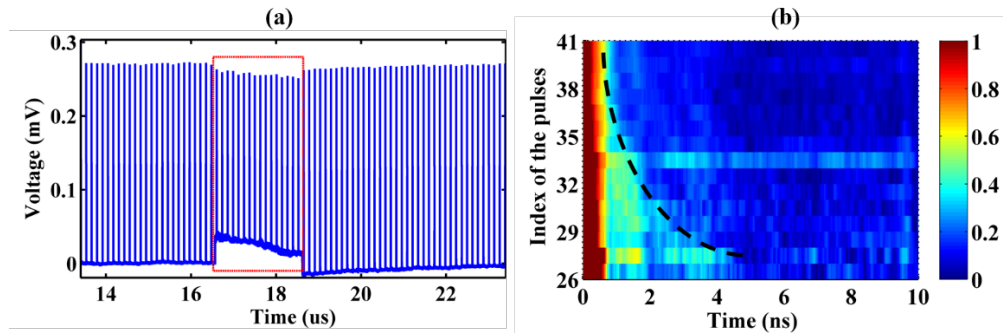


Fig. 5. Measured result of the absolute time delay for an LFM pulse. (a) The received probe pulse train after SBS interaction. The marked 16 pulses are the first 16 to interact with the LFM pulse and experience insufficient SBS interaction. (b) The distribution of the Brillouin gain for these 16 pulses. The gain is normalized to the maximum value.

According to Eq. (2) and the  $\tau$ - $B$  relationship ( $\tau$  is the range resolution for LFM pulse and  $\tau = 1/B$ ) for the LFM pulse's pulse compression [13],  $\Delta t' = \Delta t - T$  of the LFM signal can be determined by,

$$\Delta t' = (27 + l)T_p - \frac{D}{\tau_{27+l}B} \quad (4)$$

$$l = 2, 3, \dots, 15 \quad (5)$$

where  $B$  is the bandwidth of the LFM pulse and  $B = 1 \text{ GHz}$  in this study. The reason for  $l$  in Eq. (3) begins from 2 is that for the first two pulses, the theoretical  $\tau$  is larger than 10 ns, which is around the phonon lifetime of the silica fiber [21]. According to the analysis in [13], the compression results for these pulses is seriously distorted, which makes the determination of  $\tau$  for these two pulses difficult and inaccurate.

Despite a single pair of  $n$ - $\tau_n$  (i.e. the relation of the index of pulses versus the resolution of the  $n$ th pulse) is enough to calculate the time delay  $\Delta t'$ , the measurement resolution can be further improved by the parameter fitting. Figure 6 summarizes the measured  $n$ - $\tau_n$  for

different time delay of  $\Delta t' = 3.340 \mu\text{s}$ ,  $3.590 \mu\text{s}$ , and  $3.890 \mu\text{s}$ , respectively. According to Eq. (3), the fitting curves for these data are also plotted in solid lines. The fitting for  $\Delta t'$  are  $3.338 \mu\text{s}$ ,  $3.589 \mu\text{s}$ , and  $3.883 \mu\text{s}$ , respectively. The estimation results are close to the ideal values with the maximum error of about 7 ns.

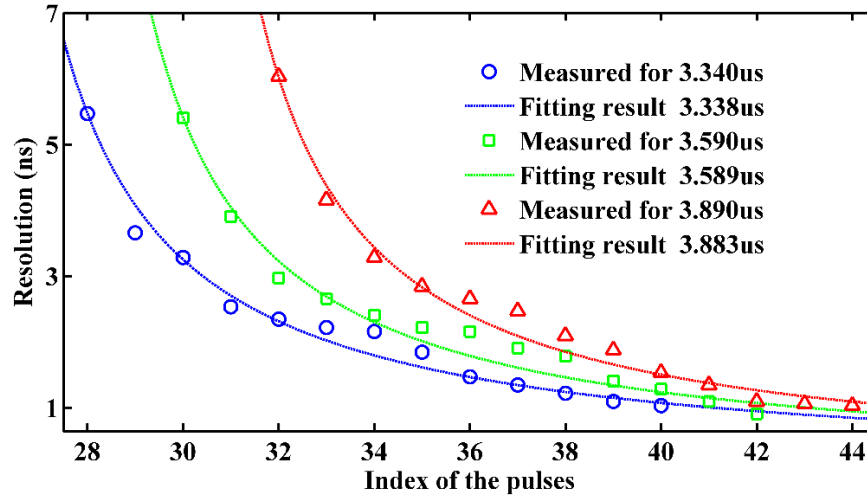


Fig. 6. Measured relation of the index of pulses versus the resolution of the  $n$ th pulse ( $n-\tau_n$ ) and the corresponding fitting results with  $\Delta t' = 3.340 \mu\text{s}$ ,  $3.590 \mu\text{s}$ , and  $3.890 \mu\text{s}$ , respectively. The estimation of the time delays are  $3.338 \mu\text{s}$ ,  $3.589 \mu\text{s}$ , and  $3.883 \mu\text{s}$ , respectively.

#### 4. Conclusion

We have demonstrated a novel scheme to measure the absolute time delay of an unknown broadband microwave signal processed in an SBS based pulse compression system. Through using the probe pulse train with high repetition rate, the absolute time delay of the microwave signal can be reconstructed due to the insufficient SBS interaction. Measurement for an LFM pulse with 1 GHz bandwidth at the center frequency of 10 GHz 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 the principle of this scheme is general so that the practical waveform is not limited to the LFM pulse. The further experimental verification of the scheme to other waveforms (such as a frequency Costas coded pulse) is now under study.

#### Funding

National Natural Science Foundation of China (grant no. 61571292 and 61535006)