Fast BOTDA acquiring method based on broadband light as a probe signal

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Abstract: We propose a fast BOTDA-based large dynamic strain measurement technique with a broadband ASE probe light. We demonstrate the distributed measurement of 25 Hz vibration with the 380 με amplitude.

1. Introduction

Dynamic strain (vibration) measurement by using distributed optical fiber sensing has gathered great attention to expand a value of communication optical fiber network. The Rayleigh-scattering-based technique is a major distributed dynamic strain sensing technique, widely known as distributed acoustic sensing (DAS). This technique has a competitive advantage in its high sensitivity and measurements of relatively weak dynamic strains such as traffic vibrations [1]. However, it is not suitable to measure dynamic strain with large amplitude over a few με accurately [2]. On the other hand, the Brillouin sensing technique has been utilized to measure the large amplitude of quasi-static strain over tens of με or more. Especially, Brillouin optical time domain analysis (BOTDA) is highly sensitive, and it has the potential to measure not only quasi-static but also dynamic strain. However, it is difficult to measure dynamic strain, because of measurement speed. The measurement of the typical BOTDA must be repeated with varying frequency differences between the pump and probe beams to obtain the Brillouin gain spectrum (BGS) by BOTDA. Recently, some cutting-edge techniques have been proposed to overcome this problem of measurement speed such as the optical frequency comb approach [3], optical chirped pulse approach [4] and optical chirped pulse chain approach [5]. These approaches realize high-speed measurement by eliminating the wavelength-sweep process. However, these approaches require complex setups such as the modulation of the complicated probe and the according detection system. In this paper, to realize the distributed dynamic strain measurement with the simple setup, we propose the fast BOTDA technique which utilizes the amplified spontaneous emission (ASE) light. By using the broadband ASE as the probe light and obtaining the BGS, we demonstrate the measurement of dynamic strain with the frequency of 25 Hz and the amplitude of 380 με.

2. Principle

Fig. 1 shows the overview of our fast BOTDA technique. In this technique, we utilize a broadband light source as a probe light. The bandwidth of the probe light is arranged to cover the spectral width of the Brillouin scattering. In this work, we adopt an ASE light as the broadband light because it can be prepared with a simple setup. We counter-propagate the normal narrow-bandwidth pump pulse and the continuous broadband ASE probe light along the fiber. By tuning the optical frequency difference between the pump pulse and the center of the continuous ASE probe to the Brillouin frequency shift (BFS) of the fiber (typically 10 ~ 11 GHz), they induce the stimulated Brillouin scattering along the fiber. At each fiber position, the energy of the pump is transferred to the ASE probe. Different from the typical BOTDA, the power change of the ASE probe occurs simultaneously at each frequency of BGS.

After the interaction along the fiber, we obtain the output light, which contains both the Rayleigh scattering component and the Brillouin scattering signal. We eliminate the Rayleigh scattering component and extract the Brillouin signal by using band pass filters (BPF) to enhance the measurement accuracy. We detect the Brillouin signal by using heterodyne detection so that the BGS is down-converted and transferred to the electrical signal domain with the center of the beat frequency between the used local light and the probe light. The obtained analog electrical signal is converted into a digital signal by using ADC, followed by digital signal processing. Because the electrical signal contains the entire obtained Brillouin scattering, the spectrum analysis such as the fast Fourier transform (FFT) of the signal gives the BGS information. Therefore, this method enables very fast dynamic strain measurement. Furthermore, this method uses the normal pulse width for the pump pulse, so it maintains the capability of the distributed measurement as the typical BOTDA.

As the concrete frequency analysis procedures, we adopt FFT processing with zero-padding. Obtained Brillouin scattering is separately analyzed by range of distance, we can obtain BGS at each range of distance by calculating FFT. This FFT window size can flexibly change its range of data and range of zero. After calculating the whole distance of BGS, to averaging the polarization state and conducting precisemeasurement, we calculate move mean of BGS at time axis. The maximum values of these BGS are BFS and we can plot by two dimension of distance axis and time axis.

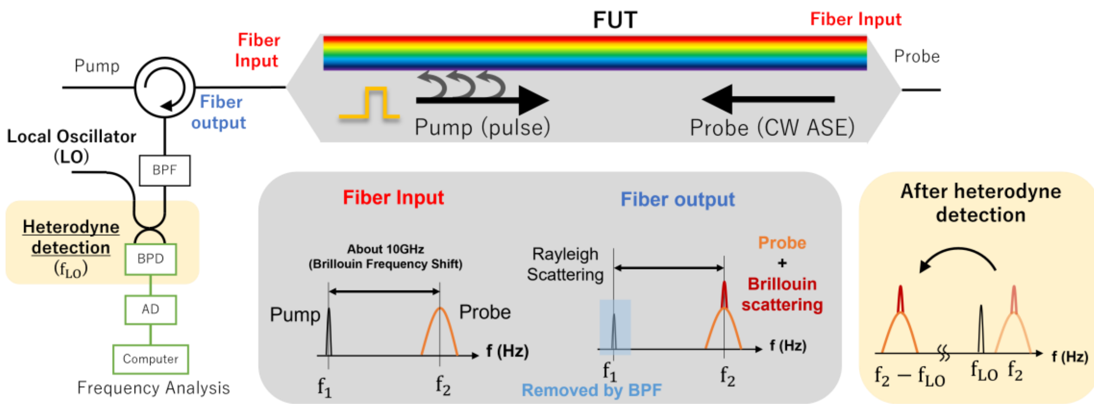

Fig. 1. Principle of ASE based BOTDA

3. Experiment and Result

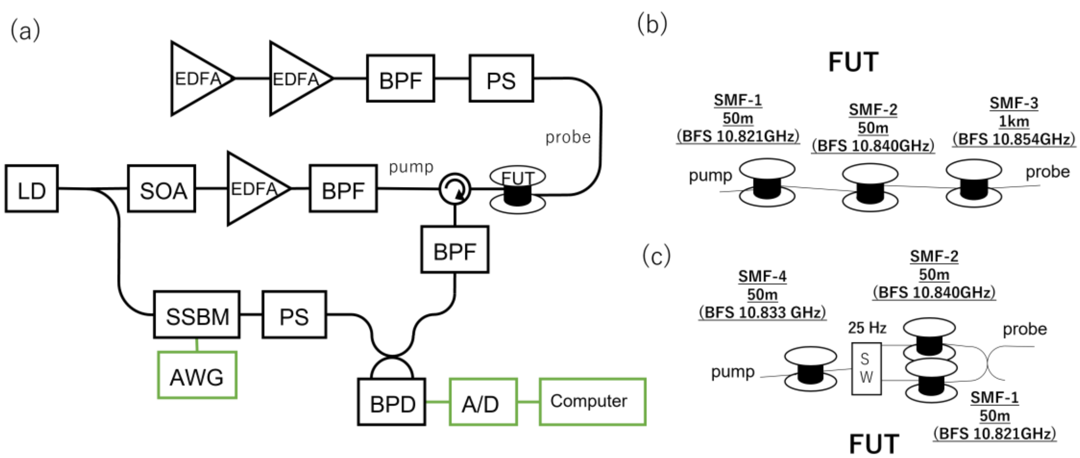

Fig. 2. Experimental setup

Fig.2 (a) shows a schematic of the experimental setup. In this experiment, we used a narrow linewidth laser to generate a source of the pump pulse. The operating wavelength and linewidth were 1550.088nm and 0.5 kHz, respectively. The semiconductor optical amplifier (SOA) reshaped laser source from CW to 100 ns pulse. We placed an optical filter to cut noise by an EDFA and passed the frequency of the pump pulse. On the other hand, probe light which was a CW ASE was generated by two EDFA. The first EDFA generate an ASE seed light and the second EDFA amplified it. Subsequently, we filtered outside range of BFS by BPF.

Fig. 2 (b) shows the configuration of the fiber under test (FUT) which consisted of 50m (SMF-1), 50m (SMF-2) and 1km (SMF-3). We utilized this FUT for static strain measurement. Fig. 2 (c) also shows the configuration of the fiber under test (FUT) which consisted of 50m (SMF-4), 50m redundant part (SMF-1 SMF-2) with a 1×2 optical switch to apply quasi-dynamic strain [4]. The BFS difference of the redundant part is 19 MHz (corresponding to 380 με [6]) and each BFS is 10.840 GHz (SMF-2) and 10.821 GHz (SMF-1). We can control the frequency of quasi-dynamic strain by changing the frequency of an electric signal applied to an optical switch. We conducted zero-padding FFT to 20 ns (corresponding to 2m of FUT) of output data. FFT window size was 1 μs, in which the signal length was 20 ns and we add zeros to no signal resion. In this way, we could detect the BFS with high accuracy.

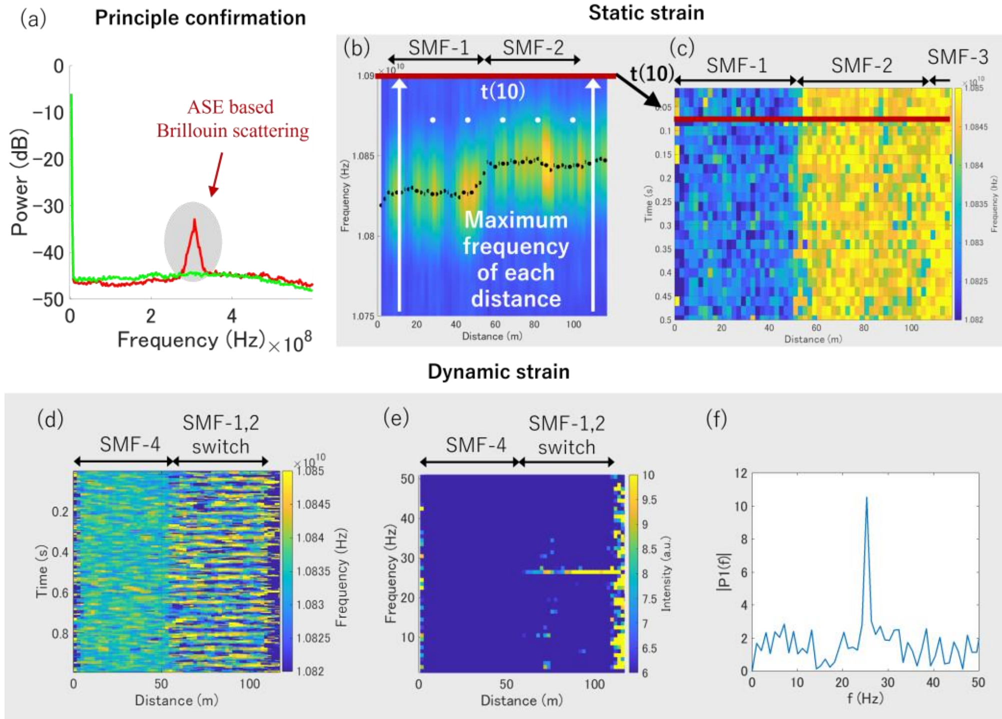

Fig. 3. Measurement result of Brillouin scattering by using the proposed technique. (a) BGS observed with the proposed method (red line), compared with the only ASE spectrum obtained without the pump pulse (green line). (b) Measured BGS along the FUT in the static condition at the single time. (c) Waterfall graph (distance vs. time) of the BFS variation in the static FUT condition. (d) Waterfall graph of the BFS representing the strain amplitude when the FUT experienced the vibration. (e) Obtained vibration spectrum map. (f) Vibration frequency spectrum at the single position.

Fig. 3 (a) shows fundamental concept validation. We connected 1km of the optical fiber as FUT and conducted measurements by the proposed method. We can find Brillouin scattering as the peak of the red line. On the other hand, the green line shows only measured probe ASE light, and we cannot find any peaks of frequency. This result implies Brillouin scattering occurred by ASE. Therefore, we experimentally confirmed that we can measure stimulated Brillouin scattering by the proposed method.

We conducted an experiment to apply static and quasi-dynamic strain to FUT and measured 50m spatial resolution fibers and 25 Hz quasi-dynamic strain. Fig. 3 (b) shows the BFS change along two different fibers with 50 m lengths. As a result, we recognized difference of BFSs of the two fibers by this technique. Therefore, the spatial resolution of this technique is greater than 50 m. Next, we conducted a timeseries measurement by same FUT. Fig. 3 (c) shows timeseries BFS of the calm situation we can identify two fibers clearly from 0 m to 50 m and after 50 m. Fig.3 (d) shows a result of quasi-dynamic strain measurement. We applied a 25 Hz quasi-dynamic strain. The period after 50 m shows periodic BFS change at colormap. This periodicity is each 0.04 s and corresponds to 25 Hz. Fig. 3 (e) shows the frequency of each distance by time axis and Fig. 3(f) shows the frequency spectrum and has a 25 Hz peak. Therefore, we correctly measured 25 Hz by this technique.

4. Conclusion

We proposed ASE based BOTDA measurement and conduct principal confirmation by laboratory experiment. The quasi-dynamic strain is applied to FUT, and we measure distributed dynamic strain with greater than 50 m spatial resolution and dynamic strain with frequency of 25 Hz.

5. References

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