

# Strain event detection using a double-pulse technique of a Brillouin scattering-based distributed optical fiber sensor

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**Abstract:** Stimulated Brillouin scattering in optical fibers can be used to measure strain or temperature in a distributed manner. Brillouin optical time domain analysis (BOTDA) is the most common sensor system based on the Brillouin scattering. To improve the spatial resolution of these measurements, shorter pulses must be used, resulting in reduced signal powers causing a decrease of the dynamic range. In this paper, a double-pulse technique was proposed to enhance the spatial resolution of BOTDA. Experimental results showed that the ability to resolve two adjacent events could be enhanced, about twice, by using a double-pulsed pump light without decreases in the dynamic range.

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## References and links

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## 1. Introduction

A large number of optical fiber sensors have been proposed and developed throughout the world [1]. Among these, distributed fiber sensors are the most attractive because they can operate over long distances because of the low loss optical fiber and their cost may be less than that of a large number of point sensors combined with an information-gathering network.

Distributed sensing techniques are commonly based on optical time domain reflectometry (OTDR) [2]. In OTDR, optical pulses are launched into an optical fiber and the variations in backscattering intensity caused by physical change of the fiber is detected as a function of

time. However, since Rayleigh scattering is very weak especially in single mode optical fiber and at long wavelength, and since it has a low signal to noise ratio, a new class of optical fiber attenuation measurement techniques, that are based not on Rayleigh backscattering but on Brillouin scattering, have been proposed and experimentally demonstrated [3]. Brillouin optical time domain analysis (BOTDA) was first proposed as a nondestructive attenuation measurement technique for optical fibers [4]. BOTDA uses Brillouin gain spectroscopy, in which a pulsed light and a counter-propagating continuous-wave (CW) light are launched into an optical fiber. Brillouin scattering-based distributed optical fiber sensing allows for determination of either strain or temperature changes through measurement of the Brillouin spectrum of a fiber. The position at which the measured strains and temperatures are located along the fiber is determined by the time of flight for a pulse to propagate down and back through the fiber.

Since BOTDA uses a pulsed light as a pump light, the accuracy in determining the exact location and amount of physical changes (spatial resolution) depends on the width of the pulse. Spatial resolution of BOTDA is inversely proportional to the width of pulse. Therefore, a short pulse must be used for high spatial resolution. However, as the pulse width is reduced there is a decrease in the detected signal power and this low signal power, due to its low dynamic range, causes the length of an optical fiber used in measurements to be shortened.

BOTDA sensor system is very attractive for the health monitoring of a large structure due to its large number of sensing points and comparative low cost compared to its number of sensing points. The fracture mechanism of a structure is, generally, initiated by the micro-crack of the structure, and the large strain caused by a large deformation can be distributed around the micro-crack. For a structural health monitoring, it is important to get information about the local area where the large strain was distributed, such as amount of the strain, location and size of the local area. Here, the length of the spatial resolution of the BOTDA sensor must be shorter than the size of the local area to measure the strain values more exactly. However, the location and the size of the local area can be, comparatively, accurately detected through the high rate acquisition and signal analysis of the Brillouin backscattering light even for the longer length of the spatial resolution than the size of the local area. The resolution which is determined by the sampling rate of the Brillouin signal is, generally, called distance resolution.

In this paper, a new technique that enhances the spatial resolution of BOTDA is proposed. Experimental results reported in section 4 showed that the spatial resolution (particularly, the determination of the exact location of a fiber under strain changes) could be enhanced, without severe decrease of the dynamic range, by using a double-pulse that has same width as a single pulse.

## 2. Theory

### 2.1. Stimulated Brillouin scattering and Brillouin gain

When electromagnetic radiation of optical frequencies travels through matter various spontaneous scattering processes can occur such as Rayleigh scattering, Brillouin scattering and Raman scattering. When light is scattered by acoustic phonons we speak of Brillouin scattering. Acoustic phonons (thermally excited lattice vibration with acoustic mode) produce a periodic modulation of the refractive index. Brillouin scattering occurs when light is diffracted backward on this moving grating, giving rise to frequency shifted Stokes and anti-Stokes waves. Since the scattered light undergoes a Doppler frequency shift, the Brillouin frequency (frequency difference between pump light and scattered light)  $\nu_B$  depends on the acoustic wave velocity and is given by

$$\nu_B = \frac{2nV_a}{\lambda_p} \quad (1)$$

where  $V_a$  is the acoustic wave velocity within the fiber,  $n$  is the refractive index and  $\lambda_p$  is the wavelength of the incident pump lightwave. The spectral width  $\Delta\nu_B$  is very small and is related to the damping time of acoustic waves or the phonon lifetime  $T_B$ . In fact, if the acoustic waves are assumed to decay as  $\exp(-t/T_B)$ , the Brillouin gain has a Lorentzian spectral profile given by

$$g_B(\nu) = g_B(\nu_B) \frac{(\Delta\nu_B/2)^2}{(\nu - \nu_B)^2 + (\Delta\nu_B/2)^2} \quad (2)$$

where  $\nu_B$  is the full width at half maximum (FWHM). The Brillouin gain spectrum (BGS) peaks at the Brillouin frequency  $\nu_B$ , and the peak value is given by the Brillouin gain coefficient  $g_0$

$$g_B(\nu_B) = g_0 = \frac{2\pi n^7 p_{12}^2}{c \lambda_p^2 \rho_0 V_a \Delta\nu_B} \quad (3)$$

where  $p_{12}$  is the longitudinal elasto-optic coefficient,  $\rho_0$  is the material density,  $c$  is the vacuum velocity of light and  $\lambda_p$  is the pump light wavelength [5][ 6].

## 2.2. Backscattering signal of single and double-pulse

The widely used measurement technique of the Brillouin gain spectrum to date is the so-called pump and probe technique. It is based on two separate light sources. The first is used to pump the medium whereas the second generates a frequency tunable probe signal. The BGS is determined by measuring the amplification of the probe light when the frequency difference between the pump and probe light corresponds to the Brillouin frequency. BOTDA launches pulsed pump light into a fiber and then measures, as a function of time after the launch, the power of Brillouin backscattering signal returned to the photo detector. By measuring the arrival time of the returning light, the locations and magnitudes of physical changes can be determined. One way to detect the positions of the optical fiber under strain or temperature changes is to measure the backscattering power at fixed frequency modulation of the probe light near the Brillouin frequency. If backscattering signal is observed in the time (or distance) domain, it can easily be seen that the signal value of the fiber position under Brillouin frequency shift caused by strain or temperature changes is lower than signal values of other positions.

The difference between single pulse and double-pulse is whether the pulse has a separation or not. A double-pulse consists of two single pulses and there is a separation between the two identical single pulses. In the case of a single pulse, when the leading pulse edge falls in the strain section the backscattering signal power begins to decrease and starts to recover when the trailing pulse edge falls in the strain section. There is a similar variation of backscattering signal power in the case of a double-pulse except showing an additional peak caused by its separation. An example of the schematic diagram of expected backscattering signal power is shown in Fig. 1 and Fig. 2. As shown in Fig. 1 and Fig. 2, the location of a fiber under strain or temperature changes can be detected by observing the valley points of signal power for single pulse and peak points for double-pulse.

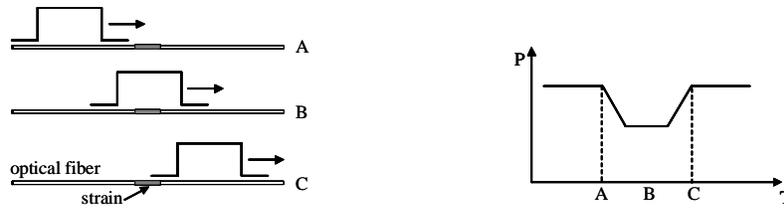


Fig. 1. Locations of a single pulse (left) and its corresponding scattering power (right) at fixed frequency modulation of probe light.

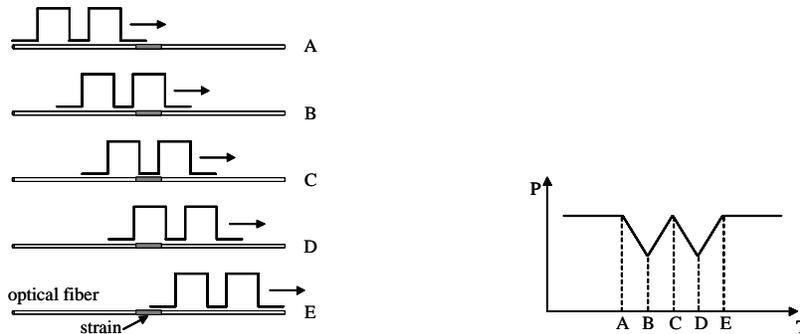


Fig. 2. Locations of a double-pulse (left) and its corresponding scattering power (right) at fixed frequency modulation of probe light.

### 3. Experimental setup

The pump and probe configuration shown in Fig. 3 was used to measure the Brillouin gain spectrum. The output of DFB LD at 1553 nm is first split by a coupler. One output of the coupler is amplitude-modulated by a 2.5 Gb/s electro-optic modulator to generate pulses. This pump light is amplified by Erbium-doped fiber amplifier (EDFA) and is launched into a test fiber. The other output of the coupler is frequency-modulated by a 10 Gb/s electro-optic modulator and is launched into opposite ends of the test fiber. This configuration offers determining advantages such as no dependence on the laser frequency drift and no need of a tunable laser source [7].

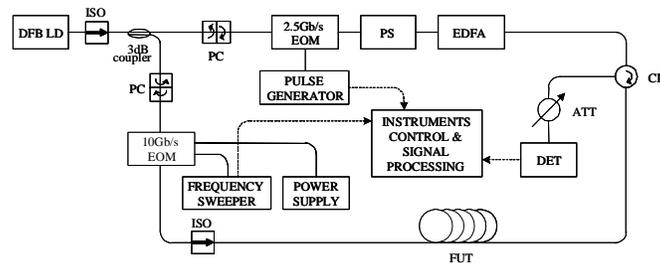


Fig. 3. Experimental setup for Brillouin gain spectrum measurements. (ISO = isolator, PC = polarization controller, PS = polarization scrambler, DET = detector, ATT = attenuator, CIR = circulator.)

The BGS was measured by sweeping the modulation frequency  $f_m$  in the vicinity of the Brillouin frequency  $\nu_B$  and by detecting the total intensity of the probe light using photo receiver. The output voltage signals of the photo receiver were acquired by a data acquisition (DAQ) board at 100 MHz sampling rate, which corresponds to 1 m distance resolution.

The probe light signal detected by a photo detector is classified into two power signals such as the power detected before the launch of the pulse-top and the power detected after the launch of the pulse-top. Hence, the net Brillouin gain amplified by a contribution of the pulse-top was obtained through subtracting the power detected before the launch of the pulse-top from the power detected after the launch of the pulse-top.

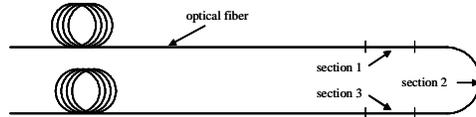


Fig. 4. Configuration of the fiber under test. (section 1 and section 3: strained sections, section 2: free fiber section.)

Figure 4 shows the configuration of the fiber under test. Section 1 and section 3 were elongated fiber sections both of which were 2m in length. The strain of section 1 and section 3 was about  $1000 \mu\epsilon$ . Section 2 was a free fiber section and was inserted between the two elongated sections. Single pulse of 80 ns and double-pulse of 40-20 ns were launched into the test fiber. Here, '40-20 ns double-pulse' means the double-pulse which consists of two identical 40 ns single pulses and 20 ns separation between the two single pulses. In this paper, from now on, double-pulse will be expressed like above notation. The Brillouin gain signals of single and double-pulse were compared each other in the several cases of section 2 such as 2 m, 3 m, and 4 m. About 2.1 km dispersion-shifted single-mode fiber (DSF) manufactured by Sumitomo Electronic Industries was used in these experiments.

#### 4. Experimental results

First, BGS's were obtained with and without the 2m elongated fiber section for both single and double-pulse cases. The optical power of the pulse-top was 360 mW. The results are shown in Fig. 5 and Fig. 6. The elongated fiber section was located approximately at the position of 1850 m. Figure 5 shows the 3-dimensional BGS obtained through the injection of a 80 ns single pulse and the BGS's for different widths of launched pulses at the fiber position of 1800 m. Brillouin gain decrease and linewidth broadening of the BGS were observed, as shown in the Fig. 5, as the pulse width was reduced. The BGS's of single and double-pulses were compared, as shown in Fig. 6, and BGS's of double-pulses for different separation widths were also compared. It is noticed that the Brillouin gain of the double-pulse slightly decrease due to the separation when compared to the single pulse which has the same pulse-top width as the double-pulse, and it is also noticed that the Brillouin gain of the double-pulse decreases as the separation width is increased, as shown in Fig. 6.

The locations of a fiber under strain change can be determined by scanning the backscattering signal power and by detecting the signal power-decreased point. If the signal powers are normalized through subtracting the signal powers measured without strained section from those measured with strained section, the locations of a fiber under strain change can easily be detected. The signal power values of a Brillouin frequency 10.509 GHz were considered to search for the signal power-decreased point. Figure 7 shows the normalized backscattering power values along the fiber. When a single pulse is used as a pump light wave, the position that corresponds to the valley point can be estimated as the location of the fiber under strain. On the other hand, in the case of a double-pulse, the peak point can be considered to be the location of a fiber under strain change.

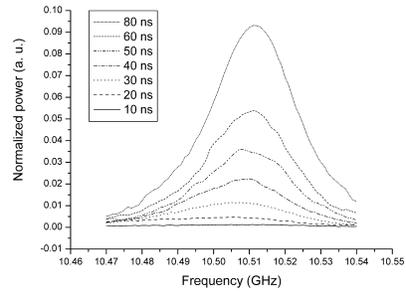
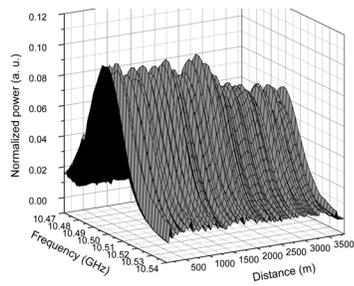


Fig. 5. BGS of 80 ns single pulse (left) and BGS's of single pulses (right) at the position of 1800 m

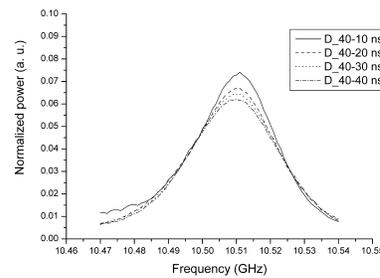
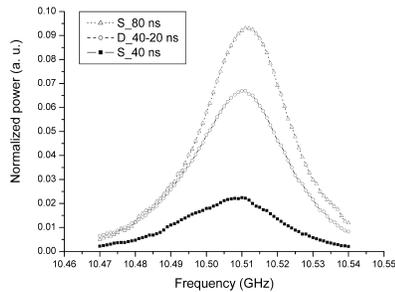


Fig. 6. BGS's of single and double-pulses. (S: single pulse, D: double-pulse, D\_A-B ns: A = pulse width, B = separation width)

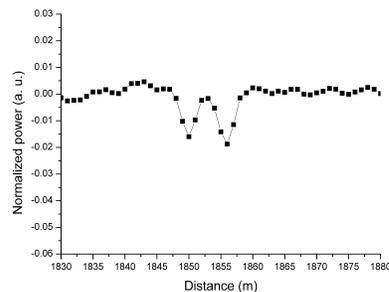
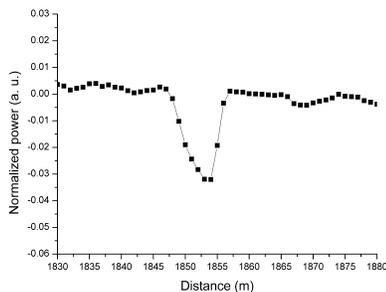


Fig. 7 Normalized backscattering power of 80 ns single pulse (left) and 40-20 ns double-pulse (right) along the fiber. (with 2 m strained fiber section.)

Additional experiments were performed and normalized backscattering power signals were obtained for 2 m, 3 m and 4 m lengths of section 2 fiber. Some of the results are shown in Fig. 8 and 9. When the length of a section 2 was set as 4m, for both the single and double-pulses, it was detected that there were two fiber sections under strain change. However, in the case of 2 m and 3 m section 2, only with the double-pulse were the two fiber sections detected. These results show that the resolvable lengths between the two adjacent strained sections were 4 m and 2 m for the 80 ns single pulse and 40-20 ns double-pulse respectively. This means that the two adjacent strained fiber sections could be resolved more precisely, about twice, with the double-pulse than with the single pulse.

Of course, the twice higher spatial resolution than the 80 ns single pulse can also be obtained with a 40 ns single pulse instead of using a 40-20 ns double-pulse. However, a longer fiber can be covered in the measurement with the 40-20 ns double-pulse than with the 40 ns single pulse because the Brillouin gain obtained with the 40-20 ns double-pulse is about

three and a half times higher than that obtained with the 40 ns single pulse, as shown in Fig. 6. Furthermore, in case of a 20 ns single pulse, as shown in Fig. 5, the Brillouin linewidth broadening is too serious for the 20 ns single pulse to be used for the structural health monitoring. However, as shown in Fig. 10, the BGS that has the sufficient Brillouin gain power for the structural health monitoring can be obtained with a 20-10 ns double-pulse. The 20-10 ns double-pulse has a twice higher spatial resolution than the 40-20 ns double-pulse.

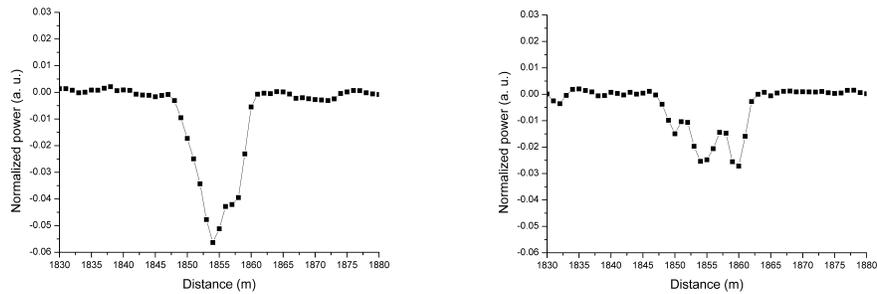


Fig. 8 Normalized backscattering power of 80 ns single pulse (left) and 40-20 ns double-pulse (right) along the fiber. (section 1 and section 3 = 2 m, section 2 = 2 m.)

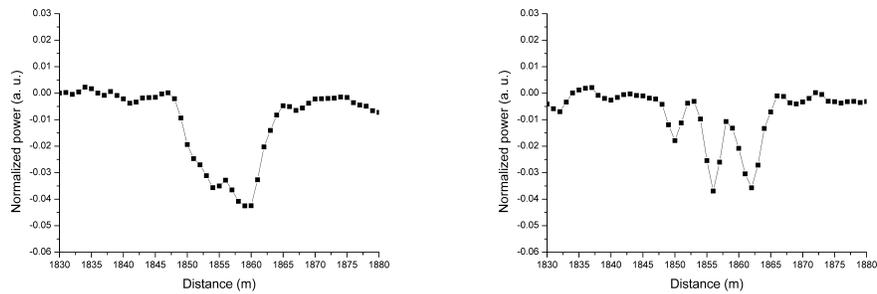


Fig. 9. Normalized backscattering power of 80 ns single pulse (left) and 40-20 ns double-pulse (right) along the fiber. (section 1 and section 3 = 2 m, section 2 = 4 m.)

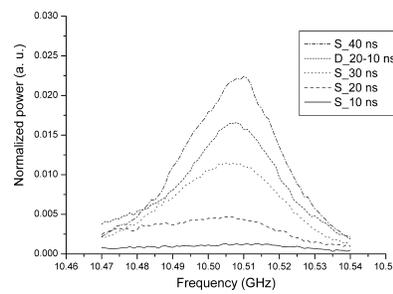


Fig. 10. BGS's of single and double-pulses. ( S: single pulse, D: double-pulse, D\_A-B ns: A = pulse width, B = separation width)

In this study, the sampling rate of the DAQ board was 100 MHz, which means the 1 m distance resolution. Therefore, the experimental situations, such as the length of the strained section and width of the single and double pulses, were set up based on the sampling rate of

the DAQ board. It is thought that the better experimental output can be obtained than the presented results with a higher rate sampling DAQ board than the DAQ board used in these experiments.

## **5. Conclusion**

A double-pulse technique was proposed to enhance the spatial resolution of BOTDA without decrease in the dynamic range. In a BOTDA sensor system, the spatial resolution determines two significances; one is the accuracy in the measurement of the strain or temperature change, and the other is the ability to resolve the two adjacent events. The double-pulse technique has an object of enhancing the latter performance of the two. Double-pulse was launched into the test fiber and Brillouin gain signal was measured to detect the locations of the fiber under strain changes, and the result was compared with that of the single pulse. Experimental results showed that the ability to resolve two adjacent events could be enhanced twice as much by using a double-pulsed pump light without severe decrease of the dynamic range. Viewed from the ability to resolve two adjacent events, the spatial resolution of the double-pulse is equal to that of the single pulse which has half width of the double-pulse. For example, the resolution of 40 ns single pulse and 40-20 ns double-pulse are equal each other. Therefore, the double-pulse receives more gain when compared to the single pulse that has a same resolution because the total width of the double-pulse is twice larger than that of the single pulse.

The point of this technique lies in the utilization of separation of the double-pulse. The higher resolution can be obtained by setting the separation width to be shorter than the one of the single pulses of the double-pulse. The suitable width of separation can be selected through the consideration of the pulse width and measurand situations.

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