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Pulse pre-pump-BOTDA technology for new generation of distributed strain measuring system

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ABSTRACT: Pulse Pre-Pump (PPP)-BOTDA is a new technology for distributed strain measurements by means of optical fiber. The leakage effect on pump light is elaborately designed to stimulate the phonon when the pump pulse length is much smaller than the relaxation time of phonon. This results in immediate time response and the narrow Brillouin spectrum at the same time. In commercialized application (Neubrescope), spatial resolution of 10 centimeter and strain accuracy of 25 micro-strains were achieved. Both properties are of one order higher than that available in current products. We do believe it will meet requirements of SHM. This paper discusses the theoretical model and experimental validation of the system.

1 INTRODUCTION

The Brillouin optical time domain analysis (BOTDA) was first used in 1990, Horiguchi et al (1990). Despite the fact that its original application was in telecommunication, it presents enormous potential in structural health monitoring (SHM) systems. The BOTDA employs the single mode fibers, allowing one to monitor large-scale structures, including bridges, dams, and pipelines. Unfortunately, the currently available spatial resolution of the technology is usually limited to 1 meter, while the strain precision to around 100 με, and both are about one-order lower, than required by practical applications.

Several attempts to achieve the centimeter order BOTDA were already made and reported, Bao et al (1999), Lecoeuche et al (2000). Bao et al (1999) employed a leakage light ahead of the pump pulse, obtaining the high spatial resolution and the narrow Brillouin spectrum at the same time. The technique, however, is not applicable, in its original form, to commercial technology.

In this work, we present the theoretical model, which considers the leakage effect. Based on this development, the pulse pre-pump (PPP) method is suggested and its commercial application demonstrated. Our optical fiber system achieves the spatial resolution of 10 cm, precision for strain measurement of ± 25 με, and more that 1 km sensing distance, all at the same time. To the author's best knowledge, this is the first report on results of such high accuracy BOTDA measurements.

2 THEORETICAL MODEL OF STIMULATED BRILLOUIN SCATTERING (SBS) WITH LEAKAGE EFFECT

The stimulated Brillouin scattering is presented schematically in Figure 1. Let assume that the probe light is continuous wave (CW) from right-hand side.

The pump light with a leakage can be described as follows:

$$A_P(t) = \begin{cases} A_p + C_p, & D_{pre} - D \le t \le D_{pre} \\ C_p, & 0 \le t \le D_{pre} - D \\ 0, & \text{elsewhere} \end{cases} \quad (1)$$

where D denotes the pump pulse duration, while D_{pre} the pre-pump duration, respectively. The extinct ratio, R_x, is defined as $(A_p + C_p)/C_p$. This model can also include the original work of Bao et al (1999), by assuming $D_{pre} = \infty$. The resulting Maxwell equation can be

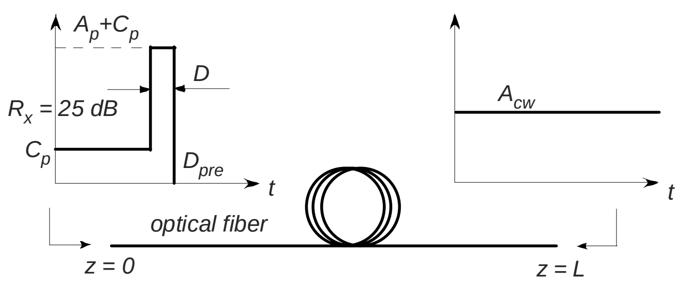


Figure 1 Model of SBS

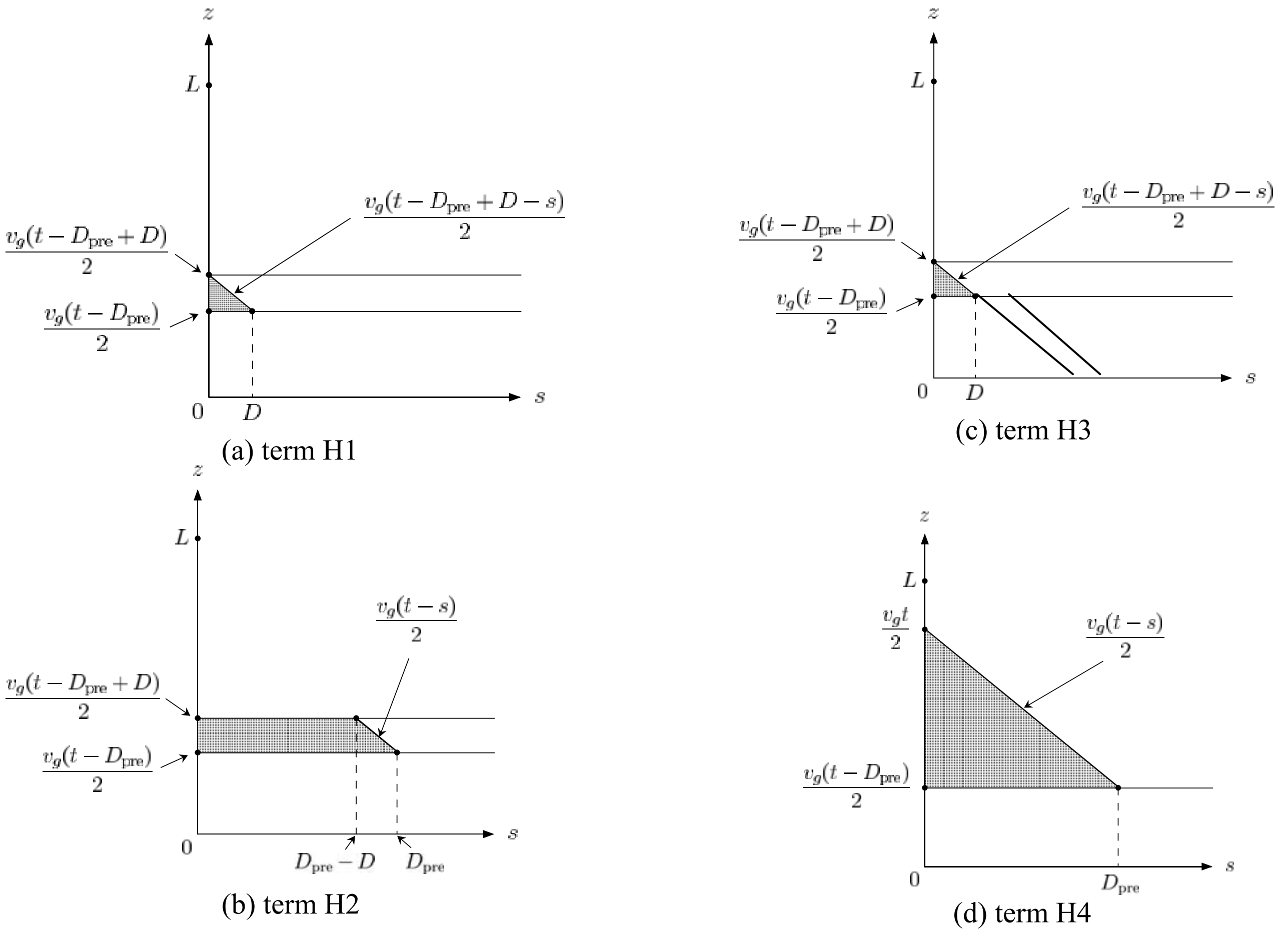


Figure 2. Integral area of each term in equation (4)

solved by means of the perturbation theory, leading to the following equation for amplitude of the probe light:

$$E_{CW}(0,t) = A_{CW}\left[(1+\beta H(t,\Omega)\right] \qquad (2)$$

The last term on the right hand side of (2) represents the SBS, while β stands for the perturbation parameter (in this work $\beta = 2.2\times10^{-4}$), Ω is the frequency of phonon, that is, the difference between frequencies of pump and probe light, and *t* stands for time. The SBS term is in general, a double integral of pump profile, and a convolution of pump profile with phonon term, namely:

$$H(t,\Omega) = \int_0^L A\left(t-\frac{2z}{\upsilon_g}\right)\int_0^\infty h(z,s)\,A\left(t-s-\frac{2z}{\upsilon_g}\right)ds\,dz \qquad (3)$$

where υ_g is the light wave speed, *h* (z, s) expresses the phonon behavior:

$$h(z,s) = \Gamma e^{-[\Gamma + i(\Omega_B(z)-\Omega)]s},$$

L is the length of fiber, Ω_B *(z)* is the Brillouin center frequency. Further more, $\Gamma = \Gamma_B/2$, and Γ_B is the full width at half maximum (FWHM) of Brillouin spec trum. The power of Brillouin Gain Spectrum (BGS) can be expressed as:

$$V(t,\Omega) = \frac{1}{2}\beta A_{CW}{}^2 H(t,\Omega) + c.c. \qquad (4)$$

If the pump profile shape is described by the step function, as in equation (1), H can be split into 4 terms:

$$H(t,\Omega) = H_1(t,\Omega) + H_2(t,\Omega) + H_3(t,\Omega) + H_4(t,\Omega) \qquad (5)$$

Table1. Physical meaning of terms in equation (5).

	meaning	character
H1	Pump pulse	High spatial resolution, wide spectrum span
H2	Interaction of pump with pre-pump	High spatial resolution, narrow spectrum span
H3	Interaction of pre-pump and pump	Vibration noise and complicate contents
H4	Pre-pump pulse	Low spatial resolution, narrow spectrum span

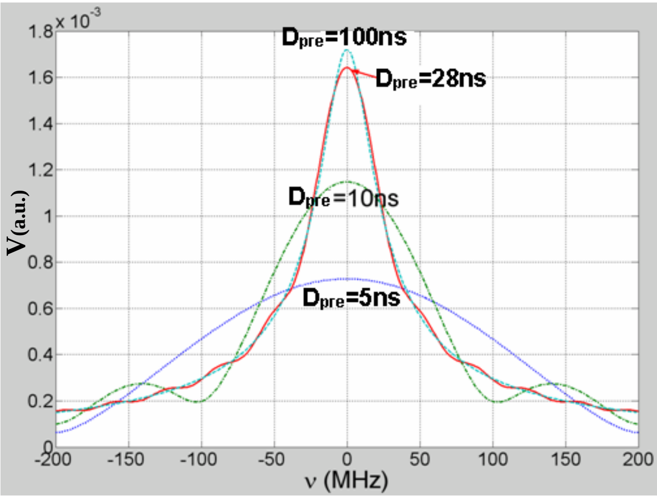


Figure 3. Influence of pre-pump duration

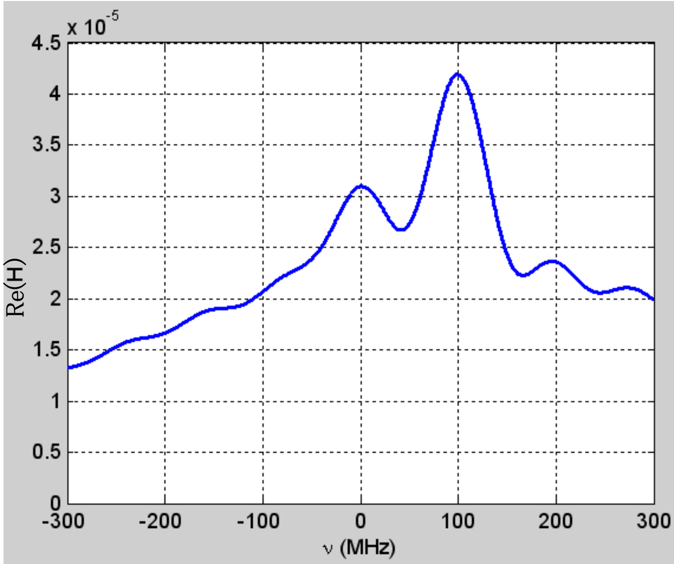


Figure 4. BGS of pulse pre-pump method

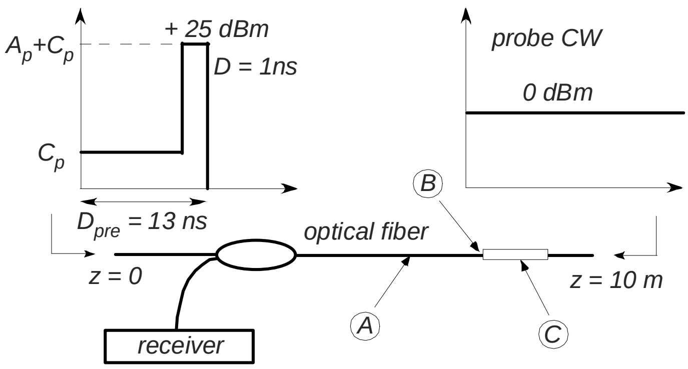


Figure 5. Experimental stand scheme

The physical meaning of each of these four terms can be revealed by analysis of their integral areas. This is demonstrated in Fig. 2 (a-d).

The physical meaning of terms H1-H4 is also summarized in the Table 1. It is interesting to note, that term H2 contains the spatial information of pump pulse and the growth duration of pre-pump for the phonon. Using the scheme of Bao et al (1999), it means that spectrum of H2 has the same FWHM as continuous wave (CW). As term H4 has a direct link with the total fiber length, it is not suitable for commercial applications. The H1 is the traditional term in BOTDA, Kishida et al (2004).

Numerical simulations using present theory demonstrated a good agreement with experimental results, Nishiguchi et al (2004).

The improvement to the method is to employ the pulse pre-pump to in order to ensure that D_{pre} is of finite duration. In such case, the only modification is that H3 has the same area as H1, while H4 is limited to the pre-pump length of pump light. If the optical fiber is longer than pre-pump pulse, the GBS will not change. All that means that commercial application is possible.

In Fig. 3 the influence of the D_{pre} on the power of Brillouin Gain Spectrum is examined, and demonstrates that value of 28 ns is sufficient to produce a distinctive peak shape. Fig. 4 shows an example for the values of $D = 1$ ns and $D_{pre} = 13$ ns and $R_x = 25$ dB. The maximum peak of the spectrum belongs to H2 term. That will result in resolution of size of D and FWHM of D_{pre}.

3 EXPERIMENTAL VALIDATION

The theoretical model and analysis are validated on the experimental stand, which scheme is depicted in Fig. 5. Three cases of pump profiles are considered to measure the SBS. In the first case, a single pulse of A_p and D is used, in the second the pre-pump pulse of C_p and D_{pre} only are employed, while the third deals with both pulse and pre-pump. Strain as high as 0.12 % is applied to the fiber of length of 20 cm.

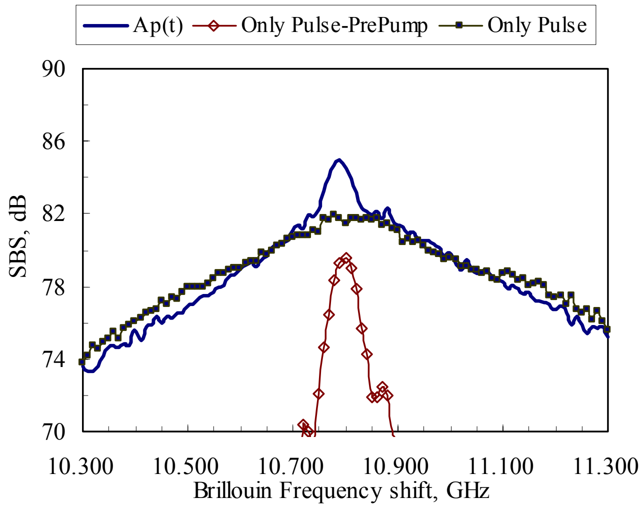


Figure 6. Spectrums at point A (all cases)

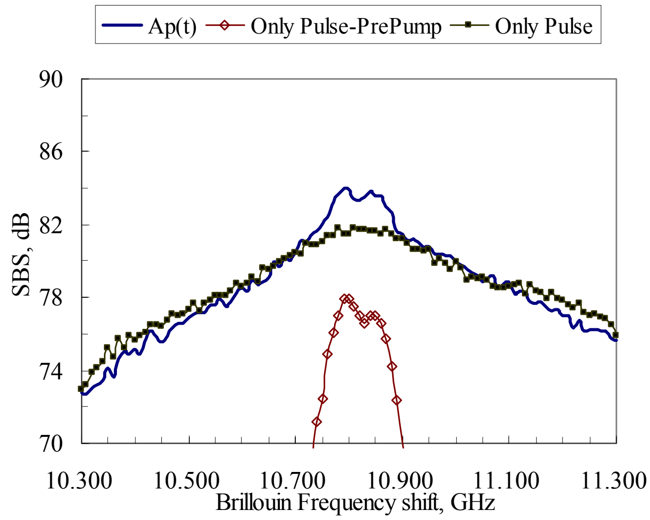


Figure 7. Spectrums at point B (all cases)

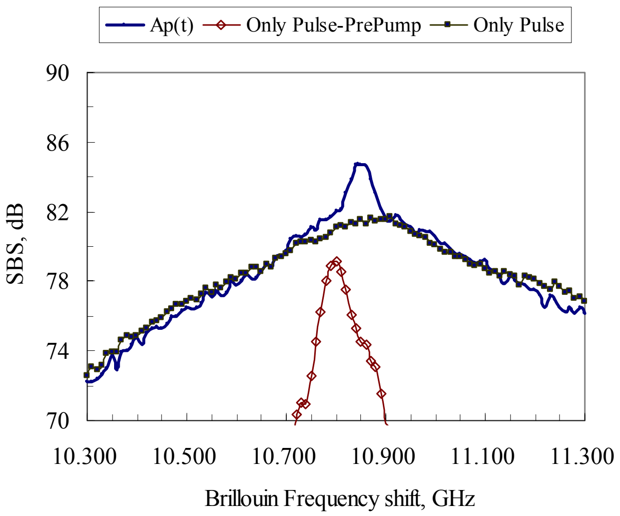


Figure 8. Spectrums at point C (all cases)

The measurements results are examined at three selected points (A, B, and C, see Fig. 5). The obtained results are presented in Fig. 6 to 8.

These results clearly show that equation (5) describes the phenomena accurately. In the case of single pulse, phonon is not fully stimulated, and the width of BGS is over 500 MHz. For the pre-pump case (leakage pulse), phonon is simulated up to 50% of it maximum value (see Fig. 3) and the width of BGS is considerably reduced, to around 80 MHz. In the last case, namely the pulse PPP, we obtain a cap above broad shape of single pulse, which has the same width as that of spectrum with leakage pulse. The shift of frequency value in BGS is especially clearly seen in Fig. 7, and it means that high spatial resolution is achieved.

4 PPP-BOTDA IMPLEMENTATION

The scheme of commercial implementation of described PPP-BOTDA system is shown in Fig. 9. The entire system is divided into four basic parts, namely, user interface and data processing, signal processing/control, and light sources, receiver and recording.

The interface part contains a notebook computer, linked to mainframe of PXI via the bridgeboard. This type of design allows one to increase the speed of data processing by upgrading the notebook computer along the time.

The digitizer has a bandwidth of 1 GHz, sampling rate of 2Gs, and memory of 4 Mw. With these specifications, the measuring time is within several minutes, even for long distances. Two wavelengths lock LD are adopted in this system and the absolute wavelength control is performed separately. The precision is found to be within 1 MHz, between two laser modules. The method of wavelength control is illustrated in detail in Li et al (2005).

A PPP pulse is produced by serially connecting to EOM modules. Fig. 10 depicts the resulting PPP pump light.

5 PEFORMANCE TEST

One of the most important issues in successful commercial implementation of the system is performance. The performance of NBX-6000 is benchmarked using spliced fiber specimen, as shown in Fig. 11. The fiber segment of one type is sandwiched in another type fiber. The length of the sandwiched parts varies from 5m to 5cm. The measured strain, equivalent to center frequency, is presented in Fig. 12.

The spatial resolution of 10 cm is obtained with accuracy of 25 με. The strain distribution is shown in Fig. 13, for both 15 cm and 10 cm portions. Fig. 14

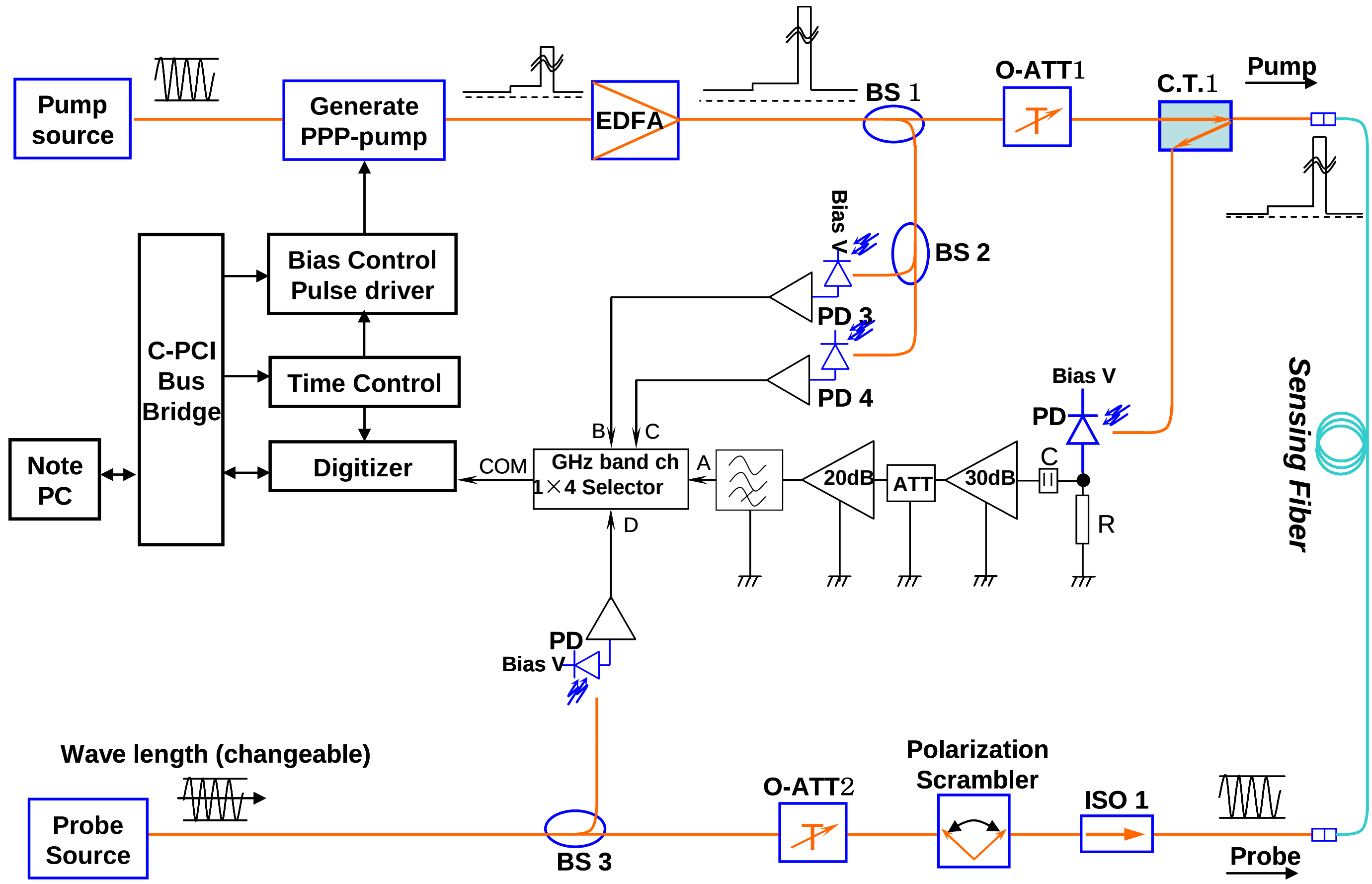
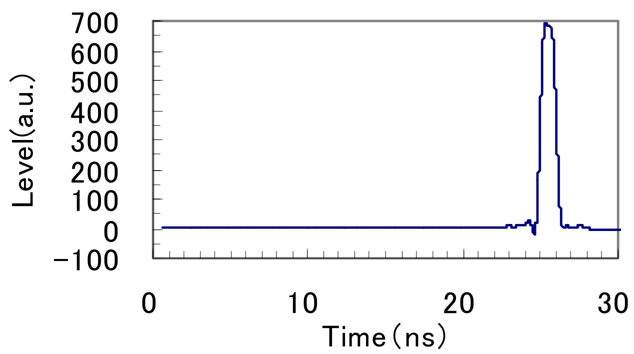
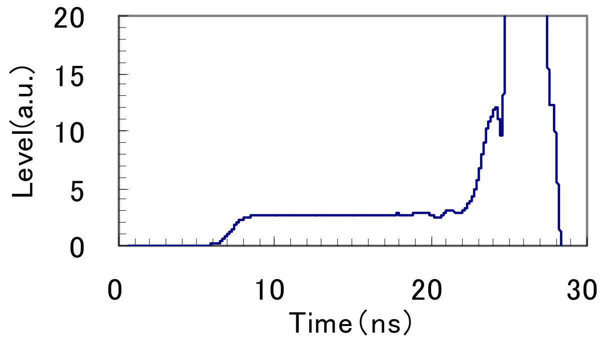


Figure 9. Scheme of NBX-6000



(a) Pump pulse of PPP



(b) detail of (a)

Figure 10. PPP-pump pulse example

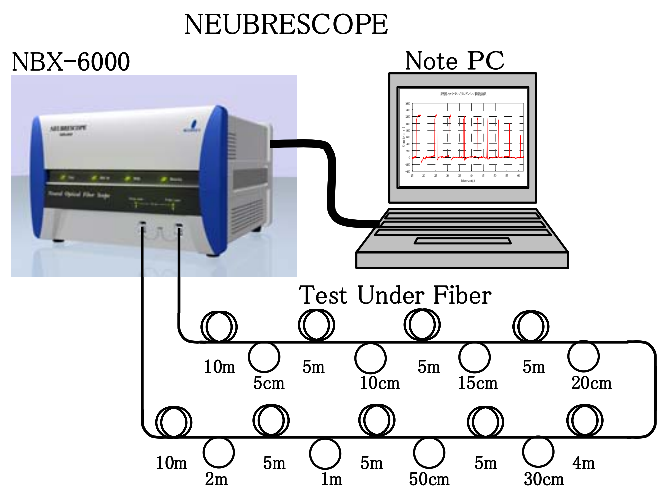


Figure 11. Standard performance test

and 16 present the SBS in time domain. A very good signal-noise ratio (SNR) is obtained with high spatial resolution. The spectrums, at the portions corresponding to positions of Fig. 13, are given in Fig. 16. The transition of frequency is clearly illustrated.

6 CONCLUSION

In the paper, the PPP-BOTDA method is presented and illustrated, both theoretically and experimentally. The

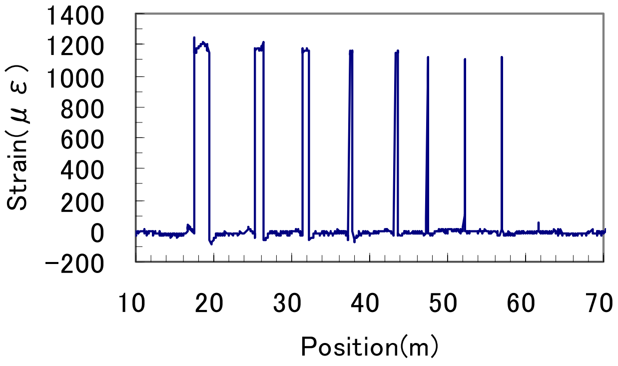


Figure12. Example of strain results of NBX-6000

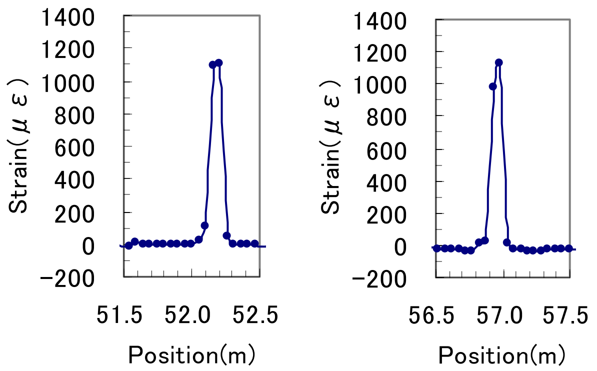


Figure13. Details of results for 15cm and 10cm

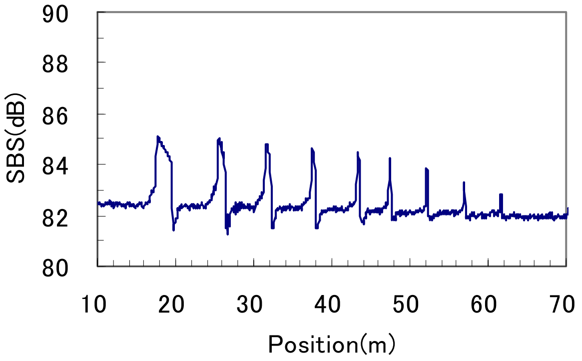


Figure 14. SBS example at frequency 10.850 GHz

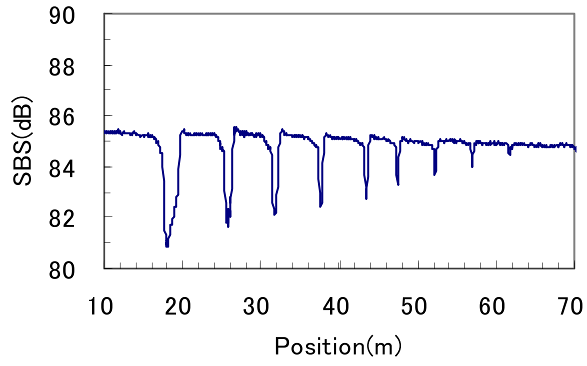


Figure 15. SBS example at frequency 10.800 GHz

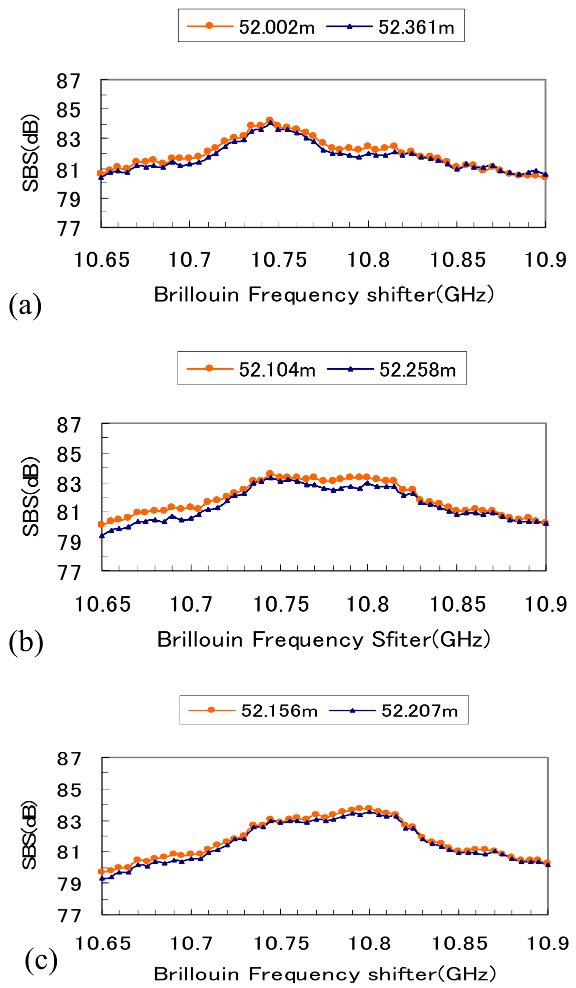


Figure 16. Examples of spectrum at strain transition points.

results demonstrate that spatial resolution will not have a low limit from phonon stimulation. The strain accuracy of the same order as in long pump pulse systems can be achieved. The commercial implementation adopts the described method.

We deeply believe that the discussed optical fiber sensing technology is capable of becoming an important tool in SHM systems.

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