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**Abstract.** A time-division Brillouin optical correlation domain analysis system was successfully achieved using simplified laser diode (LD) modulation and pump lightwave optimization. A complicated transfer function for a precise output waveform of a LD was required for the conventional system. However, a very simple modulation function gave a power output very close to a required ideal rectangle waveform without sacrificing optical output spectrum. An electrical input waveform applied into a gate in the pump lightwave path was also optimized for eliminating a probe lightwave included in a pump lightwave and for passing consecutive pump pulses alternatively. So the stimulated Brillouin scattering gain was attained without seriously distorting FM modulation, and the targeted spatial resolution was clearly accomplished. Additionally, using high speed response of a semiconductor optical amplifier (SOA), unlike an erbium-doped fiber amplifier (EDFA), the possibility was investigated that an SOA was going to replace an EDFA and a modulator used as a gate in the same time.  [DOI: 10.1117/1.OE.53.1.016105]

Keywords: Brillouin scattering; fiber optics; optical amplifier.

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## 1 Introduction

Optical fiber sensors using Brillouin scattering have become effective tools for distributed measurement sensing strain or temperature in construction materials and structures. Brillouin scattering is a three-wave interaction between an incident photon, a backscattered photon, and an acoustic phonon. Pump and probe lightwaves propagating reversely to each other in an optical fiber interfere and excite the acoustic wave, and the refractive index grating caused by the acoustic wave couples the two lightwaves. This coupling gives rise to optical power transfer from the pump to the probe. The probe lightwave experiences gain through the stimulated Brillouin scattering (SBS) process when the optical frequency difference $\Delta\nu$ between the probe and the pump is tuned to around the Brillouin frequency shift ($\nu_B$) of the fiber.[1,2] The Brillouin gain spectrum (BGS) is narrow (30 MHz) and can be recovered by sweeping the frequency difference between the two lightwaves.[3] The center frequency of BGS is shifted in proportion to longitudinal strain or temperature applied to it.

A pulse lightwave was first used for the wave interaction and the BGS was measured as a function of time. It is called Brillouin optical fiber time domain analysis (BOTDA). This technology made it possible to measure longer than a 10-km optical fiber.[4,5] Due to the finite time required for the acoustic wave to be excited by the interaction of pulse pump and continuous probe, however, the spatial resolution of the conventional BOTDA systems is known to be limited to ∼1 m. Small amounts of backscattering induced by a pulsed lightwave need a large number of light pulses to obtain a sufficient signal-to-noise ratio. So a long time is required to obtain the distribution information, and it has difficulty for dynamic distribution measurement of the strain or temperature.[6]

Instead of a pulse lightwave, continuous pump and prove lightwaves were used and the correlation between two lightwaves to generate SBS in a fiber were synthesized, so that SBS was generated only at a narrow section along the fiber. This technology is called Brillouin optical correlation domain analysis (BOCDA). Because of using the continuous lightwave, the BOCDA system has given attractive advantages, including high spatial resolution, dynamic measurement, and randomly accessible positioning, though the periodicity of sensing points causes the limitation of fiber measurement range.[7] The BOCDA technology has been revised and enhanced using complicated systems and advanced devices for longer measurement distance and higher spatial resolution.

Recently, the simplification of the system has become an essential concern for industrial applications. So instead of using an expensive optical modulator to generate the frequency difference, $\Delta\nu$, between probe and pump lightwaves, a time division scheme was applied to a directly modulated light source.[8] The modulated laser diode (LD) generated alternately pump and probe without an optical modulator. However, the production of the time-divided waveform was not so simple because the LD transfer function was required to be measured by calculating the Fourier series of both the LD input and output. In this article, a time division BOCDA system was demonstrated using a simplified LD modulation scheme. Three simplified functions were compared for replacing the transfer function. Among them, a function which was composed of two linear lines for a time period of each lightwave was chosen. An electrical input waveform applied into a gate in the pump lightwave path was also optimized. So this method was applied to a test fiber which is composed of five 30-cm optical fibers. Its

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BGS at each position was measured and the spatial resolution was attained. Additionally, the possibility was investigated for further system simplification that a single semiconductor optical amplifier (SOA) was going to replace an erbium-doped fiber amplifier (EDFA) and a modulator used as a gate together.

## 2 Experiments and Results

The experimental setup was presented in Fig. 1. One high power distributed feedback laser diode (DFB LD) was used for lightwave generation of both probe and pump in the system. When only 270 mA was applied to the DC current port was applied, it gave 30-mW output of 1553.25-nm peak wavelength. Two modulation frequencies of 20 MHz and 50 kHz were directly applied to its AC current port simultaneously with the DC current. This frequency-modulated (FM) continuous lightwave of 20 MHz caused the interaction of a probe and a pump to induce the correlation peak at a specific portion of an optical fiber. In this case, the spatial resolution ($\Delta z$) is concerned with the width of the correlation peak. It is given by $\Delta z = (v_g \cdot \Delta v_B)/(2\pi \cdot f_m \cdot \Delta f)$, where $\Delta v_B$ is the linewidth of intrinsic BGS, $\Delta f$ is the FM amplitude, and $f_m$ is the FM frequency. The correlation peak is repeated by the interval $d_m = v_g/2f_m$.[7] The rectangle-like waveform of 50 kHz caused two time-divided frequency peaks, higher frequency ($f1$) and lower frequency ($f2$). They were generated at high and low current conditions, respectively, and were used as a pump and a probe. The difference ($f_d$) between $f1$ and $f2$ was tuned to around 11 GHz for inducing SBS. The combined AC current input waveform was given in inset (a) of Fig. 1.

The modulated lightwave was divided by a 3-dB coupler and was launched into both arms as a probe and a pump. A probe lightwave was first delayed by 0.05 ms using an optical single mode fiber (SMF) of 2 km and the delay made no time difference between two lightwaves. It was explained as graphs in the middle of the figure, where a probe and a pump are presented as solid and dashed lines in the time axis. After a polarization controller (PC) and an isolator, a probe was launched into the optical fiber under test. The correlation between two lightwaves was very sensitive to the polarization condition, which was tuned by this controller. Another PC was used for a pump and reduced the insertion loss into the gate. A Mach-Zehender (MZ) modulator of maximal 20-dB extinction ratio was used as a gate, which cut off a probe and passed only a pump. After a gate, a pump was amplified by an EDFA of 17-dBm output and was launched into a circulator. A pump and a probe interacted at the fiber under test and the interaction transferred the pump power into the probe power. They could not propagate to opposite fiber paths furthermore due to an isolator and a circulator. With a circulator, a probe lightwave amplified by the SBS was inserted into a photo-detector and was converted to an electrical signal. A small SBS gain needed a lock-in-amplifier (LIA) electrically to amplify the converted signal again. Signal chopping was required for the LIA operation and a chopping frequency was applied to an MZ modulator, which was used simultaneously as a gate and a chopper. The electrical signals for a DFB LD and an MZ modulator were synchronized by a function generator. The graph in inset (b) of Fig. 1 showed the combined electric wave function applied to a modulator.

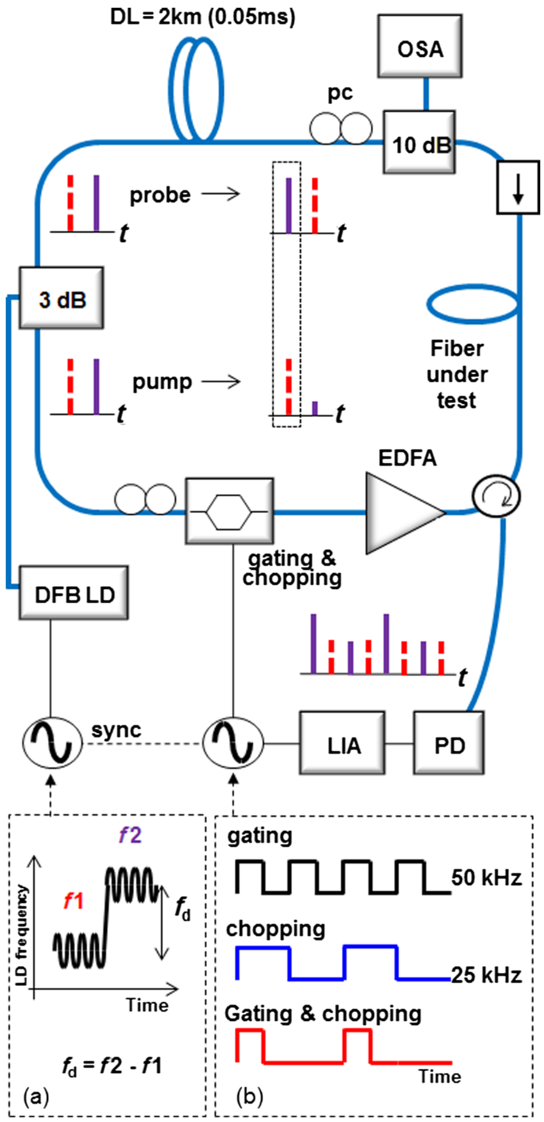


**Fig. 1** The schematic of the experiment setup with a modulated input function (a), and a gating and chopping function (b). A distributed feedback laser diode (DFB LD), lock-in-amplifier (LIA), and optical spectrum analyzer (OSA).

When a rectangle waveform was applied to an LD for two time-divided lightwaves, the stable frequency difference was not achieved because of nonideal FM response of an LD. Instead of acquiring the precise transfer function between the LD input and output, simple compensated functions were applied and their responses were analyzed. An ideal rectangle and three compensated waveforms were compared, as shown in Fig. 2. The compensation type I was composed of two linear line functions for each lightwave part. Also, the compensation type II and III were composed of three and four line functions for each lightwave part, respectively. A waveform of optical output power and its optical output spectrum as well were measured for each compensation type. There were clearly two peaks in the spectrum to correspond to time-divided probe and pump. The frequency difference of the two peaks was used to adjust the frequency shift between a probe and a pump, the center of BGS, in

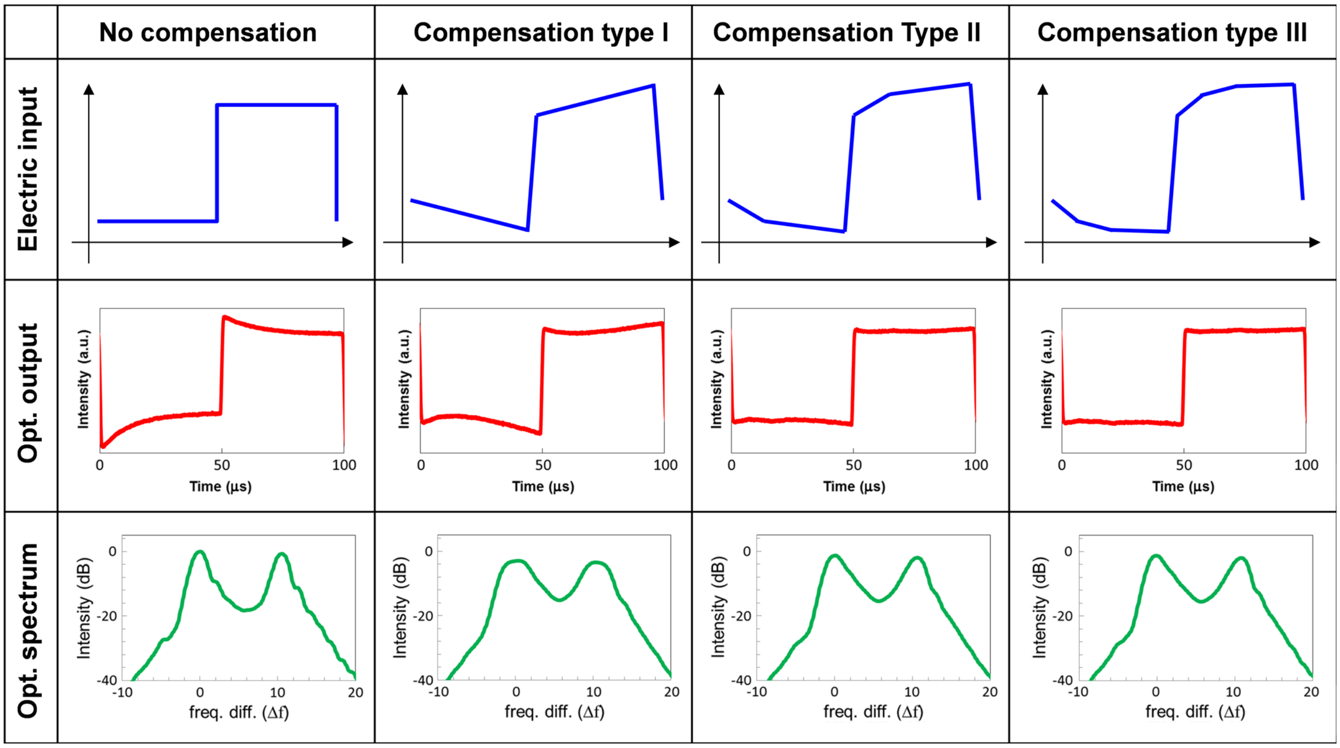


**Fig. 2** Four different types of electrical input waveforms (the first row) into a laser diode (LD) for generating two time-divided lightwaves and their optical output powers (the second row) and spectra (the third row).

the fiber. When an ideal rectangle function was applied as electrical input, optical output power showed a seriously distorted waveform. However, as the number of a linear line function increased for the compensated input waveform, the optical output was close to a rectangle function. There was nearly no difference between compensation type II and III for optical output power and optical spectrum, unlike compensation type I. So compensation type II was chosen as an electric input signal for a DFB LD. The amplitude of the compensated function was adjusted by monitoring optical spectrum of a probe lightwave using a 1:9 coupler.

Before a pump lightwave was correlated with a probe delayed by a 2-km SMF, a probe lightwave included in a pump lightwave was eliminated by a gate and was optically amplified by an EDFA. The left graph of Fig. 3 presented an optical spectrum of a pump after a gate. The short wavelength (high frequency) peak between two peaks in the third row spectra of Fig. 2 held fast, but the long wavelength (low frequency) peak was removed by a 13-dB loss. In order to examine the symmetry of the gating operation, a probe lightwave was inserted into the gate and the right graph of Fig. 3 presented a spectrum with a single peak at a long wavelength and without a short wavelength peak. Two graphs showed a mirror image to each other. A modulator used as a gate was switched with 2.5 peak-to-peak voltage and 50 KHz. The modulator was simultaneously used as a chopper, which passed consecutive pump pulses alternatively for an LIA. So the operating frequency as a chopper should be 25 kHz, half of that of the gating operation. Actually, the combined function of gating and chopping frequencies was applied to a modulator, as shown in inset (b) of Fig. 1. This rectangle-like function was also compensated like the direct modulation of the DFB LD and was optimized for better SBS gain. The time width in the combined input waveform for pump passing should be 5 $\mu$s according to the graph, but it was reduced to 1.8 $\mu$s. The narrow pulse width intensified the transient effect of an EDFA because of the long lifetime of Er3+ ions in EDF and caused a higher EDFA output by rapid overshooting. A pulse pump power after the modulator was $-10$ dBm and output power after EDFA was $+10.5$ dBm.

A probe lightwave amplified by SBS after a two-lightwave correlation was launched into a circulator and its output power waveform was measured in Fig. 4. In the

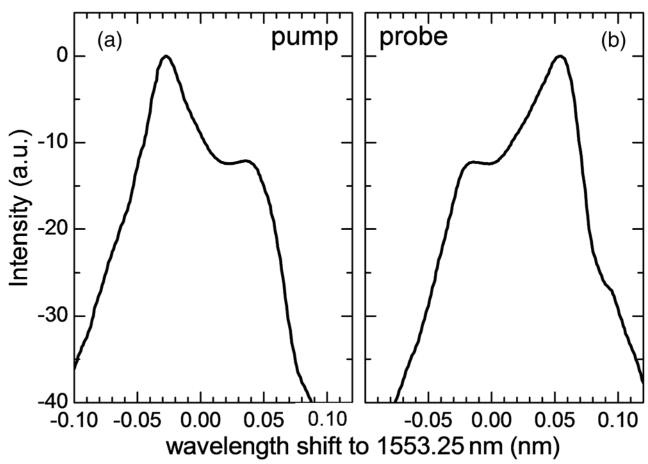


**Fig. 3** An optical spectrum (a) of a pump after a probe lightwave (b) included in a pump lightwave was eliminated by a pump gate.

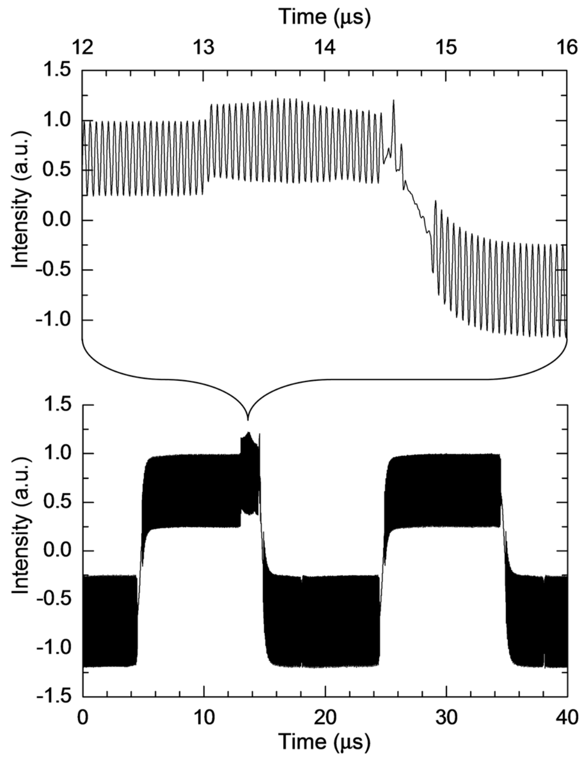


**Fig. 4** A power waveform of a probe lightwave measured after the stimulated Brillouin scattering amplification.

bottom graph, the time-divided waveform was exactly a rectangle function. Two Periodic intensity regions corresponded to a probe and a pump, respectively, and both of them were modulated with much higher FM frequency. In the intensity region of a probe lightwave, there was a single higher intensity area between two consecutive probe lightwaves, and a gated pump lightwave in 1.8-$\mu$s time width induced this amplification. This area was magnified in the top graph of Fig. 4, where 20-MHz FM modulation frequency was confirmed and the SBS amplification was achieved without seriously distorting the 20-MHz modulation.

As a test fiber, five SMFs and dispersion shifted fibers (DSFs) were alternatively spliced. Each fiber was 30 cm and both ends of a total 1.5-m test fiber were spliced to 1-m SMF fibers pigtailed to a circulator and an isolator, respectively, as shown in Fig. 5(a). The frequency shift of a Brillouin gain peak in the DSF was 10.52 GHz, and is different from that of the SMF (10.84 GHz). This difference between two kinds of optical fibers corresponded to an applied strain difference of 0.55% or a temperature difference of 270 K.[9] The FM amplitude ($\Delta f$) of 2 GHz with an FM frequency ($f_m$) of 20 MHz was applied to a DFB LD, and a theoretical spatial resolution of this system was 24 cm. This resolution was chosen to differentiate five 30-cm fibers in a test fiber. The change of FM frequency chooses the fiber measurement position in the conventional BOTDA systems, whereas time-division BOCDA systems choose the position by changing the phase difference between probe and pump lightwaves. The relation between the phase difference and the fiber position is linear, unlike that between the FM frequency and the position in the conventional BOCDA. At each fiber position, the BGS

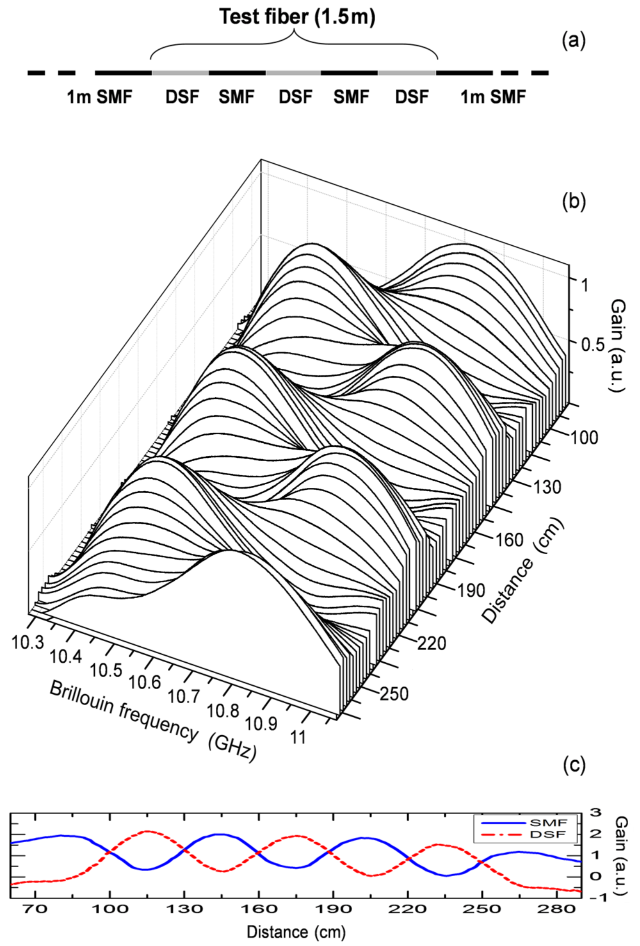


**Fig. 5** A test fiber (a) composed of five single mode fibers and dispersion shifted fibers, a three-dimensional graph of Brillouin gain spectra (b) and Brillouin gain variations at the fixed Brillouin frequencies according to the distance (c).

was measured by sweeping the amplitude of a rectangle input waveform into a DFB LD. The result was given in the three-dimensional graph of Fig. 5(b). There were five clear peaks with leaving out half peaks at both ends. Three peaks at 10.52 GHz and two peaks at 10.84 GHz correspond to three DSFs and two SMFs, respectively. Their positions matched well with that of each fiber at the test fiber. Figure 5(c) showed gain variations at two peak frequencies according to the fiber position. In the figure, the solid and dashed lines corresponded to Brillouin gain variations with the fixed frequency shifts of 10.84 GHz (SMF) and 10.52 GHz (DSF), respectively. The center

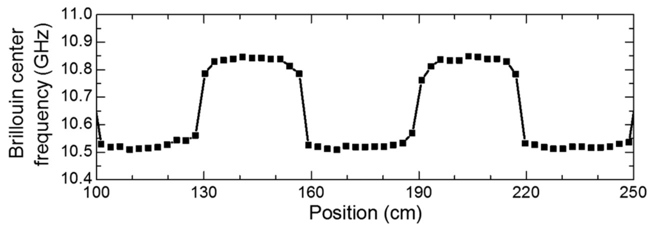


**Fig. 6** The center frequency shift in a Brillouin gain spectrum according to the optical fiber position.

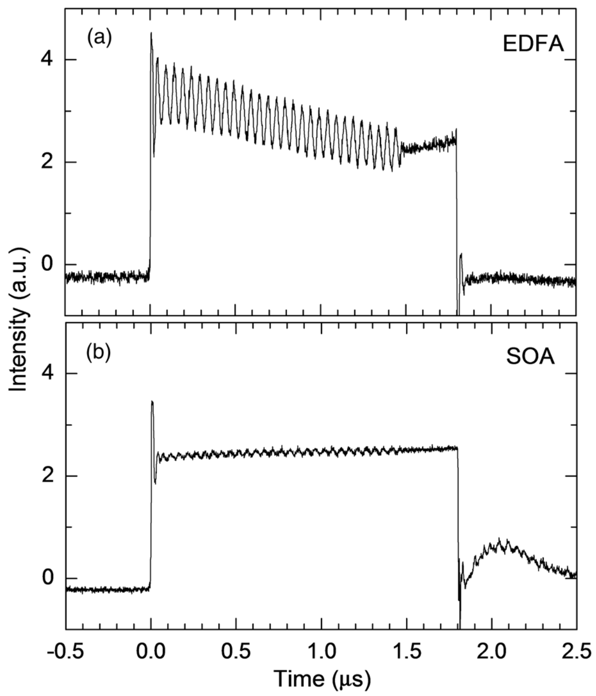


**Fig. 7** Amplified output power variations of a frequency-modulated pump lightwave after an erbium-doped fiber amplifier (a) and a semiconductor optical amplifier (b) according to time.

frequency shift of a BGS at each position was also measured and presented in Fig. 6. There was definite position distinction between SMFs and DSFs. It is clear from Figs. 5 and 6 that the simplification for an input modulation waveform applied into a LD worked properly, and this method achieved the spatial resolution required from the theoretical equation. There is strong possibility given from the shapes of crossing points between two gains and gain top shapes that this method can also support less spatial resolutions.

In order to simplify the time-division BOCDA systems further, an SOA was applied instead of an EDFA for amplifying a pump lightwave. If an SOA can replace an EDFA, a modulator for gating and chopping can be removed. An SOA is able to be directly modulated with higher frequency than a few MHz, but an EDFA is not due to very long rising and falling times. However, this approach was not successful. The system with an SOA could not have proper Brillouin gain even though an SOA had the same output power and signal gain with those of an EDFA. The reason was explained in Fig. 7, where the upper and lower graphs are for an EDFA and an SOA, respectively. These are output power variations according to time. When a gating and chopping pump pulse was inserted, an EDFA gave very long time overshooting and an SOA gave short time overshooting, which was well confirmed in the past experiment.[10] The important thing was that an FM frequency of a signal after an SOA was almost removed, but that after an EDFA was clearly maintained. This is because an input power value of an SOA for output power saturation is more than 10 dB lower than that of an EDFA. So not just high input power points, but also low power points in an FM modulated pump gave similar saturated output powers after an SOA. The BOCDA system with an SOA could not give enough SBS gain to measure the position difference between DSF and SMF.

## 3 Conclusions

A time-division BOCDA system was successfully achieved using a simplified LD modulation scheme. In the system, two modulation frequencies of 20 MHz and 50 kHz were simultaneously applied to a DFB LD, the former for correlating probe and pump lightwaves, and the latter for generating the two time-divided lightwaves. For time-divided lightwave generation, the complicated transfer function for a precise rectangle waveform output from a DFB LD was required, but three simplified functions were compared for replacing the transfer function. Among them, a function which was composed of two linear lines for a time period of each lightwave was chosen. The function gave a power output very close to an ideal rectangle waveform without sacrificing output optical spectrum. An electrical input waveform applied into a gate in the pump lightwave path was also optimized for eliminating a probe lightwave included in a pump lightwave and for passing consecutive pump pulses alternatively. So the SBS amplification was accomplished without seriously distorting FM modulation. As a test fiber, five SMFs and DSFs were alternatively spliced and each fiber was 30-cm long. A BGS was measured at each fiber distance and its center frequency shift showed that the simplification for input modulation waveform worked properly and there was strong possibility to support less spatial resolutions using this scheme. Additionally, in order to replace an EDFA and a modulator used as a gate and a chopper at the same time, an SOA was applied to the system and was compared with an EDFA. The Brillouin gain with an SOA was too small for measurement. The reason was that an FM frequency modulation in a pump lightwave was washed out during amplification because of its low saturation power level.

### *Acknowledgments*

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