# Fiber-Optic Nerve Systems for Safety and Security

Kazuo Hotate and Zuyuan He
Department of Electrical Engineering and Information Systems, School of Engineering, The University of Tokyo
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan
Phone: +81-3-5841-6683, FAX: +81-3-5841-6683, E-mail: hotate@sagnac.t.u-tokyo.ac.jp

**Abstract**
"Fiber optic nerve systems" have been studied to make structures and materials that can feel pain. We have developed the nerve systems with mm-order spatial resolution and kHz-order measurement speed, using optical correlation domain techniques.

**Introduction**

Optical fibers can act as a sensor for strain or temperature through the properties, such as scatter-ing. By applying ways to analyze distribution of the property along the fiber, "fiber optic nerve systems" are realized to sense damages induced in materials and structures, in which the fiber is embedded.

Time domain techniques with pulsed lightwave have been studied for distribution sensing. However, these have difficulties in realizing ultimate perfor-mances. We have proposed an optical correlation domain technique with continuous lightwaves [1]. By applying the technique to fiber Brillouin distributed strain sensing, we have realized 1.6mm spatial resolution, which is 600 times higher than the time domain techniques. A multiplexed fiber Bragg grating sensors has been developed also using the correlation domain technique.

**Brillouin optical correlation domain analysis system**

Brillouin scattering has a frequency of about 11GHz down-shifted from the input lightwave. The frequency shift is changed by longitudinal strain applied to the fiber [2]. Time domain techniques developed for distribution measurement, however, have a spatial resolution limit of about 1 meter [2]. The pulse-based systems also require several minutes of measurement time, because the scattered power by a single pulse is quite tiny.

To improve these difficulties, we have proposed and developed a technique named "Brillouin Optical Correlation Domain Analysis; BOCDA" [3]. It is based on control of the correlation between the pump and probe continuous lightwaves, which excite the Stimulated Brillouin Scattering (SBS).

Figure 1 shows the BOCDA system, in which we have recently added new schemes to improve the performances [4-6]. The pump, which is chopped by an electro-optic modulator with a radio frequency, is launched into the fiber under test. A Single Side Band (SSB) Modulator is introduced, which is driven with a microwave frequency. The SSB modulator can act as an ideal frequency shifter, and generate a probe ligtwave

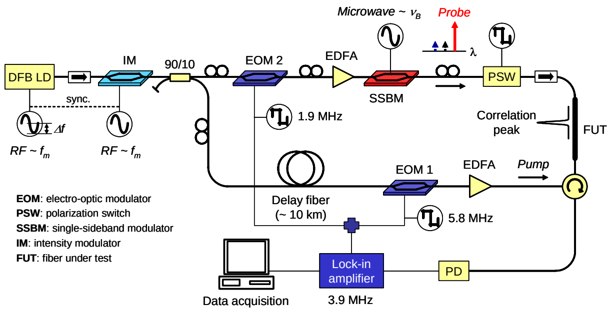


Fig. 1. BOCDA system with the SSB modulator, the beat lock-in scheme, and the intensity modulation scheme for improvement of the spatial resolution and the measurement range [4-6].

with a downshifted frequency. The probe propagates against the pump in the fiber and reaches the detector.

It is the point in our system that the pump and the probe are identically frequency-modulated at the laser diode. As a result, SBS occurs exclusively at the correlation peak position, where the two lightwaves are highly correlated. We can shift the correlation peak position along the fiber by simply changing the FM frequency. The increase in the probe power due to the Brillouin gain is detected by a lock-in amplifier.

In the system [4-6], the probe is also chopped with another frequency, and the detector output is demodu-lated with the two chopping frequencies. By this double

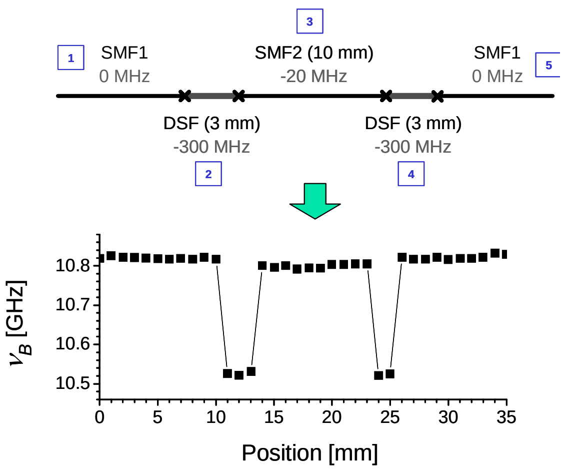


Fig. 2. Demonstration of 1.6mm spatial resolution with 5.5m measurement range by the improved BOCDA system [6].

lock-in or beat lock-in demodulation, the signal is distinguished form non-desired reflection of the pump, and noises are reduced.

In Fig. 1, an intensity modulation is also introduced to manipulate time-averaging source spectrum. We have found that the Brillouin gain, which are induced at non-measuring portions, are much reduced by the spectrum manipulation. By using the double or beat lock-in scheme and the intensity modulation scheme, we can enhance the ratio between the measurement range and the spatial resolution.

A strain distribution measurement with a long range has been demonstrated. Measurement range is 1,010m and the spatial resolution is 28cm. The ratio is about 3,500, which is about 10 times larger than the previous systems. Fig. 2 shows another measurement with the large ratio. The spatial resolution is 1.6mm and the range is 5.5m. The resolution is 600 time higher than the time domain techniques [6].

Recently, a new system, in which distribution of spontaneous Brillouin scattering can be measured, has also been proposed and demonstrated [7]. Simultane-ous measurement of strain and temperature distribution has also been demonstrated by using a BOCDA system with a new scheme [8,9].

## Multiplexed fiber Bragg grating sensors with same Bragg wavelength

Fiber Bragg grating multiplexed strain sensing has been widely studied [2]. We have proposed a scheme, in which the FBGs with the same Bragg wavelength can be multiplexed by using the correlation domain technique [7]. Fig.3 shows the setup. Location of the coherence peak, synthesized by a simple sinusoidal frequency modulation, is tuned so that one FBG is selected, and the center frequency $f_0$ of the LD is swept to measure the FBG reflection spectrum.

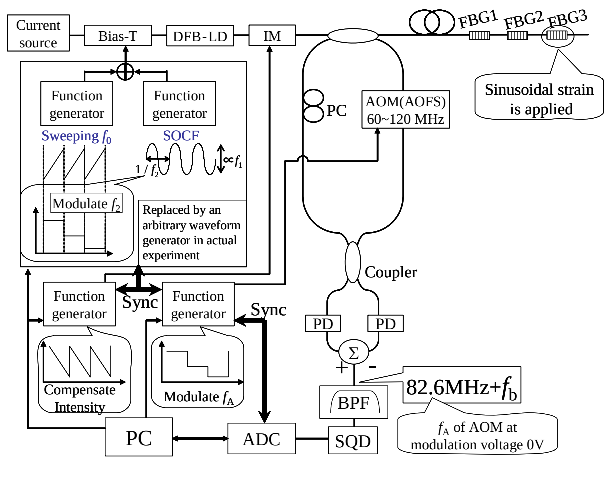


Fig. 3. High-speed FBG multiplexing sensor system by the optical correlation domain technique [11].

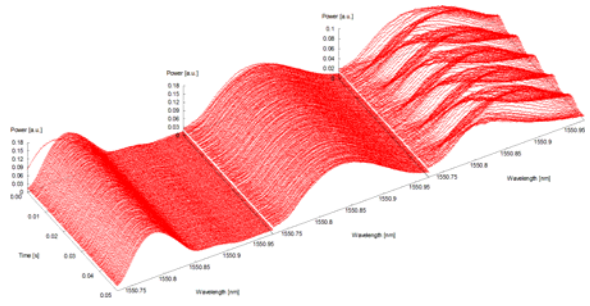

Fig. 4. Multiplexed and dynamic FBG sensing with 10kHz sampling speed [11].

By newly introduced a scheme to enhance the measurement speed, dynamic strain measurement has been demonstrated with 10kHz sampling rate, as shown in Fig.4.

Recently, we have newly developed a system, in which the Bragg wavelength distribution inside a long-length FBG can be measured by the correlation domain technique [12].

## Conclusion

By the correlation domain technique with continuous lightwaves, the BOCDA system has been developed as a fiber optic nerve system having a mm-order spatial resolution. We have also developed the multiplexing scheme for the Bragg grating sensors with the same Bragg wavelength having a higher measurement speed.

## References


1. K. Hotate and Z. He, J. Lightwave technol., 24 (2006) p.2541 <Invited>.
2. J.Dakin and B.Culshaw, Ed., "Optical Fiber Sensors IV", Artech House, (1997) p. 309.
3. K. Hotate and M. Tanaka, IEICE Trans. on Electronics, E84-C (2001) p. 1823 <Invited>.
4. K.-Y. Song and K. Hotate, Photonics Technol. Lett., 18 (2006) p.499.
5. K.-Y. Song, Z. He and K. Hotate, Optics Express, 14 (2006) p.4256.
6. K.-Y. Song, Z. He and K. Hotate, Optics Lett., 31 (2006) p.2526.
7. Y. Mizuno, Z. He and K. Hotate, IEEE Photonics Technol. Lett., 21 (2009) p.474.
8. Zou, Z. He and K. Hotate, OSA Optics Express, 17 (2009) p. 1248.
9. W. Zou, Z. He, and K. Hotate, ECOC2008, Brusseles, (Sept. 2008) We.3.B.3.
10. K. Hotate, M. Enyama, S. Yamashita, and Y. Nasu, Measurement Science and Technol., 15 (2004) p.148.
11. T. Hayashi, Z. He and K. Hotat, 18th Intern. Conf. on Optical Fiber Sensors, Cancun, (Oct. 2006) FA2.
12. K. Hotate and K. Kajiwara, OSA Optics Express,.16 (2008) p. 7881.