博士論文（要約）

Research on the Spatial Resolution in Optical Correlation Domain Distributed Measurement of Brillouin Dynamic Grating along Optical Fibers

（光相関領域法による光ファイバ中のブリルアンダイナミックグレーティング
の分布測定における空間分解能に関する研究）

Submitted on December 2nd, 2013
2013 年 12 月 2 日　提出

Supervisor　　Professor Kazuo Hotate
指導教員　　保立　和夫　教授

The University of Tokyo, Graduate School of Engineering
Department of Electrical Engineering and Information Systems
東京大学大学院　工学系研究科
電気系工学専攻

37-117100
Yamashita Rodrigo Kendy
山下　健二　ホドリーゴ

Tunnels, bridges and aircrafts are submitted to various environmental changes and heavy loads during its lifetime. Detection of cracks, overloads and displacements in those structures is vital to keep the safety in their usage, preventing big collapses and accidents that may take many lives. Many kinds of sensors have been developed to detect those failures in the structures, giving birth to the structure health monitoring research field. The structures with that self monitoring function are referred as smart structures, and fiber-optic sensing is one of the most promising technologies to realize smart structures.

Optical fiber sensors have been advantages over other types of sensors due to its small size, light weight, flexibility and immunity to electro-magnetic interference. Standard single mode fiber that has already been developed for telecommunications can be used both as the sensing head and the sensing data transmission medium. Several types of fiber-optic sensors have already been developed, measuring strain, temperature, rotation, current, concentration of chemicals, etc. In this thesis, the focus was on the development of a fiber-optic sensor that can measure strain and temperature simultaneously along an optical fiber.

In some cases, a fiber Bragg grating (FBG) is inscribed in a fiber to perform the sensing function. In that case, the FBGs can be multiplexed, performing quasi-distributed sensing, but there are still blind positions, where the system cannot obtain information of stress and strain. In this research, stimulated Brillouin scattering (SBS) is utilized to perform sensing and this phenomenon occurs at any point of the fiber, without any special treatment. Therefore, to perform distributed sensing using SBS, some localization technique is necessary to acquire the strain and temperature information of a particular position on the fiber.

In SBS, there are three waves participating: two counter-propagating lightwaves and an acoustic wave. The lightwave with higher frequency is called pump, and the acoustic waves propagates in the same direction as the pump. The other lightwave is called probe, and when the frequency difference between the pump and probe matches the frequency of the acoustic wave, the pump-probe interaction excites the acoustic wave through electrostriction. On the other hand, the acoustic wave is a longitudinal wave that modulates the density of the glass in the core of the fiber. That creates a periodic grating of refractive index, which reflects the pump light. Due to the progressive nature of the acoustic grating, the reflected pump suffers a Doppler frequency downshift and drops to the probe frequency. Therefore, SBS causes optical power transference from pump to probe, and the excitation of an index grating called Brillouin dynamic grating (BDG).

The acoustic frequency in the core of the fiber is called Brilloin frequency shift (BFS), because it is the amount of frequency shift the pump suffers during the SBS process. The BFS has a linear response to strain and temperature, so it is possible to measure strain or temperature variations, by monitoring the BFS change. To measure BFS, the pump-probe frequency difference is varied while monitoring the probe gain during the SBS process. The curve obtained during this measurement is called Brillouin gain spectrum (BGS), which is a Lorentzian of 30-MHz width and peaks around 10.8 GHz, which is a common value for BFS in standard silica fibers.

Research in Hotate laboratory has shown that in polarization maintaining fibers (PMFs), the BDG excited in one polarization axis of the fiber can reflect light launched through the orthogonal axis. This is because the BDG is produced by a longitudinal wave, which is inert to the transversal asymmetry of the PMF. In this thesis, SBS and BDG excitation is held on the slow x-axis of the PMF, which has a refractive index higher than the fast y-axis. In this case, the condition for BDG reflection to occur in the y-axis is that the frequency of the light launched through the y-axis has to be higher than that of the x-axis by an amount f_{xy}, which depends on the fiber birefringence. If one inverts the axes, and excites the BDG in y-axis, the x-axis input needs to have a frequency lower than the y-axis by f_{xy}.

In a standard silica PMF, BFS has a positive dependence for both strain and temperature. The birefringence has a positive response for strain while a negative, for temperature. This means that it is possible to calculate the strain and temperature variations independently by determining both the BFS and f_{xy}. The measurement to determine f_{xy} is called BDG spectrum and it consists of exciting the BDG by the x-polarized x-pump and x-probe lightwaves, while launching a y-polarized y-read lightwave through the same end as the x-pump. By varying the frequency between x-pump and y-read, while monitoring the y-read reflection, the BDG spectrum is observed as a Gaussian, which width depends on the BDG length and peaks at f_{xy}.

Above, it was described how to measure strain and temperature simultaneously using the BDG measurement in a PMF. Now, it will be explained how one can perform distributed measurement by localizing the SBS phenomenon. The first localization technique to be proposed was the time domain technique, where SBS is localized by pulse intensity modulation (IM) of the pump or probe. After IM, the Brillouin gain obtained at each position can be acquired as a function of time at the detector. The system which uses this technique is called Brillouin optical time domain analysis (BOTDA) and its spatial resolution is related to the pulse width. However, if one tries to enhance spatial resolution by narrowing the pulse length, the optical spectrum broadens, thus the measured BGS does not show a clear peak, and accurate sensing is not possible. Due to this restriction, the highest spatial resolution achieved by BOTDA in a basic setup is 1m. However, km-order measurement lengths are easily achieved. Several researches have been presented to increase spatial resolution. To the best of our knowledge, the best performances in spatial resolution were 5.5 mm, using the BDG principle to enhance spatial resolution, and 20 cm with strain-temperature simultaneous measurement by the BDG technique.

After that, the correlation domain technique was proposed with the Brillouin correlation domain analysis (BOCDA) system. In this case, modulated continuous wave (CW) is used, circumventing spectral broadening by the pulse modulation. For SBS to take place, the pump-probe frequency difference has to be set to a 10-GHz order BFS with a 30-MHz precision. Therefore, if we apply modulation to both pump and probe waves, SBS will not occur in general, because the pump-probe frequency difference is not precisely controlled. However, at those points called correlation peaks, where the modulations are in phase, the frequency difference is constant and SBS occurs steadily. However, as the modulation is periodic, correlation peaks are also periodic on the fiber. To localize the SBS on fiber in a single point, the total measurement range is limited by half of the period of modulation.

The first BOCDA demonstrated was based on the direct modulation of a distributed feedback laser diode, applying sinusoidal frequency modulation (FM) to the lightwaves. The spatial resolution depends on the FM amplitude and frequency, and cm-order spatial resolution can be easily achieved in a basic BOCDA configuration. However, the correlation peak distance, thus the measurement range is limited to tens of meters. The best performance for a BFS distribution measurement system was 1.6 mm, while a 10-cm spatial resolution was achieved for a strain-temperature simultaneous measurement.

Recently, a novel correlation domain proposal was raised with the random phase modulation (PM) of pump and probe by an external phase modulator. In this case, the measurement range depends on the length of the modulating random code, while the nominal spatial resolution is equivalent to the length of 1 bit of the code. The real spatial resolution is deteriorated by the fact the created codes are not ideally random, but results show that 1-cm spatial resolution along a 1-km measurement length is achievable. Although demonstration has not been reported yet, the authors say same standards can be achieved for BDG spectra distributed measurement and therefore, strain-temperature simultaneous measurement.

The main goal of this thesis is to develop the highest spatial resolution fiber-optic sensing system of distributed simultaneous measurement of strain and temperature, using the original technology of Hotate laboratory, direct modulation BOCDA. The first step for enhancement of spatial resolution is to understand what determines spatial resolution, also to understand why the spatial resolution for BGS measurement is worse than that of BDG spectra measurements. The first approach was to calculate the acoustic wave complex amplitude created by the x-polarized waves and consider the scattering of light by that acoustic wave. From that calculation, it was possible to evaluate the effective length of the BDG after localization in correlation domain. The result was that the BDG works as a reflector in a region that extends beyond the nominal spatial resolution of BOCDA.

According to the theoretical analysis of BOCDA, the intensity of SBS is proportional to the beat power spectrum of the pump-probe lightwaves, which is a function of both position and frequency. To evaluate the spatial resolution of BOCDA, both the intensity of the beat power spectrum and its spectral broadening are considered. However, in this thesis, I formulated the hypothesis that this logic does not work for the BDG spectrum, because the *y*-read lightwave is under the same FM as the *x*-polarized waves. Therefore, its spectrum is broadened and it is reflected by all the BDG length, including the side lobes on the sides on the main correlation peak. So, to enhance the spatial resolution, it is necessary to suppress the correlation peaks, what can be realized by applying a proper IM synchronized with the FM applied to the laser source. Experiments showed the IM has the effect of spatial resolution enhancement, and under the conditions of the experiment, the observed enhancement was from 75 cm without the IM scheme to 17.5 cm with the proposed scheme.

To develop a stable high spatial resolution system, it is important to guarantee a good signal to noise ratio and avoid all sources of noise. A technique that has been developed to extend the measurement range of BOCDA is called temporal gating, which is based on pulse modulation of pump and probe waves. Although its efficiency in elongating the measurement range has been demonstrated, a solid theoretical analysis was not held. I assumed that the total beat power spectrum when two types of modulation are applied is the convolution of the beat power spectrum of each modulation. Based on that, it was possible to theoretically predict the optimum synchronization between the FM and the pulse modulation in a temporal gating scheme. Also, when spatial resolution is short and the signal coming from this tiny length of fiber is small, considerations about the signal acquisition scheme are necessary. The best solution for the strain-temperature simultaneous measurement BOCDA system was the beat lock-in detection.

By a cooperative research with a construction company, the proposed system was used to measure temperature and strain on a fiber glued to the surface of a concrete block. It is expected that the system can be adjusted to realize smart structures.