Fiber Optic Nerve Systems for Materials and Structures that can Feel Pain

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When we touch something sharp, we feel pain and jerk away our hand. Thanks to this sensation, we can protect our bodies from injury. There are millions of pain sensors called pain spots on a human body. These sensors are receptors consisting of sensory nerve cells, from which the sense of pain is transmitted to the brain via the nerve network. In addition to pain spots, there are many sensors on the body to protect us, such as cool spots, warm spots, pressure spots, and touch spots.

The theme of this paper is to deploy a “nerve network” on structures and materials such as bridges, bridge piers, pipelines for oil and natural gas, large-scale plants, and aircraft wings, in order to provide them with “pain” sensing capability.

Various human sensors for strain, pressure, and temperature have been technologically emulated, and implemented as small, precise sensors using MEMS technology. However, it is not so easy to place a large number of these sensors on structures or materials in order to build a “nerve network”. Since each sensor needs at least two lead wires, a huge number of lead wires must be managed for configuring a nerve network. Recently, research on nerve networks requiring no lead wires has been active, aiming at wireless communications between sensors by using integrated circuit technology. Its challenges include development of a means to supply power to sensors, and an extremely low power communication technology.

This paper describes the fiber optic technology for a nerve network. A multipoint type fiber optic sensing system is currently being developed. In this system, many sensors equivalent to pain spots or heat spots are embedded in an optical fiber in the longitudinal direction, and information from multiple sensors can be obtained by using only one light source and one photodetector. If physical phenomena at each point of an optical fiber can be used for sensing, the whole optical fiber will be able to function as a sensor. Combined with technology that can acquire the positional information along the optical fiber, it becomes a nerve network. This type of sensor system is called a “distributed fiber optic sensing system”. Whichever technology is applied, the system can eliminate the problem of a huge number of lead wires.

The author named these distributed or multipoint type fiber optic sensing systems “Fiber Optic Nerve Systems for Materials and Structures that can Feel Pain.”

Fiber Optic Nerve Systems can help achieve the kind of safe, secure and sustainable environment required in a modern society. For conserving nature and energy, people are shifting their lifestyles from “use and disposal” to “use with proper maintenance” in many aspects of society, and management technology for extending the service life of infrastructure such as highways, bridges, bridge piers, tunnels, etc., is being demanded. Fiber Optic Nerve Systems can help resolve these issues.

In a multipoint type fiber optic sensing system, many point type sensors are embedded in an optical fiber in the longitudinal direction. By using multiplexing technologies such as wavelength multiplexing and time multiplexing, this system can obtain information from many sensors with only one light source and one photodetector. A Fiber Bragg Grating (FBG) is used as a point type sensor for strain and temperature. The FBG is a fiber optic device in which a periodic variation in the refractive index of the fiber core in the longitudinal direction is built in. This grating selectively reflects a certain wavelength of light. This reflection is called the Bragg reflection. When a tensile or compressive strain, or heat or cold is applied to the optical fiber, the Bragg wavelength at the corresponding position changes. Thus FBG serves as a sensor for strain or temperature. There already are many products using FBG sensors for Fiber Optic Nerve Systems. Some are being used for monitoring the structural health of a tower in Guanzhou, China, and a large bridge across Tokyo Bay, as well as for other structures.

In the distributed fiber optic sensing system, its sensing principle is based on some of the physical phenomena of the optical fiber. Example phenomena include three kinds of backscattering: Rayleigh scattering, Raman scattering, and Brillouin scattering. Rayleigh scattering light has the same frequency as the incident light. Its intensity and phase change in accordance with the temperature and strain, and thus it can serve as a sensing principle. Raman scattering comprises a pair of scattered lights with frequencies about 10 THz higher or lower than the incident light respectively. These shifts are caused by phonons, thermal oscillations of molecules of the material SiO_2 of the optical fiber. Since the intensity ratio of both components is a function of temperature, this can serve as a temperature sensing principle. The frequency of Brillouin scattering light caused by acoustic phonons is about 10 GHz lower than the incident light. Since the amount of this shift changes linearly to temperature and strain, this also can serve as a principle for sensing these physical quantities.

To create distribution information, it is necessary to obtain the status of the scatterings described above at each position along the fiber. One of the technologies frequently used for this purpose is that of optical time domain reflectometry (OTDR), in which a series of optical pulses are transmitted into an optical fiber, and its time-resolved back scattering is measured. The time axis corresponds to the position, enabling distribution sensing. The first OTDR experiment was conducted at AT&T Bell Laboratories in the U.S. in 1976, when OTDR was used for measuring the distribution of Rayleigh scattering. OTDR is now widely used for diagnosing the healthiness of fiber optic communications networks, and also for diagnosing transoceanic optical cables. The distribution of Rayleigh scattering can be also measured by using the principle of FM radar, and the achieved spatial resolution is of the centimeter or millimeter order. Products for measuring distribution of temperature or strain based on this technology are available.

Temperature distribution sensing based on Raman scattering was proposed by a group at Southampton University in the U.K. in 1984. This method, also using OTDR, called Raman-OTDR (ROTDR), has been continuously improved around the world, and is widely used for measuring temperature distribution in up-to-date oil or natural gas wells, with its usage for monitoring and diagnosing various plants expanding.

Brillouin scattering has been studied in the R&D of Nippon Telegraph and Telephone Corporation (NTT) in Japan since 1989 as a principle for detecting temperature and strain. Using optical pulse technology, a method to sense their distribution was proposed and demonstrated. Fiber Optic Nerve Systems based on the Brillouin scattering is an original Japanese technology.

If a light with a frequency differing by the Brillouin frequency shift enters an optical fiber at both ends, Brillouin scattering is amplified. This phenomenon is called "stimulated Brillouin scattering". Meanwhile, when an incident light enters it at only one end, its backscattering is called "spontaneous Brillouin scattering". The former provides strong signals, but measurement along the whole fiber position becomes impossible if the fiber is disconnected even at one position. On the other hand, although the signals in the latter case are weak, the measurement is possible up to the disconnected position. These measuring methods are called "Brillouin optical time domain analysis" (BOTDA) and" Brillouin optical time domain reflectometry" (BOTDR) respectively. Their studies are expanding around the world, and their commercialization and activities for practical use are in expansion.

Brillouin scattering has a spectral line width of about 30 MHz, and the central frequency provides information on temperature and strain. When optical pulse width is of a time equivalent to one meter in light speed, a spatial resolution of 1 m is supposed. However, its spectral line width is about 100 MHz, wider than that of Brillouin scattering. This indicates that there is a trade-off relation between the spatial resolution and the reading accuracy of strain and temperature when using optical pulse technology. Recently, various new ideas are being incorporated into both the BOTDA and BOTDR to significantly improve spatial resolution and other features, and the commercialization of products using these technologies is advancing.

The author and co-researchers proposed "Brillouin optical correlation domain analysis" (BOCDA) in 1998, which measures the distribution of the Brillouin scattering spectrum along an optical fiber by using our proprietary technology that synthesizes the interference characteristics of light waves. BOCDA can eliminate the trade-off problem in the optical pulse technology described above. We have already achieved a spatial resolution of 1.6 mm, high speed measurement of 1,000 samples per second, a random access function which enables simultaneous measurements of dynamic changes in strain at any multiple points along an optical fiber, and other results. In addition to the BOCDA, in which light is input from both ends of an optical fiber, we also proposed and demonstrated the Brillouin optical correlation domain reflectometry (BOCDR) method, which measures the distribution by light input from one end. A measurement speed of 50 samples per second and a spatial resolution of 10 mm were achieved, both of which are superior to those of the BOTDR. Furthermore, we proposed and demonstrated a technology based on the BOCDA method that simultaneously measures the distribution of temperature and strain by using a single polarization maintaining fiber.

Research on the practical uses of the BOCDA is also expanding. In the civil engineering and construction fields, the BOCDA is already used for monitoring the healthiness of various structures. Our laboratory worked with manufacturers of aircrafts and measuring instruments, and developed a prototype using the BOCDA. A Fiber Optic Nerve System was configured on the surface of a small business jet, and the distribution of strain on the fuselage during the flight and dynamic changes in strain at multiple designated points were successfully measured. We also succeeded in measuring the distribution of temperature and strain simultaneously and independently during the flight.

As described above, a Fiber Optic Nerve System features various unique functions that electric sensors cannot provide. They include high spatial resolution of the order of millimeters, high speed measurement of the order of kilohertz, measurement of dynamic changes in strain at any multiple points along an optical fiber, and simultaneous and independent measurement of the distribution of temperature and strain. Various Fiber Optic Nerve Systems have been implemented by using various techniques around the world. Potential application targets are infrastructure such as buildings, bridges and highways, and various plants, railroad networks, aircraft, vessels and the like. If the Fiber Optic Nerve Systems are configured across them and their healthiness is diagnosed, it will greatly help achieve a safer, more secure and more sustainable society in the 21th century. To establish a total system which enables diagnosis of the healthiness of structures and materials by using Fiber Optic Nerve Systems as a core technology, research and development across different fields are required. Advancing these activities is expected to create new industries and contribute towards encouraging innovation.