Title	Multi-Channel Fiber-Optic Temperature Sensor System using An Optical Time-Domain Reflectometer
Author(s)	Kim, H.J.; Byun, H.; Song, Y.B.; Shin, S.H.; Cho, S.; Pyeon, C.H.; Lee, B.
Citation	Results in Physics (2018), 11: 743-748
Issue Date	2018-12
URL	http://hdl.handle.net/2433/236666
Right	© 2018 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/BY-NC-ND/4.0/).
Type	Journal Article
Textversion	publisher

Results in Physics 11 (2018) 743–748

Contents lists available at ScienceDirect

Results in Physics

journal homepage: www.elsevier.com/locate/rinp

Multi-channel fiber-optic temperature sensor system using an optical time-domain reflectometer

H.J. Kim[a], H. Byun[a], Y.B. Song[a], S.H. Shin[a], S. Cho[b], C.H. Pyeon[c], B. Lee[a,*]

[a] *School of Energy Systems Engineering, Chung-Ang University, 84, Heukseok-ro, Dongjak-gu, Seoul 06974, Republic of Korea*
[b] *Department of Organic Materials and Fiber Engineering, Soongsil University, 369, Sangdo-ro, Dongjak-gu, Seoul 06978, Republic of Korea*
[c] *Research Reactor Institute, Kyoto University, Asashiro-nishi, Kumatori-cho, Sennan-gun, Osaka 590-0494, Japan*

ARTICLE INFO

Keywords:
Fiber-optic temperature sensor
Optical time-domain reflectometer
Fresnel reflection
Multi-channel

ABSTRACT

In this study, we developed a multi-channel fiber-optic temperature sensor system (FTSS) using an optical time-domain reflectometer (OTDR). The developed FTSS consists of fiber-optic temperature-sensing probes, a fiber-optic coupler, a transmitting optical fiber, and an OTDR. The fiber-optic temperature-sensing probes comprise silicon oil, a nickel-plated brass cap, a fiber channel (FC) terminator, and a single-mode optical fiber. The developed FTSS has four channels, which have fiber-optic temperature-sensing probes, connected using single-mode optical fibers of different lengths. Silicon oil is employed as a temperature-sensing material, as its refractive index changes with the temperature variations. We measured the optical powers of the reflected light signals (Fresnel reflection), which are generated at the interface between the silicon oil and core of the single-mode optical fiber in the distal ends of the sensing probes. The optical powers of the four channels of the FTSS were measured to simultaneously determine individual temperatures at four different points using an OTDR.

Introduction

Temperature is a very important physical quantity in various phenomena in natural science fields including physics, chemistry, medicine, and biology. It is necessary to monitor and control temperature in various industries such as food and beverage processing, plastic production, and metal processing. In order to be able to measure the temperature, various types of devices including thermocouples, resistance temperature detectors, thermistors, infrared radiation thermometers, and heating labels, can be employed according to their suitability for a given measurement. It is often necessary to simultaneously measure the temperature at multiple points using the same type of temperature measuring devices with the same level of performance.

If the measuring points are distributed far away from each other, fiber-optic based sensor can be employed, as one of the most suitable devices for temperature measurements at multiple distributed points [1–3]. The fiber-optic based sensor offers many advantages such as a small size, good flexibility, remote operation, immunity to electromagnetic field and radio-frequency interference, and ability to operate in harsh environments [4–6]. Various fiber-optic-based temperature sensors have been developed and it has been reported that they can measure temperature using fiber Bragg gratings (FBGs), infrared (IR) optical fibers, or special materials that can change their physical characteristics including their color, absorbance, and reflectance, as a function of the temperature [7–15]. However, the above fiber-optic-based temperature sensors are not suitable for monitoring temperatures at widely-distributed multiple points even if they use long optical fibers. In some cases, it is needed to simultaneously measure temperatures at points that are hundreds of meters or several kilometers apart. For example, it is necessary to measure or monitor temperatures at the inaccessible hazardous environments such as a nuclear power plant, a radioactive waste site and a chemical plant.

In this study, we developed a multi-channel fiber-optic temperature sensor system (FTSS) based on silicon oil using optical time-domain reflectometer (OTDR) for the simultaneous measurements of temperature at several arbitrary points. OTDR is an optoelectronic instrument which can be employed to characterize optical fibers and reveal fiber break locations in fiber-optic communication networks. As a part of the FTSS, OTDR can be used as a light source and an optical measuring device. It can measure several different optical signals that are simultaneously generated with the temperature changes at distributed multiple points. We measured and analyzed the optical powers of the four channels of the FTSS in order to simultaneously determine individual temperatures at four different points using an OTDR.

---

[*] Corresponding author.
E-mail address: bslee@cau.ac.kr (B. Lee).

https://doi.org/10.1016/j.rinp.2018.10.024
Received 19 September 2018; Received in revised form 16 October 2018; Accepted 17 October 2018

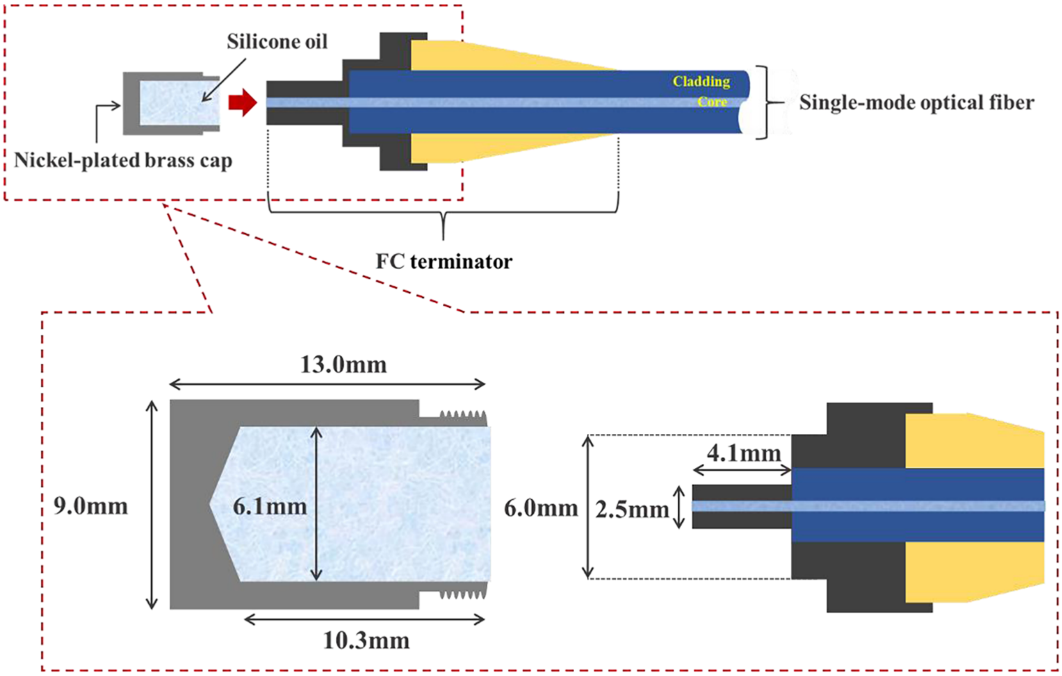

Fig. 1. Structure of the temperature sensing probe.

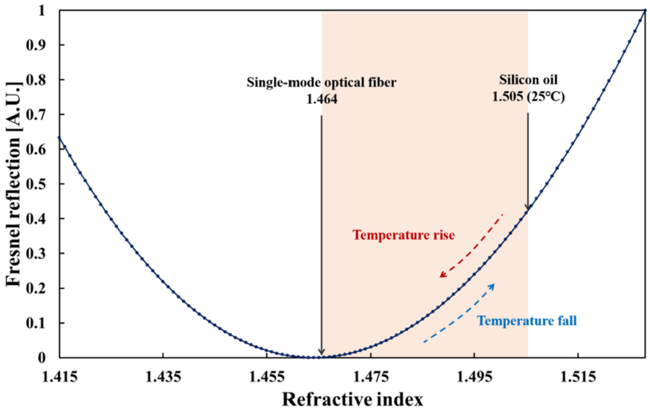

Fig. 2. Dependence of the Fresnel reflection as a function of the refractive index of silicon oil.

Materials and methods

For the real-time simultaneous temperature measurements, we developed a multi-channel FTSS. It consists of fiber-optic temperature-sensing probes, a fiber-optic coupler, a transmitting optical fiber, and the OTDR. The temperature-sensing probe consists of a temperature-sensing material, a nickel-plated brass cap, a fiber channel (FC) terminator, and a single-mode optical fiber, as shown in Fig. 1. As the temperature-sensing material, we used silicon oil (KF-54, Shin-Etsu), whose refractive index changes with the temperature variations. In addition, it exhibits temperature stability, good heat-transfer characteristics, and it is very clear in the temperature range of −35 °C to 250 °C. A nickel-plated brass cap, which has a pretty good thermal conductivity, is used to increase the temperature sensitivity and nickel plating can prevent corrosion caused by external contaminants. The height of a cylindrical shape of nickel-plated brass cap is 13.0 mm and the outer and inner diameter of the cap are 9.0 and 6.1 mm, respectively. For a simple and accurate connection of the optical fiber to the optical instruments (such as OTDR and fiber-optic coupler), we employed an FC terminator (30126C3, Thorlabs Inc.), which facilitates the rapid and simple manipulation with the nickel-plated brass caps, owing to the spiral structure of the inside groove. In order to transmit the light signals from the temperature-sensing probe to the OTDR, we used a single-mode optical fiber (980HP, Thorlabs Inc.) which has a core/cladding structure. The outer diameter of the single-mode optical fiber is 245 µm and it is made of fluorinated polymer that has a refractive index of 1.402. The core has a diameter of 3.6 µm, and it is made of silica, which has a refractive index of 1.46.

In this study, OTDR (AQ7275-735041, Yokogawa Inc.) was used as a light source and a light measuring device. It is commonly used to measure failure points of buried optical lines in the field of optical communications. It can measure and display a series of optical pulses that are generated by the light that is scattered (Rayleigh backscattering) or reflected (Fresnel reflection) from end-points along optical fibers. The advantage of the OTDR is that it can simultaneously measure multiple optical signals in real-time and extend the length of the optical fiber up to several hundreds of kilometers.

We measured the optical power of reflected light (Fresnel reflection) using the OTDR. Fresnel reflection is the reflection of a portion of incident light at a discrete interface between two media which have different refractive indices. In the FTSS, the Fresnel reflection is generated at the interface between the silicon oil and core of the single-

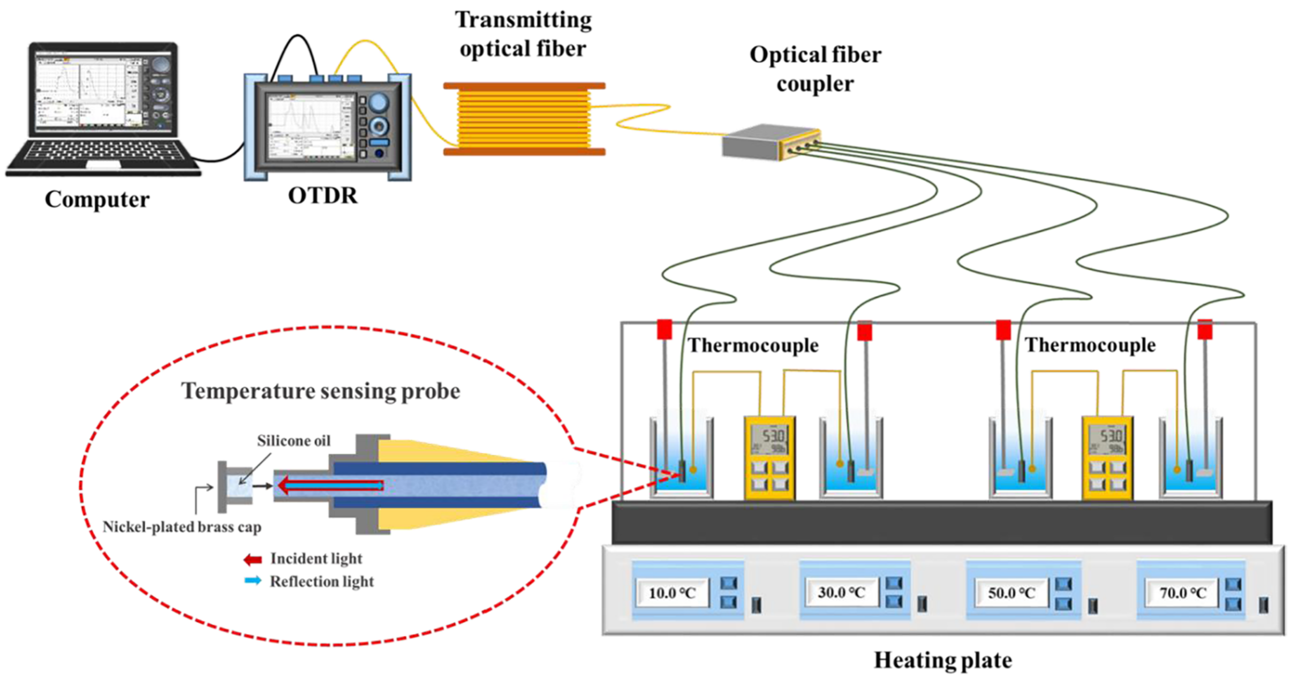

Fig. 3. Experimental setup of the water temperature measurement using temperature-sensing probe.

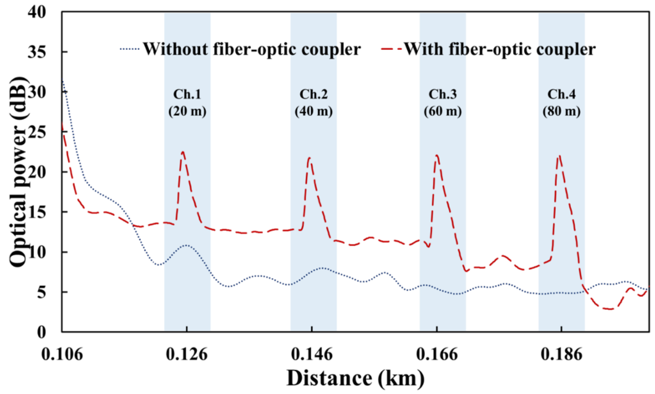

Fig. 4. Comparison of the FTSS optical powers with and without the use of 1 × 4 fiber-optic coupler.

mode optical fiber at the distal end of the sensing probe. The intensity ratio of the reflected light (Fresnel reflection) is:

$$R = \left(\frac{(n_1 - n_2)}{(n_1 + n_2)}\right)^2 \tag{1}$$

where R is the reflection coefficient, and n_1 and n_2 are the refractive indices of the core of a single-mode optical fiber and silicon oil, respectively. The dependence between the refractive index of silicon oil and Fresnel reflection intensity (Eq. (1)) varies with the temperature, as shown in Fig. 2.

The refractive index of silicone oil decreases with the increase of the temperature, and approaches the refractive index value of the core of the single-mode optical fiber, which causes a decrease of the intensity of the Fresnel reflection. Accordingly, the amount of Fresnel reflection increases with the decrease of the temperature of the silicon oil [16,17]. Therefore, the temperature at an arbitrary point can be determined by measuring the light intensity of the reflected light, which is directly related to the change of the refractive index of the silicone oil.

The experimental setup, employed to evaluate the temperature-sensing probe is shown in Fig. 3. Once the four channels, which have temperature-sensing probes, were placed in the four beakers, the water temperature in each beaker was independently controlled and maintained using a heating plate (Combi mantle, Global Lab). The temperature of the water was measured using a thermocouple (54II thermometer, Fluke), which was employed as a reference thermometer. The measured temperatures using the thermocouple and optical powers using OTDR in the four channels, were compared and analyzed to determine the water temperatures in the four beakers. A 1 × 4 fiber-optic coupler (FCQ1315-FC, Thorlabs Inc.) was employed to distribute the optical source signal from the OTDR to the temperature-sensing probe as well as to gather and transfer the Fresnel reflection signals from the probes to the OTDR.

Experimental results

Fig. 4 shows the optical signals that are independently generated from the distal ends of the four single-mode optical fibers in the temperature-sensing probes, when the 1 × 4 fiber-optic coupler is used. In this experiment, four single-mode optical fibers that have lengths of 20, 40, 60, and 80 m were connected to a 1 × 4 fiber-optic coupler. In Fig. 4, the X-axis denotes the total length of optical fiber by the distance from the starting point of the optical fiber connected from the OTDR to the end of the temperature sensing probe, including a transmitting optical fiber of 106 m in length. Different optical signals can be measured, according to the temperature-sensing positions. In addition, we could confirm that the optical peaks are independently generated in the

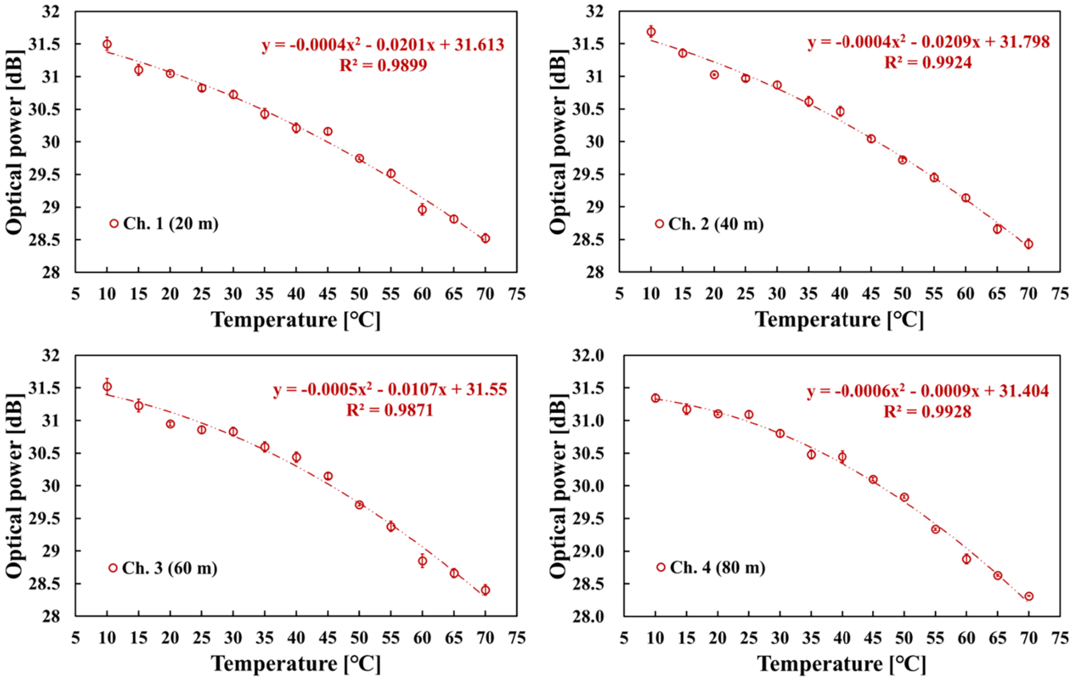

Fig. 5. Responses of the four channels of the FTSS as a function of the water temperature.

four channels and that our FTSS can be employed as a multi-channel sensor.

Fig. 5 shows the optical powers in the four channels as a function of the temperature. We measured the optical powers to simultaneously and independently determine the water temperatures in the four channels in the temperature range of 10–70 °C. In each channel, the optical power output signals as a function of the temperature showed almost the same trend. For the four channels, the relationship between the optical power and temperature was revealed and was shown in Fig. 5, respectively. Using the developed FTSS, we measured the optical powers repeatedly five times at the same temperature, and all of the measured data are within the error range of 0.114%, with respect to the average values.

Fig. 6 shows the measured optical powers for the four channels at temperatures in the range of 10–70 °C and X-axis denotes the total length of optical fiber by the distance including a transmitting optical fiber as shown in Fig. 4. In Fig. 6, it can be noticed that the measured optical signals change with the water temperatures in the four beakers. The water temperatures of the four beakers were maintained at 10, 30, 50, and 70 °C. We measured the optical powers of each channel by moving the temperature-sensing probe from one beaker to another. The temperature-sensing probes were immersed in each beaker for 1 min. In all channels, the optical powers, which are related to the peak values of the optical pulses, are measured with the variations of the temperature. Also, the peak values of the optical pulses which can decide the water temperatures in each channel are shown in Fig. 6.

Fig. 7 shows the real-time monitoring of the FTSS to measure reproducibility and response time in the temperature range between 10 ± 1 °C and 70 ± 1 °C. The response time of the FTSS is in the range from 47 to 48 sec and the sensing time per degree Celsius could be calculated as about 0.79 sec/°C.

Conclusions

In this study, we developed a multi-channel FTSS based on silicon oil, whose refractive index changes with temperature variations. The developed FTSS consists of four channels with fiber-optic temperature-sensing probes, a fiber-optic coupler, a transmitting optical fiber, and an OTDR. The fiber-optic temperature-sensing probes of the channels comprised silicon oil, a nickel-plated brass cap, an FC terminator, and a single-mode optical fiber.

The optical powers of the reflected light signals from the temperature-sensing probes were measured using OTDR. They depended on the temperature variations in the channels and were analyzed in order to evaluate the FTSS performance. In addition, the relationships between the measured optical power and temperature were obtained, which can be employed to determine the temperature values at desired points. The obtained results show that the proposed FTSS can accurately measure temperature in the range of 10–70 °C, and can be used as a multi-channel temperature sensor in real-time. As a result, we confirmed that the FTSS has good reproducibility and the response time is in the range from 47 to 48 sec and the sensing time per degree Celsius could be calculated as about 0.79 sec/°C. The response time could be reduced if the sensing probe is fabricated with a cap which has a smaller size and a higher thermal conductivity. However, it was very difficult to fabricate a proper cap and it was not commercially available. Based on the results of this study, the proposed multi-channel FTSS could be used to effectively monitor temperatures at a long distance as industrial applications and especially it can be used in chemical or power plant.

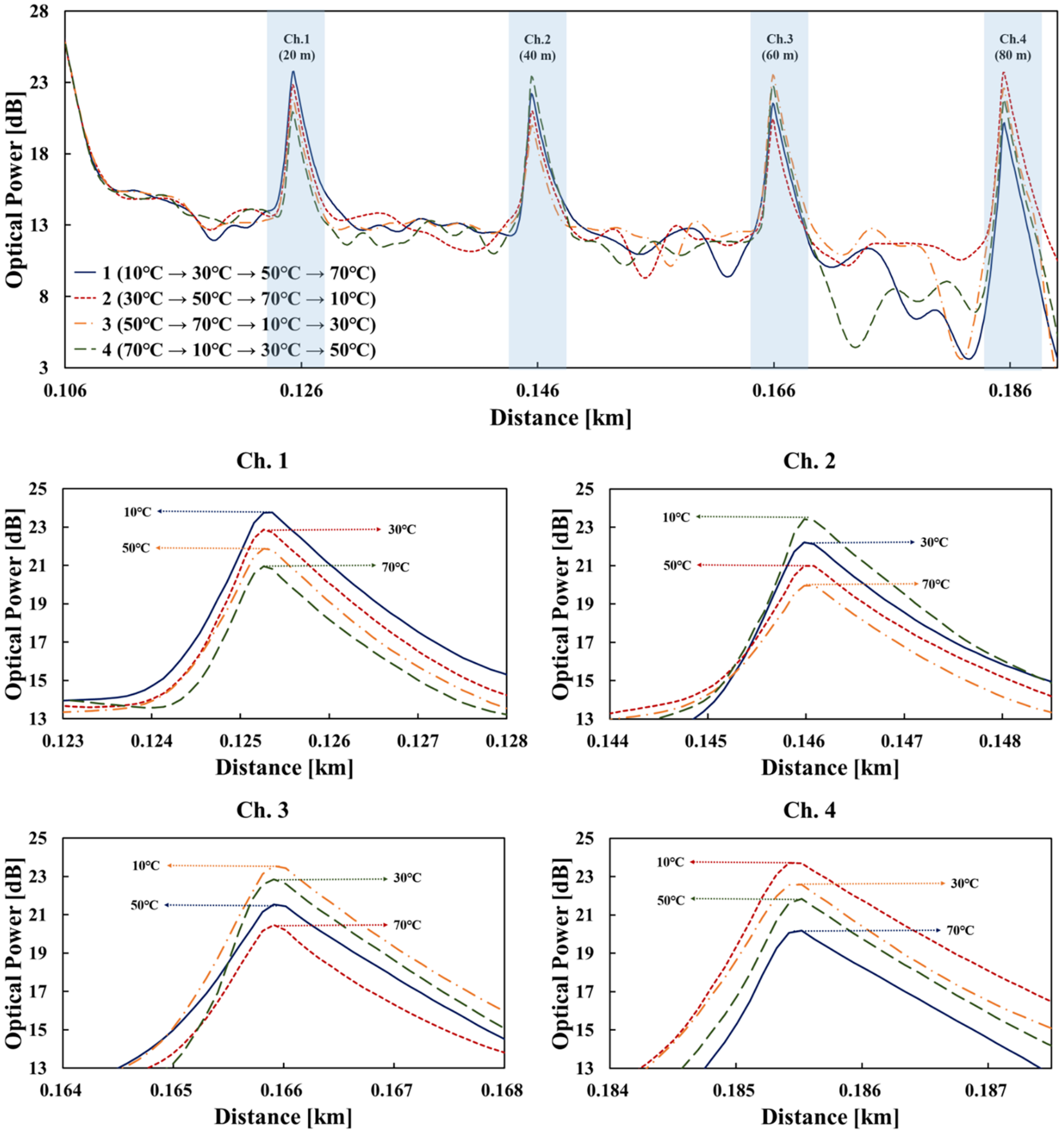

Fig. 6. Measured optical powers in the four channels for different temperatures in the range of 10–70 °C.

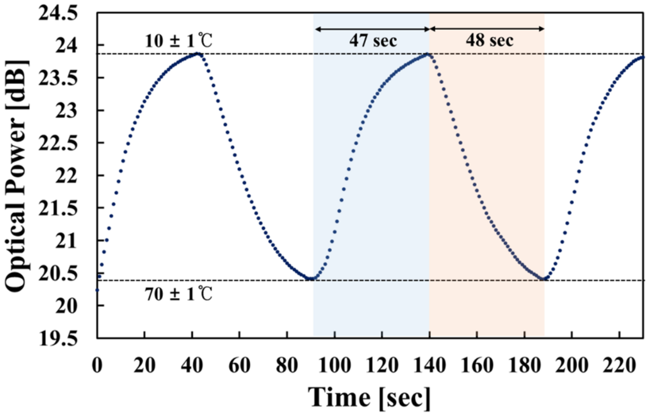

Fig. 7. Reproducibility and response time of the FTSS in the range of 10–70 °C.

Declarations of interest

None.

Acknowledgements

This study was supported by the National Nuclear R&D Program through the National Research Foundation of Korea (NRF), funded by the Ministry of Science, ICT and Future Planning (No. 2016M2B2B1945255) and by the Basic Science Research Program through the NRF of Korea, funded by the Ministry of Science, ICT and Future Planning (No. 2017R1A2B2009480).

References

[1] Perez-Herrera RA, Lopez-Amo M. Fiber optic sensor networks. Opt Fiber Technol 2013;19:689–99. https://doi.org/10.1016/j.yofte.2013.07.014.
[2] Thomas PJ, Hellevang JO. A fully distributed fibre optic sensor for relative humidity measurements. Sens Act B Chem 2017;247:284–9. https://doi.org/10.1016/j.snb.2017.02.027.
[3] Sim HI, Yoo WJ, Shin SH, Jang J, Kim JS, Jang KW, et al. Real-time measurements of water level and temperature using fiber-optic sensors based on an OTDR. Trans Kor Inst Elect Eng 2014;63:1239–44. https://doi.org/10.5370/KIEE.2014.63.9.1239.

[4] Lee B. Review of the present status of optical fiber sensors. Opt Fiber Technol 2003;9:57–79. https://doi.org/10.1016/S1068-5200(02)00527-8.

[5] Wang A, Xiao H, Wang J, Wang Z, Zhao W, May RG. Self-calibrated interferometric-intensity-based optical fiber sensors. J Lightwave Technol 2001;19:1495. https://doi.org/10.1109/50.956136.

[6] Moreda FJG, Arregui FJ, Achaerandio M, Matias IR. Study of indicators for the development of fluorescence based optical fiber temperature sensors. Sens Act B Chem 2006;118:425–32. https://doi.org/10.1016/j.snb.2006.04.079.

[7] Ding M, Yang B, Jiang P, Liu X, Dai L, Hu Y, et al. High-sensitivity thermometer based on singlemode-multimode FBG-singlemode fiber. Opt Laser Technol 2017;96:313–7. https://doi.org/10.1016/j.optlastec.2017.05.031.

[8] Hsiao TC, Hsieh TS, Chen YC, Huang SC, Chiang CC. Metal-coated fiber Bragg grating for dynamic temperature sensor. Optik 2009;127:10740–5. https://doi.org/10.1016/j.ijleo.2016.08.110.

[9] Leich M, Fiebrandt J, Schwuchow A, Unger S, Jetschke S, Bartelt H. Femtosecond pulse-induced fiber Bragg gratings for in-core temperature measurement in optically pumped Yb-doped silica fibers. Opt Commun 2012;285:4387–90. https://doi.org/10.1016/j.optcom.2012.07.031.

[10] Yoo WJ, Cho DH, Jang KW, Shin SH, Seo JK, Chung SC, et al. Infrared radiation thermometer using a silver halide optical fiber for thermal ablation. Opt Rev 2009;16:387. https://doi.org/10.1007/s10043-009-0073-9.

[11] Zou X, Chao A, Tian Y, Wu N, Zhang H, Yu TY, et al. An experimental study on the concrete hydration process using Fabry-Perot fiber optic temperature sensors. Measurement 2012;45:1077–82. https://doi.org/10.1016/j.measurement.2012.01.034.

[12] Tao S, Jayaprakash A. A fiber optic temperature sensor with an epoxy-glue membrane as a temperature indicator. Sens Act B Chem 2006;119:615–20. https://doi.org/10.1016/j.snb.2006.01.034.

[13] Fernandez-Valdivielso C, Egozkue E, Matıas IR, Arregui FJ, Bariain C. Experimental study of a thermochromic material based optical fiber sensor for monitoring the temperature of the water in several applications. Sens Act B Chem 2003;91:231–40. https://doi.org/10.1016/S0925-4005(03)00118-7.

[14] Lee B, Tack GR, Chung SC, Yi JH, Kim S, Cho HS. Fiber-optic temperature sensor using a liquid crystal film for laser-induced interstitial thermotherapy. J Kor Phys Soc 2005;46:1347–51.

[15] Lee B, Cho DH, Tack GR, Chung SC, Yi JH, Jun JH, et al. Feasibility study of development of plastic optical fiber temperature sensor using thermosensitive clouding material. Jpn J Appl Phys 2006;45:4234. https://doi.org/10.1143/JJAP.45.4234.

[16] Jang JS, Yoo WJ, Shin SH, Lee DE, Kim M, Kim HJ, et al. Fiber-optic temperature sensor using a silicone oil and an OTDR. Trans Kor Inst Elect Eng 2015;64:1592–7. https://doi.org/10.5370/KIEE.2015.64.11.1592.

[17] Lee DE, Yoo WJ, Shin SH, Kim M, Song YB, Kim HJ, et al. Silicon oil-based 2-channel fiber-optic temperature sensor using a subtraction method. J Sens Sci Tech 2016;25:344–8. https://doi.org/10.5369/JSST.2016.25.5.344.