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Improvement of Temperature Sensitivity of Long-period Fiber Gratings Using Liquids with High Thermo-optic Coefficients

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To realize a highly sensitive glass-capillary-encapsulated long-period fiber grating (LPFG) sensor, we propose filling the capillary with a liquid-phase material, which was not proposed previously. It was found theoretically that high sensitivity can be achieved by using a liquid-phase filler with a thermal conductivity of 0.1 W/(m · K) or more, large negative thermo-optic coefficient (TOC), and a refractive index of 1.46 (optical fiber cladding refractive index) or less. On the basis of theoretical results, ethanol, ethylene glycol, silicone oil #TSF-431, and silicone oil #TSF-451 were selected as liquid-phase fillers in this study. The shift of the resonance wavelength spectrum with respect to the unit temperature was used as the temperature sensitivity. The temperature sensitivity was determined to be 75.5 pm/°C when LPFG was filled with ethanol, 70.0 pm/°C when filled with ethylene glycol, 84.8 pm/°C when filled with silicone oil #TSF-431, and 86.8 pm/°C when filled with silicone oil #TSF-451. The use of liquid fillers with high thermal conductivity, a refractive index close to 1.46, and high TOC can significantly improve the temperature sensitivity compared with the case without fillers. It was also experimentally confirmed that high sensitivity is possible. Furthermore, a capillary-encapsulated LPFG sensor with a temperature sensitivity of 83.3 pm/°C was realized using silicone oil #TSF-451, which showed the highest temperature sensitivity in our experiments.

1. Introduction

Compared with electric sensors, optical fiber sensors are less susceptible to electromagnetic waves and radiation, smaller in diameter, lighter in weight, easier to install, maintenance-free, and can be used over long distances. Therefore, their practical use is being promoted and a lot of research and development is being conducted to further improve their characteristics.[1–4]

One type of optical fiber sensor is the diffraction grating type, which forms diffraction gratings through periodic refractive index changes in the core or cladding of an optical fiber to enable the sensing of temperature, strain, and so on. This optical fiber sensor is characterized by its high compatibility with transmission optical fibers because diffraction gratings are formed nondestructively and directly on the core or cladding without mechanical processing. Since only

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the formed diffraction gratings function as sensors, they are suitable for local sensing and multipoint measurement systems.

There are two types of diffraction-grating-type optical fiber sensor: fiber Bragg grating (FBG)(5) and long-period fiber grating (LPFG).(6,7) FBGs use an interferometric exposure method to form a fine analytical grating with a period as long as the wavelength of light. LPFGs, on the other hand, create relatively long-period diffraction gratings with periods ranging from tens to hundreds of micrometers by applying periodic mechanical external forces,(8) acoustic wave excitation,(9) electric discharge,(10) or infrared laser heating.(11) Thus, we are working on our study aimed at realizing a practical temperature sensor using an LPFG, which is expected to be easy and inexpensive to manufacture.

When using an LPFG as a practical sensor, improving the mechanical damage resistance and temperature sensitivity of the LPFG are important issues. Mechanical damage resistance can generally be improved by packaging in which an optical fiber section on which an LPFG is formed is enclosed in a capillary section. Note that packaging causes a decrease in temperature sensitivity due to the thermal resistance of the capillary and the thermal resistance of air that exists between the capillary and the optical fiber in which the LPFG is formed. The former is determined by the material and thickness of the capillary in order to ensure the necessary mechanical strength in the environment in which the LPFG is installed. On the other hand, for the latter, filling the space between the capillary and the optical fiber, where the LPFG is formed, with a filler that has low thermal resistance and large thermo-optic coefficient (TOC) reduces thermal resistance due to air and increases temperature sensitivity.

Until now, many reports have been made on improving temperature sensitivity using solid-phase fillers.(12–14) However, liquid materials, which have not been considered as fillers in the past, are generally characterized by having a larger TOC than solid-phase materials. Moreover, like solid-phase fillers, liquid-phase fillers also have thermal resistance well above that of air.

In this paper, we theoretically investigate the liquid-phase material to be filled in the capillary and conduct experiments on the basis of the results of the theoretical investigation to realize a capillary-encapsulated LPFG sensor with excellent temperature sensitivity. A glass capillary with excellent mechanical strength and corrosion resistance is used. The effect of the liquid-phase filler on reducing sensitivity deterioration due to thermal resistance and the improvement of temperature sensitivity using the TOC have been investigated in a theoretical study, and temperature characteristics were evaluated by using ethanol, ethylene glycol, and silicone oil as liquid-phase fillers in the experiment. Temperature sensitivity characteristics were evaluated on the basis of the amount of change in the resonance wavelength of an LPFG due to the filling material with respect to temperature. In addition, we report a glass-capillary-encapsulated LPFG sensor with a temperature sensitivity of 83.3 pm/°C by using silicone oil, which showed the highest temperature sensitivity in our experiments.

2. Structure and Theoretical Study of Glass-capillary-encapsulated LPFG Sensor

2.1 Glass-capillary-encapsulated LPFG sensor structure

Figure 1 shows a schematic diagram of our glass-capillary-encapsulated LPFG sensor. The LPFG section formed in the optical fiber is encapsulated in a glass capillary with excellent corrosion resistance, and the space between the capillary and the LPFG is filled with a liquid-phase filler. The glass capillary has an inner diameter of 1.5 mm, an outer diameter of 2.1 mm, and a length of 80 mm.

2.2 Theoretical study

In a temperature sensor using an LPFG, changes in the transmission spectrum of the LPFG and the resonance wavelength spectrum that appears on the same spectrum with respect to temperature are observed. Therefore, the temperature sensitivity of the LPFG can be evaluated on the basis of the amount of change in resonance wavelength per unit temperature ($\Delta\lambda_{res}$). $\Delta\lambda_{res}$ can also be expressed as the resonance wavelength change amount $\Delta\lambda_{res}^{F}$ due to the change in the glass refractive index of the optical fiber in which the LPFG is formed,[15] the resonance wavelength change amount $\Delta\lambda_{res}^{T}$ due to the temperature-dependent tension applied to the LPFG section,[16] the resonance wavelength change amount $\Delta\lambda_{res}^{TOC}$ due to the temperature-dependent TOC and refractive index of the filler, and the sensitivity degradation R due to the thermal resistance of the package and filler.

$$\Delta\lambda_{res} \approx \Delta\lambda_{res}^{F} + \Delta\lambda_{res}^{T} + \Delta\lambda_{res}^{TOC} - R \tag{1}$$

In this study, we will consider increasing the temperature sensitivity using fillers. Therefore, the following two points are discussed below to examine the temperature sensitivity characteristics using filler material only.

(a) Effect of filler material on the reduction in sensitivity degradation R due to thermal resistance

(b) Effects of TOC and refractive index of filler material on the resonance wavelength change amount $\Delta\lambda_{res}^{TOC}$ due to temperature change.

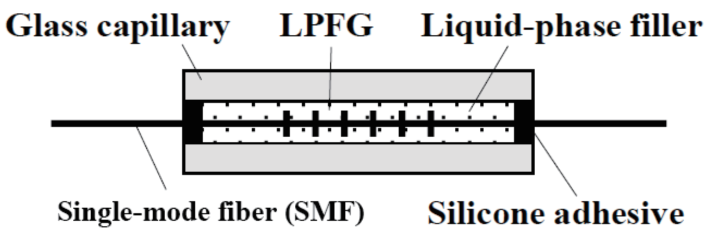

Fig. 1. Glass-capillary-encapsulated LPFG sensor.

2.2.1 Reduction effect of sensitivity degradation caused by thermal resistance due to filler material

Figure 2 shows a cross-sectional view of an LPFG sealed in a glass capillary. r_0, r_1, r_2, Q_1, Q_2, k_1, k_2, T_A, T_1, T_2, and L are the optical fiber outer radius, the capillary inner radius, the capillary outer radius, the amount of heat passing through the material filled in the capillary, the amount of heat passing through the capillary glass, the thermal conductivity of the material being filled, the thermal conductivity of the capillary glass, the boundary temperature between the optical fiber and the filling material, the boundary temperature between the filling material and the capillary glass, the boundary temperature between the glass capillary and the outer circumference, and the length of the glass capillary encapsulating the LPFG, respectively. Fourier's law[17] is applied to the filler section and the glass section of the glass capillary.

$$Q_1 = \frac{T_A - T_1}{\frac{\ln(r_1/r_0)}{2\pi k_1 L}}, Q_2 = \frac{T_2 - T_1}{\frac{\ln(r_2/r_1)}{2\pi k_2 L}} \tag{2}$$

In the steady state ($Q_1 = Q_2$), the difference ΔT_P between the temperature T_2 of the capillary outer portion of the packaged LPFG and the temperature T_A of the LPFG can be expressed as

$$\Delta T_P = T_2 - T_A = -\left(\frac{\ln(r_1/r_0)}{2\pi k_1 L} - \frac{\ln(r_2/r_1)}{2\pi k_2 L}\right). \tag{3}$$

Figure 3 shows the relationship between T_2 at the capillary periphery after 180 (s) and ΔT_P when the thermal conductivity of the filling material (k_1) is 0.1 to 0.3 W/(m · K). Also shown is the case where there is no filler, that is, the case where there is air [k_1 = 0.026 W/(m · K)]. The r_0, r_1, r_2, and L values used in the calculations are 0.0625, 0.75, 1.05, and 80 mm, respectively. The

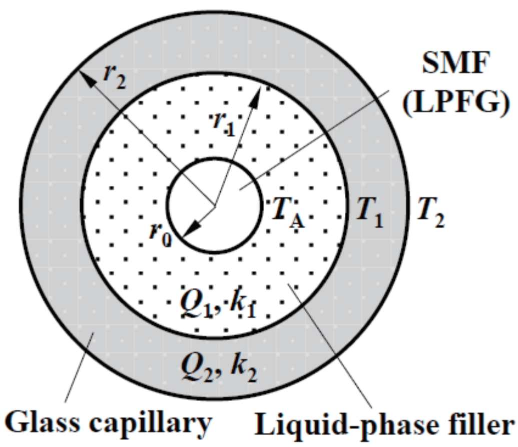

Fig. 2. Calculation model.

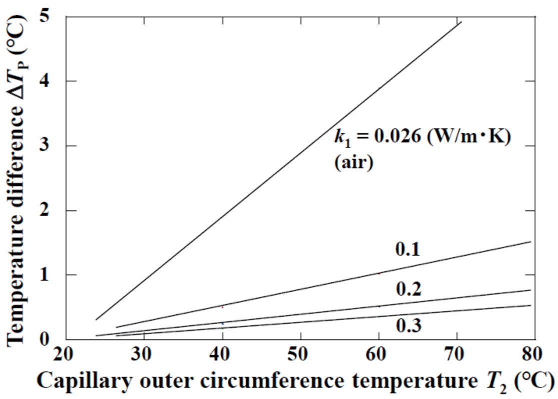

Fig. 3. Relationship between T_2 and ΔT_P.

thermal conductivity of the capillary glass (k_2) is 1 W/(m · K). It is clear that the use of a filler with a thermal conductivity of ~0.1 or higher reduces ΔT_P significantly compared with the case without fillers, and the sensitivity degradation due to the thermal resistance of the packaging can be significantly reduced.

2.2.2 Resonance wavelength change due to temperature change in refractive index of filler

The resonance wavelength λ_{res} of the LPFG can be expressed using the following equation, which expresses the phase matching condition between the fundamental core mode light and the cladding mode light propagating in the optical fiber.[18]

$$\lambda_{res} = \left(n_{eff,co}(\lambda) - n_{eff,cl}^{m}(\lambda)\right)\Lambda \quad (4)$$

Here, $n_{eff,co}(\lambda)$, $n_{eff,cl}^{m}(\lambda)$, λ, and Λ are the effective refractive index of the core mode, the effective refractive index of the mth cladding mode, wavelength, and LPFG grating period, respectively. Note that m is the mode order of the cladding mode. Therefore, $\Delta\lambda_{res}^{TOC}$ in Eq. (1) can be increased by using a filler that has a large refractive index change with respect to temperature, that is, a filler that has a large TOC. Note that the TOC of the optical fiber core and cladding with respect to $\Delta\lambda_{res}^{F}$ in Eq. (1) is 8.6×10^{-6} (1/°C),[15] whereas the TOC of the filler is generally negative on the order of -10^{-4} (1/°C).

Thus, the change in $n_{eff,co}(\lambda)$ in Eq. (4) is neglected and only the TOC of the filler material is considered. $n_{eff,cl}^{m}(\lambda)$, which considers the refractive index change of the filler material, can be written as[19]

$$n_{eff,cl}^{m} = \beta_{cl}^{m} / p, \quad (5)$$

$$\beta_{cl}^{m} = \sqrt{(pn_{cl})^2 - (u_{cl}^{m} / a_{cl})^2}. \quad (6)$$

Here, β_{cl}^{m} is the propagation constant of the mth cladding mode, p is the wavenumber (=1/λ), n_{cl} is the refractive index of the cladding, u_{cl}^{m} is the normalized transverse wavenumber, and a_{cl} is the cladding radius. Furthermore, u_{cl}^{m} is obtained from the following equation, which can be described by the V value of the optical fiber, the normalized transverse wavenumber w_{cl}^{m}, the refractive index $n_{ext}(T)$ of the filling material at temperature T, and the TOC c_{ext} of the filling material. The refractive index of the filler material is less than or equal to the cladding refractive index of 1.46.

$$V^2 = \left(u_{cl}^{m}\right)^2 + \left(w_{cl}^{m}\right)^2 \tag{7}$$

$$V = \frac{2\pi a_{cl}}{\lambda}\sqrt{n_{cl}^2 - n_{ext}^2(T)} \tag{8}$$

$$n_{ext}(T) = n_{ext}(T_0) + (T - T_0)c_{ext} \tag{9}$$

$$u_{cl}^{m}\frac{J_1(u_{cl}^{m})}{J_0(u_{cl}^{m})} = w_{cl}^{m}\frac{K_1(w_{cl}^{m})}{K_0(w_{cl}^{m})} \tag{10}$$

Here, J_0 and J_1 are the zero-order and first-order Bessel functions of the first kind, and K_0 and K_1 are the zero-order and first-order Bessel functions of the second kind, respectively, and T_0 is the reference temperature. From the above, it can be seen that the resonance wavelength λ_{res} of the LPFG at temperature T can be calculated using Eqs. (4)–(10), and that the temperature characteristics are highly dependent on the refractive index $n_{ext}(T)$ and TOC c_{ext} of the filler material.

Figures 4 and 5 show the calculation results of the resonance wavelength shift with respect to temperature, calculated using the TOC and the filler refractive index $n_{ext}(T)$ as parameters, respectively. The reference temperature T_0 for both is 20 °C, and simulations were performed using negative TOCs since fillers generally have negative TOCs. The values of m, $n_{eff,co}(\lambda)$, n_{cl}, a_{cl}, and n_{ext} at the reference temperature were set to 2, 1.465, 1.46, 1.41, and 62.5 µm, respectively. Furthermore, Fig. 6 shows the amount of shift in the resonance frequency per unit temperature when the filler refractive index n_{ext} is used as a parameter, which was obtained by summarizing the results in Figs. 4 and 5. As shown in Figs. 4–6, the high sensitivity of the glass-capillary-encapsulated LPFG sensor can be achieved by using a filler with a large negative TOC and using a surrounding medium with a refractive index close to the cladding refractive index of 1.46. In addition, it is also reported in the reference that the increase in sensitivity due to the use of a filler with a refractive index close to 1.46 is caused by mode coupling due to index matching.[20]

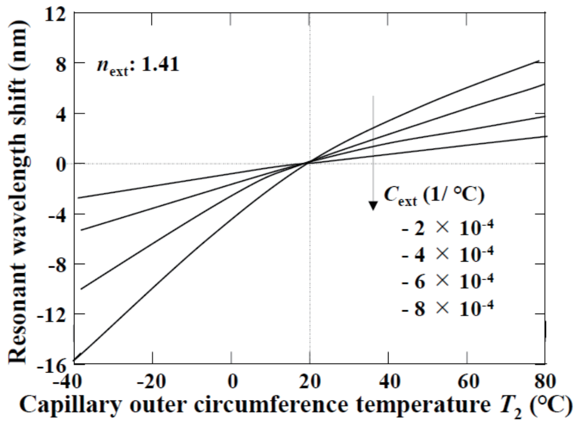

Fig. 4. Resonance wavelength shift (parameter: c_{ext}).

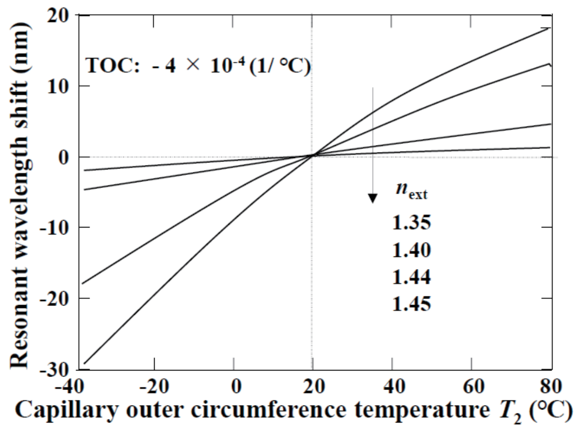

Fig. 5. Resonance wavelength shift (parameter: refractive index).

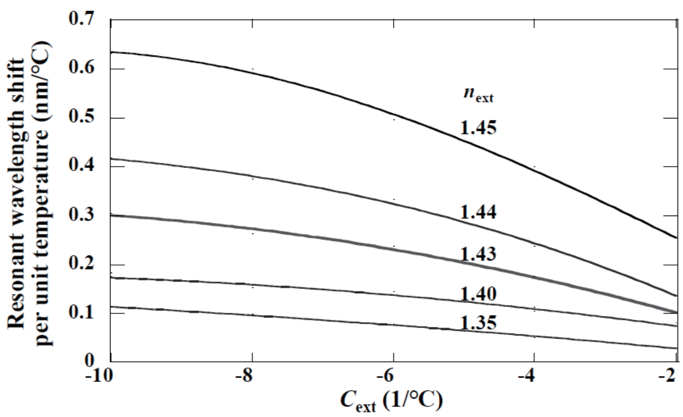

Fig. 6. Amount of shift in resonance frequency per unit temperature (parameter: refractive index n_{ext}).

3. Experiment

3.1 Filler selection

Table 1 shows the TOCs, filler refractive index n_{ext} values at 20 °C, melting points, boiling points, and thermal conductivities of candidate liquid-phase fillers with refractive indices ~1.46 or lower and high TOCs and thermal conductivities. The table also shows polymer, urethane, and acrylic resins, which are solid-phase coating agents commonly used in LPFGs, for reference, and indicates the toxicity. Compared with solid-phase materials, liquid-phase materials have TOCs that are 2 to 4 times larger and are expected to contribute significantly to improving the temperature characteristics of LPFGs. In general, the TOCs of liquid-phase materials are found to be negative.

In this study, four types of liquid were used in our experiment as candidate fillers, namely, two types of silicone oil (#TSF-431 and #TSF-451), ethanol, and ethylene glycol, which are nontoxic and easily available, and have high refractive index and TOC.

3.2. LPFG structure and experimental system for filler investigation

Figure 7 shows the structure of the LPFG for this filler study. An LPFG section prepared by irradiating an optical fiber with CO_2 laser light was inserted into a hollow glass capillary [inner diameter (hollow part): 1.5 mm; glass thickness: 0.6 mm]. After injecting the filler, one end of the glass capillary was fixed with silicone adhesive. Note that originally, after inserting the fiber with the LPFG formed into the capillary and injecting the filler, it is necessary to fix both ends

Table 1
Characteristics of filler candidates.

		TOC (1/°C)	Refractive index	Melting temp. (°C)	Boiling temp. (°C)	Thermal conductivity (W/(m · K))	Reference
Filler candidate (liquid)	Methyl alcohol	-3.73×10^{-4}	1.329	−98	68.8	0.212	(21)
	n−pentane*	-5.08×10^{-4}	1.3572	−129.8	36.1	0.136	(21)
	n−heptane*	-5.03×10^{-4}	1.387	−91	98	0.14	(21)
	n−hexane*	-5.28×10^{-4}	1.375	−95	69	0.137	(21)
	n−octane*	-4.78×10^{-4}	1.3974	−57	125	0.143	(21)
	Ethanol	-4.0×10^{-4}	1.352	−114	78	0.168	(21)
	Ethylene glycol	-2.6×10^{-4}	1.4176	−20	197	0.258	(21)
	Silicone oil #TSF−451	-4.45×10^{-4}	1.424	<−70	>200	0.134	(22)
	Silicone oil #TSF−431	-4.5×10^{-4}	1.403	<−55	>280	0.155	(22)
Coating material (solid)	Polymethyl methacrylate	-1.21×10^{-4}	1.49	125–160	—	0.17–0.25	(23)
	Polystyrene	-1.44×10^{-4}	1.588	100	—	0.15	(23)
	Polycarbonate	-1.24×10^{-4}	1.58	150–155	—	0.19	(23)
	Air	-1×10^{-6}	1.00	—	—	0.026	—

*low toxicity

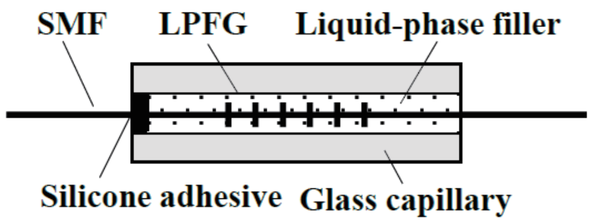

Fig. 7. Structure of LPFG for this filler study.

of the optical fiber to the capillary, but in this study, only one end was fixed. This is to eliminate effects such as the thermal expansion of the capillary material and to evaluate the improvements in temperature characteristics due only to the filler.

Figure 8 shows the experimental setup for measuring the transmission spectrum of the LPFG used in this filler study. The prepared LPFGs were placed in a thermostatic chamber, and the temperature of the chamber was varied to measure the transmission spectrum of the LPFGs. A 1.3 mm superluminescent diode (SLD) light source and an optical spectrum analyzer were used for spectrum measurement. In addition, to evaluate the improvements in temperature characteristics due to the filler, an experiment was conducted using a pulley and weight (10 g) at the end of the optical fiber that was not fixed to the LPFG capillary. As a result, constant tension is always applied to the LPFG section regardless of temperature changes, and spectral changes due to the thermal expansion of the capillary can be eliminated.

4. Experimental Results

4.1 Experimental results on the improvements in temperature characteristics by fillers

Figures 9(a)–9(d) show the temperature variation of the transmission spectra of the LPFG for this filler study using ethanol, ethylene glycol, silicone oil #TSF-431, and silicone oil #TSF-451 as fillers, respectively. The loss peak wavelength of each spectrum shifts toward longer wavelengths as the temperature increases. This is due to the fact that the filler has a negative TOC.

Figure 10 shows the loss peak wavelength shift versus temperature from the peak wavelength at 20 °C, obtained from the results shown in Figs. 9(a)–9(d). This figure also shows the characteristics of the bare LPFG (which is the LPFG before it is filled into the capillary) and the LPFG with no filler for the filler study (i.e., the filler is air).

From these results, it can be confirmed that the amount of shift in loss peak wavelength has a linear relationship with temperature. The respective temperature sensitivity (resonance wavelength spectrum change per unit temperature) was determined to be 51.0 pm/°C for the bare LPFG, 46.4 pm/°C when the LPFG was not filled with liquid (the filler is air), 75.5 pm/°C when the LPFG was filled with ethanol, 70.0 pm/°C when filled with ethylene glycol, 84.8 pm/°C when filled with silicone oil #TSF-431, and 86.8 pm/°C when filled with silicone oil #TSF-451.

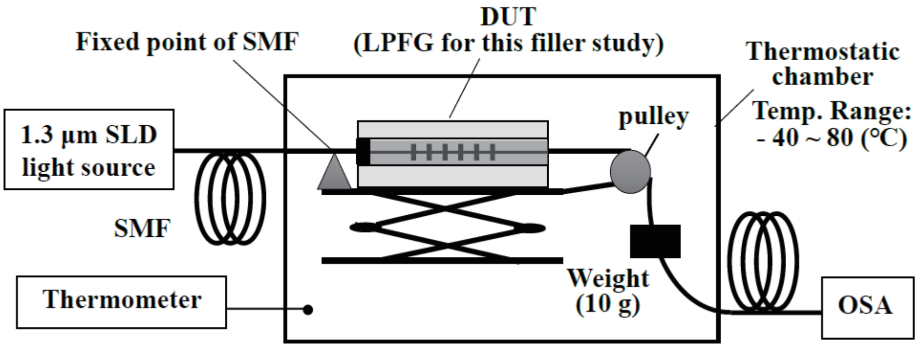

Fig. 8. Experimental setup.

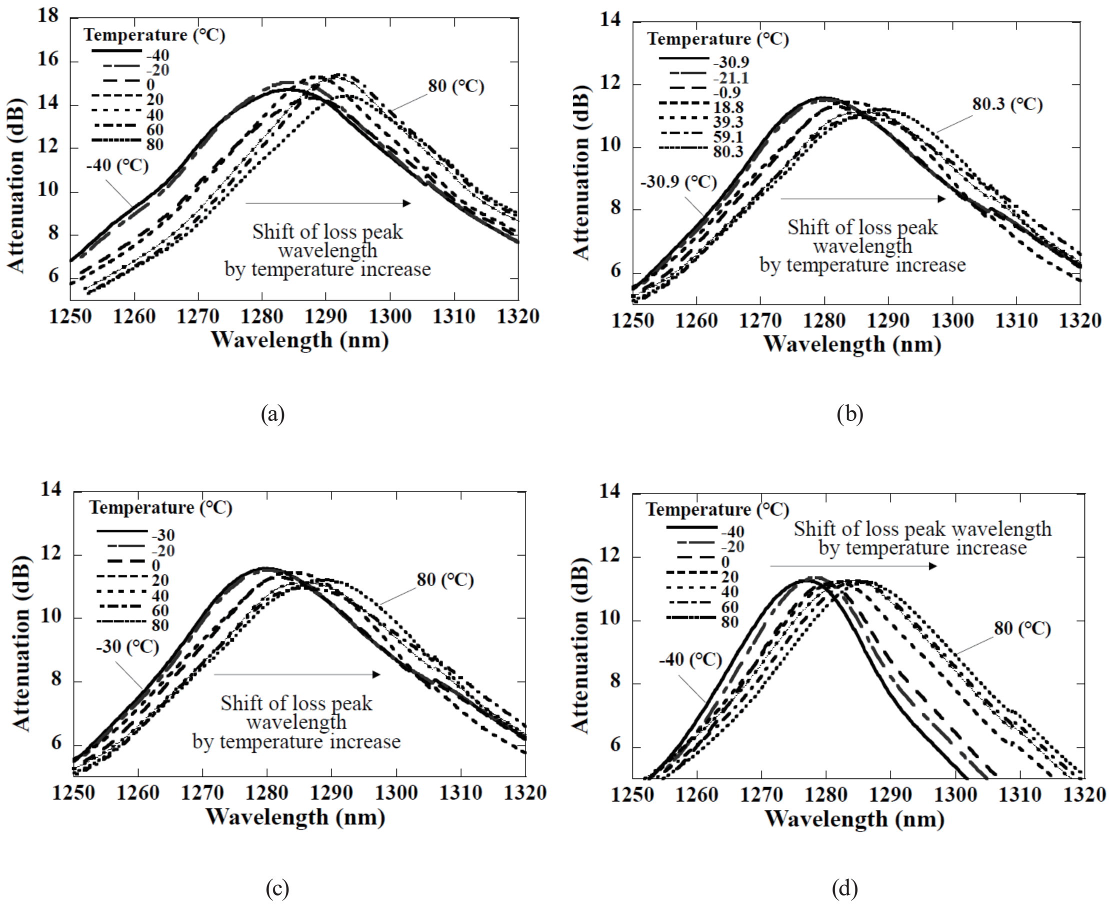

Fig. 9. Resonance wavelength shift of LPFG for this filler study as a function of temperature. (a) Ethanol. (b) Ethylene glycol. (c) Silicon oil #TSF-431. (d) Silicon oil #TSF-451.

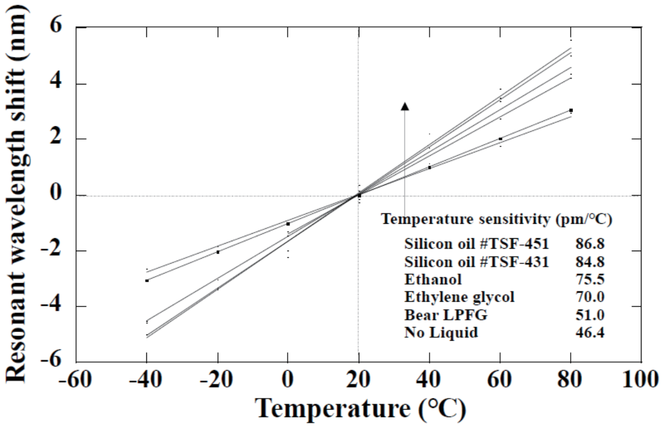

Fig. 10. Loss spectrum peak wavelength shift as a function of temperature.

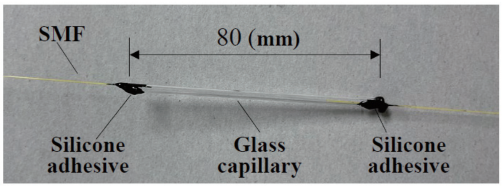

Fig. 11. (Color online) Glass-capillary-encapsulated LPFG sensor.

The LPFG with no filler has a lower temperature sensitivity than the bare LPFG because of the thermal resistance of air and the glass capillary. It was also revealed that filling with silicone oil #TSF-451 can achieve the highest sensitivity and improve the sensitivity by 1.87 times compared with that for the LPFG with no filler and by 1.66 times compared with that for the bare LPFG.

4.2 Temperature sensitivities of glass-capillary-encapsulated LPFG sensor

Using the filler that achieved the highest sensitivity as shown in Fig. 10, namely, silicone oil #TSF-451, we realized the glass-capillary-encapsulated LPFG sensor shown in Fig. 1 and measured its temperature sensitivity. Figure 11 shows a photograph of the sensor filled with silicone oil #TSF-451, which we fabricated, and Fig. 12 shows the resonance wavelength shift by temperature. The temperature sensitivity was 83.3 pm/°C. It is clear that a glass-capillary-encapsulated LPFG sensor with temperature sensitivity equivalent to that reported in Fig. 10 can be realized. In Fig. 12, the slight decrease in temperature sensitivity can be caused by a slight decrease in the tension applied to the LPFG section during packaging.[16]

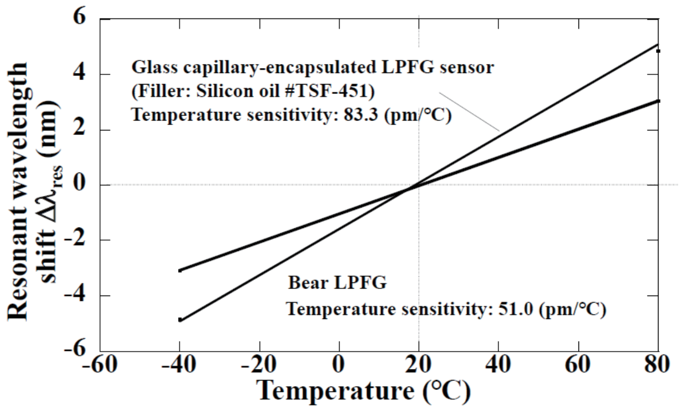

Fig. 12. Resonance wavelength shift by temperature of glass-capillary-encapsulated LPFG sensor with #TSF-451.

5. Conclusion

We investigated how to improve the sensitivity of an LPFG temperature sensor sealed in a glass capillary. Mechanical damage resistance can be improved by enclosing and packaging the optical fiber portion in which the LPFG is formed in the capillary portion. However, the temperature sensitivity decreases owing to the thermal resistance of the air region that exists between the capillary and the optical fiber in which the LPFG is formed.

In this study, we proposed filling the air region with a liquid, which has not been reported so far, and investigated the effectiveness of this proposal theoretically and experimentally. This proposal uses a liquid-phase filler with high thermal conductivity and TOC to suppress the reduction in temperature sensitivity caused by the air region. Furthermore, the temperature sensitivity of the LPFG before being encapsulated in the capillary can be considerably improved by the effect of the TOC of the filler.

Theoretical investigations have shown that (1) thermal resistance in the air region is almost negligible if the thermal conductivity is greater than 0.1 W/m-K. (2) It was shown that the temperature sensitivity can be considerably improved by using a filler with a large TOC and a refractive index close to that of the optical fiber cladding. In the experiment, on the basis of theoretical studies, we evaluated four types of solution (ethanol, ethylene glycol, silicone oil #TSF-431, and silicone oil #TSF-451) that had a high thermal conductivity, a refractive index close to 1.46, and a high TOC as fillers. In this evaluation, a comparison was made using the shift of the resonance wavelength spectrum with respect to the unit temperature considered as the temperature sensitivity. The measured results are 75.5 pm/°C when filled with ethanol, 70.0 pm/°C when filled with ethylene glycol, 84.8 pm/°C when filled with silicone oil #TSF-431, and 86.8 pm/°C when filled with silicone oil #TSF-451. The temperature sensitivity of the LPFG was greatly improved by using a liquid filler with a high thermal conductivity, a refractive index close to 1.46, and a high TOC. In particular, the temperature sensitivity was improved up to 1.87 times compared with that of 46.4 pm/°C for the LPFG with no filler. Furthermore, a glass-capillary-encapsulated LPFG sensor was realized using silicone oil #TSF-451, which showed the highest temperature sensitivity in our experiments, and its temperature sensitivity was 83.3 pm/°C.

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