Fiber-optic temperature sensor based on inline core-cladding-mode Mach–Zehnder interferometry with dynamically controllable sensing length

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A variety of fiber-optic temperature sensors based on inline Mach–Zehnder interferometry (MZI) have been implemented for their ease of fabrication and cost efficiency, but it is difficult to control the length of the sensing area (i.e., the fiber section with sensitivity). Herein, we develop a new temperature sensor based on inline MZI by connecting two single-mode fibers (SMFs) with different mode-field diameters and by applying a load to one of the SMFs. The fiber section between the connector and the load operates as the sensing area, the length of which can be dynamically controlled by changing the load position. © 2022 The Author(s). Published on behalf of The Japan Society of Applied Physics by IOP Publishing Ltd

Temperature sensing using optical fibers has been an active research field owing to its unique merits, such as light weight, small size, and insensitivity to electromagnetic noise. While numerous methods using fiber Bragg gratings,1,2) long-period gratings,3,4) Raman scattering,5,6) and Brillouin scattering7–11) have been reported, one of the simple and easy implementations is based on inline Mach–Zehnder interferometry (MZI).

A variety of configurations of fiber-optic MZI-based temperature sensors have been developed using specialty fibers (other than silica single-mode fibers (SMFs)), such as photonic crystal fibers, multicore fibers, dispersion-compensating fibers, and few-mode fibers.12–21) Although their performances are high in some cases, the use of these specialty fibers is not ideal from an economical viewpoint. Not a few types of inline MZI-based temperature sensors that use only standard silica SMFs have also been reported so far.22–29) They have different inline MZI structures, which pose their own advantages including high-temperature sensitivity, ease of fabrication, cost efficiency, high stability, discriminative measurability of additional physical parameters, etc. However, as the length of the inline MZI part in the conventional schemes (both special fiber-based and standard SMF-based ones) is constant and cannot be largely changed (though slightly changeable by strain), it is difficult to dynamically control the length of the sensing area (i.e., the fiber section with temperature sensitivity). Controllability of the sensing length is an attractive nature required for wider applications, such as temperature monitoring for industrial tanks/pipes of various sizes. Specifically speaking, when average temperatures in such tanks/pipes are to be measured, the sensing lengths need to be changed according to the tank/pipe sizes; the sensing length as short as possible is not necessarily desirable in this case. Another advantage is that, when the tank/pipe sizes are changed, the sensing length can be adjusted with no need to install a new sensor.

In this work, to mitigate the uncontrollability of the sensing length of the conventional sensors, we implement a new inline MZI-based sensor by connecting two SMFs with different mode-field diameters and by applying a load to one of the SMFs. In this configuration, the fiber section between the connector and the load works as the sensing area, the length of which is dynamically adjustable by changing the load position. First, we observe a transmitted light spectrum and verify the appearance of spectral patterns. Subsequently, we investigate the dependence of the wavelength interval (of the interference patterns) on the sensing length. The interval is shown to be inversely proportional to the sensing length, proving the core-cladding-mode MZI-based operation of this sensor. We also investigate the temperature dependence of the interference patterns (when the sensing length is 0.3 m) and show that this scheme is potentially applicable to temperature sensing.

The newly developed inline MZI-based temperature sensor is conceptually illustrated in Fig. 1. Two SMFs with different mode-field diameters are connected using an angled physical contact (APC) connector. When broadband light is injected into this structure, most of the light emitted from the SMF1 is coupled with the core mode of the SMF2 (or the core modes, when the optical wavelength is shorter than the cut-off wavelength of the SMF2, but here let us think of the lowest-order mode with the highest energy). However, as the mode-field diameters of the fundamental modes are different between the two SMFs, a non-zero amount of light is coupled with the cladding modes of the SMF2. If a load is locally applied to the SMF2, part of the cladding mode (let us assume the lowest-order mode) returns to the core and interferes with the core mode. As a result, inline MZI of the core and cladding modes is formed in the area between the connector and the load position. If temperature change is applied to this area, the optical lengths (i.e., the lengths and the effective refractive indices) of the core and cladding modes are changed with different dependencies, leading to the shift of the interference pattern. Consequently, only the fiber section between the connector and the load position operates as the sensing area which is sensitive to temperature, and the length of the sensing area can be controlled by adjusting the load position.

The actual setup used in our experiment is depicted in Fig. 2. The broadband light from a super-continuum source
(440–2200 nm) was injected into two SMFs, and the transmitted light spectrum was observed using an optical spectrum analyzer (OSA; AQ6370, Yokogawa Electric). The SMF1 on the input side was a 1.0 m long fiber (HI1060, Corning; mode-field diameter: ∼6.2 μm (at 1060 nm); cut-off wavelength: ∼920 nm; 3 mm jacketed), and the SMF2 on the output side was a 7.0 m long fiber (SMF-28e+, Corning; mode-field diameter: ∼10.4 μm (at 1550 nm); cut-off wavelength: ∼1260 nm; bare). A load of ∼2 N was locally applied to the SMF2 by vertically pressing the tip of a screwdriver (pressed fiber length: 0.8 mm). The load position was varied from 0.1 to 1.6 m from the APC connector. The sensing area was heated using a hot plate.

The difference between the transmitted light spectra measured with and without loading in the range from 900 to 1450 nm (sensing length: 0.25 m) is shown in Fig. 3. This spectral difference was obtained using a “trace calculation and analysis” function of the OSA (subtraction between traces); subtraction was performed in the log scale, which corresponds to division in the linear scale. A clear interference pattern was observed around 1230 nm. The amplitude of the interference pattern decreased as the wavelength became shorter or longer than this wavelength, but the pattern was observed in the range from ∼1060 to ∼1350 nm. Although the mechanism has not been fully clarified yet, the appearance of this interference pattern at this specific wavelength is an interesting phenomenon. Note that the amplitude of the interference pattern was confirmed to increase with increasing load (in the range from 0 to 2 N); with the same load, the amplitude will probably increase with decreasing pressed fiber length.

Subsequently, the sensing length dependence of the interference pattern was investigated. The spectral difference around 1230 nm were measured when the sensing lengths were 0.2, 0.6, and 1.3 m [Fig. 4(a)]. Each spectrum was vertically shifted by 3 dB (average power in this span). As the sensing length increased, the spectral amplitude decreased, probably because the cladding mode was attenuated during the longer propagation. With increasing sensing length, the wavelength interval also decreased. Figure 4(b) shows the wavelength interval plotted as a function of the sensing length; the interval plotted as a function of the inverse of the sensing length is also shown in the inset, which indicates that the wavelength interval is in inverse proportion to the sensing length. This result supports our hypothesis that the observed pattern originates from the MZI of the core and cladding modes.

Finally, the temperature dependence of the interference pattern was investigated when the sensing length was 0.3 m. Figure 5(a) shows the measured interference patterns around 1233 nm at temperatures from 30 °C to 95 °C (step: 5 °C). Part of each pattern was omitted for higher readability. The pattern clearly shifted to the longer wavelength with increasing temperature. The wavelength of the spectral peak plotted as a function of temperature [Fig. 5(b)] shows that the dependence is almost linear with a coefficient of 0.074 nm °C⁻¹, indicating the
potential feasibility of temperature sensing using this scheme. Note that, in this wavelength range, the peak power of the pattern slightly increased with increasing temperature, but the power of the dip at a shorter wavelength non-monotonically changed. This behavior was probably caused by the existence of the multiple cladding modes, being analogous to a modal interference sensor based on a single-mode-multimode-single-mode structure.30–34 This may limit the temperature dynamic range, and on this point, further study is required.

In conclusion, an inline MZI-based temperature sensor was developed by connecting two SMFs with different mode-field diameters and by applying a load to one of the SMFs. In this

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Fig. 4. (Color online) (a) Interference patterns observed when the sensing lengths were 0.2, 0.6, and 1.3 m. Each spectrum was vertically shifted by 3 dB. (b) Wavelength interval plotted as a function of the sensing length. The inset shows the interval plotted as a function of the inverse of the sensing length, and the dotted line is a linear fit.

Fig. 5. (Color online) (a) Temperature dependence of the interference pattern (from 30 °C to 95 °C with a step of 5 °C) when the sensing length was 0.3 m. (b) Temperature dependence of the peak wavelength. The dotted line is a linear fit.
scheme, the sensing length can be dynamically controlled by altering the load position. The transmitted light spectrum was shown to involve unique spectral patterns around a certain wavelength region (∼1.230 nm in this experiment). The temperature dependence of the interference pattern was then investigated and the potential applicability of this scheme to temperature sensing was experimentally proved. We believe that the concept of our modal interference sensor will be of significant use in developing fiber-optic temperature sensors with sensing length controllability in the near future.

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