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Integrated-optic temperature sensors based on guided-mode radiation in polymer waveguide

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ABSTRACT

Optical temperature sensors consisting of low-loss polymer waveguides with a glass lower cladding are demonstrated. The refractive index of the optical polymer is precisely controlled to have a certain initial refractive index contrast with the glass substrate used for lower cladding. Depending on the initial index contrast, the operating temperature ranges of the sensors are determined. The polymer devices are fabricated by spin-coating and UV curing, which could be replaced by the cost-effective imprinting or injection molding process. The sensor exhibits a monotonic decrease of the transmission intensity corresponding to the temperature increase, which enables straightforward reading of temperature from the measured optical power.

1. Introduction

Optical temperature sensors have become indispensable devices for monitoring the temperature of equipment operating in an environment subject to strong electromagnetic interference (EMI). Electrical transformers handling extremely high voltages, medical imaging systems based on magnetic resonance interference, and motorized electrical devices producing strong electromagnetic fields could be the major application fields of optical temperature sensors.

In-situ temperature monitoring in power transformers to prevent the overheating of the insulation oil has become mandatory because the failure of a high capacity transformer can lead to a large scale power failure [1]. To monitor many hot spots in the transformer, multipoint monitoring method using cascaded array sensors was also demonstrated based on polarization interferometers and fiber-optic Bragg gratings [2,3]. Early phase commercialized optical temperature sensors are based on a semiconductor absorber, in which the absorption bandgap decreases in proportion to the increasing temperature [4]. To provide a cost-effective solution, Fabry–Perot interferometric sensors using a light emitting diode were demonstrated [5]. Phosphors were utilized as the temperature sensor, based on the temperature dependence of the luminescence intensity and the decay time constant [6].

In this work, we propose a cost-effective, simply fabricated optical temperature sensor based on polymeric integrated-optic technology. Polymer devices have acquired increased interest due to the merit of low-cost mass production by means of the UV-assisted imprinting method or the injection molding process [7,8]. Though, there have been previous studies of optical temperature sensors using polymer materials [9–11], no reference has been found regarding the incorporation of the polymer waveguide for the temperature sensors. In the previous works, polymers were utilized as the cladding of a partially etched silica optical fiber. However, in this work, a rib-type polymer waveguide is fabricated on a glass substrate used as the lower cladding. The core polymer material has a refractive index tuned precisely to be just above that of the glass lower cladding [8]. The temperature can be obtained directly by measuring the output optical power, without the need for any complicated optical signal processing such as wavelength interrogation or Fabry–Perot interferometry. Compared to the previous silica optical fiber sensor, the polymer waveguide sensor enables tailoring of the sensor characteristics with good repeatability in the mass production.

2. Design and fabrication

For the purpose of demonstrating cost-effective optical temperature sensors, as shown in Fig. 1, we incorporate a simple straight waveguide comprising a polymer core fabricated on a glass substrate. The upper cladding material is another polymer material with a lower refractive index than that of the core. The refractive index of polymer core material is precisely tuned to have a slightly higher value than the glass substrate. When the temperature goes

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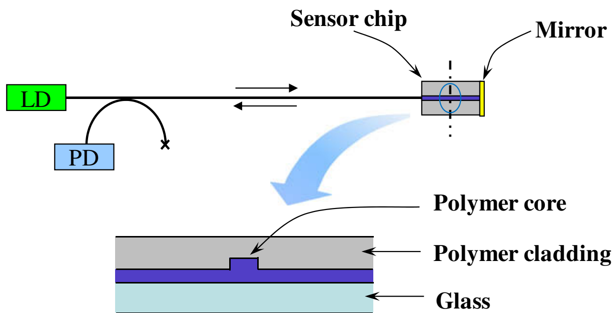

Fig. 1. Schematic diagram of the proposed optical temperature sensor consisting of straight single mode polymer waveguide fabricated on a glass substrate.

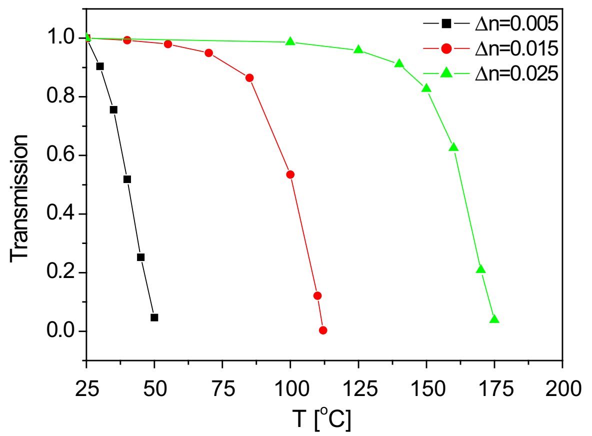

Fig. 2. BPM simulation results of sensor transmission output plotted as a function of the temperature for the three sensors with index contrasts Δn of 0.005, 0.015, and 0.025, respectively.

up, the polymer core index decreases whereas the glass cladding index increases so that the index contrast of the waveguide decreases. The initial refractive index contrast between the polymer core and the glass substrate determines the characteristics of the temperature dependent power change. To make the sensor easily attachable to an object, the waveguide could be terminated with a mirror on one side, and then the reflected signal could be observed by using a coupler [12].

The operating characteristics of the temperature sensors were investigated by performing 3-dimensional beam propagation method (BPM) simulation. For three sensors with refractive index contrasts Δn of 0.005, 0.015, and 0.025, the BPM simulations were performed and the results are summarized as shown in Fig. 2. The transmission powers of sensors are drawn as a function of the applied temperature. The temperature dependent power loss exhibits monotonically decreasing behavior, which is important for the direct reading of the temperature from the measured optical power. Sensor characteristics such as the threshold temperature at which the optical power starts to decrease, as well as the cut-off temperature at which no transmitted power remains, are seen to depend directly on the initial index contrast.

To form the polymer waveguide on the glass wafer, we spin coated ZPU polymer supplied from ChemOptics, Inc. Several devices were fabricated by using the core polymers with refractive indices of 1.460, 1.470, and 1.480, respectively. TO coefficient of the ZPU polymer is typically -1.8×10^{-4}/°C, whereas the glass has the value of 1.0×10^{-5}/°C. Hence, if the sensor has Δn of 0.015 initially, it can maintain the positive index contrast until the temperature increase of 79 °C. The three polymer materials were spin coated on each wafer to form a polymer film with a thickness of 8.4 μm, 4.2 μm, and 3.1 μm, respectively. The film was cured by exposing UV light and baked at 160 °C for an hour. Oversized rib type straight waveguides satisfying the single mode condition were formed in terms of conventional photolithography and oxygen plasma etching. The etch depths were 6.8 μm, 1.8 μm, and 0.9 μm for the samples with index contrast of 0.004, 0.014 and 0.024, respectively. The waveguide had a width of 6 μm. Four-inch glass wafers of Pyrex 7740 with a thickness of 500 μm and a refractive index of 1.456 at 1550 nm were used as a substrate. As a preliminary test of the temperature sensing, the sample was heated using an electrical heating pad placed between sample stage and the sample. Bright single mode was observed from the fabricated polymer waveguide sensor as shown in Fig. 3. When the sample was heated, the decrease of the guided mode power was clearly observed and the light was radiated toward the glass substrate. To measure the device performance in an oven with a temperature controller, the sample was pigtailed using a normal single mode (SM) fiber and a polarization maintaining (PM) fiber on each side.

3. Measurement of the sensor characteristics

For the temperature sensing experiment, the pigtailed device was placed in an oven with an ordinary temperature controller. A low-cost Fabry–Perot laser diode was used as a light source. To prevent polarization dependence issues, the light input was launched through the PM fiber to excite TE mode in the waveguide, and then the transmitted output power was observed through the SM fiber. When the input polarization was changed to excite TM mode, the transmission power change was negligible, which indicates the device has low polarization dependence. The oven temperature was raised until the sensor reached the cut-off condition where the transmitted optical signal had almost disappeared, and then the oven was cooled down. The actual temperature of the sample was monitored by attaching an electrical thermo-couple temperature sensor on the substrate. The transmission power of the sensor behaved as shown in Fig. 4a for the sample with an initial index contrast Δn of 0.014. The optical power decreased monotonically as the temperature increased, until the temperature reached to the cut-off temperature of about 85 °C, at which point negligible transmitted optical power remained. Then,

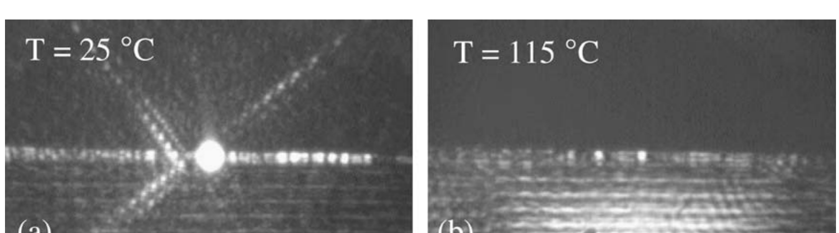

Fig. 3. Output mode profiles of the polymer waveguide sensor observed by using a CCD: (a) before the sensor was heated and (b) when the temperature was increased to 115 °C by means of a heating pad under the sample.