Evanescent field-based optical fiber sensing device for measuring the refractive index of liquids in microfluidic channels

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We report a simple optical sensing device capable of measuring the refractive index of liquids propagating in microfluidic channels. The sensor is based on a single-mode optical fiber that is tapered to submicrometer dimensions and immersed in a transparent curable soft polymer. A channel for liquid analyte is created in the immediate vicinity of the taper waist. Light propagating through the tapered section of the fiber extends into the channel, making the optical loss in the system sensitive to the refractive-index difference between the polymer and the liquid. The fabrication process and testing of the prototype sensing devices are described. The sensor can operate both as a highly responsive on–off device and in the continuous measurement mode, with an estimated accuracy of refractive-index measurement of $\sim 5\times 10^{-4}$. © 2005 Optical Society of America

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Microfluidic technology is rapidly developing nowadays. These efforts are primarily motivated by the prospects of creating practical laboratories on a chip, miniaturized devices that perform diverse chemical analyses in pharmaceutical, medical, and sensing applications.[1] Of the various fabrication techniques used in microfluidics research and development, soft lithography has several unique advantages.[2,3] Thus combining the convenience of precise analyte delivery offered by soft-lithography-based microfluidics with optical detection and sensing can potentially result in new applications of the technology and add functionality to existing devices.

Several optical sensors that potentially can be integrated with microfluidics have recently been reported, including a reverse-symmetry waveguide sensor[4] and a photonic crystal–based microcavity sensor.[5] In both of the above approaches, complex techniques are used to fabricate the sensing devices, and spectral analysis of light transmitted through the device is essential, which requires bulky equipment. In this Letter we report an alternative sensing concept, based on a simple measurement of optical power transmitted through a tapered single-mode fiber.

Tapered fibers have been used previously to measure the refractive index of the external liquid environment.[6–9] The reported sensors have all been based on multimode fibers or fiber couplers. Since the light is strongly guided by a multimode fiber, to achieve high sensitivity to external refractive-index variations, the liquid analyte had to be in direct physical contact with the tapered fiber surface, which could be damaging to the fiber material. In addition, a substantial length of the sensing region was required, making seamless integration of these sensors with microfluidic channels problematic.

It has been recently shown that the single-mode silica fibers can be successfully pulled down to submicrometer size while maintaining low transmission loss.[10,11] For such ultrathin tapered fibers, the guided optical field can extend considerably beyond the fiber surface, making the tapered fiber suitable for efficient noncontact sensing of the optical properties of the surrounding environment.

The tapers used in our experiments are made from a commercial single-mode fiber (SMF-28, Corning). An ~3-cm-long section of the fiber is stripped of its protective plastic jacket and pulled in the flame of a butane torch in one step. The total length of the tapered section is ~3 cm. The optical transmission through the taper is measured by launching the light from a single-mode fiber-pigtailed LED at 1.5-μm wavelength from one side and measuring the transmitted power at the other side with an optical powermeter. For tapers surrounded by air, and with a waist size ranging from a fraction of a micrometer to several micrometers, the typical transmission loss is 1.5 dB (~70% transmission). To verify the repeatability of our tapering process we made several taper samples of various sizes and by measuring the waist diameter with a scanning electron microscope confirmed that the targeted waist size was reproducible to within ~±200 nm.

Our sensing devices are fabricated as follows: A rectangular cuvette made from Teflon serves as a mold for the transparent curable soft polymer (Sylgard 184, Dow Corning, commonly referred to as PDMS). The mold is 6 cm long, 1 cm wide, and 0.5 cm high (inside dimensions). A slit is machined through the bottom of the cuvette to snugly accommodate a 3-mm-thick glass rod that defines the channel for the liquid analyte in the sensor. When the rod is in place, it is sticking out of the bottom of the cuvette by approximately one half of its diameter. Thus the resulting 1-cm-long and 3-mm-wide channel has a semicircular cross section. (Instead of this simple arrangement, an epoxy-defined template common in fabricating microfluidic channels by injection molding can also be used.) After the mold is filled with liquid PDMS, the fiber taper oriented orthogonally to the glass rod is slowly lowered into the uncured poly-

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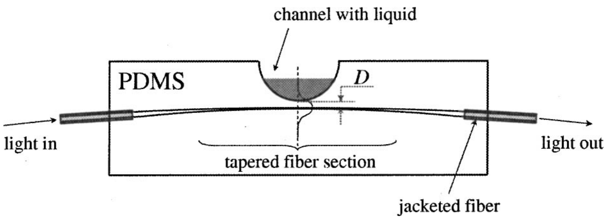

Fig. 1. Schematic side view of the sensor.

mer from the top while the optical transmission through the taper is monitored. For the taper fully immersed in the polymer, optical transmission was measured at ~50%. The glass rod used to define the channel has a high refractive index of 1.55. For comparison, we have measured the index of the cured PDMS at 1.402, and the index of fused silica, the fiber material, is 1.445, all at 1.5-μm wavelength. Optical transmission drops abruptly to zero when the taper waist is in close proximity to the surface of the rod. After the PDMS is cured at room temperature, the device is flipped over and the glass rod is removed, exposing the channel for the analyte. The resulting sensor is shown schematically in Fig. 1.

In Fig. 2 we plot the calculated mode-field diameter of the guided fiber mode at the taper waist as a function of the waist diameter for a taper in PDMS.[12] Since the refractive index of fused silica exceeds that of PDMS by a small amount (~0.043, as noted above), the MFD can be as large as 140 μm for the 700-nm-thick taper. Thus, even though the taper is fully surrounded by the polymer in our setup, the evanescent tail of the guided mode that propagates outside the tapered fiber and can reach the channel can carry a substantial fraction of the optical power. For comparison, in the same figure we plot the mode-field diameter for a taper surrounded by air. In this case the fraction of the optical power propagating outside the fiber is reduced substantially.

To test the sensitivity of our device to variations of the refractive index of liquid in the channel we measured the optical transmission through the device at room temperature with the channel filled with solutions of glycerol in water. By using different concentrations of glycerol, we could vary the refractive index of the solution at 1.5-μm wavelength from 1.311 for pure water to 1.459 for pure glycerol.[13,14] After each data point was taken, the channel was flushed with water and blow dried. It has been verified that at each point the optical transmission returns to the same level for both water and air in the channel, indicating that the tapered fiber section is protected by a thin PDMS film. The exact film thickness (*D* in Fig. 1) is unknown. We speculate that it is a few micrometers to a few tens of micrometers.

The resulting calibration curves are shown in Fig. 3 for two different sensors: with (1.6±0.2)-μm-thick and (700±200)-nm-thick tapered fiber sections. We have verified that the dependence of the optical transmission on polarization of the input light is negligible. Further, as expected, in both cases the transmission is at maximum when the refractive index of the liquid matches that of the surrounding polymer, and the thinner taper is more sensitive to index variations in the channel. The sensing mechanism can be described as follows: As the weakly guided optical mode travels through the sensing region, the shape of the mode is modified by the presence of the index contrast between the liquid in the channel and the polymer environment. If the index in the channel is higher, the mode is attracted into the channel, where the light is effectively scattered because of the presence of the channel boundaries and is absorbed in the liquid. If the channel is filled with lower-index liquid, the mode propagates mostly in the uniform, transparent polymer. In this case the effect on transmission through the stronger-guiding, thick taper is minimal, while for the weakly guiding thin taper this perturbation is sufficiently strong to affect the optical loss. Thus the thicker taper is more appropriate for highly responsive on–off-type sensing, and the submicrometer taper-based sensing device is suitable for refractive-index measurements in a wider range, on the rising edge of calibration curve 2 in Fig. 3.

In practice, the measurement accuracy will depend on a variety of factors such as launched optical power, stability of the light source, detection bandwidth, and most importantly the mechanical rigidity of the sensor. If we conservatively assume that the

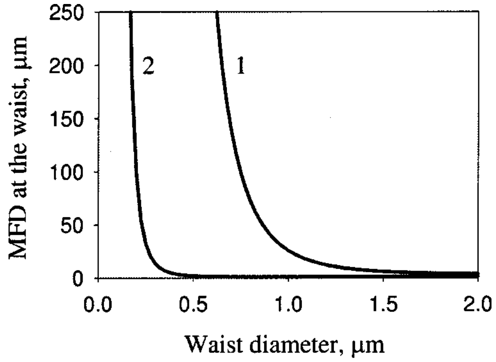

Fig. 2. Calculated optical mode-field diameter at the taper waist as a function of the waist diameter for a taper in 1, PDMS and 2, air. The effect of the fiber core at the waist is assumed to be negligible.

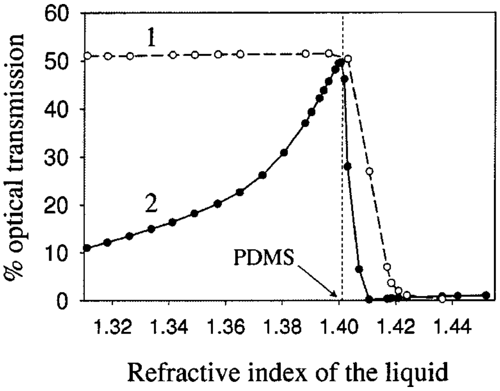

Fig. 3. Measured optical transmission versus refractive index of the liquid in the channel for two sensors with different taper thicknesses at the waist: 1, ~1.6 μm; 2, ~700 nm. Circles, data points; arrow, refractive index of the surrounding polymer.

transmitted optical power is measured with an accuracy of 1% of its maximum value, the slope of the calibration curve for the analyte refractive index in the range 1.37–1.40 is such that the measurement accuracy in that range can be roughly estimated as $\Delta n \sim 5 \times 10^{-4}$. This estimated accuracy is close to that achievable with commercial laboratory refractometers. Further, the sensitivity of our device exceeds that of sensors suitable for integration with microfluidic devices that were reported in Refs. 4 and 5 ($\Delta n \sim 2 \times 10^{-3}$ in both cases). Note that in our approach the sensor is primarily responsive to the refractive-index contrast between the liquid analyte and the polymer surroundings and not to absorption in the liquid, thus the liquid does not have to be transparent. In the on–off regime, with the refractive index of the analyte higher than that of the polymer, the absorption in the liquid only makes the sensor response sharper. In the opposite case of the lower-index liquid, the guided light propagates mostly in the transparent polymer, and the optical transmission through the device is virtually unaffected by absorption in the analyte.

The sensing approach reported here has several distinct advantages: The fabrication process is simple, and the sensor can be straightforwardly integrated into compact microfluidic devices fabricated by replica molding. The device is automatically fiber pigtailed and has a simple optical power readout. Physical contact between the liquid analyte and the fragile sensing element (the taper) is not required, and the taper is fully protected by the soft polymer. Finally, the refractive index of the polymer can be chemically adjusted to shift the measurement interval as needed.

In conclusion, we have reported a simple sensing concept suitable for measurement of the refractive index of liquids in microfluidic devices. The sensing principle is based on the dependence of the optical transmission through a single-mode fiber tapered to the submicrometer dimensions on refractive-index variations in the vicinity of the taper. The fabrication process and the testing of prototype sensing devices have been described, showing the potential measurement accuracy to be of the order of $\Delta n \sim 5 \times 10^{-4}$. The device can potentially operate in both the highly sensitive on–off regime and the continuous measurement mode.

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