High-sensitivity ultrasound interferometric single-mode polymer optical fiber sensors for biomedical applications

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Received March 10, 2009; accepted April 24, 2009; posted May 12, 2009 (Doc. ID 108563); published June 8, 2009

This work describes the results of ultrasonic wideband sensors based on single-mode polymer optical fibers that may be used for biomedical applications. We have compared the ultrasonic sensitivities of two Mach–Zehnder interferometric intrinsic optical fiber sensors. One is based on a single-mode polymethylmethacrylate optical fiber and the second on single-mode silica optical fiber, both operating at 632.8 nm. At a frequency of 1 MHz these sensitivities are 13.1 and 0.85 mrad/kPa, respectively. The ultrasonic phase sensitivity of the polymer optical fiber is more than 12 times larger than that from the fused silica fiber in the 1–5 MHz range. © 2009 Optical Society of America

OCIS codes: 060.2370, 120.3180, 170.5120, 170.7170.

The detection technology traditionally used in conventional ultrasonic for biomedical application is based on piezoelectric transducers (PZTs), which are highly sensitive but have narrow bandwidth owing to their resonant nature. The detectors based on thin piezoelectric polymer film, such as polyvinylidene fluoride, are wideband; however, the sensitivity decreases as their size is reduced. This is a problem at high ultrasonic frequencies when the detector size must be shorter than half of the wavelength or when it needs to be miniaturized for integration in an array of sensors. Another drawback of piezoelectric sensors, related to their electrical nature, is that they are not immune to electromagnetic interference.

The optical detection of ultrasound for biomedical applications has been studied as an alternative to piezoelectric technology for decades. We can distinguish two kinds of ultrasound optical sensors: ones that monitor pressure induced displacements of a membrane or resonant optical cavity and the others that work based on a pressure induced index refraction variation in or around the sensor material, thus modulating the phase of the light passing through the sensor. In the first group the following are included: etalons [1,2], fiber Bragg gratings [3], and dielectric multilayer interference filters [4]. Intrinsic fiber optic interferometric sensors [5] and sensors based on changes of the reflectance of an interface [6] are in the second group. All these optical sensors, contrary to PZTs, are not affected by external electromagnetic disturbances or other artifacts such as electrical noise and thermal signals produced by the direct laser pulse illumination.

In particular, the fabrication of intrinsic fiber optic interferometric sensors is straightforward and involves the use of low-cost materials. The sensitivity of these sensors can be improved by folding or coiling of the fiber [7,8] by increasing the surface area where the acoustic field interacts with the optical fiber. Moreover intrinsic fiber optic Fabry–Perot sensors have been proposed as line detectors for optoacoustic imaging tomography [9]. By using a free beam laser Mach–Zehnder interferometer as the line detector [10], optoacoustic images have been obtained with a spatial resolution (100–300 μm) ultimately limited by the beam diameter (90 μm).

Recent developments in the field of single-mode polymer optical fibers (POFs) have offered the possibility of developing a new class of high-sensitivity interferometric sensors. This increase in ultrasonic sensitivity of POF based sensors over silica optical fiber (SOF) based sensors is because typical POF bulk material has a lower Young’s modulus than fused silica and the acoustic impedance of the POF is matched to water with greater efficiency when compared with the SOF. Intrinsic POF interferometric sensors have been tested successfully as sensors for large quantities of low frequency strain [11,12], exceeding the performance of single-mode SOF in sensitivity and in its strain failure.

In this Letter we show for the first time, to the best of our knowledge, an ultrasonic intrinsic optical fiber interferometric sensor at frequencies for biomedical applications made with single-mode POF. The objective of the experimental work carried out and described in this Letter is a comparative analysis of the ultrasonic sensitivity, expressed in milliradian/kilopascal, in the megahertz range from a single-mode polymer optical fiber and the second on single-mode silica optical fiber, both operating at 632.8 nm. At a frequency of 1 MHz these sensitivities are 13.1 and 0.85 mrad/kPa, respectively. The ultrasonic phase sensitivity of the polymer optical fiber is more than 12 times larger than that from the fused silica fiber in the 1–5 MHz range. © 2009 Optical Society of America

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the same experimental conditions to guarantee that differences in ultrasonic sensitivities arise from the optical fiber material.

The polymethylmethacrylate single-mode POF (from Paradigm Optics, Vancouver, Wash.) used in these experiments has a cladding diameter of 125 μm and a core diameter of 8 μm. The fiber has been designed to have a cutoff wavelength of less than 750 nm. However, in our experiments at 632.8 nm we only observe the fundamental mode, since the light that leaves the POF segment under test is coupled to a single-mode SOF via a fiber splice. Any cladding modes of the POF segment are removed by the single-mode SOF. We compare this POF with a conventional single-mode SOF (StockerYale Inc., Salem, N.H.) at 633 nm. The SOF cladding diameter is 125 μm, and the mode field diameter at 633 nm is 4.0 μm.

In Fig. 1, a scheme of the experimental setup is presented. We have used a Mach–Zehnder interferometer to obtain the phase induced in the optical fiber segment from the ultrasonic wave. The light from an He–Ne laser, which is linearly polarized and emits a wavelength of 632.8 nm, is divided using a 50/50 optical beam splitter and coupled into two SOFs (i.e., the two arms of the interferometer). In the middle of the measurement arm a segment of the optical fiber to be characterized is introduced using two splices. This segment of fiber passes through a tank filled with water. The ultrasonic emitter is placed inside the water tank at a fixed distance from the fiber segment measured using the acoustic time of flight. The water is used to ensure consistent acoustic coupling and repeatability between the emitter and the optical fiber segment. In the reference arm a phase modulator, composed of a fiber coil around a cylindrical PZT, is used to obtain the interferometric visibility at the time of measurement. The visibility is optimized by matching the polarization at the output of each fiber arm using polarization controllers.

The light at the output of each arm is recombined. This interferential optical signal is measured using an avalanche photodiode module (Hamamatsu C5331) and monitored using a digital oscilloscope. The bandwidth of this optical detector is 100 MHz, with a lower cutoff frequency of 4 kHz. The signal captured from the oscilloscope is sent to a computer for postprocessing to obtain the phase.

As ultrasonic emitters two immersion transducers from Panametrics (V303 and V326) with central resonant frequencies of 1 and 5 MHz are used. These transducers are excited using a square pulse genera-
tor (Panametics 5077PR). The amplitude of the square pulse is varied between 100 and 400 V at steps of 100 V. The oscilloscope and the wave generator, which feed the phase modulator, are synchronized with the square pulse generator.

We have measured ultrasonic signals, which have been produced by the PZT emitters from a segment length of 6 cm of both the single-mode SOF and single-mode POF. In the same way we have measured the ultrasonic signals produced using calibrated PZT receivers (Panametrics V303 for 1 MHz and Panametrics V326 for 5 MHz) to calculate the amplitude of acoustic pressure. Figure 2 presents typical 1 MHz signals captured from the digital oscilloscope with the bandwidth limited to 20 MHz. The distance between the emitter and the sensors is adjusted, so the time of flight is the same in all measurements.

From the interferential signals displayed in Figs. 2(c) and 2(d) we can see the ultrasonic signal of 1 MHz added to a low frequency signal produced by the phase modulator in the reference arm. From this low-frequency signal we can determine the interferometric visibility. This reference signal is visibly slower than the acoustic signal produced from the emitter and can easily be removed in postprocessing using a high pass filter applied to the recovered phase signal.

Figure 3(a) shows the signals obtained from the narrowband 1 MHz ultrasonic PZT detector for voltages of 100–400 V in the Panametrics V303 emitter. Figures 3(b) and 3(c) represent the phase induced from the same ultrasonic pressure waves in the single-mode POF and single-mode SOF, respectively. These phase signals have been digitally filtered using a low-pass filter with a cutoff frequency of 3 MHz and a high-pass filter with a cutoff frequency of 0.3 MHz to remove the reference arm signal. The waveform of the signal obtained in the PZT is similar to both fiber sensors.

In Table 1 a summary of the experimental results obtained is presented. In this table we can see the increase in sensitivity of the POF single-mode fiber over the SOF single-mode fiber. At the working frequency of 1 MHz the acoustic sensitivity of the POF is measured with the value of 13.1±0.3 mrad/kPa, while for the SOF the value of 0.85±0.07 mrad/kPa is obtained. This represents an increase in the acoustic sensitivity of more than 15 times. A similar analysis has been done with the 5 MHz emitter obtaining an acoustic sensitivity for the POF 12 times larger than the SOF. The sensor based on single-mode POF with an interferometric system with a resolution of 5 mrad has a noise equivalent pressure (NEP) of 0.4 kPa at 1 MHz. On the other hand, the single-mode SOF sensor in the same conditions has a NEP of 6 kPa.

Wen et al. [7] obtained a sensitivity between 10 and 20 mrad/kPa proposing SOF interferometric sensor designs for medical applications that involve the use of long distributions of fiber shaped in planar disks or cones. We achieve a comparable sensitivity with more than 15 times shorter segment of POF. The use of shorter optical fiber segments has a positive impact on directivity and the wide bandwidth of the sensor. Besides, the high sensitivity and the line shape make POF sensors good candidates for an integrating line detector in optoacoustic tomography systems [10].

In this work we have demonstrated experimentally the high sensitivity of single-mode POF as an interferometric sensor in the detection of ultrasonic waves in the megahertz range. We have shown that this sensitivity is more than 1 order of magnitude greater than that of traditional single-mode SOFs.

Table 1. Comparison of 1 MHz Sensitivity Experimental Results Between Single-Mode SOF and Single-Mode POF

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References