Fiber-optic sensor array without polarization-induced signal fading

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A new method that uses polarization switching for the suppression of polarization-induced signal fading in interferometric sensors is described. An experimental demonstration with a remote sensor shows full recovery of visibility without degradation of sensitivity.

Signals from fiber-optic interferometric sensors formed with conventional single-mode fibers may be lost because of the random fluctuation of the polarization states of two interfering optical waves. The so-called polarization-induced signal fading (PSF) problem has to be overcome to realize practical sensors, especially when the sensors have to be passive and remotely located. A straightforward way to eliminate PSF is to use polarization-maintaining fiber. However, polarization cross coupling at spliced points and high cost restrict its practical applications. A number of techniques for the elimination of PSF, including polarization masking, remote control of polarization states, and input polarization scanning, have been tried. The most promising and technically simple approach demonstrated thus far uses Faraday rotating mirrors, which tend to increase the cost and the complexity of an optical circuit. In this Letter a new simple method for avoiding PSF in interferometric sensors by polarization switching is described. The interferometric sensor array consists of a compensating interferometer that contains a polarization switch and remote sensors that are highly unbalanced interferometers and are time division multiplexed (TDM) by short optical pulses. An experimental demonstration of the operating principle is also presented.

Figure 1 shows a ladder configuration for a remote sensor array composed of highly unbalanced Mach–Zehnder interferometers. The interferometer between the source and the passive sensors is used as a compensating interferometer. The compensating interferometer and the sensing interferometers have identical imbalance in optical paths. The width of the pulsed light source should be shorter than the optical path-length difference of the interferometers. An optical pulse launched into the input fiber bus is separated into two light pulses after the compensating interferometer. For an array with \( N \) sensors, \( N + 2 \) pulses return to the detector for each input pulse. Except for the first and the last pulses, each pulse contains an interference signal from corresponding sensor that can be separated for further signal processing. Each of the signal-bearing pulses is an overlap of two pulses that went through different optical paths. As long as the differences in path imbalance in the sensors and the compensating interferometer are much smaller than the coherence length of the source, excellent sensitivity can be obtained from a source with a relatively short coherence length.

If the two interfering pulses have the same intensities, only the relative polarizations of the two determine the visibility of the interference signal. For example, the fringe visibility is unity if their polarizations are identical and zero if they are orthogonal to each other. The latter case corresponds to PSF. When PSF occurs, the visibility can be recovered if the state of polarization (SOP) of one of the two interfering pulses can be converted to an orthogonal SOP. Figure 2 shows the time-domain principle schematically for a system with one remote sensor, where (a) and (b) show the optical pulses at locations (a) and (b) in Fig. 1. The third pulse train in (b) results from the addition of the pulse trains in the first and second rows of (b). To simplify the explanation, all the pulses are assumed to have linear polarizations even though they can have general ones. The polarization orientations of pulses are represented by the arrows in the boxes. Consider only the pulses in column (A), which corresponds to the case of PSF. The first pulse in (a) splits into two as the first row of (b) after the sensing interferometer, and the second pulse in (a) also splits into two as the second row of (b). The SOP of each pulse evolves according to the birefringence of each arm of the interferometer.
The SOP's of the two interfering pulses may be orthogonal to each other as shown here, and the fringe visibility becomes zero. Consider then the pulses in column (B), where the only change compared with column (A) is that the SOP of the second pulse in (a) is rotated by 90°. This change results in parallel SOP's for the two interfering pulses and, thus, the fringe visibility expressed by the shaded area of the interference pulse in the figure is maximized. The same argument holds for generalized elliptical SOP's as long as two mutually orthogonal SOP's launched into a fiber remain orthogonal along the fiber, regardless of the fiber birefringence and the input SOP's.

Polarization switching can be realized by insertion of a polarization switch in one arm of the compensating interferometer that switches the SOP of every other input pulse in the arm of the compensating interferometer to orthogonal SOP. At the sensor array output, the two sets of signal pulses corresponding to the two SOP's will be separated and processed independently. If one set of the signals experiences PSF, the other will exhibit maximum visibility.

We used a TDM-based sensor array with one sensing interferometer as shown in Fig. 3 for the demonstration of the operating principle. A laser diode with single longitudinal mode (λ ~ 830 nm) was gated by an acousto-optic modulator to produce optical pulses. The width and the repetition rate of the optical pulses were 160 ns and 940 kHz, respectively. The optical path-length differences of the two unbalanced Mach–Zehnder interferometers were ~70 μm, and the difference between them was matched within 3 cm. A short length of polarization-maintaining fiber and a polarization-maintaining fiber directional coupler were used to preserve the linear SOP of the input pulse to the polarization switch. The rest of the interferometer was constructed with conventional fiber. The phase modulator in the compensating interferometer was used for synthetic heterodyne signal processing to prevent the signal fading as a result of random phase drift. The polarization controller and the phase modulator in the sensing interferometer were used for control of the SOP and for signal simulation, respectively. The polarization switch employed in the compensating interferometer was an ordinary cylindrical piezoelectric phase modulator that produces a large birefringence modulation when driven at a few hundred kilohertz. The birefringence modulation originates from a large lateral stress exerted on the fiber wrapped around the piezoelectric cylinder. The stress produces differential phase modulation between the mutually orthogonal SOP’s that are parallel and perpendicular to the cylinder wall. When the peak-to-peak differential phase modulation amplitude is π rad, an input SOP making a 45° angle with the cylinder axis can be modulated between two orthogonal SOP’s. When the input optical pulses, much shorter than the modulation period, are synchronized at the maxima and the minima of a sinusoidal birefringence modulation waveform, the polarization states of adjacent optical pulses can thus be switched between two or-
orthogonal SOP's. For our experiment, the polarization switch was driven at 470 kHz, which was half the repetition rate of the input optical pulses. The two sets of signals are separated with a switch and processed independently before they can be combined to produce a nonfading signal.

Figure 4 shows an example of the sensor array output for two successive input pulses. The amplitude of the blurred part of the interference pulse represents the visibility. The polarization controller was adjusted so that the relative polarization was orthogonal in the first set of pulses. It can be clearly seen that the visibility of the center pulse in the second set of pulses became maximum as predicted. Figure 5 is a measured output spectrum when a signal with an amplitude of 10 mrad at 2 kHz was applied to the phase modulator in the sensing interferometer. Because the carrier frequency for the synthetic heterodyne signal processing was 25 kHz, the signal appears at 25 ± 2 kHz. Figures 5(a) and 5(b) correspond to the signal-faded pulse and the signal-recovered pulse, respectively, in Fig. 4. The sensitivity of the sensor was approximately 40 μrad/√Hz, limited by source phase-induced intensity noise owing to the optical path-length difference mismatch between the two unbalanced interferometers. No degradation in sensitivity as a result of polarization switching was observed.

The most important advantage of this technique is simplicity in both the optical circuit and the electronic signal processor. It uses only one polarization switch in the compensating interferometer, and the polarization switch is lossless, simple, and practical. The technique that uses Faraday rotating mirrors, on the other hand, requires many expensive mirrors in proportion to the number of sensors. With this technique two sets of electronic signal processors are sufficient for each sensing interferometer, compared with three sets for the methods in Refs. 2 and 4. Other types of polarization switches can be used, depending on the required switching frequencies. Ideally, an electro-optic polarization switch in the form of an integrated-optical waveguide would be the best choice for a wide range of switching frequencies.

In conclusion, a new practical method employing polarization switching to overcome polarization-induced signal fading has been proposed and demonstrated with a TDM-based sensor array. The polarization switching does not degrade the sensitivity of the sensor.

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References