Technique for referencing of fiber-optic intensity-modulated sensors by use of counterpropagating signals

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We present a new all-optical fiber-referencing scheme for intensity-modulated sensors. It consists of a closed loop traversed by sensing and reference optical signals in opposite directions. With the proposed scheme the noise induced by power fluctuations of the optical source and mechanical perturbations can be greatly reduced. We experimentally demonstrate the efficiency of the scheme and discuss its use in a sensor array. © 2004 Optical Society of America

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Intensity-modulated fiber-optic sensors (IMFOSs) have been demonstrated to be good candidates for efficient and low-cost sensors for a wide variety of physical, chemical, and biological applications.[1] Some relevant advantages offered by these sensors are simplicity, high sensitivity, reliability, and small size. However, IMFOSs are susceptible to drifts and noise induced by source intensity variations as well as to random attenuation in fibers and connectors caused by mechanical and thermal perturbations that may be misinterpreted as a measurand modulation. All these factors cause a decrease in resolution and strongly limit the use of IMFOSs in remote-sensing arrangements outside the laboratory.

To overcome these inconveniences, reference techniques based on interferometric schemes have been proposed. These techniques include the use of methods based on resonant amplitude–phase conversion with fiber Bragg gratings[2] and the coherent spectral interference of a Fabry–Perot cavity.[3] However, they add a certain degree of complexity to the system and a high mechanical and thermal dependence. Another proposed interferometric technique is the Q-modulation method for differential intensity modulation,[4] which allows for the cancellation of source intensity variations. Despite the performances that have been reported, to the best of our knowledge none of the systems proposed so far has been efficiently tested and shown to cancel mechanically induced noises along fiber-optic links.

In this Letter we propose a referencing technique for IMFOSs that is based on a simple configuration that can efficiently cancel both source power fluctuations and mechanical perturbations. It consists of a closed-loop traversed by sensing and reference optical signals in opposite directions, in which the reference signal bypasses the sensor element (SE). In general, the SE can be any optical device, either bulk or fiber optic, whose features such as transmissivity or reflectivity are affected by the measurand.

The experimental arrangement used to demonstrate the referencing technique is shown in Fig. 1. Light from a laser diode provides the sensing and reference beams, which are launched into a fiber loop through a 3-dB coupler. Both beams are coupled out from the loop by two directional couplers. Two photodetectors are used for monitoring both signals. Additionally, a variable attenuator may be used at the exit port of the reference signal when necessary to compensate for the transmission factor of the SE that is not present on the reference path. For the practical realization of a sensing system using this referencing technique, the bypass along the reference path can be introduced by two fiber-optic circulators, as shown in Fig. 1. Alternatively, two 3-dB fiber-optic couplers and two fiber-optic isolators can replace the circulators.

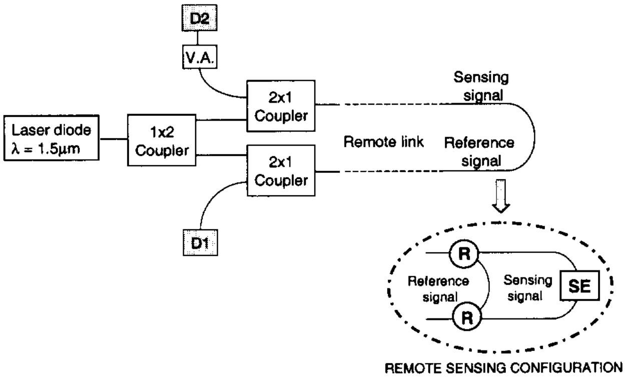

Fig. 1. Schematic of the fiber-optic referencing scheme. D1, D2, photodetectors; V.A., variable attenuator; Rs, fiber-optic circulators.

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Although this latter configuration costs less, it has the inconvenience that half of the optical power is lost.

Under the scheme shown in Fig. 1, the output signal (S_{out}) of the system is taken as the ratio of the signal voltage (V_s) and the reference voltage (V_r):

$$S_{\text{out}} = \frac{V_s}{V_r} = \frac{A_s T_{\text{fol}}{}^{+} \kappa}{A_r T_{\text{va}}{}^{-} T_{\text{fol}}{}^{-}(1 - \kappa)} T_{\text{SE}}, \qquad (1)$$

where A_s and A_r are the amplification factors of the signal and the reference detectors, respectively (in units of volts per watt), $T_{\text{fol}}{}^{+}$ is the transmission coefficient of the arrangement in the clockwise direction, and $T_{\text{fol}}{}^{-}$ is the transmission coefficient in the opposite direction. $T_{\text{va}}{}^{-}$ is the transmission factor added when a variable attenuator is used, and T_{SE} is the transmission coefficient of the SE. Finally, factor κ corresponds to the coupling ratio at the input of the arrangement. Thus, the optical power entering the loop and propagating in the clockwise direction can be expressed as $P_{\text{in}}{}^{+} = \kappa P_0$; P_0 is the laser output power. Similarly, the power propagating in the opposite direction is given by $P_{\text{in}}{}^{-} = (1 - \kappa)P_0$. Note that the output signal, as given by Eq. (1), is independent of laser power P_0. Furthermore, after adjustments of the gain in the detectors (A_s, A_r) or in the variable attenuator ($T_{\text{va}}{}^{-}$), Eq. (1) becomes $S_{\text{out}} = T_{\text{SE}}$. Hence, in principle, the noise induced by laser variations is canceled. However, any small nonlinearity in the detectors may introduce a small dependence of the output signal on P_0. Another possible source of noise could be the polarization dependence of the input coupler. In this case, polarization fluctuations will cause a drift in the output signal that would not be canceled by the referencing system.

Now, considering that an external mechanical perturbation is applied along the fiber-optic link, an additional intensity factor along the clockwise (α^+) and counterclockwise (α^-) directions is induced. Then, the output signal in the presence of a perturbation, $S_{\text{out}}{}^{p}$, would be given by

$$S_{\text{out}}{}^{p} = \frac{\alpha^+}{\alpha^-} T_{\text{SE}}. \qquad (2)$$

For noise cancellation the referencing technique relies on the hypothesis that the intensity factors in both directions (α^+ and α^-) are equal. However, in many cases the perturbation may not produce exactly reciprocal intensity factors and the noise may not be canceled entirely. We may define a noise cancellation ratio (NCR) as the ratio of the change in the output signal as a result of an external perturbation without a reference signal and the corresponding change of the output signal in the referenced system. We get

$$\text{NCR} = \frac{\alpha^-(\alpha^+ - 1)}{\Delta\alpha}, \qquad (3)$$

where $\Delta\alpha \equiv \alpha^+ - \alpha^-$.

To evaluate the performance of the scheme for noise cancellation we assembled a fiber-optic system as depicted in Fig. 1 from single-mode fibers. The fiber loop was closed when the fibers carrying the signal and reference beams were fused. We did not introduce a SE or a bypass, either, since our intentions were only to verify that the output signal was independent of the laser output power and to measure NCR for bending losses. The light source used was a fiber-coupled Luminent laser diode operating at $\lambda = 1.55$ μm coupled to a single-mode fiber optic. The fiber-optic loop was ~3 m long. We used two fiber-coupled AlGaAs photodiodes with variable-gain transimpedance amplifiers to detect the sensing and reference beams. The output voltages were read either with a six-digit voltmeter (Agilent 34401A) or a digital oscilloscope (Tektronix TDS520C).

The stability of the output signal under laser variations was tested by measuring the signal and reference output voltages when the laser output power was increased by 100%. The system was initially balanced by adjustment of the gain of the detectors, thereby compensating for any offset. In Fig. 2 we plot V_s, $-V_r$, and the difference $V_s - V_r$ for different time intervals before and after the laser's output power was increased. At 400 s we increased the laser power by 100%. A magnification of the difference of the signals ($V_s - V_r$) shown in the inset evidences a small step of ~3 mV in the laser's variation. The NCR calculated with the values for α^+ and α^- obtained from Fig. 2 is 950. Finally, to show the applied laser power variation explicitly, V_s and $-V_r$ were registered separately after 500 s.

Figure 3 shows the signal and reference voltages versus time when bending of ~5-mm radius was induced in the fiber used for the remote link. The waveforms for both signals are greatly similar, indicating good loss reciprocity in absolute terms. The inset shows the relative variation of the output signal from the reference scheme ($V_s/V_r - 1$) and the variation of the normalized output signal without reference ($V_s/V_{\text{initial}} - 1$). The NCR is evaluated by taking the ratio of these two curves. The mean value of the NCR in the time interval from 400 to 450 ms is

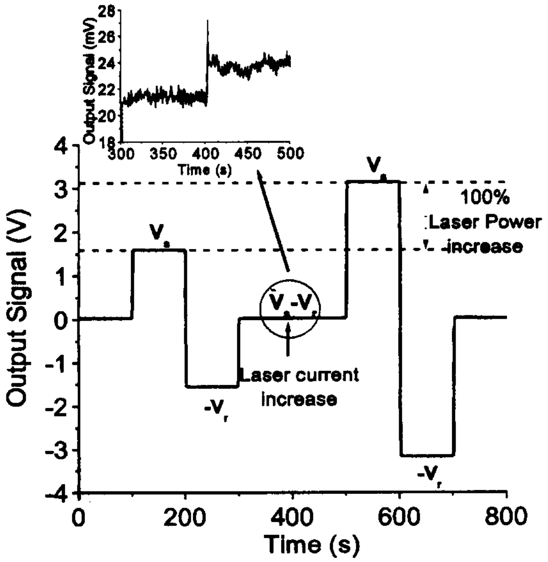

Fig. 2. Output voltages for a laser power increase of 100% at 400 s.

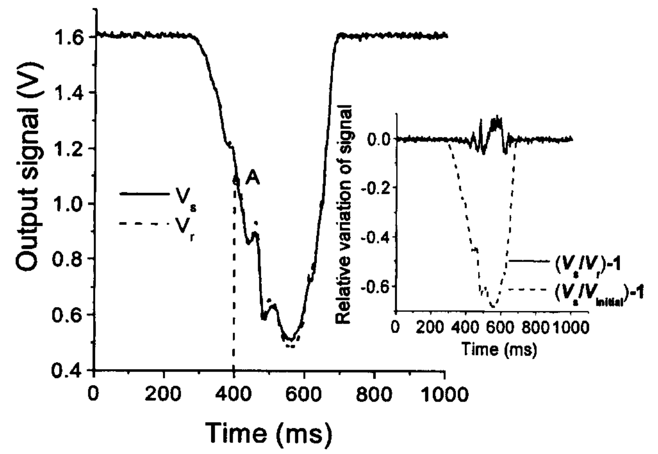

Fig. 3. Output voltages V_s, V_r, and $V_s - V_r$ with induced microbending of 5-mm radius.

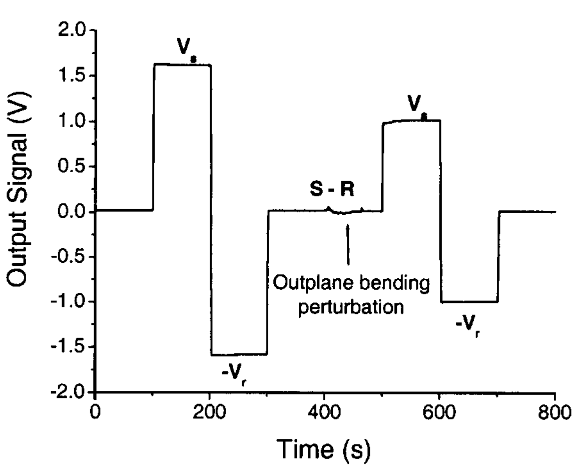

Fig. 4. Output voltages with a bend perturbation of 3 dB applied between 400 and 700 s.

33. However, for the deepest region (~550 ms) the NCR decreases to ~12. We believe that the actual NCR values are in reality better than those estimated here, mainly because our measurements were limited by electronic noise in each of the measured voltages. This noise is ~2.5% of the signal around point A in Fig. 3 and 6% near the deepest point in the curves.

A second set of experiments involving large bending radius perturbations were performed in a similar way as the previous experiments on the laser power variations. In Fig. 4 we plot the measured voltage versus time during one of these experiments. A 3-dB loss perturbation was induced between 400 and 460 s by wrapping a portion of the fiber-optic link around a 20-mm-radius cylinder. From this plot we can estimate the values of α^+ and α^- and thus calculate a NCR of 50. This NCR shows that the referenced system will perform better than a simple nonreferenced scheme.

The difference between α^+ and α^- induced by mechanical perturbations producing a nonreciprocity for the sensing and the reference signals can be explained if polarizing elements are present along the fiber-optic links. Then, it is not difficult to show that α^+ and α^- can be different under polarization rotation and birefringence which is usually present in optic fibers. We can point out some factors that could limit the noise-cancellation performance. In particular, the fusion splices may present a polarization-dependent transmission factor, as well as the directional couplers. In future work, therefore, the use of polarization-insensitive fiber devices should be considered.

In conclusion, we have proposed a simple technique for referencing remote intensity-modulated fiber-optic sensors. Such a technique can be realized with all-fiber components and potentially with off-the-shelf devices. Noise-cancellation performance was evaluated through several experiments intended to induce losses similar to those encountered in long fiber-optic links. The referencing technique performs extremely well for noise induced by laser power fluctuations. Under this kind of perturbation, NCRs as high as 10^3 were measured. For bending losses, NCRs of 33 (5-mm bending radius) and 50 (curvature losses) were registered. The lower efficiency of the system for canceling mechanically induced noise than for canceling source power variations can be attributed to polarization effects. Nonetheless, an improvement over nonreferenced systems was observed in all cases.

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