Intermodal fiber interferometer based on broadband source and optical spectrum analyzer: experimental demonstration of the correlation approach

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The operation principle of intermodal fiber interferometers (IFIs) is to analyze the interferometric speckle pattern at the multimode fiber (MMF) output. However, such IFIs are affected by a signal fading and have a strongly nonlinear transfer function that limits the scope of their applications. In this work, we report on an experimental research of the IFI based on broadband light source and an optical spectrum analyzer (OSA). This scheme can be considered as a set of IFIs operating on their own wavelengths according to the resolution of the OSA. We experimentally demonstrate that using such a scheme and the correlation signal processing enables stable and linear response to external fiber perturbation in real time.

Introduction

Fiber optic sensors based on intermodal fiber interferometers (IFIs) have been attracting growing interest due to their high sensitivity, simplicity and low cost [1]. Sensing designs for temperature, pressure, vibrations and other physical quantities were recently proposed and investigated [2-4]. The operating principle of IFIs is to analyze an interferometric speckle pattern at the multimode fiber (MMF) output facet: external fiber perturbations (EFPs) change modes' phase differences that leads to changes of light intensity distribution in the speckle pattern. However, substantial limitation of IFIs measurement capabilities are strongly nonlinear transfer function and signal fading [5]. Therefore, significant research attention is focused on methods to overcome these problems. The two most practical concepts utilize the speckle pattern spatial distribution (image processing, spatial averaging of an IFI signal or calculating a spatial correlation function) and optical frequency scanning (frequency averaging or calculating the correlation function of frequency scans repeatedly followed by each other) [6,7].

In [7], we demonstrated that using frequency scanning approach it is possible to obtain not only stable IFI response to EFPs (i.e. realize effective signal averaging), but also to provide linear transfer function. The IFI response stability is achieved by calculating the correlation function between IFI signals formed by repeating optical frequency scans and a reference scan recorded at undisturbed fiber conditions. Herewith, using special modifications of the correlation coefficient formula and introducing a frequency shift between the current and the reference scans, we provided linearity of a sensor response. No spatial averaging was used in this case.

In this work, we experimentally verify the frequency scanning approach using a singlemode-multimode-singlemode (SMS) scheme based on a broadband source (BS) and an optical spectrum analyzer (OSA). We apply the shifted correlation function [7] to provide stability and linearity of the IFI transfer function. And, we demonstrate obtained IFI signals and compare them with unprocessed signals under changing environment conditions.

Principle of operation and experimental setup

We developed the IFI scheme based on the superluminescent diode Exalos EXS210066-01 (1400-1700 nm FWHM, 5mW output power) and the OSA Ibsen Photonics spectrometer I-MON 512 USB (scanning range 1510-1595 nm, resolution 160 pm, scanning rate 1000 scans/s) (Fig. 1(a)). Both the BS output and the OSA input were SMF pigtails. Sensitive MMF (standard graded-index 50/125 fiber) was connected between these two SMFs. We introduced a small air gap between the input SMF and the MMF to reduce the power fraction propagating in the fundamental mode and to redistribute the power via higher order modes. The output SMF served as a spatial filter for the near-field speckle pattern due to smaller SMF's core diameter.

The use of the BS itself did not provide a contrast speckle pattern at the MMF output because of low coherence of the source. However, passing the output light through the diffraction grating of the OSA decomposes light into narrowband spectral components, which are recorded by a photodetector array (Fig. 1(a)). In this case, time signal of each photodetector represents an interferometric IFI signal operating at given optical frequency (wavelength) (Fig. 1(b)). On the other hand, each recorded spectrum by the OSA represents an IFI signal formed by a frequency scan of the light source similar to the scheme based on a scanning laser and a photodetector [8]. We consider that the repetition rate of the OSA (1000 scans per second) significantly exceeds typical EFPs frequencies, so the EFP remains unchanged during one scan of the OSA. Thus, the correlation processing approach presented in [7] can be applied. External fiber perturbations transform a frequency scan, and real-time IFI signal can be obtained as a correlation coefficient between the reference and current frequency scan.

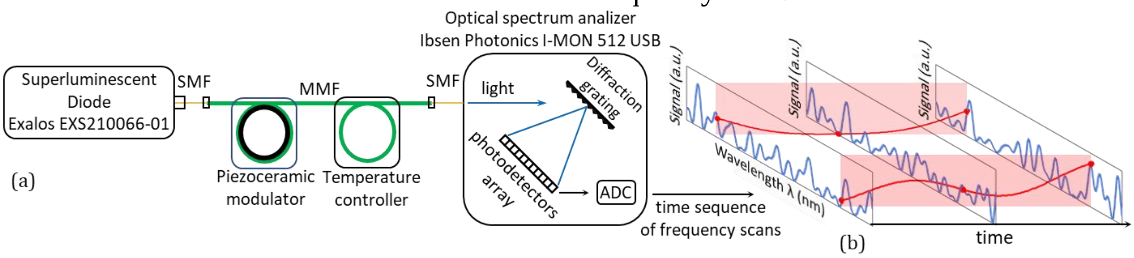

Fig. 1. Schematic of the experimental setup (a) and illustration of IFI signals in time and wavelength (optical frequency) domains (b).

We used a cylinder-shape piezoceramic modulator (5 cm diameter) as a source of external perturbations with controlled shape and amplitude. MMF of 50 m length was wrapped on the modulator that provided maximum 190 μm amplitude of fiber length modulation. We used sine and triangle shapes of the signal with 10 Hz frequency. To imitate slowly changing environment conditions in a wide range (about 2 mm of a fiber effective length change) as a source of signal fading, we used a temperature controller based on a Peltier element with 3-m fiber section placed on it. A total MMF length including sections not used in the modulators was 60 meters. Both piezoceramic and temperature modulators were calibrated using Mach-Zehnder interferometer.

Experimental results

To demonstrate the IFI response instability when no signal processing is applied, we plot three examples of signals obtained at different wavelengths (1540 nm, 1549 nm and 1558 nm) as a response to the same triangle-shape EFP (Fig. 2(a)). In Fig. 2(b), we show fragments of two frequency scans corresponding to unperturbed fiber and fiber strained by 190 μm. These are typical frequency scans to which we applied the correlation signal processing (we subtract the constant component for both scans prior to the correlation function calculation). Fig. 2(c) demonstrates the correlation function $K(\delta L)$ that in fact can be considered as an IFI transfer function (it was obtained using a temperature modulation for higher range of perturbations amplitude). It is seen that it is not linear around zero value (zone A), and obviously, linear IFI response can be obtained if the operating point is located at the linear part of the correlation function (zone B).

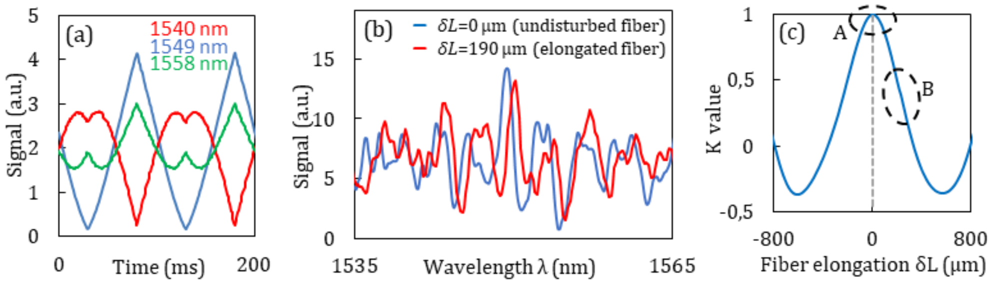

Fig. 2. Unprocessed IFI signal recorded at three different wavelengths as a response to the same external perturbation of triangle shape (a); a fragment of the spectrometer's wavelength scan for unperturbed and strained MMF (b); normalized correlation function calculated as a correlation coefficient between a reference and a signal wavelength scans for a 1600 μm fiber elongation range (c).

In [7] we showed that $K(\delta L)$ can be shifted so that the operating point is located at the linear zone (zone B). This is achieved by introducing an optical frequency shift ζ to the signal frequency scan, and the sensor's response obtains a form

$$SCF(\delta L,\zeta)=1-\frac{K_{\zeta}(\delta L,\zeta)}{K_{\zeta}(\delta L=0,\zeta=0)} \quad , \tag{1}$$

where the *SCF* is an abbreviation of the term "shifted correlation function", $K_{\zeta}(\delta L, \zeta)$ is a correlation function between signal and reference frequency scans shifted from each other by ζ, the denominator is introduced for normalization and has a value of the correlation function at its maximum.

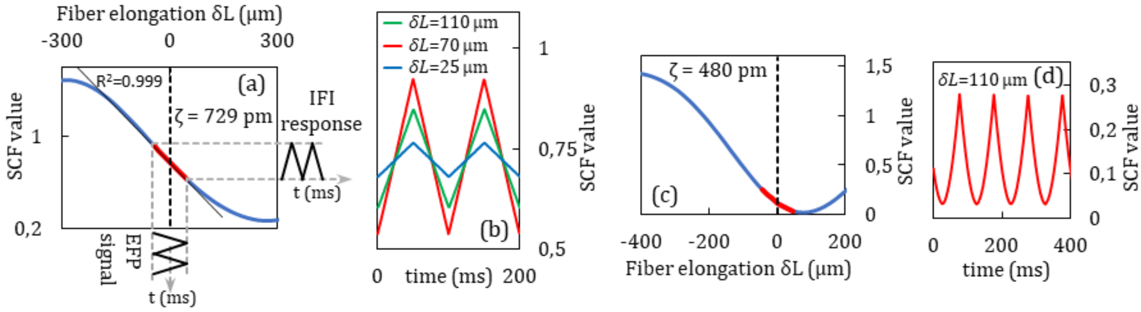

Fig. 3. Shifted correlation function and illustration of the IFI response calculation (a); the SCF signal response to a triangle-shaped fiber perturbation of different amplitudes (b); example of the SCF response when the frequency shift ζ is not selected optimally (c, d).

Fig. 3 (a) demonstrates the SCF obtained from experimental data using Eq. (1) (blue line). For the convenience frequency shift ζ was replaced by a wavelength shift, which was chosen to be 729 pm. It is seen that at the absence of external perturbations δL the value of the SCF (i.e. the operating point) is located near the center of the linear part of the correlation function. Fig. 3(b) demonstrates the SCF values as a response to the fiber length modulation of triangle shape with three different amplitudes. We can see that the response's amplitude linearly depends on the amplitude of the external perturbation and the signal shape is well reproduced. Figs. 3 (c, d) illustrate the case when the frequency shift ζ is not selected optimally: the operating point is located near the end of the SCF linear part and therefore the signal shows significant distortions.

We tested the IFI signal stability under changing environment conditions. For this purpose, we simultaneously applied a sine-shaped piezoceramic modulation with a 70-μm amplitude and 10 Hz frequency and linear heating by Peltier element from 40 ºC to 80 ºC during 200 seconds (slowly changing environment conditions). Fig. 4 shows fragments (ΔT=1ºC during 5 seconds) of obtained dependences for unprocessed IFI signal (recorded by the spectrometer at λ=1520 nm) and for the signal calculated by the SCF method. It is clearly seen that the unprocessed signal is affected by a strong fading, while the SCF signal amplitude remains stable. During whole temperature change of 40 ºC the amplitude of the unprocessed signal changed 200 times, while the SCF signal changed not more than 1.6 times that confirms significant improvement of the IFI signal stability.

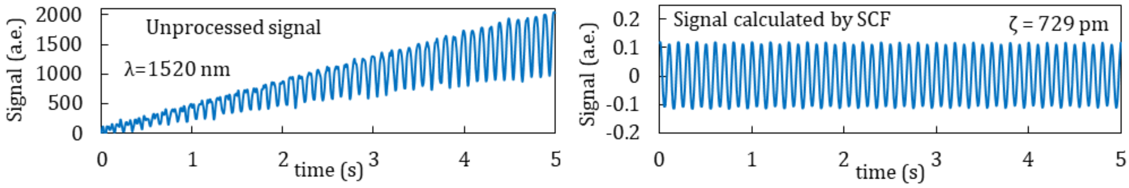

Fig. 4. Unprocessed signal response (a) and the SCF response (b) to a sine-shaped fiber perturbation under strongly changing environment conditions.

Conclusion

We experimentally investigated the IFI based on the broadband source and optical spectrometer. Significant improvement of the IFI signal linearity and stability under strong environmental condition changes is demonstrated experimentally using the shifted correlation function approach in real time.

References

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