Radial processing scheme of speckle patterns for sensing applications

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Abstract: A processing scheme to enhance the speckle sensitivity to dynamic perturbation has been proposed and experimentally tested. Considering different areas within speckle patterns where highest order modes interfere, a better dynamic sensitivity has been achieved.
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1. Introduction

Optical fiber sensors have been applied to very different applications from aerospace industry to domestic scenarios. Despite the efforts to get a low cost technology, sensing system based on single mode fibers (typically with a small core diameter ≈ 10 µm) offer extremely high performance and multiplexing capabilities but are usually expensive for many commercial applications. On the other hand, multimode optical fibers (with a larger core diameter ≥ 50 µm) offer enough performance for many commercial applications, but their cost is lower because injecting light inside a larger core is easier. Besides, multimode fibers when illuminated by a coherent light source, a granulated pattern of light can be observed at the end of the fiber. This effect is the speckle pattern, which is produced by an interference phenomenon between modes propagated inside of the fiber. These particular characteristics of the speckle phenomenon obtained in multimode fibers are used in sensing technology. In recent years several studies have been reported in vibration sensing [1], displacement [2], distance [3], cracks in concrete structures [4], and blood flow [5]. In all these cases, they have used multimode optical fibers with core diameters from 50 to 100 µm and, usually, silica fibers. Besides, reported processing methods employ the outputs speckle patterns (specklegrams) as a whole distribution, processing each speckle dot independently of its location.

This paper proposes a new processing scheme based on analyzing different areas of the output specklegram which are related to propagation statistics. This new analysis exhibits certain advantages, getting more information about the speckle pattern and fiber perturbation just by employing extra information of the speckle dot position. By analyzing the propagation within a multimode fiber, different modes follow different optical paths being more (or less) influenced by the external perturbation to be measured. An experimental setup based on applying vibration to different Polymer Optical Fibers (POFs) has been employed to evaluate the processing scheme. Several vibrations of different frequency and same amplitude have been applied to two POF of 250 µm and 980 µm of core diameter and their specklegram sequence has been radially processed. The achieved results exhibit a good sensitivity increase when employing radial processing schemes over the uniform processing method. This new technique can enhance the overall sensitivity of specklegram sensors for critical applications.

2. Speckle in multimode fiber

Multimode fibers can spread a large number of modes with different phase velocities. The propagation modes corresponding to different optical paths used by the beams coupled into the fiber suffer different phase delays. The output field distribution consists of a sum of all individual contributions of each mode. If the contributions phase delay varies over 2π radians, having a sufficiently coherent source then, the interference effects are well structured and can be observed in the intensity distribution through the end of the fiber. The number of modes, M, which supports an optical fiber break index is given by the expression [6]

$$M = \frac{V^2}{2}$$

(1)

where *V* is called normalized frequency given by,

$$V = \frac{2a\pi}{\lambda}\sqrt{n_{co}^2 - n_{cl}^2}$$

(2)

where a is the core radius, λ wavelength the laser and n_{co} and n_{cl} are the refractive indexes of core and shell, respectively. Particularly, for the employed multimode POFs, the number of modes (calculated for He-Ne wavelength, λ=0.6328 μm) are M≈190E3 for the 250 μm and M≈3E6 for the 980 μm.

Proposed scheme is based on the geometrical distribution of propagated modes within the optical fiber [7]. Low order modes, which optical path are close to fiber longitudinal axis, will produce speckle dots (or darks) centered in the middle of the speckle pattern. On the contrary, high order modes, which optical path passes far from longitudinal fiber axis, will produce speckle dots (or darks) all over the output speckle pattern. As modes order decreases, their output positions change from being confined in the middle of the spot to be distributed all over the output speckle pattern.
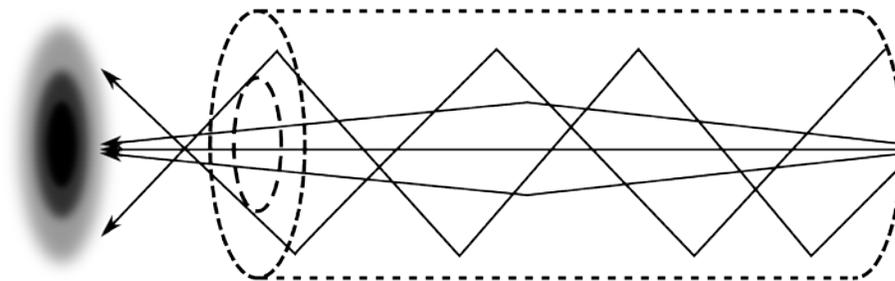

Fig. 1. Propagation basis within a multimode optical fiber. Outer section of the speckle pattern is mainly caused by higher order modes.

When number of modes of the employed optical fiber is high, statistically, outer speckle dots are caused by the interference of the higher order modes, which are more influenced by the perturbation to be measured. Otherwise, central speckle dots are mainly influenced by low order modes, which are less sensitive to external perturbations.

3. Radial processing

Based on the statistical relation between modal orders and speckle dot's positions, the differential processing scheme has been adapted to compute the difference for different rings varying their radius.
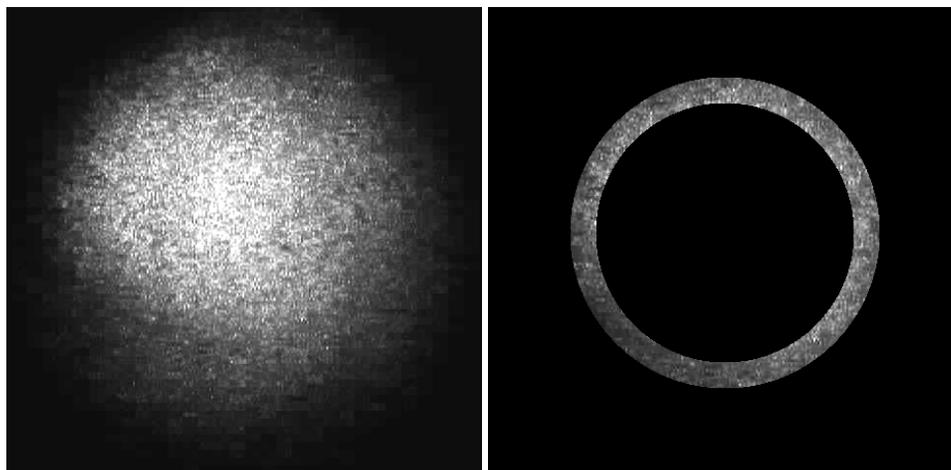

Fig. 2. Processing scheme. Different rings of the same width are considered for each specklegram

Several rings of different radius but constant width have been employed as binary mask to compute the correlation between consecutive specklegrams. Because number of pixels of different rings is not the same, correlation value has to be scaled with the processed area, to obtain the correlation per pixel. Since the amount of light of each pixel is not the same (lower intensities are located in outer regions), the averaged intensity within each ring has been employed as scale factor to correct this difference.

4. Experimental setup and results

Two POFs have been perturbed with a speaker that creates vibration from 1Hz to 10Hz using the same amplitude. One edge of the fiber has been connected to a laser diode and the other side to a USB camera capturing at 25 fps. A sequence of several specklegrams of 640 by 480 pixels has been captured for each fiber and frequency.
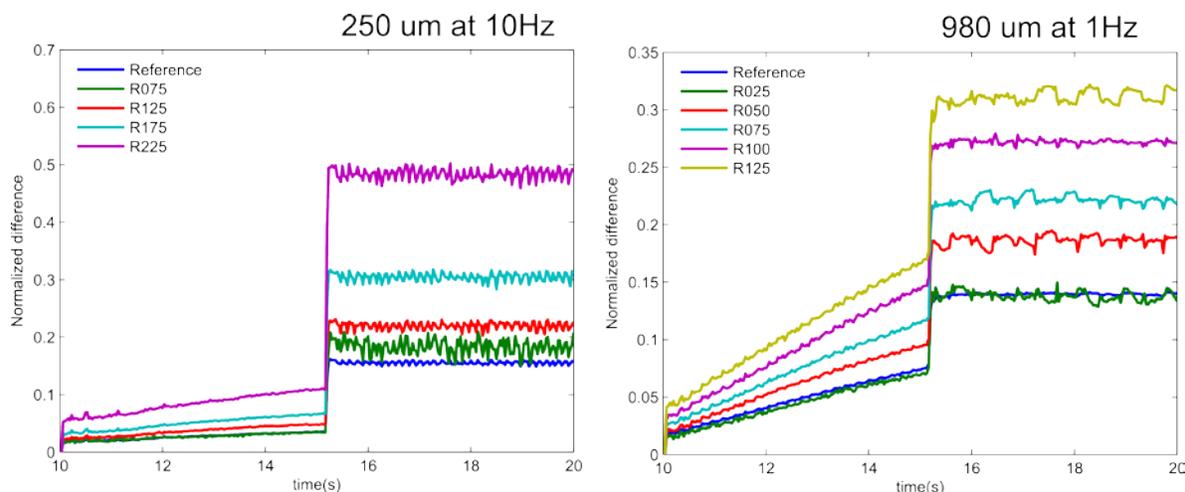
Fig. 3. Processed specklegram sequences of 250 um fiber and 980 um for different ring radius (pixels)

Depending on the NA of each fiber and on the distance to the camera, different spot's sizes are achieved so different radiuses have been considered. In Fig. 3, two specklegram sequences of both tested fibers have been processed and compared to a uniform differential processing scheme. Each sequence comprises a low perturbation section (mainly influenced by environmental conditions) and a high perturbation section (induced vibration) after second 15. As the radius is increased (maintaining their width), the obtained sensitivity also increases, because these areas are mainly influenced by higher order modes, which also are more exposed to the external perturbation. The reference signal has been computed considering the whole spot: a circle (instead of a ring) with the maximum tested radio. Since the proposed scheme is based on speckle statistics, it works properly in fibers with a very high number of modes where speckle dots are smaller and enough speckle dots are comprised in each ring. If small ring diameters are considered, there would not be enough speckles within each ring so, final sequence will be noisy.

5. Conclusion

In this work, a new processing scheme to enhance the speckle sensitivity to dynamic perturbation has been proposed and experimentally tested. Considering different areas of interest within a speckle pattern, each area is statistically related to higher modes that are more sensitive to external fiber perturbations. The radial processing scheme has been experimentally validated using two highly multimode POFs that have been subjected to an external vibration while their speckle pattern were recorded using an USB camera. The achieved results exhibit a sensitivity increase when areas far from the longitudinal fiber axis (corresponding to higher order modes) were processed. This new technique enhances the application of Fiber Specklegram Sensors (FSS) to applications where extremely high sensitivity is required.

6. Acknowledgement

7. References

[1]   Spillman, W.B.Jr., Kline, B.R., Maurice, L.B., and Fuhr, P.L., "Statistical-mode sensor for fiber optic vibration sensing uses", Applied Optics, **28**, 3166-3176, (1989).
[2]   Yu, F.T.S., Wen, M., Jing, S., and Uang, C.M., "Submicrometer displacement sensing using inner-product multimode fiber speckle fields", Applied Optics, **32**, 4685-4689, (1993).
[3]   Kitagawa, Y., and Hayashi, A., "Fiber-optic sensor for distance and velocity measurements using speckle dynamics", Applied Optics, **24**, 955-959, (1985).
[4]   Zhang, Z., and Ansari, F., "Fiber-optic laser speckle-intensity crack sensor for embedment in concrete", Sensors and Actuators **A-126**, 107–111, (2006).
[5]   Dietsche, G., Ninck, M., Ortolf, C., Li, J., Jaillon, F., and Gisler, T., "Fiber-based multispeckle detection for time-resolved diffusing-wave spectroscopy: characterization and application to blood flow detection in deep tissue", Applied Optics, **46**, 8506-8514, (2007).
[6]   Kaiser, G., *Optical Fiber Communications*, McGraw-Hill, Second Edition, Chapter 2, NY (1991).
[7]   Snyder, A.W., and Love, J., *Optical waveguide theory*, Chapman and Hall, London, Chapter 12, p.248 (1983).