Parallel-multipoint plastic optical fiber sensor based on specklegrams

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Abstract: In this work a new configuration of a plastic optical fiber sensor disposed in parallel to detect at multiple points is presented. The sensor is based on the high sensitivity of changes in the speckle pattern when the fiber is perturbed. Plastic optical fibers used are 980 and 240 um core diameter. The fibers are connected in parallel to 1mm POF fibers, both at the input and at the output. We proved that perturbation can be detected by one or more fibers arranged in parallel maintaining the properties of speckle fiber. The proposed sensor is highly sensitive and can be used in the protection of works of art.

1. Introduction

Usually, protection, security and intrusion detection systems are sophisticated and expensive. Some of these systems are based on different technologies such as electrical, optical, magnetics or acoustic: they use surveillance cameras, IR detectors, electronic alarms or optical fibers. Optical fiber sensors have several advantages including small size and low cost, they are immune to electromagnetic interferences from the surrounding environment. Optical fiber sensors are very attractive for applications in safety and security of valuable items such as works of art, being able to be also employed as optical communication systems [1]. Optical fiber sensors use different modulation techniques of light, intensity, phase, polarization or wavelength. In recent years, random interference between modes propagated by a multimode fiber are used in various sensing applications [2-4]. Particularly, the high sensitivity exhibited by the speckle pattern achieved when the fiber it is perturbed highlights over other techniques. Although its use has been since the 1980s [5], in recent years their applications have in-creased because they can be based on cheap diode lasers and CCD cameras with better performance. In addi-tion, the signal processing techniques are much faster, thanks to the advanced calculation methods and com-puter capacity.

In this paper a new multi-point sensor using changes in the speckle pattern generated in fiber is presented. A set of 12 fibers are arranged in parallel where the ends are joined and coupled to 1 mm fiber sections; input fiber is coupled to laser diode and output fiber is coupled to CCD camera. The sensor uses two types of step-index multimode plastic optical fibers (POF) of the core-cladding diameters of 240/250 μm and 980/1000 μm, respectively. Although the output beam travels through different fibers, the speckle phenomenon is present in the fiber output and recorded by the CCD. The proposed sensor can be used in safety and security systems such as works of art, it is of simple construction and low cost.

2. Sensor Concept and experimental setup.

The generation of speckle patterns when a coherent multimode beam propagates inside have been widely studied. Indeed, the phenomenon speckle fiber is obtained by random interference between modes propagated [6], observable from the output face of the fiber, the speckle pattern is highly sensitive to external perturbations in the fiber, and for this reason it is the basis for numerous applications. When a light beam is injected into the multimode fiber, the beam is decomposed into modes propagating with different phases, they are randomly distributed in the core section. The modes interfere, present at the output face of the fiber form the speckle pattern, whose amount is similar to the number of modes of the fiber. If the coherence of the light source is good enough and the lengths of the fibers are not very large, it is possible to couple the speckle pattern to another fiber, with identical or different characteristics. After this coupling, the speckle phenomenon is maintained and can be used in sensor applications, although reducing slightly its sensitivity. In order to have multiple sensitive points in a sensor system using a single source and a single CCD camera, sensor shown in Figure 1 have been proposed. Each section of the fibers can detect perturbations in parallel independent sub-systems. The advantages POF fiber, large diameter and great flexibility, allowing coupling light easily without special equipment and adapt in different fields of application.

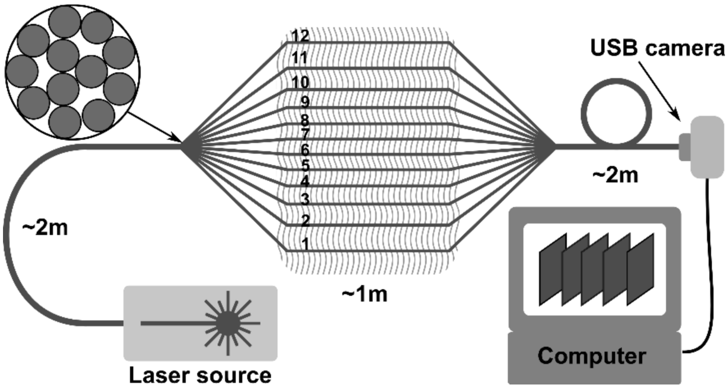

Figure 1. Experimental setup multipoint sensor based on fiber specklegrams.

The sensor shown in Fig. 1 system consists of a laser diode (λ = 653.5 nm and coherence length 0.42 mm), three sections POF (input and output POFs of 1000/980 μm diameter, sensing section of 12 POFs of 240/250 μm diameter), and the output section is connected CCD camera. Sensing fibers have a length of 1 m long. Both types of fiber are PMMA based and has a numerical aperture NA = 0.5. In operation, the CCD camera records sequences speckle patterns at a rate of 30 frames per second, called specklegrams. The specklegrams are processed in the computer to obtain a signal representative of the perturbation. When the light beam is coupled in the POF of 1 mm, over 2 million modes propagate in the fiber core, it is output has a distribution similar to the amount of speckle modes. The fiber of 250/240 mm diameter supports about 160 thousand modes.

The coupling between the fibers 12x1 and 1x12 (980/240 mm diameter ratio) was achieved within a plastic jacket 1.1 mm in diameter and 2 cm long. The separation distance between fibers core is approximately a hundred microns. Although the coupling between fibers can be considered random and complex, speckle patterns observed in each of the 12 fibers after passing a fiber of 980 μm to other 240 μm core, can be noticed in Figs. 2 (a) and (b). In Fig. 2 (c) the speckle pattern achieved at the output of a 980 μm core fiber coupled to the 12 fibers 240 μm core is depicted. The speckle pattern projected at the output end of the fiber and can be used for sensing applications.

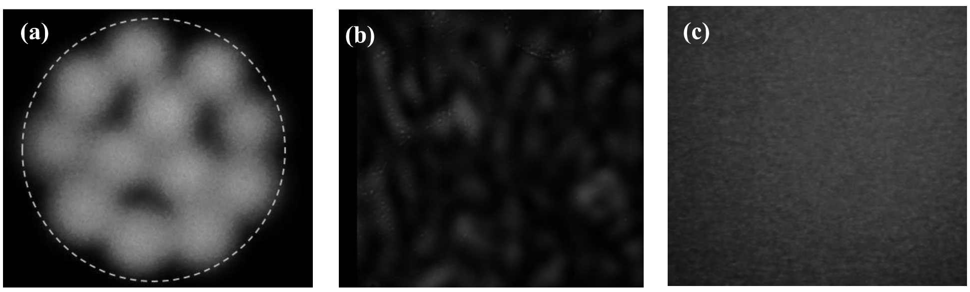

Figure 2. Speckle patterns output fiber. (a) output end 12 core fibers 240 μm coupled by a fiber of 980 μm, (b) the speckle pattern at the output of a single fiber of 240 μm core, and (c) speckle pattern output fiber 980 μm core after being coupled by 12 fibers of 240 μm core diameter.

3. Results

Using the arrangement of Fig. 1, perturbations in different sections of the arrangement of fibers have been provoked. In order to obtain a signal representative of the event, the specklegram sequence captured by the CCD images (30 frames per second) is processed by simple difference between frames using MATLAB program, as described in reference [4]. In Fig. 3 the obtained results are depicted. The method of perturbation of the fibers, with random intervals and duration, was performed in the following sequence. First, the common input fiber, of 980/1000 μm diameter, is perturbed and the other fibers are held fixed, the result is represented by the signal A. Second, the fibers in parallel, of 240/250 μm diameter, are perturbed independently according to the sequence shown in Fig. 1. The results are shown in Fig. 3 and numbered from 1 to 12 for these signals. Third, the common output fiber of diameter 980/1000 μm, is perturbed and the remaining fibers remain fixed, the result is represented by the signal B.

Based on the experimental results, each individual perturbation can be easily identified. The higher intensity of signal A can be explained by the fact that all perturbations in the input fiber modes are coupled into the fibers 12 and propagated to the recoupling in the output fiber. A similar result is observed when the output fiber (signal B) is perturbed. The lower intensity of the individual signals in the fibers parallel is due to the smaller diameter core, propagating less modes and with a lower light intensity. Thus, the contribution of each perturbation propagated to the recombined speckle pattern detected by the CCD is lower. This can be verified simultaneously perturbing multiple fibers in parallel, observing the signal increase.

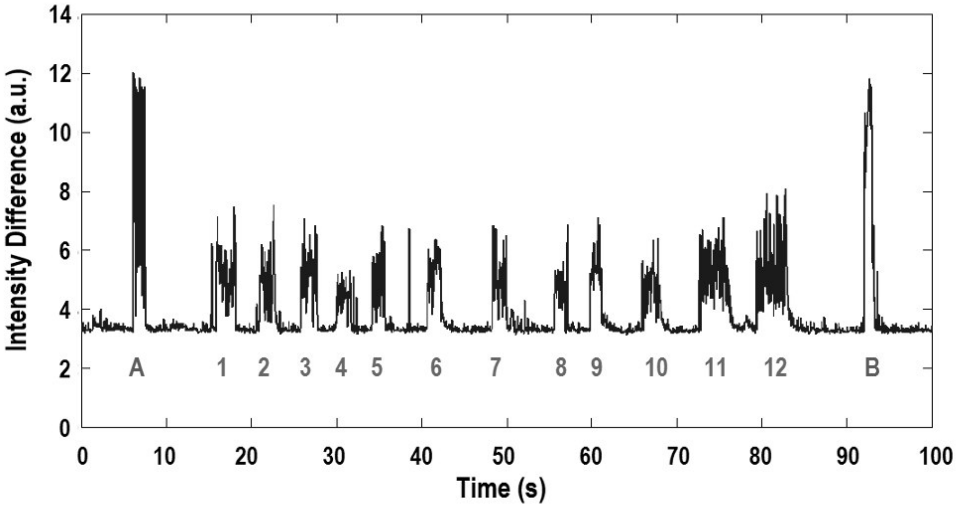

Figure. 3. Experimental results with perturbations in the fibers of the multipoint sensor.

3. Discussion

In our experimental setup, we have used short lengths fibers, where the links between the emitter and receiver fibers are performed with fibers of different diameters. Although coupling losses, the propagated modes are mixed randomly along fiber, at the output end of the fiber (980/1000 μm diameter) the speckle pattern can be observed.

However, when longer fiber must be employed for this configuration, several parameters can limit the performance of this sensor. Among other factors, the sensitivity of the sensor fiber specklegrams depends on the contrast of speckle pattern. The contrast of the speckle pattern, i.e., the difference between light and granules dark background, is mainly driven by the coherence of the laser source, which in turn is related to the spectral bandwidth. By definition, the coherence length of the light source is given by $L_c = \lambda^2/\Delta\lambda$ where λ is the center wavelength of the spectrum and $\Delta\lambda$ the bandwidth. In turn, L_c depends on the operating current of the laser diode. Typically, lasers diodes Fabry-Perot type, as in our case, have understood L_c among the tens of microns and few mm. In our experiment used a laser diode centered $\lambda = 653.5$ nm spectral width and $\Delta\lambda = 1$ nm, which has a coherence length $L_c = 0.42$mm.

On the other hand, when the laser beam propagates in multimode fiber, the maximum degree of spatial coherence at the output of the optical fiber remains unchanged if the spectral width of the source and the maximum difference in transit time between all guided modes is true that [7], $\partial\nu.\partial\tau << 2\pi$. Thus, the length l_c, critical length at which the two rays do not interfere anymore, is [7]

$$l_c \approx \frac{n_2 c}{n_1(n_1 - n_2)\partial\upsilon} \qquad (1)$$

where c is the speed of light in vacuum, $\partial\nu$ it is the spectral width in Hz, and n_1 and n_2 are the refractive indices of the core and fiber cladding, respectively. One can say therefore that from this distance speckle pattern is provided by the sum of the intensities of the separate modes, as has been demonstrated in reference [8]. Using data from the fiber and the characteristic of the laser diode used in this experiment, $n_1 = 1.49$, $n_2 = 1.4$, and $\partial\nu =$ 467 GHz, we obtain $l_c \approx 6.7$ mm. According to described, the contrast of speckle pattern generated in fiber remains acceptable up to a few tens of meters of fiber length when a laser diode Fabry-Perot type, enough to be used in sensor applications and using methods used statistical calculation, as presented in this paper. The coupling of fibers of different diameters core in different sections does not have remarkable influence on the final sensor configuration.

4. Conclusion

It has been presented and demonstrated the operation of a multipoint sensor based on changes of specklegrams when fibers are perturbed, either by vibration, pressure or contact. The high sensitivity of the fibers to external shocks are reflected in changes in specklegrams and detect signals. The excellent adaptability and flexibility of POFs can be used to distribute discreetly contacts point in the protection of works of art, such as pictures or busts in art museums or showrooms. The proposed sensor is simple to implement and represents a low-cost sensor systems for safety and security.

5. Acknowledgements

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6. References

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