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Improvement of the dynamic range of a fiber specklegram sensor based on volume speckle recording in photorefractive materials

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ABSTRACT

In this work, the improvement of the dynamic range of a micro displacement sensor based on fiber specklegrams holographically stored in a photorefractive BSO ($Bi_{12}SiO_{20}$) crystal is reported. In our experimental setup, a plastic optical fiber (POF) was used to generate a subjective speckle pattern that was recorded in the crystal using a two-wave mixing arrangement. The speckle size was controlled by modifying the diameter of a pupil aperture adjacent to a lens producing the image of the speckle. Fringe patterns were obtained at the output of the system by producing micro displacements of the fiber output end. An increase in the visibility of the fringe patterns was appreciated when the pupil aperture diameter decreased even without controlling the average modulation of the intensity of the light pattern, i.e. when the speckle length increased and the average light modulation simultaneously decreased. This behavior allowed recovering the autocorrelation functions of fringe patterns associated with displacements that initially led to decorrelation, and therefore, significantly to improve the dynamic range of the metrological system. To the best of our knowledge this is the first report about the influence of speckle size on the dynamic range of fiber specklegrams sensors recorded on photorefractive materials.

1. Introduction

When coherent light goes through a multimode optical fiber, a speckle pattern appears at the output end of the fiber, as a result of modal interference. This speckle pattern is troublesome in signal transmission but, however, contains information on the physical state of the fiber. For this reason, it can be used in sensing systems [1]. Sensing systems based on speckle patterns obtained by modal interference in multimode optical fibers are known as fiber specklegram sensors (FSS). These sensors have been widely studied for their potential applications in several engineering fields [2–12]. Techniques that are non-holographic and holographic are highlighted in the literature of FSS. In non-holographic techniques two possibilities are commonly reported. In the first case, image processing is used to calculate the normalized inner product (NIP) from the speckle patterns captured by a CCD camera at the output end of a multimode optical fiber before and after perturbation on the fiber [7–9]. In the second case, experimental arrangements of multimode fibers (most recently photonic crystal fibers) followed of a single mode fiber are used to generate and filter the speckle patterns. In this way, power variation sensing systems are obtained. This kind of detection systems is very simple and very cheap, but present low sensitivity [10–12]. On the other hand, holographic FSS have been mainly developed by recording speckle patterns on photorefractive materials and optically performing self-correlation operations [3–5]. Holographic FSS have shown to be more sensitive than any non holographic FSS and this property has been explained by the inclusion of phase information in the holographic register [4]. Now, because of its easy implementation and potentialities in engineering measures, double exposure is one of the most used techniques in speckle metrology with photorefractive materials [13,14]. However, to the best of our knowledge it has not been explored in FSS. Moreover, the influence of the volume speckle has not been analyzed in this type of sensor. Additionally, reports on the use of photorefractive materials in FSS have been commonly limited to crystals with high diffraction efficiency but with low time response, such as $Ce{:}Fe{:}LiNbO_3$, which make difficult the quasi real time performance of the sensing systems [3–5,15].

In this work, a novelty analysis about the influence of the average speckle size in a micro displacement FSS using the double exposure technique is developed using a two-wave mixing arrangement in a BSO ($Bi_{12}SiO_{20}$) crystal. This type of crystal belongs to the sillenite family, which exhibits high sensitivity and fast response [16]. In our experimental setup, the speckle pattern was created by the interference of the propagation modes transmitted by a step index plastic optical fiber (POF) of 1 mm diameter, which supports around 10^6 propagation modes when laser radiation with a wavelength of 532 nm is used. An optical fiber used as a transducer medium in a

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holographic FSS results in being useful in double exposure setups, due to fiber characteristics such as small diameter, flexibility, and electromagnetic immunity. The imaged speckle pattern and a reference beam were mixed in a 10 mm × 10 mm × 10 mm BSO crystal. The average size of the speckle grains was controlled varying a pupil aperture adjacent to the lens of the speckle imaging system [17–25]. For a particular pupil aperture, several fringe patterns were obtained for different micro displacements of the fiber output end. An increase in the visibility of the fringe patterns was appreciated when the pupil aperture diameter decreased even without controlling the average modulation of the intensity of the light pattern, i.e. when the speckle length increased but the average light modulation simultaneously decreased. This behavior allowed recovering the autocorrelation functions for fringe patterns associated to displacements that previously led to decorrelation of the shifted speckle patterns. Therefore, a significant improvement in the dynamic range of the metrological system was obtained by the very simple tuning procedure of varying the pupil aperture diameter. We want to point out that, for example, in Ref. [22], coauthored by one of us, the behavior of the diffraction efficiency for high frequency modulated speckle patterns recorded in a BSO ($Bi_{12}SiO_{20}$) crystal was theoretically and experimentally studied. In that work, the diffraction efficiency was evaluated considering two cases. In the first one, the speckle size was fixed and the average light modulation was increased. An increase in the diffraction efficiency was observed. In the second one, the average light modulation of the speckle pattern was fixed and the speckle size was varied. In this case, the diffraction efficiency decreased when the speckle length decreased too. A perspective of that study was suggested for metrological applications of the double exposure technique using speckle pattern recording in photorefractive materials. Fringe patterns with good visibility obtained using a fixed speckle size were shown. However, the influence of the speckle length on the visibility of the fringe patterns was not reported in Ref. [22]. Even more, the effect of the speckle size on the dynamic range of a particular metrological system was not studied. To the best of our knowledge this is the first report on the influence of the speckle size on the dynamic range of fiber specklegrams sensors recorded for photorefractive materials.

2. Theoretical and experimental analysis

It is well known that propagation modes with different phase velocities appear in a multimode optical fiber when coherent light travels through it. In this way, a speckle pattern is generated at the output end of the fiber due to the superposition of individual fields, each one with different phase delays [26]. In a step index profile optical fiber, the refraction index changes suddenly between the core and cladding interface, which produces a high temporal dispersion and a lesser standard deviation of the amplitude distribution than in a gradual index profile optical fiber [27]. In this case, the number of propagation modes can be estimated by

$$M \approx V^2/2 \tag{1}$$

where

$$V = 2\pi \frac{a}{\lambda_o} NA \tag{2}$$

is the propagation parameter, a the fiber core radius, λ_o the wavelength of the laser source, and NA the numerical aperture of the fiber, which is given by [28]

$$NA = (n_1^2 - n_2^2)^{1/2} \tag{3}$$

where $n_1$and n_2 are the fiber core and cladding refraction index, respectively. In our experimental setup, $n_1 \approx 1.492$, $n_2 \approx 1.412$, $a = 480\ \mu m$ and $\lambda_o = 532$ nm. Therefore, the propagation parameter $V \approx 2.7 \times 10^3$ and the number of propagation modes $M \approx 3.7 \times 10^6$. Due to the propagation characteristics of a step index multimode fiber, and the amount of propagation modes present in our arrangement, it is possible to assume as a first approximation a Gaussian treatment for the speckle statistics [29]. Moreover, it has been shown that the average speckle length for a subjective speckle produced in the image plane of a lens with a circular aperture is given by [30]

$$Ls \approx \lambda_o \left(\frac{z_c}{D}\right)^2 \tag{4}$$

where z_c is the image distance and D is the pupil aperture diameter of the subjective speckle system.

For speckle patterns recorded in a photorefractive crystal by two-wave mixing, the light intensity modulation depends on the intensity of the speckle signal beam imaged in the crystal and the intensity of the reference plane wave. The speckle pattern is characterized by a randomly varying intensity. Therefore, a statistical distribution of light intensity modulation is present into the crystal. As a consequence, the index grating modulation has similarly a statistical nature because it depends on the input intensity modulation. In principle, this statistical behavior must be taken into account. In several works [18–25] it has been shown that Kogelnik's theory [31] can adequately predict the experimental behavior of the diffraction efficiency for specklegrams in photorefractive materials if, as a first approximation, an average light modulation is considered, and if the interaction length, i.e. the crystal thickness, is replaced by the average of the speckle length when the latter is shorter than the crystal depth. In particular, in Ref. [22], the case of a high frequency modulated speckle in a BSO crystal was studied and it was successfully demonstrated that Kogelnik's result can be used to predict the experimental behavior of the diffraction efficiency in this two-wave mixing arrangement for speckle recording. In our work, we have used some of these previous experimental and theoretical reports to show and put in evidence that the dependence of diffraction efficiency on speckle size can be used to improve the dynamic range of a micro displacement sensor based on double exposure of fiber specklegrams recorded in the volume media. As shown in Ref. [22] for a subjective speckle setup, a speckle pattern recorded on a BSO crystal by a two-wave mixing arrangement with a broad inter-beam angle will produce a high frequency fringe modulation in each speckle grain, which generates a redistribution of the photo-induced electrical charges in the crystal, producing a local electric field that induces a spatial index variation by a linear electro-optic effect. In the same work, a simplified model is used, in which the diffraction efficiency for this kind of holographic registers can be written as a function of the average modulation of the light pattern and the average speckle length in the following way:

$$\eta = \begin{cases} (L/L_S)\sin^2(kLs) & \text{if } L_S < L \\ \sin^2(kL) & \text{if } L_S \geq L \end{cases} \tag{5}$$

where the phenomenological multiplicative factor L/L_S is included to take into account the speckle density in the crystal when the average speckle length L_s is shorter than crystal depth L. The coupling constant is given by

$$k = \frac{\pi n \Delta n}{\lambda_o \sqrt{n^2 - \sin^2\theta}} \tag{6}$$

θ is the external half inter-beam angle, n the refractive index at wavelength λ_o, and Δn the index grating modulation depth. The explicit expression for Δn in the diffusion regime (without an external electric field applied to the crystal) is [32]

$$\Delta n = \frac{1}{2} n^3 r_{41} \left\{ m \frac{E_D E_q}{(E_q + E_D)} \right\} \tag{7}$$