Fiber Optic Speckle Interferometry for Intrusion Monitoring Systems

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Abstract. A speckle based fiber-optic technique for perimeter intrusion-monitoring systems is discussed. The method is based on the effect of variation of the speckle pattern in the far-field of a multimode fiber. Computer processing of the speckle image provides information on the amplitude of the perturbation that hits the fiber. By proper adjustment of the modes excitation one can create conditions for localization of intrusion.

Key words: multimode fiber, speckle pattern, modal interference, CCD, variable mode distribution

I. Introduction

Existing distributed fiber optic sensing technologies are based on various operation platforms. Basically these are light scattering mechanism, interferometric approach, Bragg gratings approach, optical loss based quasidistributed sensors, etc. [1-6] Among all these the most important distributed sensing systems are those which are based on light scattering mechanism – Rayleigh, Raman or Brillouin scattering.

Fiber optic perimeter intrusion monitoring systems play an important role in monitoring and securing industrial, civil and military structures - airports, nuclear facilities, pipelines, bridges, etc. [7]. These systems can be divided into distributed and non-distributed monitoring systems. The most performant fiber optic distributed monitoring systems explore the principle of light scattering in optical fibers. The great advantage of these systems is the possibility of determination of the coordinate of intrusion with high spatial resolution. For example, some of distributed fiber optic sensing systems provide determination of the perturbation coordinate with millimeter order spatial resolution based on Brillouin optical correlation domain analysis [8]. The disadvantage of distributed sensing systems is related to their complexity and high costs.

In this context it seems very attractive to investige alternative methods for intrusion localization, for example, based on fiber optic speckle interferometry. Fiber optic speckle based intrusion monitoring systems have been developed and implemented in commercial use [7,9-12. The main advantage of these systems referes to their simplicity and low cost. On the other side, such systems do not alow intrusion localization. Efforts have been made for development of methods for intrusion localization in the case of speckle based intrusion monitoring systems [13-14].

In the present paper we focuse on investigation of the possibility of intrusion localization on the basis of modes interference in the far field of the optical fiber, exploring the principle of non-uniform modes distribution in the fiber.

When injecting a coherent light beam into a multimode optical fiber the light is guided in a determined number of propagation modes. Each of these modes has a specific propagation constant, spatial field distribution and polarization. At the exit end of the fiber the propagation modes interfere in the far field producing a random interference image – the speckle pattern. This pattern is highly sensitive to external perturbations and carries information on the conditions of light propagation in the fibers. This effect is laid dawn on the basis of measurement techniques that employ modal interference in an optical fiber.

Speckle-based methods are widely used for registration of physical parameters. These methods have been extensively used for industrial applications in measurement of deformation and displacement, object shape, vibrations, etc. [9-10]. Electronic speckle interferometry combined with PC processing technique offer powerful tools for registration of physical quantities and industrial control [10-12]. In previous papers we reported a fiber optic perimeter intrusion monitoring system based on the effect of interference of propagation modes in the far field of a multimode fiber [15,16]. In this paper we present new results on the method.

II. Experimental set-up

The experimental set-up (Fig. 1) consists of a multimode optical fiber coupled to a coherent light source, a CCD detector, and a PC for processing of the speckle image. The probing light from a coherent light source is injected into the input face of the fiber and at the output end of the fiber in the far-field the light intensity in the speckle image is registered. When a physical perturbation hits the fiber the speckle pattern changes. The CCD is used for registration of the variations of the speckle pattern of the multimode fiber for subsequent PC processing. The probing light source was a laser source at 405 nm or at 633 nm. A segment of multimode commercially available optical fiber with a step-index profile (Fig. 2) and the core/cladding diameter 50/125 μm was used as sensing element. The speckle pattern in the far field of the fiber was registered with a HDCS-1020 CMOS image sensor with the pixel size 7.4×7.4 μm and image array sizes VGA 640×480. The full frame video rate at 8-bit resolution was 30 fps.

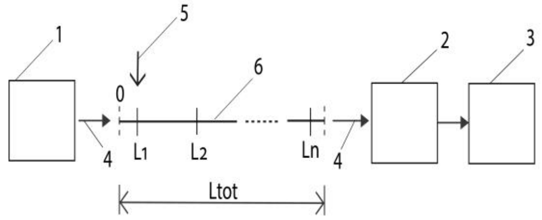


Fig. 1. Schematic representation of experimental set-up: 1 – a coherent light source; 2 – CCD detector; 3 – PC; 4 – probing light beam; 5 – intrusion deformation; 6 – multimode optical fiber;

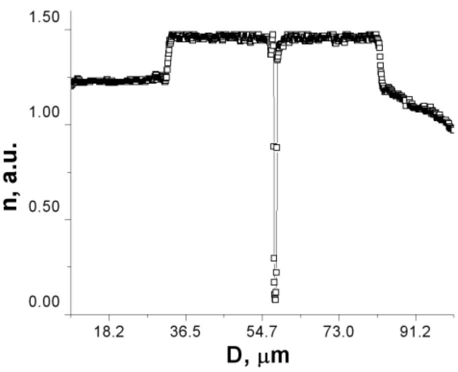


Fig. 2. Refractive index profile distribution for optical fiber sample used in the experiments

The total number of propagation modes N in a step-index fiber for the steady-state mode distribution is given by [17]:

$$N = \frac{V^2}{2}, \qquad (1)$$

where V is the normalized frequency, given by the relation:

$$V = ak_0 NA, \qquad (2)$$

where a is the core radius, $k_0 = 2\pi / \lambda_0$, and NA is the numerical aperture, given by:

$$NA = \left(n_{core}^2 - n_{clad}^2\right)^{1/2} \qquad (3)$$

In this way, for the investigated fiber sample in the case of probing light λ_0 = 633 nm, the total number of modes N can be estimated at ~ 1250 modes.

We investigated the dependence of the output signal in the far field of the fiber from the distance, where the perturbation is applied (Fig. 1). For each point we have taken 10 measurements, and the mean value has been calculated.

III. Interference of propagation modes in the far field of the fiber

A typical speckle pattern of the fiber used for measurements is shown in Fig. 3a. Analyses of spatial distribution of light intensity in the speckle pattern *I(x,y)* in the far-field of the fiber provides information about the amplitude of perturbation that affect the optical fiber. The speckle image represents the result of destructive and constructive interference of propagating modes in the far field of the fiber (Fig. 3b). For a separate mode the magnitude of electric field E can be represented as [18-19]:

$$E = A_0 \cos(\omega t + \varphi), \qquad (4)$$

where A_0 is the amplitude of electrical field, ω is the frequency of electromagnetic wave, t is the time. The phase for a separate mode φ is determined by the geometrical path length L, the wavelength λ and the effective index of refraction n ($\varphi = 2\pi n \frac{L}{\lambda}$). The total amplitude of the electric field in any point of speckle pattern in the plane of CCD sensor can be represented as the sum of contributions of all N propagating modes of the fiber:

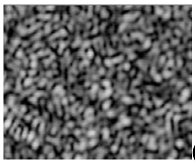
$$E = \sum_{k=1}^{N} |A_k| \exp(j\varphi_k), \qquad (5)$$

where A_k is the amplitude of the *k-th* mode of the fiber, φ_k is the phase for the *k-th* mode at the output end of the fiber, N is the total number of modes propagating in the core of the fiber.

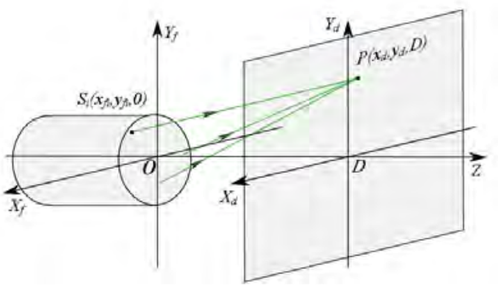
The algorithm for processing of the speckle images is based on comparison of speckle image taken at $t = 0$ and each one of the subsequent speckle images taken in the time moment t_k, where $k = 1,2,3, \ldots k_{max}$. An illustration of the speckle processing algorithm is represented in the Fig. 4. The CCD camera takes an image of the speckle at the initial time t_0, and this image is stored in the buffer memory. The following (*current*) speckle images are taken at consecutive time intervals t_k. The initial image I_0 is subtracted pixel-by-pixel from each of the current image I_k, and the current difference image I_k^d is obtained. The next processing step represents summation of all pixels' intensity from the image I_k^d and determination of the current sum S_k as follows [19]:

$$S_k = \sum_{i=1}^{r_1} \sum_{j=1}^{r_2} I_k^d\left(x_i, y_j\right), \qquad (6)$$

The resulting value of the sum S_k is plotted on the PC screen as the output signal of the CCD detector for a specific time moment t_k. For sufficient large range the magnitude S_k is proportional to the amplitude of the perturbation that hits the fiber and can be calibrated to represent exactly the amplitude of the perturbation. On the other hand, because we do not take into account the coordinate of the pixels, this algorithm does not permit to eliminate the elements that are symmetric in the speckle images.



(a)



(b)

Fig. 3. Illustration of the far field speckle pattern of the fiber registered by CCD sensor *(a);* schematic representation of the interference of the modes in the far-field of the fiber *(b)* [19].

Consequently, this reduces the sensitivity and dynamic range of the method. The dependence of the output signal vs. the amplitude of the perturbation keeps linear for a sufficient wide segment of the speckle spot. So, the output signal plotted on the PC screen keeps linear for a sufficient large range of the perturbation amplitude.

According to the Huygens' principle each of the point on the fiber end face $s(x_f, y_f)$ can be considered as a source of spherical waves (Fig. 3) [19]. These waves interfere constructively or destructively in the image plane of CCD. The speckle pattern represents the contributions of propagating modes with a certain mutual phase difference. The first speckle image I_0 is captured by CCD camera at initial time $t = 0$ when launching the procedure. Then at each subsequent time moment t_k (k = 1,2,3…..k_{max}) the CCD takes the current image I_k. The difference of two speckle images is calculated by subtracting pixel-by-pixel of two images and the value of the sum S_k is calculated with subsequent plotting on PC monitor.

IV. Fiber optic speckle-based intrusion monitoring system

Fiber optic speckle technique can be used in intrusion-monitoring systems. Such a system is capable of detecting intruders from the pressure of their weight on the earth's surface. The basic elements of the system set-up are the same as represented in Fig. 1. A multimode optical fiber was used as a sensing element of the intrusion-monitoring system. The presence of an intruder in proximity to the buried optical fiber induces a phase shift in light propagating along the fiber which allows for the detection of intrusions. Disturbances can be monitored and registered at the output end of the fiber. By monitoring the probing light intensity in the speckle image at the output end of the fiber one can register the phase induced shift in the fiber.

The basic elements of the intrusion-monitoring system are a multimode optical fiber, a coherent light source coupled to the input end of the fiber, a segment of sensing fiber that is positioned along the perimeter of intrusion-monitoring object, and a CCD placed at the output end of the fiber. The CCD is connected to a PC for processing the speckle image. The PC together with the PC soft represents the module for developing of the alarm signal. The algorithm of the program for processing the speckle image is illustrated in Fig. 4. Specifically, in this case the speckle image in the far field of the fiber is registered continuously with a customer-specified speed of F frames per second.

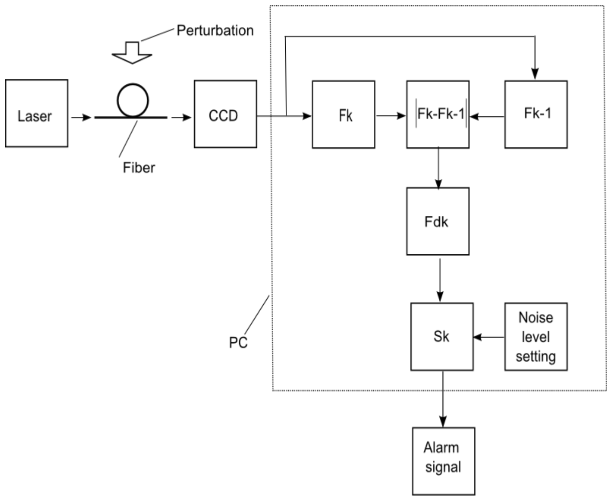


Fig. 4. Illustration of the speckle image processing algorithm for intrusion monitoring system [19].

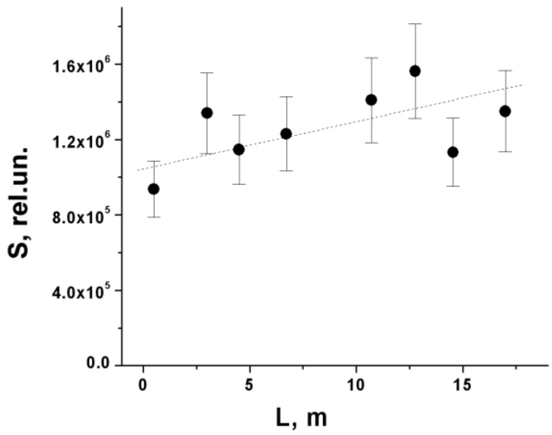


Fig. 6. Linearly variation of the output signal S as a function of the distance from the input end face of the fiber.

The output signal in the far field of the fiber S as derived by the relation (6), is a function both on the intrusion deformation P and the distance L from the input end of the fiber. The modes distribution itself determines the character of the dependence of the output signal versus the distance where the intrusion deformation is applied along the fiber. This is illustrated in Fig. 6-7. In Fig. 6 the output signal S_1 is proportional to the distance *L*, where the intrusion deformation is applied, $S_1 = k_1 PL$. While in Fig. 7 the output signal can be represented as $S_2 = k_2 P$. By proper adjustment of the modes excitation conditions one can obtain information for localization of intrusion.

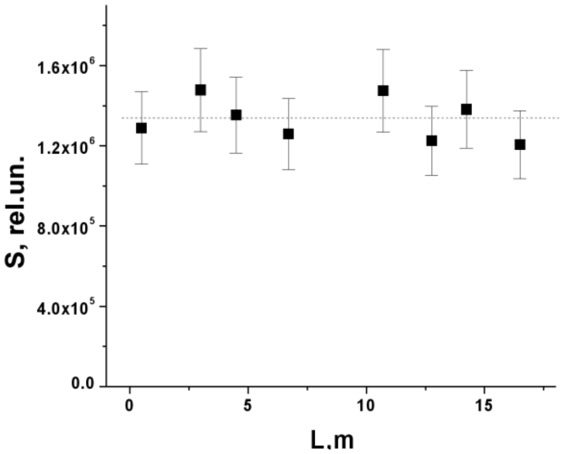


Fig. 7. Illustration of the output signal in the far field S independent of the distance from the input end face of the fiber.

Summary

A speckle based fiber-optic technique for intrusion-monitoring systems has been further developed. By proper adjustment of the modes excitation one can create conditions for localization of intrusion. Computer processing of the speckle image provides information on the amplitude of perturbation that hits the fiber, as well as offers the possibility for localization of the intrusion.

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