Fiber Optic Intrusion Monitoring System

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***Abstract* — The fiber optic intrusion monitoring system comprises a multimode optical fiber connected to a coherent light source, a CCD detector and a processor for generation of the output signal. The system is based on the principle of variation of speckle pattern in the far-field of a multimode optical fiber under the action of mechanical perturbation. By processing the speckle pattern one can derive information on the amplitude of perturbation. The algorithm for processing of the speckle pattern is based on comparison of the current speckle image with the reference image. Each of the current images is subtracted pixel-by-pixel from the reference image. The output signal is obtained by summation of absolute values of all pixels differences. Intrusion monitoring system can find application in surveillance of perimeters, and industrial objects, deposits of chemicals and radioactive waste, etc.**

***Index Terms* — CCD, far-filed, multimode optical fiber, modes interference, speckle pattern.**

I. INTRODUCTION

Intrusion monitoring systems are designed to detect unauthorized intrusion into buildings, protected territories, perimeters, etc.[1-4] Fiber optic sensor technology offers the most powerful tool for intrusion monitoring.[5-9] In recent years fiber optic sensor technology has been growing in both interior and exterior security applications with possibility for both detection and location of the intrusion.[9-12] A fiber optic intrusion monitoring systems can detect attempt to cut, lift, crawl under, climb over a fence or protected area.

Various operation techniques are being used in development of fiber optic intrusion monitoring systems.[1-3] These techniques use as operation basis the principle of variation of a specific parameter of the light beam that propagates into an optical fiber. Various different techniques basically refer to speckle effect, interferometry, Raleigh or Brillouin scattering, etc.[1,2,4] The most performing among them are fiber optic distributed intrusion monitoring systems based on light scattering in a single mode optical fiber. While these systems ensure a long surveillance perimeter as well as the possibility for location of the intrusion, they are relative complex and expensive. On the other hand the systems that are based on the principle of speckle effect in a multimode fiber are simple, reliable and cost-effective.[1,7,12]

Fiber optic intrusion monitoring systems system may find application in surveillance of perimeters and various individual objects from unauthorized intervention, e.g. civilian and military objects, deposits of radioactive or chemical waste materials, etc. We describe here a fiber optic perimeter intrusion monitoring system based on registration of the speckle pattern in the far-field of a multimode optical fiber.[12] The system employs an optical fiber that can be fence-mounted, or deployed along the protected perimeter, buried under gravel , etc.

II. DESCRIPTION OF THE SET UP

When a coherent light beam is injected into the input end face of the fiber, the far-field distribution of the probing light beam is represented by the speckle pattern (Fig. 1). This speckle pattern is highly sensitive to external perturbations that hit the lateral surface of the fiber. For example, when a mechanical perturbation hits the lateral surface of the fiber, the speckle pattern changes, this change can be used for operation of a short distance perimeter-intrusion monitoring system. By processing the speckle pattern one can derive the information on the amplitude of the perturbation that hits the fiber.

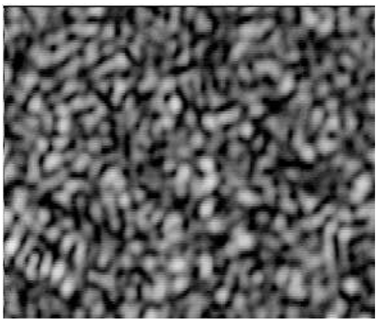

Fig. 1. Illustration of the speckle pattern in the far field of the fiber.

The experimental set-up is represented in Fig. 2. It consists of a multimode optical fiber, a coherent light source, a microscope objective, a CCD detector, and a PC for speckle image processing. The probing lightfrom a laser source is injected into the input end face of the fiber and at the output end face of the fiber the far-field distribution of the probing light intensity (the speckle pattern) 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.

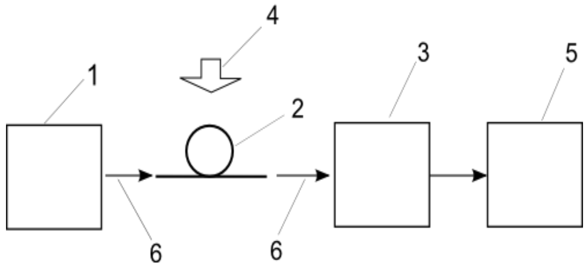

Fig. 2. Illustration of experimental set-up: 1 - coherent light source; 2 – optical fiber; 3 - photodetector; 4 – perturbation; 5 – processor; 6 - probing light beam.

The probing light source is a *He-Ne* laser (λ = 633 nm) with the output power of P = 10 mW. A multimode optical fiber with a parabolic refractive index profile and the core diameter 50 µm was used as a sensing element. The speckle pattern was registered with a HDCS-1020 CMOS image sensor with the pixel size 7.4×7.4 µm, and image array size VGA 640×480. The full frame video rate at 8 bit resolution was 30 fps. A typical speckle pattern of the fiber used for measurements is shown in Fig. 1.

Analyses of the intensity distribution $I(x, y)$ of the probing light in the far-field plane of the fiber provides information about the perturbations that hit the optical fiber.[12,13] The speckle image actually is the result of destructive and constructive interference of propagating modes in the far field of the fiber. For a separate mode at the output end of fiber the magnitude of electric field $\vec{E}$ can be represented as:[13]

$$\vec{E} = \vec{E}_0 \cos(\omega t + \varphi), \qquad (1)$$

where $\vec{E}_0$ - is the amplitude of electrical field, φ - the phase of probing light wave $\varphi = 2\pi n_{eff} \frac{L}{\lambda}$, L - is the geometrical path length of the *k-th* mode in the fiber, λ – the wavelength of probing light; n_{eff} – the effective refractive index of for the *k-th* mode, ω – the frequency of electromagnetic wave, and t - is the time. 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 core:[13]

$$E = \sum_{k=1}^{N} |E_k| \exp(j\varphi_k), \qquad (2)$$

where E_k – denotes 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 registered by the CCD camera is based on comparison of the current speckle image I_k taken at the time t_k with the previous speckle pattern image taken at the time t_{k-1}. (Here and below, when speaking of storing and processing images we mean matrices storage and processing those images). Each of the current image I_k is subtracted pixel-by-pixel from the reference image I_{k-1} as is described by the relation:

$$I_k^d(x_i, y_j) = \left| I_k(x_i, y_j) - I_{k-1}(x_i, y_j) \right|,$$

where $i = 1,2,3\ldots r_1$; $j = 1,2,3\ldots.. r_2$ and I_k^d represents the absolute value of the difference of two signals registered at the moment t_k and t_{k-1} for the *n*-th pixel with the coordinates (x_i,y_j). The next processing step represents summation of all M pixels' differences ($M = r_1 \times r_2$) for determination of the absolute value S_k for the corresponding time moment t_k:

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

where r_1 and r_2 are the number of pixels along X and Y coordinates respectively. The resulting value of the sum S_k is plotted on the PC screen as an output signal of the CCD detector at the time t_k.

In other terms, the speckle image in the far-field for a current time value t_k is put into correlation with a matrix of data F_k. Each element of this matrix <x_i,y_i> (the current matrix F_k) gives the intensity of probing light corresponding to a specific pixel with coordinates ($x_i$$y_i$) in a specific time moment t_k. The output signal is obtained by summation of the absolute values of the all matrix elements F_{dk}. Note, that the matrix F_{dk} represents the difference between the current matrix F_k and the reference matrix F_{k-1}.

The magnitude S_k correlates to the amplitude of the perturbation that hits the fiber and can be calibrated to represent exactly the amplitude of the perturbation. Because we do not utilize too many routines for image processing the rate of the procedure is sufficient high. The dependence of the output signal vs. the amplitude of the perturbation keeps linear for a sufficient wide segment of the speckle spot.[12,13]

The numerical value of the sum S_k is compared with the reference value set for triggering the alarm. Provided the value S_k exceeds the reference signal then the alarm signal is switched on (Fig. 4).

The module for generation of the output signal is represented a processor, which contains a numerical differentiator for processing the matrices of speckle images, and a summator of difference-images of two consecutive speckle patterns. The comparator, which is connected in parallel to the sensitivity module, generates the alarm signal every time when the sum of the signal-differences exceeds the sensitivity threshold of the system.

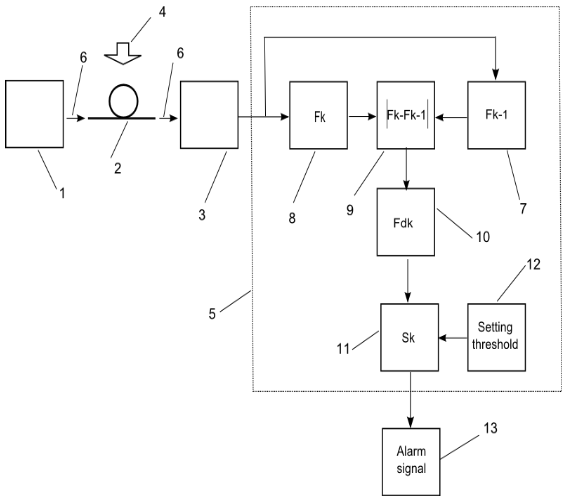

Fig. 3. Illustration of the algorithm for processing the speckle image: 1 – coherent light source; 2 – optical fiber; 3 - photodetector (CCD); 4 – intrusion perturbation; 5 – processor; 6 – probing light beam; 7 – capturing of the reference speckle pattern; 8 – capturing of the current speckle pattern; 9, 10 – subtracting matrices F_{k-1} and F_k ; 11 – summation of the elements of the matrix F_{dk} ; 12 – setting the sensitivity of the system; 13 – output signal.

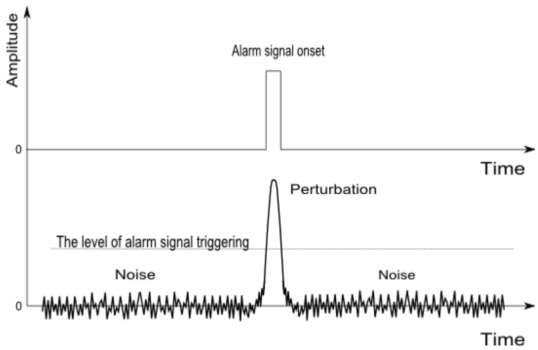

Fig. 4. Illustration of the perturbation and of the output signal. The alarm signal is triggered when the perturbation exceeds the level of alarm signal triggering.

The PC program that controls the system provides the user the possibility to monitor on the screen in real-time the output signal, and to adjust the sensitivity of the system. The sensitivity and threshold parameters can be adjusted by setting the corresponding parameters on the PC screen “Scale”, “Time”, “Frames”, “Zero” (Fig. 5).

The system is designed as an outdoor perimeter intrusion monitoring system that could provides a reliable and cost effective solution for a variety of perimeters. The sensing optical fiber can be deployed along a fence or buried under gravel along the perimeter (Fig. 6). The system is suitable for outdoor application in the extreme environmental conditions. The sensing optical fiber can be attached to the fence in a double loop configuration. The basic advantages of the system are:

- High probability of detection;
- Immune to EMI, RFI and to lightning strikes;
- Uniform detection along the entire perimeter;
- Possibility to be mounted on various types of fences;
- Stable under extreme weather conditions;
- Possibility for network integration;
- Low maintenance cost.

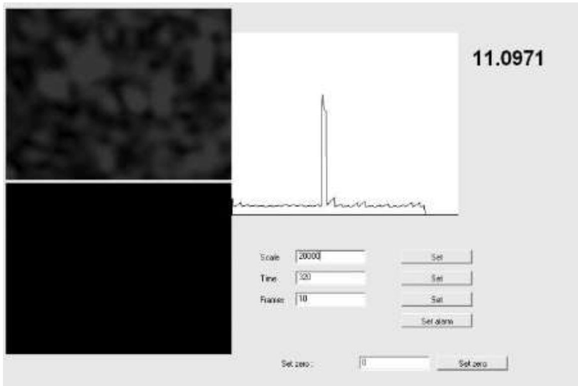

Fig. 5. The screenshot of the program

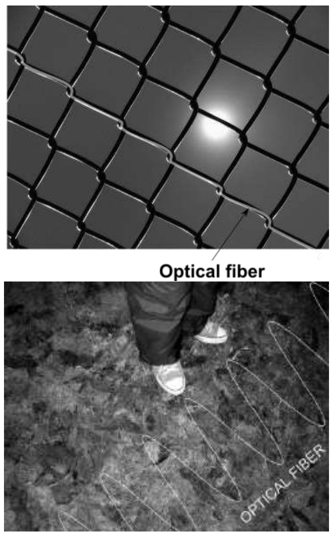

Fig. 6. Illustration of the attachment of the optical fiber to a fence and installation of the fiber in the ground.

III. CONCLUSIONS

A fiber optic perimeter intrusion monitoring system is based on a registration of speckle pattern in the far-field of a multimode optical fiber. The intrusion monitoring system comprises a multimode optical fiber connected to a coherent light source, a CCD detector and a processor for generation of the output signal. The system is based on the principle of variation of speckle pattern in the far field of a multimode optical fiber under the action of mechanical perturbation. By processing the speckle pattern one can derive the amplitude of the output signal. Intrusion monitoring system can find application in surveillance of civilian and military objects, deposits of radioactive or chemical waste materials, etc.

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