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Study the design of Speckle dependent security fiber sensor

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Abstract: *A fiber optic security sensor based on the monitoring of "speckle pattern" modal distribution in a multimode optical fiber was studied. Detection of vibrations of perimeters or fences is possible through observation of the output speckle pattern from the multimode optical fiber. An experimental working model has been built in which all used components are widely available and cheap: a CCD camera, a multimode red laser (650 nm) as a light source, a length of multimode optical fiber, and a computer to employ MATLAB platform for implementing the algorithm used in this sensor. Some vibration measurements were measured using readymade device as it has high sampling rate CCD camera to obtain more accurate results. Proposed sensor is cheap and lightweight and therefore presents an interesting alternative for monitoring large smart structure.*
Keywords: *fiber optic sensor, speckle pattern, spectral analysis*

I. Introduction

With the invention of the laser in 1960's, a great interest in optical systems for data communications began. The invention of laser, motivated researchers to study the potential of fiber optics for data communications, sensing, and other applications. Recent advances in fiber optic technology have significantly changed the telecommunications industry. The ability to carry gigabits of information at the speed of light increased the research potential in optical fibers. Simultaneous improvements and cost reductions in optoelectronic components led to similar emergence of new product areas. Last revolution emerged as designers to combine the product outgrowths of fiber optic telecommunications with optoelectronic devices to create fiber optic sensors. Soon it was discovered that, with material loss almost disappearing, and the sensitivity for detection of the losses increasing, one could sense changes in phase, intensity, and wavelength from outside perturbations on the fiber itself. Hence fiber optic sensing was born. In parallel with these developments, fiber optic sensor technology has been a significant user of technology related with the optoelectronic and fiber optic communication industry. Many of the components associated with these industries were often developed for fiber optic sensor applications. Fiber optic sensor technology in turn has often been driven by the development and subsequent mass production of components to support these industries. As component prices have decreased and quality improvements have been made, the ability of fiber optic sensors to replace traditional sensors have also increased [1]. Optical fiber sensor development has matured to the point where the impact of this new technology is now evident. Fiber sensors offer a number of advantages: [1] increased sensitivity over existing techniques, [2] geometric versatility in that fiber sensors can be configured in arbitrary shapes, [3] a common technology base from which devices to sense various physical perturbations (acoustic, magnetic, temperature, rotation, etc.) can be constructed, [4] dielectric construction so that it can be used in high voltage, electrically noisy, high temperature, corrosive, or other stressing environments, and [5] inherent compatibility with optical fiber telemetry technology [2]. Intrusion monitoring systems are designed to detect unauthorized intrusions into buildings, protected territories, perimeters, etc. Fiber optic sensor technology offers the most powerful tool for intrusion monitoring. 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. A fiber optic intrusion monitoring systems can detect an attempt to cut, lift, crawl under, and climb over a fence or protected area. Various operation techniques are being used in the development of fiber optic intrusion monitoring systems. The systems based on the principle of speckle effect in a multimode fiber are simple, reliable, and cost-effective. This system employs an optical fiber that can be fence-mounted or deployed along the protected perimeter, buried under ground. [3]

II. Fiber Optic Sensor Principle And Classification

Various ideas have been proposed and various techniques have been developed for various measurands and applications [4]. The general structure of an optical fiber sensor system is (shown in Figure 1). It consists of an optical source (Laser, LED, Laser diode etc), optical fiber, sensing or modulator element (which transducers the measurand to an optical signal), an optical detector and processing electronics (oscilloscope, optical spectrum analyzer etc)[1].

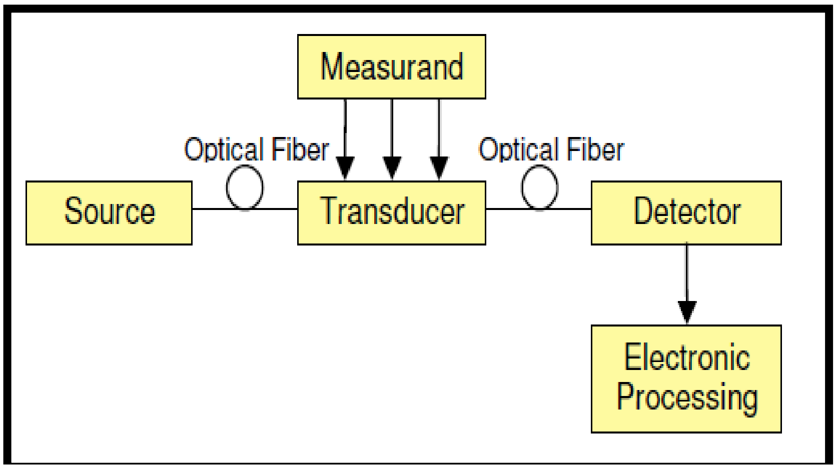

Figure 2: Basic components of an optical fiber sensor system.

The market for fiber optic sensor technology may be divided into two broad categories of sensors: intrinsic and extrinsic. Intrinsic sensors are used in medicine, defense, and aerospace applications, and they can be used to measure temperature, pressure, humidity, acceleration, and strain. Extrinsic sensors are used in telecommunications to monitor the status and performance of the optical fibers within a network [5].

There are five types of intrinsic sensors. The first uses phase modulation. Using a special optical fiber, the phase angle of the light is changed when pressure is applied to the fiber. The second is polarimetric, which is similar and measures a change in polarization. A third type of sensor, which can be either intrinsic or extrinsic, uses color modulation. In essence, this uses two detectors to measure the change in the color of light. For example, temperature can be measured with the changing color of a ruby. A fourth type of intrinsic type of sensor uses distributed micro bending of the fiber to achieve attenuation of the light.

The last type measures the change in the speckle pattern. Light projected from the end of a multimode fiber has a rather attractive pattern. This pattern is the result of the many modes or ways in which the light passes along the multimode fiber. Pressure applied to the outside of the fiber will change this speckle pattern [6] , this type is the one we interested in this paper ,and an experimental work was built to show the ability of this intrinsic fiber sensor to be employed as security sensor.

III. Theoretical Concept Of Speckle Pattern

The speckle pattern is often used in optical sensors and metrology where the granular structure of light is obtained through an optical roughened surface. In these cases, the speckle pattern depends on the properties of coherence of the incident field and surface characteristics Speckle patterns can also be obtained using multimode optical fibers. Early works on the speckle pattern in multimode fibers were made by Takahara and Crosignani, in which the effect of visibility, the spectral width of the employed source and the fiber length have been studied. As the speckle pattern in the output fiber is sensitive to any disturbances along the fiber, such as temperature, pressure or vibration, sensing of these measurands is potentially suitable with a proper processing stage of the speckle pattern [7]. Propagation of light in optical fibers is governed by the propagating modes traveling within the core of the fiber. The single mode fibers, with core diameter between 5 to 9 microns, carry only a single signal pertaining to the first mode of propagation. Multimode fibers, on the other hand, carry several modes due to the larger diameter cores ranging from 50 to 62.5 microns [8]. Multimode fiber, as a result of its large core diameter, has a relatively large number of modes that travel simultaneously through the fiber. Each mode travels with its own group velocity and propagation constant, but interferes with other modes as they share the same medium. There are around 500 modes in a typical multimode fiber. Speckle pattern consists of a large number of points with different intensities of light (Figure 2) [9].

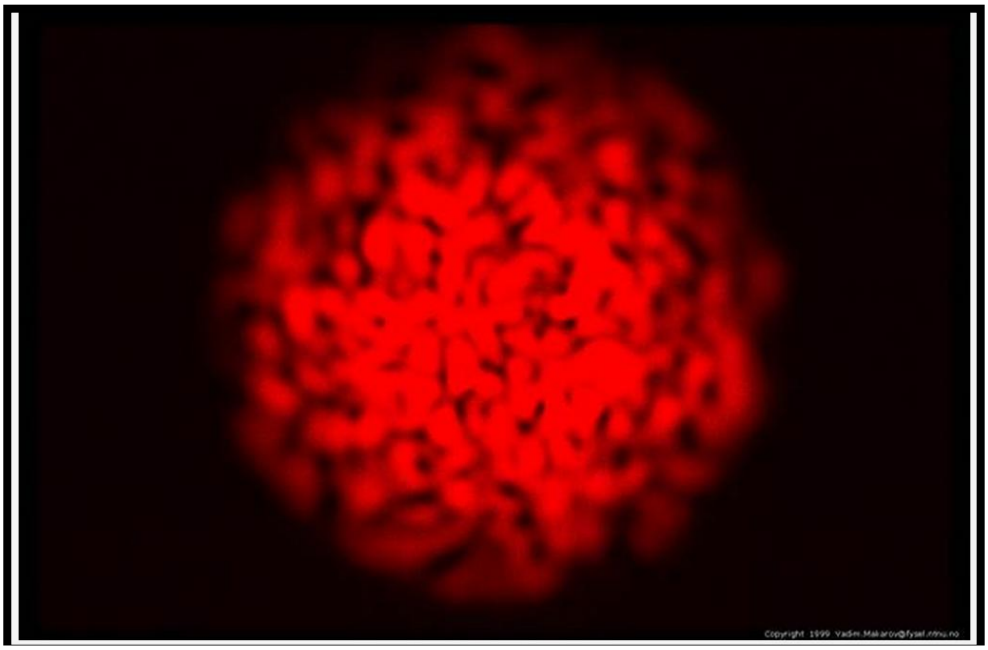

Figure (2): Speckle Pattern emerged from the end of Multimode fiber [11]

Speckle pattern changes slowly in time, but its total summed intensity remains the same. That can be expressed by equation (1),

$$I_T = \sum_{i=1}^{N} I_i \quad \dots\dots (1)$$

Where I_T is the total intensity and I_i is the intensity of each point (small area) in the speckle pattern and N is the number of points. If the fiber is exposed to some force $F(t)$, the propagation constant of each mode changes in correlation with that force (vibration or Strain …), and the difference $\Delta\beta_{ml}$ is proportional to the applied force

$$\sigma(\Delta\beta_{ml}\, z)\alpha\ F(t) \dots\dots (2)$$

In [9] it is demonstrated that the intensity of a single speckle can be found in proportion to the force ($F(t)$) perturbing the fiber by following expression

$$I_i = A_i\{1 + B_i\,[cos(\delta\ i\,) - F(t)\varphi_i\ sin(\delta\ _i\,)]\} \dots\dots (3)$$

Where A_i is the result of mode self-interaction, and the next two terms represent the mode-mode interaction, the first one (B_i) accounting for the steady state and the second one φ_i signify the modification of the mode-mode interaction if the system is perturbed. Signal output, in which the absolute value of changes in the intensity pattern is summed, is given by

$$\Delta I_T = \left[\sum_{i=1}^{N} |\mathrm{C}_i \sin(\delta\ i\,)|\right] \left|\frac{dF(t)}{dt}\right| \dots\dots (4)$$

By applying various forces upon the fiber we change the way modes propagate and therefore their interference conditions, which results in different field distribution at the fiber end [9].

IV. Experimental Design Of The Sensor

Figure (3) shows the structure of the system used to record and analyze the change in the distribution of speckle patterns caused by the vibration at the fiber.

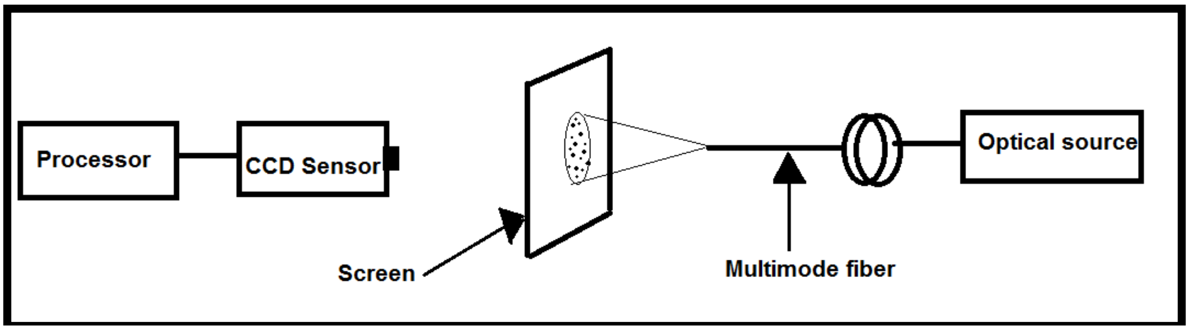

Figure (3): system used to record and analyze speckle patterns

The signal coming from the light source (in our case a laser operating in Red wavelength) travels through multimode fiber. Output signal from the fibers end is projected on screen, and is recorded by a simple CCD camera (30 frame per second) used only for demonstration of principle [9].

V. Analysis And Process Of The Output Signal

Since the data is recorded in video signal mode, it is first broken down to frames 30 per second (but in our work a 60 fps CCD camera was used) and then analyzed as a set of consecutive frames that each represent a matrix of speckle pattern point intensities in time. After data preparation, analysis takes place in Matlab where necessary functions are implemented .If the fiber is perturbed, the induced perturbation alters the optical path lengths of each propagating mode differently and the intensity pattern changes. This change can be detected by analyzing the resulting patterns using statistical features for image analysis. For speckle image analysis, two methods are image differencing and image correlation features are widely used [10], the former method (image differencing or subtraction) is the method of interest in this paper. If the reference output pattern is$I_0(x, y)$, and the output pattern when there is a perturbation, is$I(x, y)$, then the intensity variation can be determined by defining the difference image as

$$\Delta I(x, y) = I_0(x, y) - I(x, y) \dots \dots (5)$$

The speckle intensity variation can be determined by using the feature

$$ID = \sum_{x,y}^{N} |I_0(x, y) - I(x, y)| \dots \dots (6)$$

Where ID is the image difference feature [10].The image subtraction between the consecutive frames of CCD camera is performed in Matlab, and (figure 4) shows the cases when the vibration is present and when it is not present respectively.

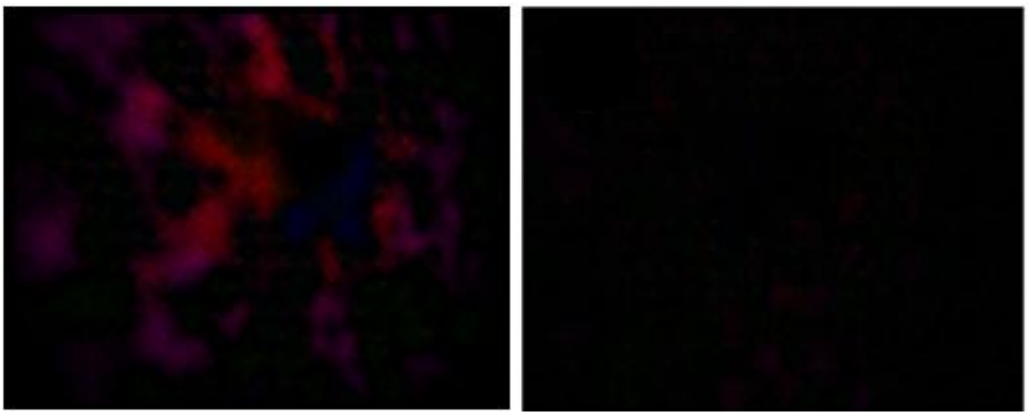

Figure 4: Image difference when the vibration is present (left) and when it is not present (right)

After the steps that included loading images in memory, calculating total intensities, differences between images, functions for extracting the frequency response of vibrations is performed. The data analysis was performed using the Fourier transformation on the matrix of intensity difference between elements on same location in consecutive pictures and then the calculation of spectral components was performed to determine the frequency response of different vibrations (see figure 5). Maximum detectable frequency is tied by sample frequency of detector in our case web camera. As it's sample frequency was around 60 frames per second, we could measure vibrations with frequencies up to approximately 30 Hz. By constructing custom CCD sensor greater frequencies can be detected. Higher sampling rate increases memory footprint requirements and complexity of calculations so some tradeoffs between processing requirements and maximum detectable frequency are present. An experimental measurements were achieved to determine the frequency response of different vibration sources these measurements were obtained using Matlab platform, and other measurements were measured using readymade device, this device has the ability to measure high vibration frequencies (up to 600 Hz) as it has high sampling CCD sensor as we will see next.

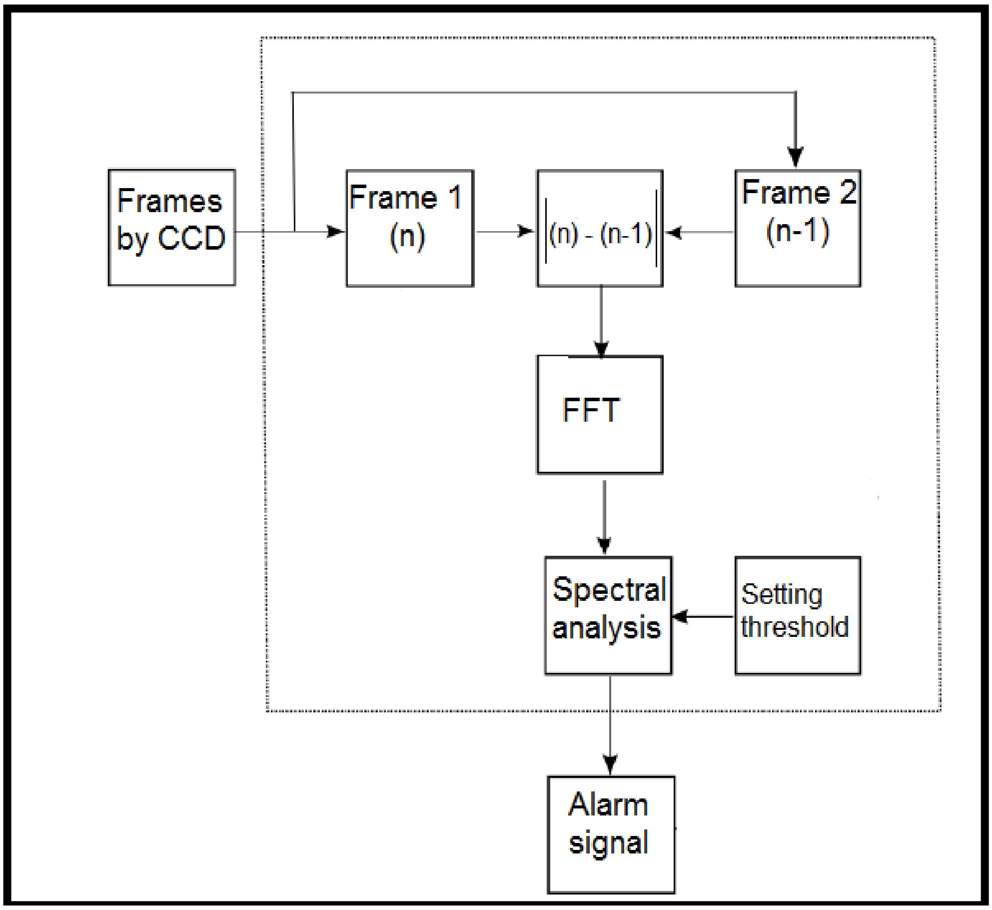

Figure 5: Algorithm used to build speckle fiber sensor

VI. Measurements

When fiber sensor based on speckle pattern is used in outdoor field, some measurements are needed to recognize the intruder event from the non-threatening event (like wind), in below some experimental measurements were made by simulating several different vibration sources. These measurements were obtained by applying the above algorithm using matlab and then it was compared to those obtained using readymade device. Figure (6) shows the frequency response of applying low vibration on the multimode fiber attached to perimeter, the upper part represents the frequency response using the experimental model while the lower part represents the corresponding measurement using readymade device. And it is clear that the two measurements are comparable.

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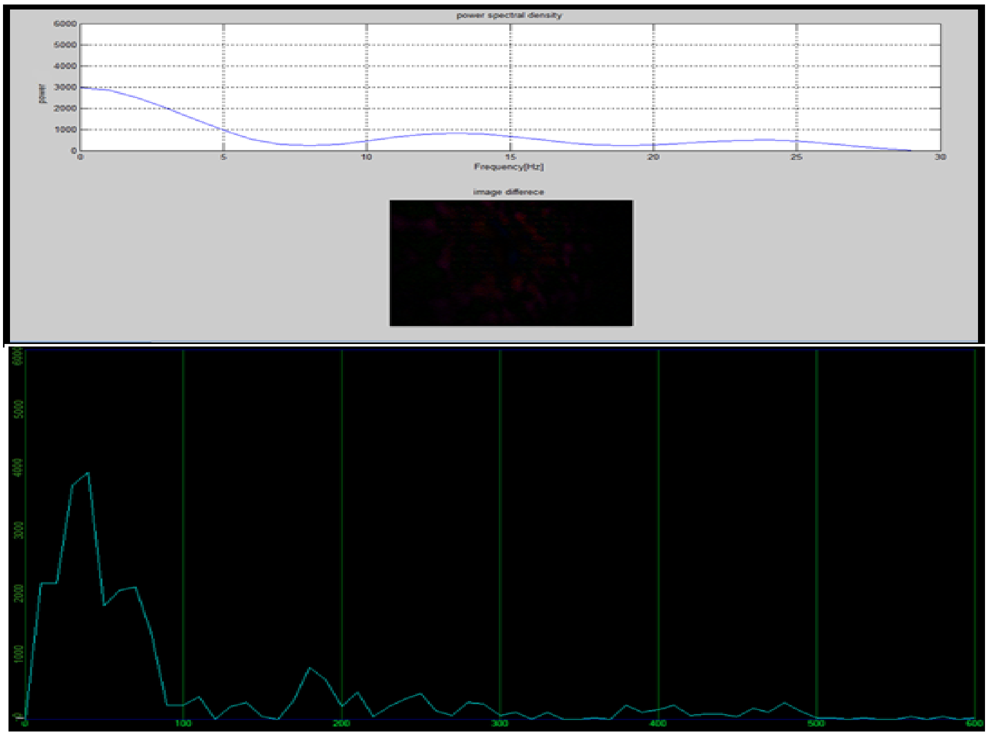

Figure 6: Frequency response due to applying low vibrations on speckle fiber sensor attached to perimeter

Figure 7 shows the frequency response of applying fair vibrations on the speckle multimode fiber sensor using the experimental model (upper part) and the ready made device (lower part).

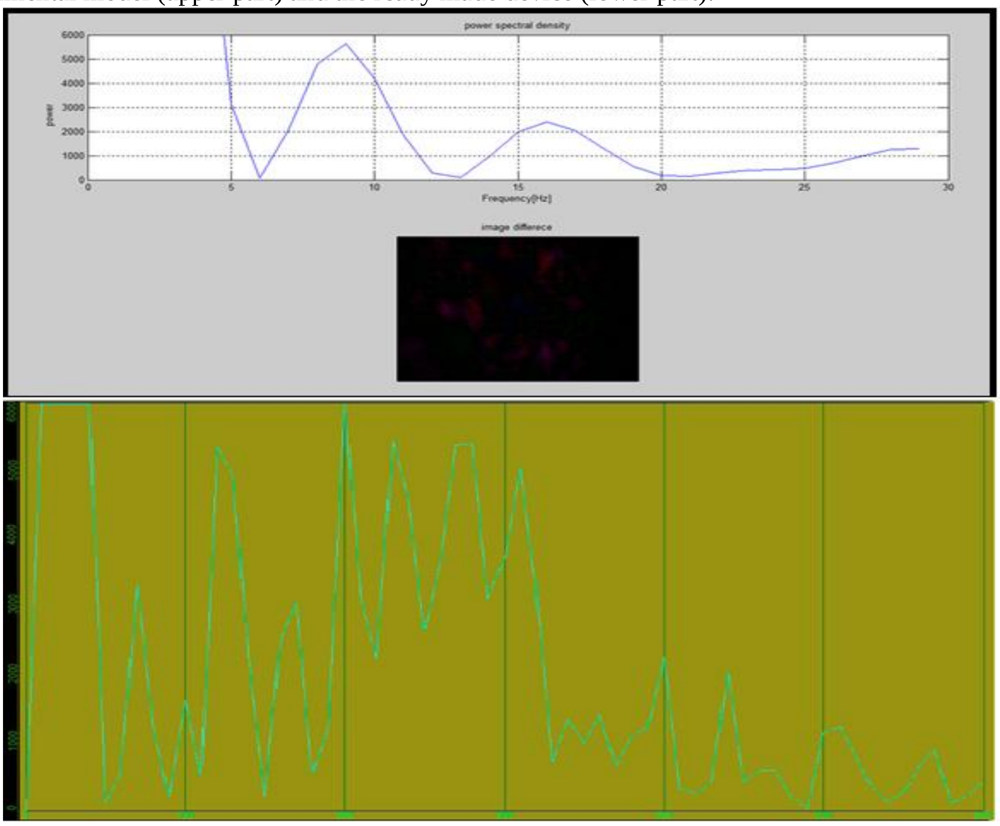

Figure 7: Frequency response due to applying fair vibrations on the speckle fiber sensor

Figure 8: shows the frequency response due to application of high vibrations on the speckle multimode fiber sensor using both the experimental model (upper part) and the readymade device (lower part).

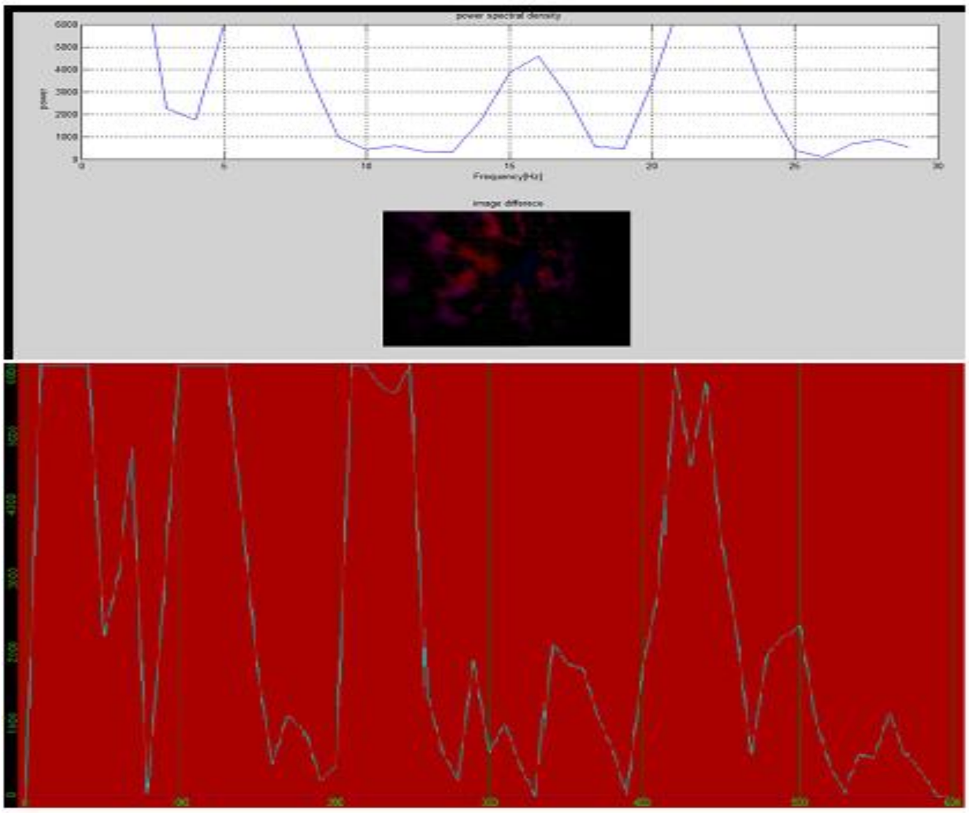

Figure 8: Frequency response due to application of high vibrations on the speckle pattern multimode fiber

VII. Conclusion

A fiber optic security intrusion monitoring system is based on the registration of the speckle pattern from the end 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 in the speckle pattern in the far field of a multimode optical fiber under the action of mechanical perturbation or vibration. By processing the speckle pattern, one can derive the frequency content of the output signal. The measurements obtained using the algorithm shown in figure (5) were comparable to those obtained using the readymade device. The power was concentrated at the lower frequency regions in the case of low vibrations while for fair and high vibrations it was distributed at higher frequency regions, by this way we were able to differentiate between different threatening and non-threatening events. Intrusion monitoring systems can be applied in surveillance of civilian and military objects, deposits of radioactive or chemical waste materials, etc.

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