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Polarization maintaining optical fiber multi-intruder sensor

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ABSTRACT

In this paper, an optical fiber multi-intruder sensor based on polarization maintaining optical fiber (PMF), without any interferometric fiber loop, is introduced. To map the local coordinates of intruders on the beating spectrum of the output modes, radiation from a ramp frequency modulated laser is injected at the input of PMF optical fiber sensor. It is shown that the local coordinates and some characteristics of intruders can be obtained by the measurement of the frequencies and amplitudes of the output mode beating spectrum. Generally the number of beating frequencies is more than the number of intruders. Among the beating frequencies, a group with maximum signal to noise ratio is chosen. The short Fourier denoising method is employed to increase the sensor resolution. Because the output signal is the superposition of finite numbers of discrete frequencies this method is a powerful tool for denoising even for negative signal to noise ratio.

1. Introduction

The distributed optical fiber intruder sensors that are used to sense and locate the intruders have been widely studied by many researchers in the last three decades [1–8].

Most familiar intruder detectors are based on the optical time domain reflectometer (OTDR) [9], the Brillouin optical time domain reflectometer (BOTDR) [10] and phase sensitive OTDR (Φ-OTDR) [11]. Complicated optical fiber intruder detectors are based on the optical fiber interferometery. To detect the intruder crossing point often a combination of Sagnac Interferometer (SI) and other interferometers such as Sagnac–Mach–Zehnder [12], Sagnac–Sagnac [13] and Sagnac–Michelson [14] are employed. In all these compound interferometers a frequency modulation technique is applied to a polarization maintaining fiber Sagnac loop. The beating frequency of the two forward coupled beams and corresponding amplitude determine the location and amplitude of an applied stress respectively [15,16]. In this paper a simple multi-intruder detector on the basis of PMF optical fiber without any interferometric loop is presented. Radiation from a ramp frequency modulated laser is used as the input signal to map the intrusion positions to the output beating frequencies. At the intruder crossing point, the stress causes the mode coupling between the HE_x^{11} and the HE_y^{11} modes of the PMF. The beating frequencies are functions of the intrusion positions and their amplitudes are functions of stress and size of the intruders. The resolution of the intruder positions are limited by the transmitter, receiver and PMF noises. The residual stress along the buried fiber causes a random mode coupling and consequently an additional noise is appeared at the output. The noise corresponding to the residual stress is saved and eliminated from the output signal, while such an operation for other noises is impossible. To improve the resolution of the intruder sensor the short Fourier denoising method is employed. The remaining part of this paper is organized as follows. In Section 2, theoretical method for finding intruder positions and some characteristics of them by analyzing the output mode beating spectrum is occurred. To check the validity of theoretical method, a numerical simulation for a specific situation of three intruders is presented in Section 3. Finally the paper is enclosed with some conclusion in Section 4.

2. Theoretical model

As shown in Fig. 1(a) radiation from a ramp frequency modulated x-polarization laser is injected to the polarization maintaining fiber as the intruder fiber sensor. Variation of the laser frequency is shown in Fig. 1(b) and it is assumed that the amplitude of laser is maintained constant. The x and y axes are chosen along the principle axes of the PMF.

In the presence of an intruder at the cross point of the optical fiber sensor and the intruder, due to the elasto-optic effect a part of E_x -polarization mode couples to the E_y-polarization in the remaining part of PMF ($Z_1 = L - Z_0$). L is the total length of PMF and Z_0 is the location of the intruder cross point. It is assumed that the input laser frequency versus time is T-periodic and is linear on the time interval [0 and T].

$$\omega(t) = \omega_0 + \omega_1 t \tag{1}$$

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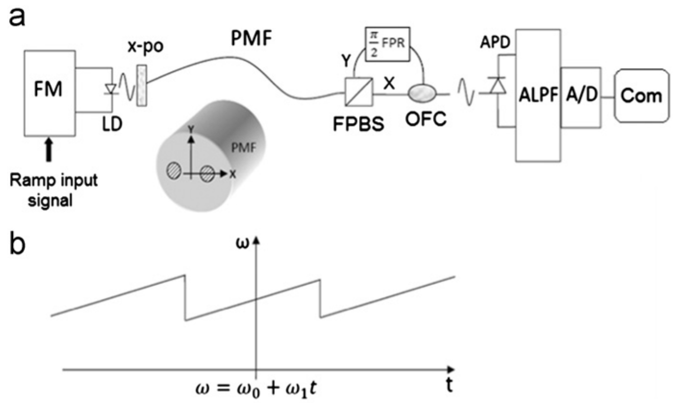

Fig. 1. (a) Schematic of a birefringent fiber intruder detection system. FM is the frequency modulator, LD is a 10 mw laser diod, x-po is a x-polarizer, PMF is a 30 km birefringent optical fiber, FPBS is a fiber polarization beam splitter, FPR is a fiber polarization rotator, OFC is an optical fiber coupler, APD is an avalanche photo-diode detector, ALPF is an active electronic low pass filter, A/D is an analog to digital convertor, Com. a computer system for signal processing and denoising. (b) Ramp input to the FM system, the center frequency $\omega_0=1.2\times10^{15}$ Hz and the slope of the ramp $\omega_1=2\pi\times10^{11}$ Hz/s.

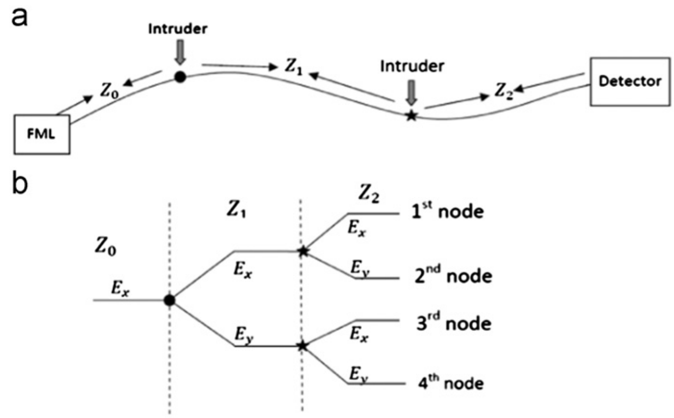

Fig. 2. (a) Intruder system with two intrusions and (b) graph of traveling times of system indicated in (a).

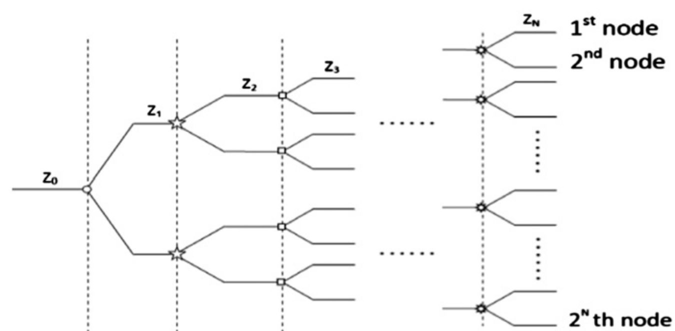

Fig. 3. General traveling time graph of an intruder system with N-intrusions.

where ω_0 and ω_1 are the initial laser frequency and ramp slope respectively.

The birefringent property of the PMF causes a delay time τ between the x and y polarization modes on the length Z_1 of the fiber sensor. The time delay τ_1 produces a constant frequency between the x (HE_x^{11}) and the y (HE_y^{11}) modes at the receiving end of the PMF:

$$\Delta\omega = 2\omega_1 Z_1(1/v_{gx} - 1/v_{gy}) \tag{2}$$

where $v_{g\mu}(\mu=x, y)$ is the group velocity of the μ mode and $\Delta\omega$ is the frequency differences of the HE_x^{11} and the HE_y^{11} modes at the end point of the PMF. At the receiving end of the PMF, the HE_x^{11} and the HE_y^{11} are separated by a polarization beam splitter (PBS). The y-polarization is $\pi/2$ rotated by a polarization rotator. Both beams are directed to the avalanche photo-diode (APD). The output beating frequency is the difference between the frequencies of HE_x^{11} and HE_y^{11} modes. The amplitude of the output is related to the strength of the intruder. Due to the motion of the intruder a vibrational wave in the acoustic range is produced on the fiber sensor which has important information about the intruder. In this paper the effect of seismic waves is neglected. The effects of acoustic and seismic waves on the output of intruder sensor are under investigation by our group and results will appear in near future.

By increasing the numbers of intruders, the numbers of coupling points also increase The HE_x^{11} and HE_y^{11} modes are coupled to each other at each intruder cross points. Because it is assumed that the input light is x-polarized at the first intruder cross point the energy is only coupled from the HE_x^{11} to the HE_y^{11} modes.

Fig. 2(b) shows the graph of possible paths for the coupling of HE_x^{11} and HE_y^{11} modes to each other in the presence of two intruders. The coupling points on the graph are called nodes. The line connecting two nearest nodes is a branch. The x and y branches are corresponding to the E_x and E_y polarization. A path is a set of branches directly connecting the first node to one of the output nodes. Corresponding to each pair of paths there is a time delay and hence a beating frequency. By employing the graph shown in Fig. 2(b) it is easy to count the numbers of independent output beating frequencies (M):

$$M = 1/2(3^N - 1) \tag{3}$$

where N is the number of intruders. The proof of Eq. (3) is presented in Appendix A.

The beating frequencies are related to the delayed times ($\Delta\omega_m = 2\omega_1\tau_m$). The delayed times are given in the following:

$$\tau_m = (1/v_{gx}\sum_i Z_i - 1/v_{gy}\sum_j Z_j) \tag{4}$$

where Z_i is the distance of the ith intruder from the nearest left neighbor intruder (Fig. 3). For each m, Z_i and Z_j are unrepeatable and randomly selected. In (3) the repeated τ_m is eliminated and only one of them is saved. Obviously corresponding to each symmetries, the numbers of repeated τ_m increase and hence the numbers of beating frequencies decrease. However as shown in (3) for $N>1$, the numbers of beating frequencies are greater than the numbers of unknown $Z_i(i=1,\ldots,N)$. To obtain the positions of intruders it is enough to choose only N beating frequencies with higher amplitude among all M beating frequencies. Since the coupling coefficients $\kappa_i(i=1,\ldots,N)$ are less than unity ($|\kappa_i| < < 1$), the larger amplitudes correspond to the paths with less alternating branches between HE_x^{11} and HE_y^{11} modes. As an example consider a sensor with two intruders as shown in Fig. 2(a). The corresponding graph is presented in Fig. 2(b). The traveling time to the ith node is denoted by $T_i(i=1, 2, 3, 4)$:

$$T_1 = (Z_0 + Z_1 + Z_2)/v_{gx} \tag{5}$$

$$T_2 = (Z_0 + Z_1)/v_{gx} + Z_2/v_{gy} \tag{6}$$

$$T_3 = (Z_0 + Z_2)/v_{gx} + Z_1/v_{gy} \tag{7}$$

$$T_4 = Z_0/v_{gx} + (Z_1 + Z_2)/v_{gy} \tag{8}$$