Coherent fiber-optic intrusion sensor for long perimeters monitoring

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Abstract: The buried fiber optic cable as a distributed intrusion sensor for detecting and locating intruders along the long perimeters is proposed. Phase changes resulting from either the pressure of the intruder on the ground immediately above the buried fiber or from seismic disturbances in the vicinity are sensed by a phase-sensitive optical time-domain reflectometer. Light pulses from a Er:fiber cw laser with a narrow, <3kHz-range, spectral width and a frequency drift of < 1 MHz/min are injected into one end of the fiber, and the backscattered light from the fiber is monitored with a photodetector. Results of preliminary studies, measurement of phase changes produced by pressure and seismic disturbances in buried fiber optic cables and simulation of ϕ-OTDR response over long fiber paths, to establish the feasibility of the concept are described. The field experiments indicate adequate phase changes, more than π-rad, are produced by intruders on foot and vehicle for burial depths in the 0.2 m to 1 m range in sand, clay and fine gravel soils. The simulations predict a range of 10 km with 35 m range resolution and 30 km with 90 m range resolution. This technology could in a cost-effective manner provide enhanced perimeter security.

Coherent sensor, intrusion sensor, fiber sensor, distributed sensor, phase sensitive sensor, Er-fiber laser.

1. INTRODUCTION

The optical time domain reflectometer (OTDR), initially demonstrated over two decades ago [1-3], is now widely used for locating breaks and other anomalies in fiber optic links and networks. In such a system, light pulses from a semiconductor laser are injected into one end of a fiber, and the light returned from the fiber by Rayleigh backscattering is monitored with a photodetector. The OTDR detects the presence and location of perturbations which affect the intensity of the light returned from the fiber, but does not in general respond to phase modulation of the light. The spectral width of the modulated laser is very broad (GHz to THz range), so that fluctuations in the return signal due to interference of backscattered components from different parts of the fiber are for the most part avoided. When present to a noticeable extent, coherent effects represent an undesirable source of noise in an OTDR trace.

Phase changes resulting from either the pressure of the intruder on the ground immediately above the buried fiber or from seismic disturbances in the vicinity are sensed by a phase-sensitive optical time-domain reflectometer (ϕ-OTDR). This application will be termed phase-sensitive OTDR (ϕ-OTDR) to distinguish it from the conventional OTDR. The sensitivity of conventional OTDRs, which utilize directly modulated semiconductor laser light sources, is orders of magnitude too low for this application because of the broad spectrum of the light source. For the ϕ-OTDR, light pulses from a cw laser with a narrow (kHz-range) spectral width are injected into one end of the fiber with a pulsed intensity, and the backscattered light from the fiber is monitored with a photodetector. As with the conventional OTDR, the ϕ-OTDR trace is a plot of returned optical power vs. time. Phase sensitivity results from coherent addition of amplitudes of the light backscattered from different parts of the fiber which arrive simultaneously at the photodetector. Although the ϕ-OTDR provides only a semi-quantitative determination of phase shift amplitude due to (1) the fact that it makes use of optical interference and (2) the stochastic nature of Rayleigh backscattering, it is a means of detecting and locating phase shift perturbations along the length of a fiber - a capability not provided by conventional OTDRs. Whereas in the conventional OTDR broad linewidth is acceptable and even desirable and frequency drift is not an issue, the ϕ-OTDR will require a laser with minimal frequency drift as well as narrow instantaneous linewidth. The Er:fiber laser is an attractive candidate because it emits in the spectral region where silica fiber losses are a minimum, it can be used with Er:fiber amplifiers to achieve high average and pulsed power levels, and it can be configured to emit in a single longitudinal mode for narrow linewidth operation.

This paper is concerned with the use of a buried fiber optic cable as a distributed sensor for detecting, locating, and (with suitable signal processing) classifying intruders. This technology could in a cost-effective manner provide enhanced perimeter security for nuclear power plants, electrical power distribution centers, storage facilities for fuel and volatile chemicals, communication hubs, airports, government offices, military bases, embassies, and national borders.

2. SIMULATION

In the ϕ-OTDR, a light pulse of width τ is coupled into the fiber and the backscattered light is converted to an electrical signal of duration T, where $T = 2L/(n_g c)$, with L the fiber length, n_g the group refractive index for the fiber mode, and c the free-space speed of light. For a silica fiber with $n_g = 1.46$, it is calculated that T = 9.73 L, with T in μs and L in km. Thus, for a 20 km fiber, the duration of the return signal is 195 μs. A signal processor for analyzing the ϕ-OTDR data will digitize the return signal at a sampling rate $1/f\tau$, with f a constant < 1. Thus, if $\tau = 1$ μs and f = 0.5, the sampling rate would be 2 MHz.

An analytical model used for predicting the ϕ-OTDR performance assumes that the Rayleigh backscattering originates from a large number of centers with equal scattering cross-sections, randomly distributed at locations $\{z_m\}$ along the fiber [4]. It is assumed that the light source is monochromatic at a wavelength of 1530 nm and that the modulator passes a square pulse of width τ. The average spacing δ for the randomly positioned mirrors is taken to be 0.02 m, much less than the spatial extent of the laser pulse in the fiber (e. g., a 1 μs pulse would have a spatial extent of 200 m).

The Monte Carlo method was used to set the random locations of the scattering centers in the fiber $\{z_m\}$. A typical result showing Rayleigh-backscattered power vs. time for a 1 km length of fiber is given in Fig. 1. The pulse width is 0.5 μs, the sampling rate is 20 MHz, and the optical power entering the fiber during the pulse is 50 mW. Shot noise calculated using the Monte Carlo method is superimposed on each sample of the Rayleigh-backscattered signal. Conditions are the same for signal records S1 and S2, except that a $\pi/4$ phase change was applied to the fiber at a distance of 500 m from the launch point prior to generating S2.

The model was used to predict the performance of the intrusion sensor system. The signal level in each time bin averaged over 10 laser pulses, $\{C_j\}_K$, K = 1, 2, ... , was calculated before a localized phase perturbation corresponding to time bin j* was applied, and compared with the signal levels $\{C_j\}_{K+1}$ determined after a phase perturbation was applied. If $\left|(C_j)_{K+1} - (C_j)_K\right| > \varepsilon_j$, a disturbance is deemed to have occurred in time bin j, while if $\left|(C_j)_{K+1} - (C_j)_K\right| < \varepsilon_j$, no disturbance is indicated.

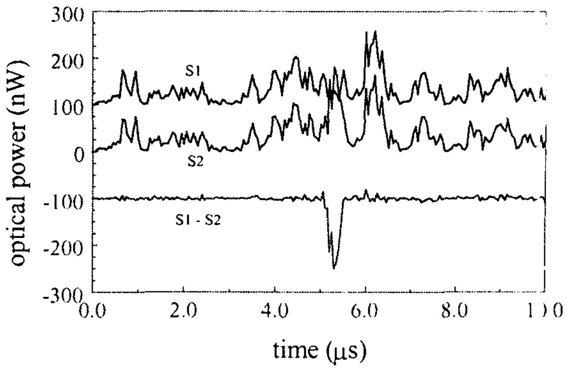


Fig. 1. Simulation result showing effect of a localized $\pi/4$ phase perturbation on the temporal dependence of Rayleigh backscattered power. The upper and lower traces have been vertically displaced by ± 100 nW so that the curves can easily be distinguished from one another.

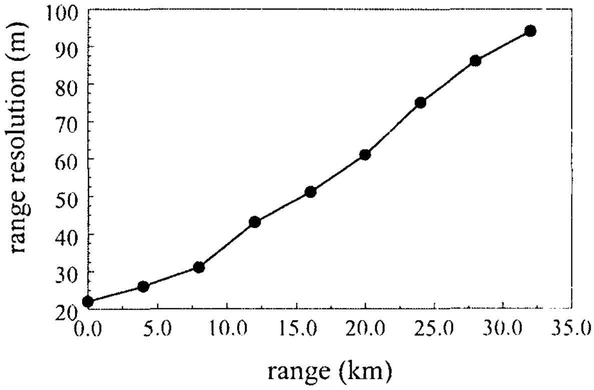


Fig. 2. Simulation result for dependence of range resolution on range in the fiber.

If the perturbation-induced change in the averaged signal in bin j* did not exceed the threshold, then a missed intruder was indicated; while a false alarm corresponded to the case that the change exceeded the threshold in a time bin in which no perturbation was applied. Threshold levels $\{\varepsilon_j\}$ for the time bins were chosen to provide low false alarm probability and low missed intruder probability. The number of missed intruders in a total of 100,000 trials was determined for time bins at different ranges. In this manner, the range consistent with a particular range resolution and missed intruder probability were determined.

Calculated system performance is shown in Fig. 2 for an assumed missed intruder probability of 10^{-4} and a false alarm rate of 10^{-10}. The range resolution was varied by changing the pulse width τ. Ten-pulse averages were used in this calculation.

3. EXPERIMENT

3.1. Light Source

The light source utilized all single mode fiber paths[5]. The Fabry-Perot cavity is formed by two fiber Bragg grating (FBG) reflectors with identical center wavelengths of 1555.6 nm and 0.4 nm spectral width. The Er^{+3} doped fiber gain medium is pumped by a 980 nm semiconductor laser. A short (2m) and a long (25km) optical feedback paths were added to improve the spectral characteristics of the laser with an in-line Er:fiber optical amplifier to suppress the frequency drift. Optical isolators ensure unidirectional propagation in the feedback loop and suppress coupling of the laser emission back into the cavity. The laser cavity and feedback loops are housed in a thermally insulated enclosure. The optical output power from this laser is about 50 μW, and the emission wavelength of 1555.6 nm measured with an optical spectrum analyzer corresponds to the reflectance peak of the FBGs.

A delayed self-heterodyne set-up consisting of a fiber Mach-Zehnder interferometer with a 63 km delay line in one arm is used for the instantaneous line-width measurement [6]. The laser shows a resolution-limited spectral width of less than 3 kHz.

The rate of frequency drift was determined by observing temporal fringes in an unbalanced fiber Mach-Zehnder interferometer. In this case two relatively short (100 m) fiber delay line sections are separated by a piezoelectric phase modulator. Temporal fringes in the interferometer output result from a frequency drift $\Delta\nu$ in the laser, which results in a phase shift of $\Delta\phi = 2\pi\Delta\nu\tau$, with τ the time delay difference in the interferometer. The frequency drift was measured to be less than 1 MHz/min .

3.2. OTDR

The experimental setup to simulate ϕ–OTDR response over 12km long fiber paths is shown in Fig. 3. As a field trial, the preliminary measurement of phase changes produced by pressure and seismic disturbances in buried fi ber optic cables over 12km(2km+10km) long fiber paths is performed. In this trial, the sensing fiber is prepared in the trench with 0.6m burial depth as shown in Figure 4. Simplex single mode fiber with 3mm yellow outer jacket is used as sensing fiber.

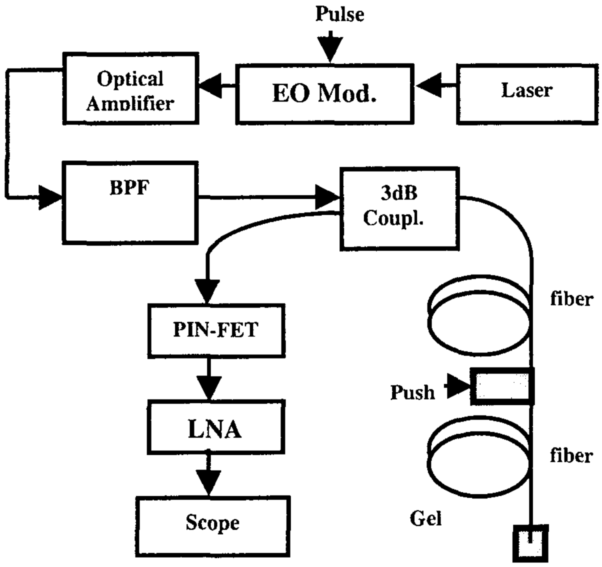


Fig. 3. The application of the cw Er:fiber laser in a ϕ-OTDR demonstration

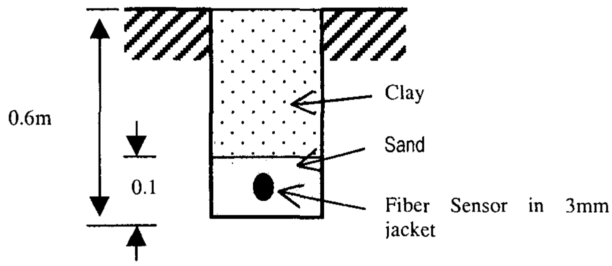
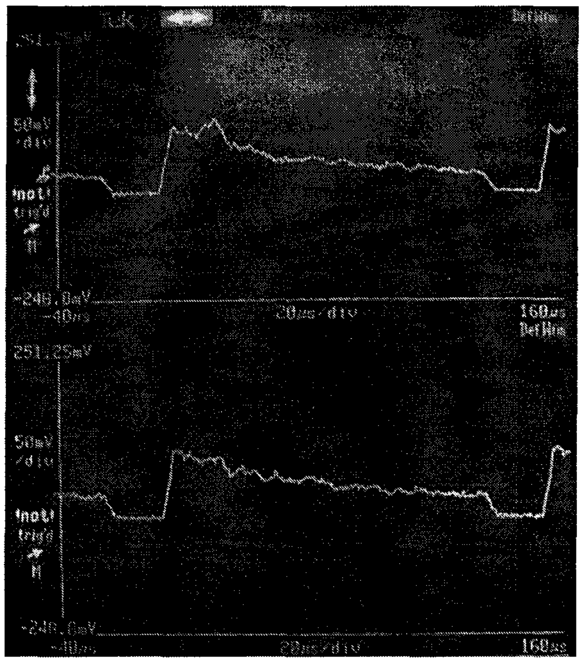
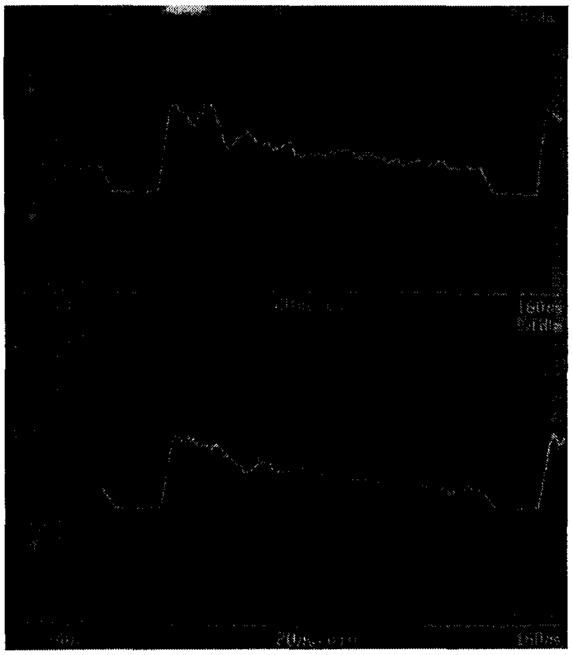


Fig. 4. Cross-section of buried fiber sensor trench for ϕ-OTDR demonstration.

In case that an intruder crosses the buried fiber sensor at a distance of 2 km from the input, the change in the return trace at 20 μsec delayed location, which is equivalent to 2 km from the input, is evident as shown in Fig.5(a), when upper trace is compared with lower trace which is the case without any intruder. This indicates that adequate phase changes (> π-rad phase shift) are produced by an intruder on foot. The displayed upper and lower return traces are obtained by averaging the traces for 64 times. A very narrow high peak, ~1 μsec width which is equivalent to ~100 m resolution, at 20 μsec delayed location, which is equivalent to 2 km from the input, is observed without averaging the return trace, although the trace is very noisy at real time measurement.



(a)



(b)

Fig. 5. Field test response of ϕ-OTDR: (a) By an intruder on foot, upper view with an intruder on foot, lower view without an intruder. (b) With an approaching vehicle, upper view with an approaching vehicle, lower view without an approaching vehicle.

In the case of approaching vehicle to the buried fiber sensor route at a distance of 2 km from the input, the vivid change in the return trace at 20 μsec delayed location is observed as shown in Fig.5(b), when upper trace is compared with lower trace which is the case without any approaching vehicle. The displayed upper and lower return traces are obtained by averaging the traces for 64 times. A strong high peak, ~5 μsec width which is equivalent to ~500 m resolution, at 20 μsec delayed location, which is equivalent to 2 km from the input, is observed without averaging the return trace, although the trace is also very noisy at real time measurement.

4. CONCLUSION

The use of a buried fiber optic cable as a distributed sensor for detecting, locating and (with suitable signal processing) classifying intruders is proposed. Phase changes resulting from either the pressure of the intruder on the ground immediately above the buried fiber or from seismic disturbances in the vicinity are sensed by a phase-sensitive optical time-domain reflectometer. Although the ϕ-OTDR provides only a semi-quantitative determination of phase shift amplitude due to (1) the fact that it makes use of optical interference and (2) the stochastic nature of Rayleigh backscattering, it is a means of detecting and locating phase shift perturbations along the length of a fiber - a capability not provided by conventional OTDRs.

Current research centers on an Er:fiber laser for use with an integrated optic modulator to inject highly coherent light pulses into the fiber. Light pulses from a Er:fiber cw laser with a narrow, <3kHz-range, spectral width and a frequency drift of < 1 MHz/min are injected into one end of the fiber, and small (< π-rad) phase perturbations have been detected and located in a long (> 10 km) fiber with a ϕ-OTDR monitoring setup by monitoring the backscattered light from the fiber with a photodetector. Results of preliminary studies, measurement of phase changes produced by pressure and seismic disturbances in buried fiber optic cables and simulation of ϕ-OTDR response over 12 km long fiber paths, to establish the feasibility of the concept are discussed. The simulations predict a range of 10 km with 35 m range resolution and 30 km with 90 m range resolution.

ϕ-OTDR monitoring setup is being packaged for field tests with buried fiber cable route between 2 km and 10 km optical fiber sensor spools. The experiments indicate adequate phase changes, more than π-rad, are produced by intruders on foot or approaching vehicle for burial depths in the 0.2 m to 1 m range in sand, clay and fine gravel soils.

This technology could in a cost-effective manner provide enhanced perimeter security for nuclear power plants, electrical power distribution centers, storage facilities for fuel and volatile chemicals, communication hubs, airports, government offices, military bases, embassies, and national borders.

References

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