Fiber-tree network for water-surface ranging beyond the fiber end using an OTDR technique

Abstract

~~In order to~~To monitor water level at long distance, a fiber-based time-domain reflectometry network is proposed. A collimator at each fiber end of a tree-type network retrieves 1.55 •m wavelength pulses that are reflected~~back~~ from remote surfaces. Since this enables a power-supply-free sensor network with non-metal media, this system is expected to be less susceptible to lightning strikes and power cuts than conventional systems that use electrically powered sensors and metal cables.In the present paper a successful simultaneous monitoring experiment of two water levels in the laboratory, as well as a trial for detecting a disturbed surface by beam-expanding and its theoretical background are reported.

Introduction: For disaster prevention and control, water levels at remote places, such as dams, lakes, rivers, and ports, need to be always monitored ~~at all times~~. Conventional sensors including those using floats, ultrasonic waves, static capacity or pressure gauges need to be powered electrically[1]. Since these devices are susceptible to power cuts, the monitoring network needs to be made power-supply-free to improve its survivability. In addition, conventional metallic telemetry systems can be easily jeopardized by a lightning strike even if it is indirect. Fiber optic networks that can cover an area of dozens of square kilometers by utilizing the low-loss nature of silica fiber are able to survive such power failures. A sensor design is required to make the network all optical and remove the need for an electric power supply for the distributed sensors.

A system ~~which~~that uses fiber optically connected '~~fiber~~Fiber Bragg ~~grating'~~Grating' (FBG) reflectors at every monitoring point has been developed [2]. It detects the shift in reflected wavelength due to a change ~~of~~in the mechanical status of the FBG, meaning the optical source usually needs to have a broad enough bandwidth to cover the wavelength before and after the shift~~. Spectral~~, as spectral analysis provides event detection. Another disadvantage is that the spectral shift in the target FBGs needs to be converted to water pressure change. A direct measurement would be better for avoiding possible errors in the conversion process.

Although 'optical time-domain reflectometry' (OTDR) has been generally limited to monitoring in fiber communication facilities for detecting cut fibers, for example [3], this letter demonstrates the ability of OTDR to measure the distances beyond the end of the fiber. Also proposed is a tree-type fiber network in conjunction with OTDR for continuous monitoring of

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the water level at several remote locations simultaneously. The proposed network is power-supply-free withnon-metal media, so the survivability is expected to be better than conventional systems with electrically powered sensors and metal cables.

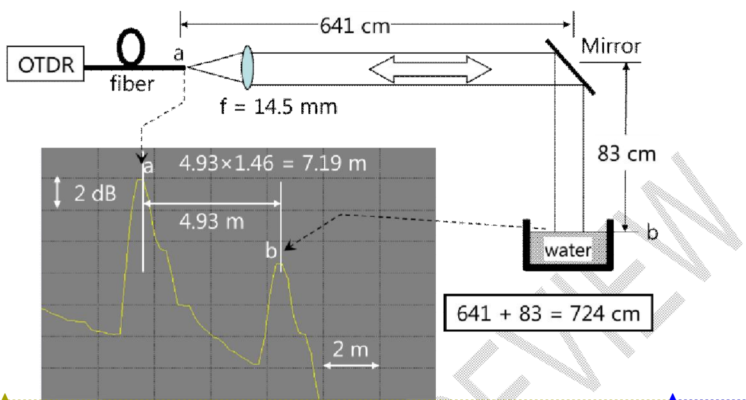

Fig. 1 Preliminary experimental setup and the resultis shown on a conventional OTDR display.

Preliminary *experiment:*In order to**experiments:**Toconfirm the applicability of conventional OTDR apparatus towater-surface ranging, a preliminary experiment was conducted, as shown in Fig. 1, with the resultant data shown on the inset display. Laser pulses 3 ns in duration from a 1.55 ·m wavelength OTDR were collimated by a lens with a focal length of 14.5 mm, and directed to vertically irradiate the water surface that was measured to be 7.24 m away from the fiber end with a tape measure. On the OTDR display, the indicated distance between the two reflection points is 4.93 m. The first peak was the reflection from the fiber-air interface (a) and the second was the reflection from the water surface (b). The instruction manual of the apparatus stated that the refractive index of the fiber was 1.46, so the displayed distance (4.93 m) was multiplied by the index (1.46) to obtain the distance from the fiber end to the water surface in the air, 7.19 m. The relative error was 0.69%. It was concluded that the conventional OTDR can be used to range a water surface by extracting and collimating the laser pulse into air, if the surface is stable and flat.The problem is that no water surface outside is flat ormirror-like due to waves. In most conditions, even in the laboratory, pulses retrieved vary greatly in amplitude and the reflection signal is easily lost due to the averaging function built ininto the OTDR apparatus.

Tree-type fiber network for OTDR water surface ranging:An experimental setup for two monitoring sites is depicted in Fig. 2, where the receiving device is replaced by a storage oscilloscope, which is capable of retainingcan retain the waveform for a desired period.Since an

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averaged water surface is horizontal, if the wavelength of the water surface is much larger than the beam width, as illustrated in Fig.2, there will be instances when the pulse is reflected vertically, although these may be infrequent.Only a storage oscilloscope can capture and display such intermittent pulses. Laser pulses from a 1.55 ·m conventional OTDR are amplified with an 'erbium-doped fiber amplifier (EDFA)' and divided with a 3 dB directional coupler after passing through an optical circulator, which directs the returning pulses to the oscilloscope. One arm is for a 5 m feeder fiber and the other is connected to a 15 m fiber. Each fiber end has a collimator to vertically illuminate the water surface. The reflections are detected with a 12 GHz-bandwidth photodiode; the observed waveform on the oscilloscope is shown in Fig. 3. Please note that the pulse polarity is inverted.

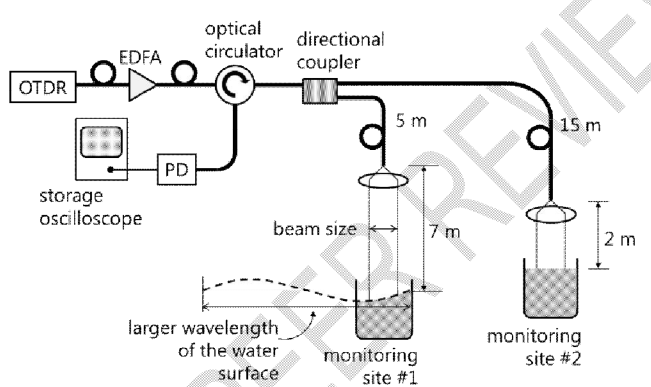

Fig. 2: Experimental setup for the tree-type fiber network with passive sensors at the fiber ends. To measure disturbed water surfaces, a storage oscilloscope is used.

A roundtrip separation time of 98 ns was observed between the reflections at the ends of the two fibers, corresponding to ~~a distance of~~ 10 (=15-5) m with thea refractive index of 1.47. Figure 3 also shows the reflections from the water surfaces 7 and 2 m away from the fiber ends as measured with a tape measure.The storage oscilloscope could measure somewhat disturbed water surfaces, as shown in the figure. It shows roundtrip delays of 47.5 ns and 14.6 ns from the two fiber facets. By multiplying by the speed of light in air, the distances of 7.1 m and 2.2 m between the water surfaces and the respective fiber ends were obtained. This scheme is a direct time delay measurement and does not require a conversion process. Furthermore, since this technique uses no power-supply at the sensor site, and the fiber is non-metal, it is not vulnerable to lightning strikes or power failures.

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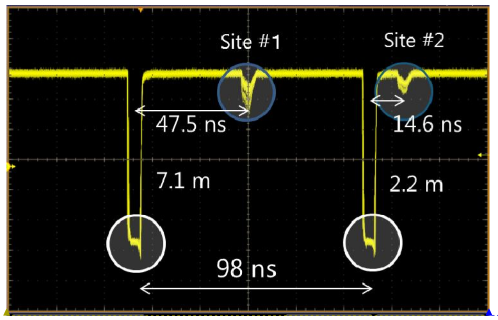
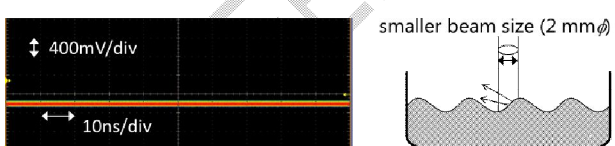
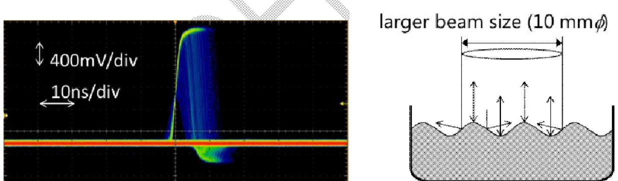


Fig. 3:Storage oscilloscope traces of the reflected pulses.

If the wavelength of the water surface is ~~similar to~~like the beam width, there will be a negligible chance of retro-reflection occurring.A beam-expander that expands the beam from about 2 mm to 10 mm in diameter was used to investigate this. ~~In order to~~ To create a continuously disturbed water surface, an ultrasonic cleaner filled with water was used. The retrieved pulses are compared in Fig. 4a and b, where the persistence period of the oscilloscope display was 30 seconds in both cases.This means that even a single pulse was observable on the display for 30 seconds.



~~*a*~~



b

Fig. ~~4~~ 4a:Pulses retrieved from disturbed water surfaces.

~~*a* No pulse without the beam expander (2 mmϕ), inset shows the smaller sized beam reflecting off the water surface.~~

~~b With the beam expander (10 mmϕ), some pulses were~~

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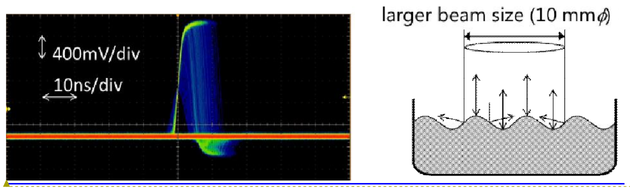

Fig. 4b: Pulses retrieved from disturbed water surfaces.

As shown in Fig. 4a, when the ultrasonic cleaner was operational, no pulse was received for 30 seconds using the 2 mm • beam. On the contrary, in Fig. 4b, with the wider beam (10 mm •), pulses reflected from the disturbed surface were detectable. This result shows that retrieving partially retro-reflected pulses from a disturbed water surface is possible by increasing the ratio of the beam size to the typical wavelength of the water surface [4].

Theoretical treatment: This fact can be supported by a calculation for feedback efficiency reflected off aflat surface back to the single-mode fiber (SMF) [5]. The optical alignment is shown in Fig. 5. Light with a vacuum wavelength λ from an SMF (effective refractive index n_1, spot size $2\omega_0$) is emitted into an air space with a refractive index n_2.The power reflectance R_1 of Fresnel reflection at this fiber end is given by the following equation (1).

$$R_1 = \left(\frac{n_1 - n_2}{n_1 + n_2} \right)^2 \quad \text{~~(1)~~ Equation1}$$

This Gaussian beam is converted into a parallel beam (beam-waist spot size $2\omega_1$) by a collimator lens (focal length f), where the distanced_1 between the lens and the waist ($2\omega_1$) is equal to d_0, the distance from the fiber facet to the lens. The spot-size ~~ω_1 is given by the following relation;~~ w_1 can be obtained in equation 1.

$$\omega_1 = \frac{\lambda f}{\pi \omega_0}. \quad \text{(Equation 2)}$$

This light is vertically reflected with power reflectance R_2 on a plane (n_3) a distance z away and returns to the SMF. In this experiment, the reflecting substance is water, so n_3 = 1.33, and the power reflectance R_2 is given~~by~~in Equation 3.

$$R_2 = \left(\frac{n_3 - n_2}{n_3 + n_2} \right)^2 \quad \text{(Equation3)}$$

The power efficiency η of this light reflected ~~back~~ to the SMF is given~~by~~in Equation 4.

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$$\eta = \frac{4}{4+\left(\frac{\lambda}{\pi\omega_1^2}\right)^2(2z)^2}(1-R_1)R_2 \quad (4)$$

Equation 4

An example of this value for the case of $d_1 + z$ = 6.2 m, is depicted in Fig. 6. This shows that the longer the focal length, the higher the efficiency, and that it reaches saturation at 40 mm or more, supporting our result shown in Fig. 4.

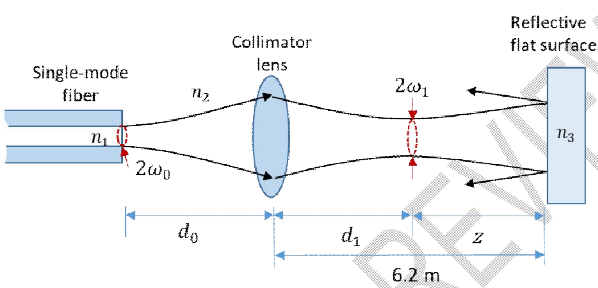

Fig. 5: Optical alignment for the power efficiency η of light reflected ~~*back*~~ to the SMF

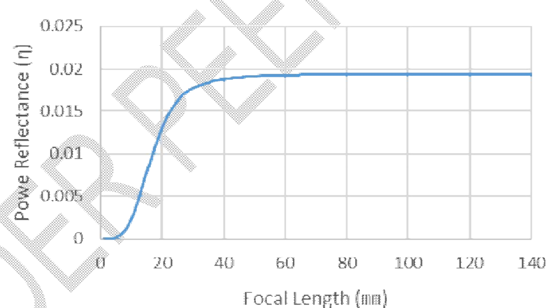

Fig. 6: A calculation result of power efficiency η of light reflected ~~*back*~~ to the SMF

~~*for*~~ In the case of ~~d_1~~ d1 + ~~z~~ z = 6.2 m

Conclusion: Laboratory experiments showed that the OTDR technique can be applied to ~~ranging~~ranges beyond the fiber facet. The proposed simple tree-network configuration ~~is capable of retrieving~~can retrieve reflections from disturbed water surfaces from multiple locations simultaneously. It can be concluded that the proposed scheme ~~isapplicable~~applies to water level monitoring networks with multiple passive sensors deployed at remote places, if a storage oscilloscope detector and a beam size different ~~to~~from the typical wavelength of the water waves are employed. Since this technique uses power-supply-free sensor sites and non-metal fibers, it is not vulnerable to lightning strikes or power failures.

References

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