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New OTDR Technique for Monitoring the Range of Reflective Markers

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Abstract

A novel OTDR technique to accurately monitor the optical path length to multiple reflective markers is described. The method can monitor changes in optical path length of 40 ppm in a 1 sec measurement time and is suitable for multiplexed optical-fibre strain sensing over gauge lengths of several metres.

Introduction

Optical fibre strain sensors[1] are desired for both aerospace applications and civil engineering. They will also form an attractive sensing method in smart structures.[2]

Many methods reported so far require complex optical hardware which is less suitable for the generally harsh environments. However, an *Optical Time Domain Reflectometry (OTDR)* system with a semiconductor laser source uses hardware already developed for telecommunications, often to aerospace standards. Hence OTDR forms a suitable basis for practical sensing systems. It allows monitoring the range of reflective markers on optical fibres,[3,4] which can then be related to strain or temperature of the fibre.[5]

To enhance the range resolution of conventional OTDR, our system design uses a modified **electrically** coherent receiver[†] (*correlator*) to detect the reflections from the fibre. Conventional OTDR uses a delay in the correlator that can only be switched in discrete steps, usually in multiples of the pulse duration. We report a method to improve range resolution by sweeping the delay continuously. We take advantage of the triangular shape of the autocorrelation function of a pulse to measure the time delay (ie optical range) of reflected signals more accurately.

Theory

An OTDR measures the reflections from an optical fibre to characterise attenuation and reflective points along the fibre.[6] Optical pulses of length τ and periodicity T (Fig 1, top left) are sent into the fibre and the returned power is monitored by an electrically coherent receiver. The output of the coherent receiver is the crosscorrelation between transmitted pulse and received signal.

If there is only one reflective point on the fibre, the output of the coherent receiver is approximately proportional to the autocorrelation of the transmitted signal (Fig 1, bottom left). If two or more pulses are received (eg from multiple reflections) the OTDR response has the form of a crosscorrelation (Fig 1, bottom right) between the two

[†] *matched filter* or *correlation detector*; to be distinguished from **optically** coherent (ie interferometric) receivers, as used eg in *coherent OTDR*

upper traces in Fig 1. The minimum distance between two reflective points to avoid any overlap is the one-way *spatial resolution*[†] s_{OTDR}

$$s_{OTDR} = \frac{c}{2\tau} \qquad [1]$$

where c is the speed of light in the fibre and τ is the duration of the pulse.

It is difficult to determine the location of the peak because the peak shape is distorted ("rounded") due to the finite rise time of the pulse and timing inaccuracies of the pulse generator. Therefore the *range accuracy*[‡] is often limited to the spatial resolution in Eq [1].

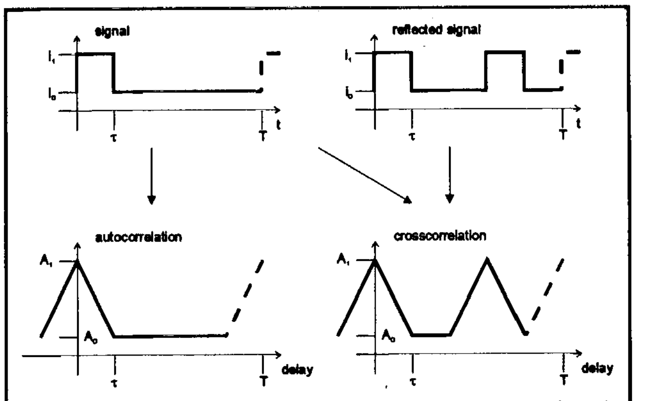

Fig 1: Correlation of a pulse of length τ with itself (*autocorrelation*) and with a two similar pulses (*crosscorrelation*)

For many sensor systems, a typical OTDR spatial resolution of 1-10 m is sufficient, but there is a need to monitor each reflective point with a range accuracy below 1 mm. Our current technique overcomes this problem by interrogating the slopes of the correlation peak.[††] These slopes (bottom of Fig 1) are normally not used because receivers of OTDRs do not allow a continuous sweep of the output.

Design of New Fibre Interrogator

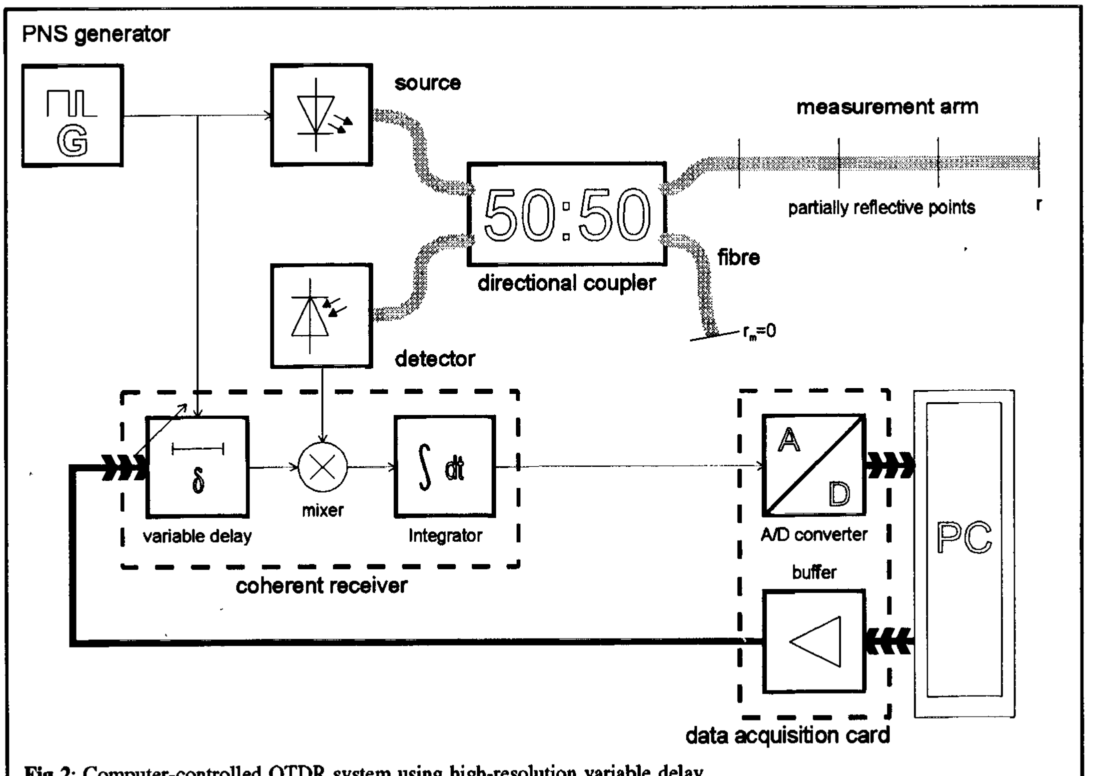

Fig 2: Computer-controlled OTDR system using high-resolution variable delay

In the system in Fig 2, a digital signal is transmitted by a 780 nm CD-type laser and received by a fast silicon photodiode. Integrated circuits for fast telecommunication links support the electro-optic design.[7]

[†] also termed *two-point resolution*

[‡] also termed *spatial accuracy* or *spatial resolution*

[††] UK patent application 9407077.8

A computer (PC) controls the high-resolution delay system and acquires the output from the coherent receiver. Hence any receiver output can be related accurately to its corresponding delay, and only data from the regions of interest (ie the slopes of the peaks) need to be acquired.

The PC varies the delay over the region of interest while acquiring the receiver output. Then it detects the peaks in the receiver output and curve-fits a line to both slopes of every received peak. The delay corresponding to the point of intercept is the time delay from the reflection.

Use of a *pseudo-random binary sequence (PRBS)* improves the duty cycle and hence the signal-to-noise ratio.[8] Because the technique relies solely on delay information, it is insensitive to both amplitude and polarisation modulation. In other approaches, amplitude modulation either limits the performance[9] or forces the use of more complex coding schemes.[10,11] Radial strain in the optical fibre could cause problems in polarisation based systems.

Experimental Results

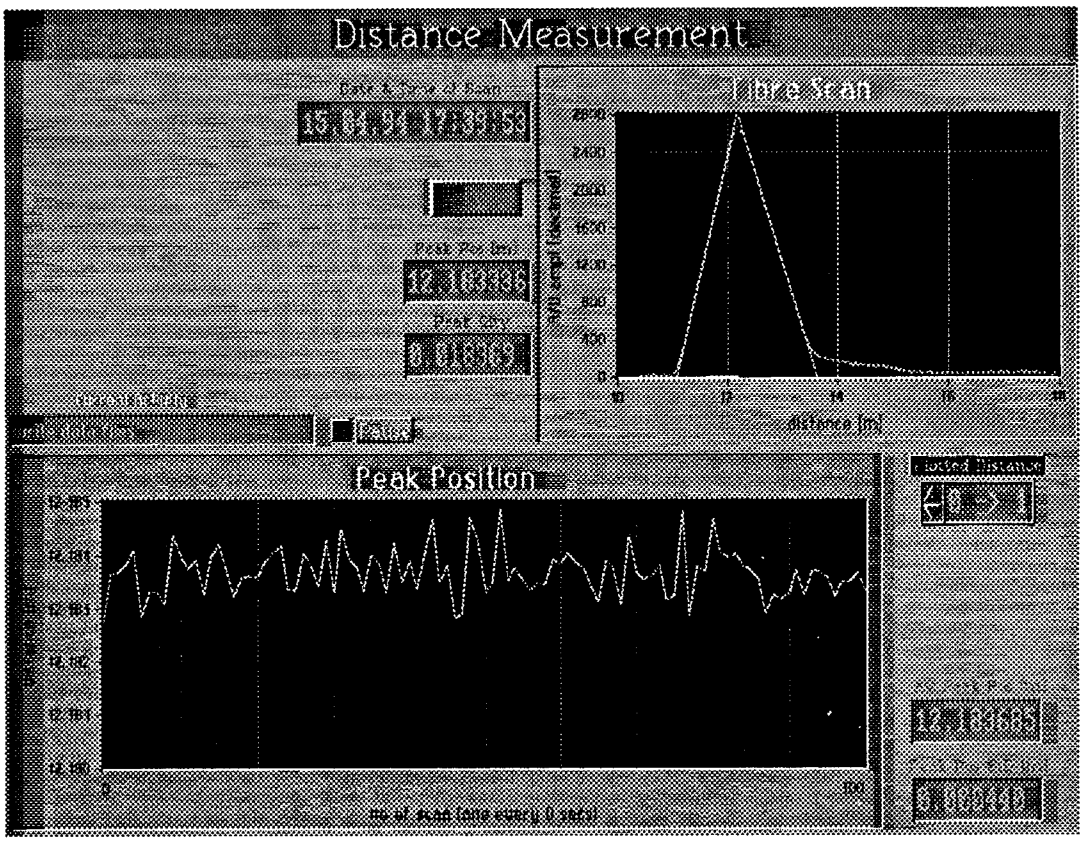

Fig 3: PC display for one reflective marker

Fig 3 shows the output of the measuring system on the PC screen when there is only one reflective point in the fibre. On the top right of the figure, the output of the correlation detector can be seen, including the lines fitted to the slopes of the peak. To simplify discussion, the speed of light is assumed to be constant at $2 \cdot 10^8$ m/s and the delay is displayed in terms of distance. The location of this particular peak then corresponds to 12.183336 m.

The 1000 points on the curve are acquired within one second. 100 sequential scans were taken and the peak position of each scan was plotted in real time on the bottom diagram. During the 100 seconds taken to plot the bottom diagram, the fibre was unstrained. To illustrate the performance of the system, the vertical axis of the bottom diagram shows distances between 12.180 and 12.185 m. On the right-hand side of this diagram, the average peak position of the 100 scans is computed as 12.183685 m, with a standard deviation of 440 μm (≈ 36 ppm).

If this system is used to measure integrated strain over the whole fibre length at constant temperature, the performance limit with this measurement time is about 36 $\mu\varepsilon^{\dagger}$. Preliminary results show that it is possible to half the standard deviation by quadrupling the measurement time.

Tests with an electronic delay (coaxial cables) rather than an optical delay has shown that the interrogation system is not restricted to optical transmission media.

Conclusion and Further Work

A new OTDR technique is presented which allows accurate monitoring of the delay from reflective markers. The technique employs a coherent receiver with a variable and agile delay and eventually should allow interrogation of both static and dynamic signals (eg strain, temperature etc) with the same measurement system. The system also allows the use of PRBS without being sensitive to non-zero crosscorrelation.

Work on the system is ongoing. The particular focus of our future work is on temperature compensation schemes and on improved digital signal processing to enhance the speed of the response.

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† microstrain