Low-Crosstalk Real-Time Monitoring of Optical Path Length in Multiple Fibre Sections using Range-Gated Subcarrier Interferometry

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Abstract

A system capable of real-time high-resolution optical-path-length monitoring of multiple sections of optical fibre is described. The low-crosstalk interrogation system relies on range-gated subcarrier interferometry and is operated under computer control. The system is attractive for long-gauge-length structural monitoring.

1. Introduction

Optical fibres have been interrogated in the frequency domain to sense physical fields, in particular strain, within advanced composite structures.[1-7] Optical frequency domain reflectometry (OFDR) may use optically coherent methods [1], however incoherent methods are particularly well suited to longer gauge-length measurements.[2-7] Incoherent OFDR (subcarrier interferometry) involves amplitude modulating a low-coherence optical source with a sinusoidal waveform and launching the light into the fibre under test. The amplitude and phase of the detected subcarrier waveform depend on the reflective properties of the fibre. An inverse Fourier transform may be applied to the amplitude and phase information to obtain a spatial image of the fibre [3], however extensive processing and interrogation frequencies from baseband up to very high frequencies are required to obtain good resolution.[4] For a 100μm resolution, interrogation frequencies must be over 1THz.

If reflective markers are placed in a fibre, more simple frequency domain techniques may be used to interrogate the markers. The separation of the markers is encoded in the peaks and nulls of the amplitude spectrum obtained from the fibre. Systems have been devised to track a null in the subcarrier amplitude spectrum. For a fibre containing only two markers, the frequency of a single null and knowledge of its order is sufficient to evaluate the separation of the markers. Lock-in systems track nulls in real-time, but early systems only functioned with two interfering sinusoids.[5] More recent techniques have extended this method to interrogate multiple sensing sections using multiplexing in both the wavelength[6] and the time domains.[7]

Multiplexing in the time domain, with broadband reflectors as markers, allows low-cost lasers to be used as the source. These have higher output power and are capable of higher modulation rates than broadband sources, thereby offering higher accuracy. A new system using broadband reflectors has been recently reported together with a multiplexing strategy for use in the time domain.[7]

Further to the preliminary results of this time-division-multiplexed strain sensor, this paper describes an improved system exhibiting higher spatial resolution and lower crosstalk levels between sensing sections. The system is now capable of displaying data in real-time and is controlled via an interactive user interface. It can be instructed to sequentially monitor each sensing length or continually monitor a chosen length. The system has potential for use, whenever there is a requirement for multiplexed strain sensing over long gauge lengths with high accuracy and wide dynamic range.

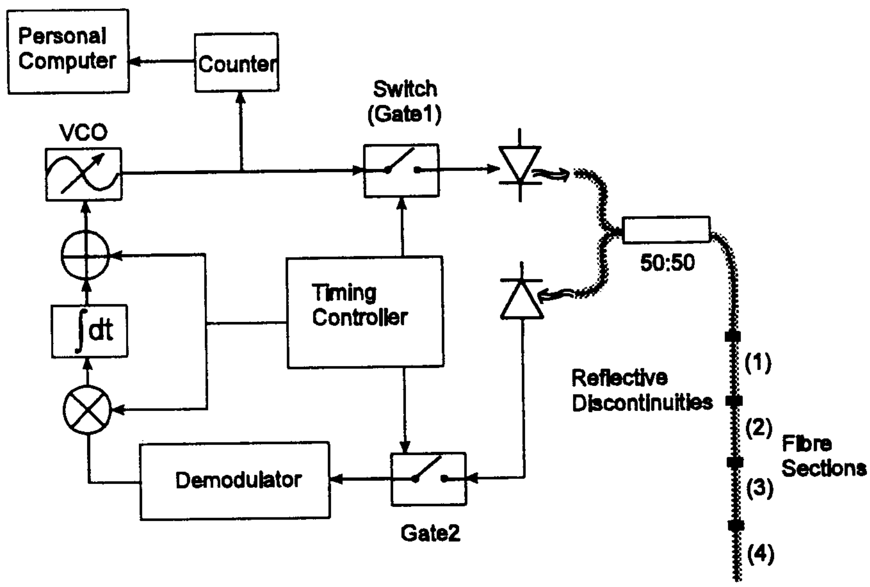

Figure 1 Schematic diagram of the interrogation system

2 System Operation

The system uses a frequency modulated, low coherence laser source to interrogate the fibre under test (Fig.1). A plot of the return subcarrier amplitude against frequency is referred to as the subcarrier frequency response of the fibre. The frequency responses become increasingly complicated to analyse as the number of markers increases. Analysis may be kept simple by only interrogating two markers at any one time. A time division multiplexing technique allows a fibre containing many reflective points to appear as though it only contained two such markers. Thus lock-in techniques, normally only appropriate for networks with two reflectors, may be applied to quantitatively track the strain in a selected section of the fibre.

In a lock-in system, the interrogating frequency is frequency-shift-keyed between two closely spaced frequencies that are a fixed interval apart. The resulting amplitude modulation on the received signal is used to lock the mean interrogation frequency to the frequency of a null in the subcarrier frequency response. The null may be formed due to two separate light paths [5], a single reflection from a fibre [6], or two reflections from a fibre.[7] The frequency of the null, f_{null} is given by:-

$$f_{null} = \frac{(1+2n)v}{4\Delta}$$

where n is the order of the null, $\boldsymbol{\Delta}$ is the path length difference and v is the velocity of light in the fibre. In this strain sensor, the computer converts the measured frequency into an equivalent length and plots the result.

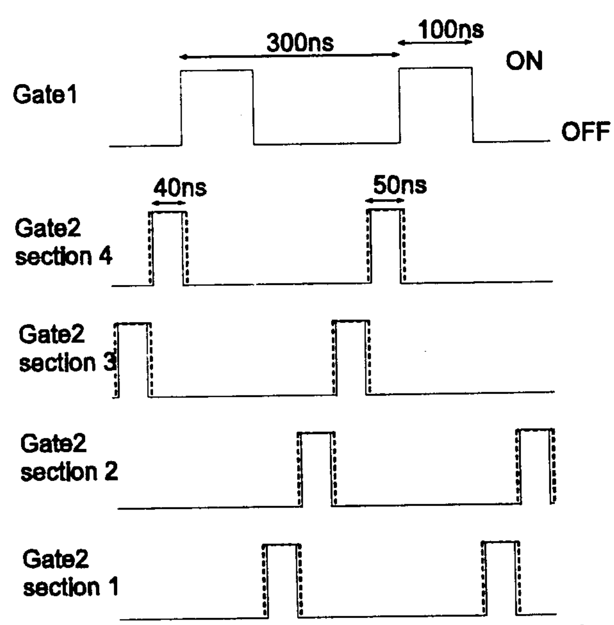

Figure 2 Control pulses applied to the gates to select a given fibre section

Sensing sections are selected by gating the RF modulation applied to the Fabry-Perot laser (HP type LST2726, 1300nm, output power 1mW) and gating the output of the photodiode receiver (Epitaxx type ERM507FJ-S, 3dB bandwidth 1.9GHz). Only signals arising from the interference of the two chosen markers are allowed to reach the lock-in electronics and are hence monitored.

3. Improvements to the Earlier System

Several modifications have been made to the earlier system to improve its performance.[7] Firstly the resolution has been increased by interrogating the fibre with higher modulation frequencies (just under 500MHz).

Secondly, crosstalk between fibre sections has been much reduced by applying shorter pulses to the receiving switch. The timing of the control pulses applied to the gates is simple when all separations are exactly 5m, however small deviations from this spacing results in high inter-section crosstalk. By reducing the pulse width of the receiving gate pulse, leaving its central time unaltered, reflections arising from neighbouring sensing sections may be blocked out. This results in much lower crosstalk levels between sensing sections. Reducing the pulse width slightly reduces the duty cycle, effecting the dynamic response of the system. The pulse length should therefore be set to the maximum value so that unwanted reflections are still effectively discarded. Fig.2 shows the timing of the pulses sent to the gates. The dashed lines indicate the gate pulses applied to the receiving gate in the earlier system [7], while the solid lines show the reduced width pulses used to ensure low crosstalk. Pulses of duration 40ns have reduced the crosstalk to below -50dB.

Thirdly, software now controls the data acquisition and processes and displays the data in a graphical format. The system can interrogate the various sections of fibre sequentially or monitor a chosen section in real time. Signal processing facilities, such as a digital filter, have also been added to the system to improve signal to noise performance, albeit with a reduced dynamic response.

4. Experiment and Results

Three broadband TiO_2 reflectors of approximately 3% reflectivity were placed in a single mode fibre at separations of 5±0.3m.[8] The system was instructed to sequentially interrogate the two fibre sections formed by the reflectors, monitoring the 20th null using a frequency deviation of 3.7MHz. Fig. 3 shows the system output.

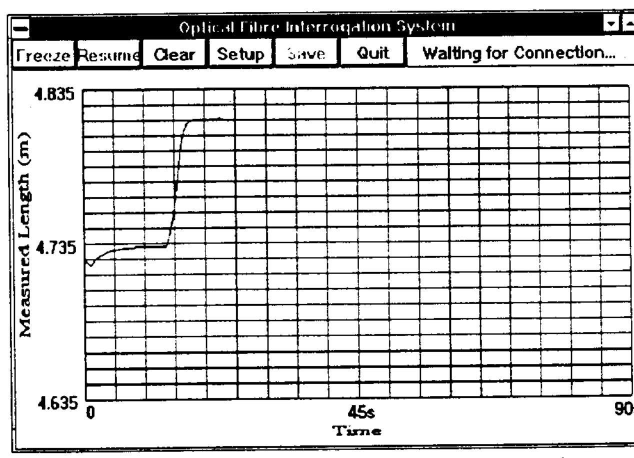

Figure 3 System response as separate sensing sections are sequentially interrogated

The system was then instructed to monitor the second section, while different strains were applied using a calibrated translation stage. The system successfully tracked the applied strain, showing an apparent strain coefficient (ratio of optical path length change to applied extension) of 0.76 (Fig.4). With a measurement time of 250 ms, RMS noise levels below 15μm (3 microstrain over 5m) were observed, when the fibre was held at a constant strain. When the digital filter was applied, the noise levels fell, as expected, as the time constant was increased. With moving window averaging of four consecutive data points, the RMS noise level fell by a factor of 2.[9]

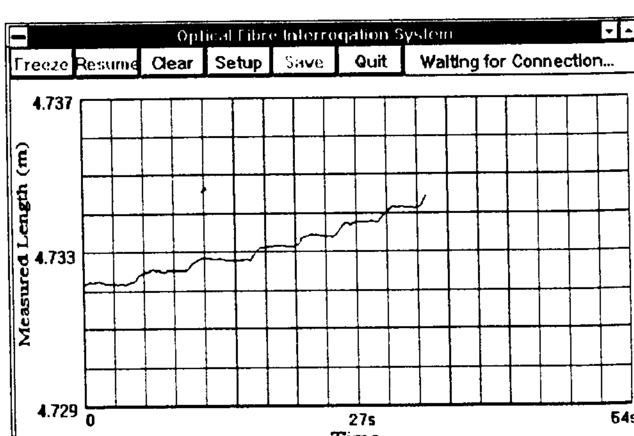

Figure 4 System response as fibre is strained in 0.5mm steps

The crosstalk between adjacent sensing sections was investigated by monitoring the length of the first section, while straining the second section. Firstly this was performed using the maximum-width gate pulses, as used on the earlier system. As a 5mm extension was applied to the second fibre section, a reduction in length of 100μm was observed by the system, corresponding to crosstalk levels of -34dB. The gate pulses to the receiver were then shortened and the crosstalk measurement was repeated. Under these conditions, no detectable change in length was observed on the first fibre section. Since the change was unobservable above the noise level of 15μm, crosstalk levels were now below -50dB.

5. Conclusions

We have demonstrated a high-resolution real-time low-crosstalk strain monitoring system for measuring the integrated path-length between multiple reflective points. The system has a higher resolution (15μm over 5m lengths) than previously reported lock-in systems and displays the results in real-time. The use of reduced-width gate pulses improved the system crosstalk by more than 15dB. The system is easily capable of detecting the levels of strain required for monitoring of modern engineering structures. Work on thermal compensation is currently in progress. The system should then be ready for field trials on real structures.

6. Acknowledgements

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7. References

[1] T. Valis, D. Hogg, R.M. Measures, "Fibre Optic Fabry-Perot Strain Gauge", IEEE Photonics Technology Letters, Vol.2, No.3, pp.227-228, 1990.

[2] R.I. Macdonald, "Frequency Domain Optical Reflectometer" Applied Optics, Vol.20, No.10, pp.1840-1844, 1981.

[3] J. Nakayama, K. Lizuka, J. Nielsen, "Optical Fiber Fault Locator by the Step Frequency Method", Applied Optics, Vol.26, No.3, pp.440-443, 1987.

[4] H. Ghafoori-Shiraz, T. Okoshi, "Optical-Fibre Diagnosis Using Optical-Frequency-Domain Reflectometry", Optics Letters, Vol.10, No.3, pp.160-162, 1985.

[5] C.A. Wade, J.P. Dakin, J. Croft, J. Wright, "Optical Fibre Displacement Sensor Based on Electrical Subcarrier Interferometry using a Mach-Zender Configuration", Conf. on Fibre Optic Sensors, Cannes, France, SPIE Vol.586, pp.223-229, 1985.

[6] M.A. Davis, A.D. Kersey, T.A. Berkoff, D.G. Bellemore, "Subcarrier Based Path-Integrating Strain Sensor Array Utilising Fiber Bragg Gratings", Conf. on Distributed and Multiplexed Fibre Optic Sensors IV, San Diego, CA, SPIE Vol.2294, pp.93-99, 1994.

[7] M. Volanthen, H. Geiger, J.P. Dakin, "Time-Division-Multiplexed Optical Frequency-Domain Reflectometer using Subcarrier Interferometry", Electronics Letters, Vol.31, No.22, pp.1943-1944, 1995.

[8] C.E. Lee, R.A. Atkins, H.F. Taylor, "Reflectively Tapped Optical Fibre Transversal Filters", Electronics Letters, Vol.23, No.11, pp.596-598, 1987.

[9] W.H. Press, S.A. Teukolsky, W.T. Vetterling, B.P. Flannery, "Numerical Recipes in C", second edition, Cambridge, pg.650, ISBN 0-521-43108-5, 1992.