Time-division-multiplexed optical fibre strain-sensor using subcarrier interferometry

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A high-resolution quasi-distributed strain sensor employing subcarrier interferometry and time-division multiplexing is reported. The system tracks a null in the subcarrier frequency response of a fibre network containing reflective discontinuities. Time gating selects the sensing section. A resolution better than 20μm over 5m lengths of fibre has been obtained.

Introduction: Subcarrier interferometry (incoherent optical frequency domain reflectometry (OFDR)) has been widely used to interrogate optical fibres [1 – 4]. The location of reflective discontinuities in the fibre may be obtained by an inverse Fourier transform of the frequency domain data [2]. If only two reflective points are present, the frequency response is straightforward, i.e. the reflected amplitude is a simple function of the applied frequency, showing sharp nulls and rounded peaks. A lock-in technique may then be used to track the optical path length between the two reflectors by tracking the frequency of a null [3], allowing real-time measurements without sophisticated signal processing.

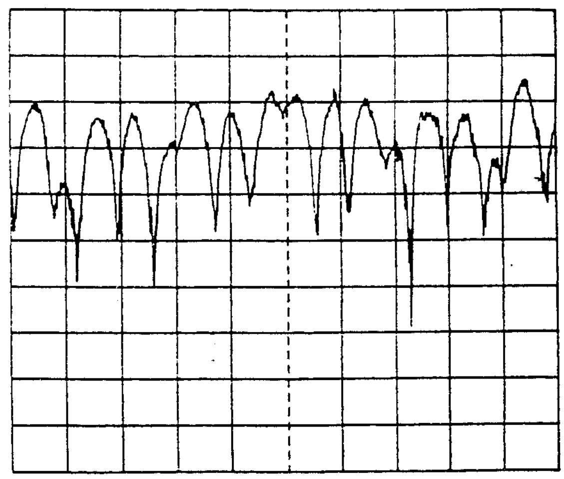

Fig. 1 *Frequency response from four reflectors in fibre: reference: 325MHz*

The frequency response becomes increasingly complicated for more than two reflections (Fig. 1) and may be difficult to interpret directly in the frequency domain. Nevertheless, the analysis may be kept simple by multiplexing the received signals from different reflective points. A wavelength-division-multiplexed system using Bragg gratings has been demonstrated [4]. We present here the first time-division-multiplexed incoherent OFDR system, using broad band reflectors [5] and a low cost laser. Our system allows higher modulation frequencies (resulting in higher resolution) than the broad band LED typically used for a Bragg grating interrogation system and does not require the matching of source and reflector wavelengths.

Theory: By suitable time gating, only reflections from adjacent pairs of mirrors may be received. The fibre will then appear to the interrogation system as though it only contains two mirrors. The frequencies of the nulls in the frequency response from two mirrors are directly related to the spatial separation of the mirrors. By tracking a null in the subcarrier frequency response, the optical path length between mirrors may be tracked. To track the nulls, the subcarrier signal was frequency shift keyed (FSK) between two values either side of the null [3]. The resulting amplitude modulation signal at the detector was used to lock the mean interrogation frequency to the position of the null. The mean frequency was measured by a counter, set to count for a period which was an integral multiple of the period of the modulating signal (Fig. 2).

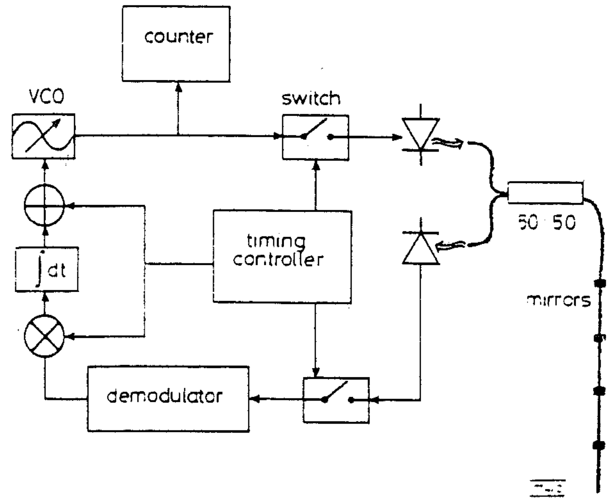

Fig. 2 *Schematic diagram of interrogation system*

Electronic gates operated on the RF signal to ensure that only information resulting from interference between light from a selected pair of mirrors was received by the feedback electronics. The first switch controlled the RF modulation to the diode laser (1300nm HP LST272X, 1mW output power), whereas the second switch controlled the received RF signals to the feedback electronics. If the mirrors are all separated by approximately the same distance, the timing control signals to the switches are simple to implement. For all the fibres under test, mirrors were placed at regular intervals, with separations of 5 m ± 10cm. The modulation to the laser was repetitively turned on for a 100ns period and a fixed delay later, the switch before the feedback electronics was opened for 50ns. This cycle was continually repeated to extract the desired information from the fibre network. By varying the delay between the timing signals to the switches, other pairs of adjacent mirrors may be interrogated.

Experimental results: To examine the performance of the lock-in system, an unstrained fibre containing two reflectors only was interrogated without use of the switches. Mean noise levels below 5 μm were observed with a 0.25s count time, corresponding to a resolution just below 1με. A second fibre was constructed with four low reflectivity (~3%) mirrors. Using an RF spectrum analyser, the frequency response from the fibre was obtained (Fig. 1). The switches were set to obtain reflections from the second and third reflectors only. Reflected signals were detected with an Epitaxx ERM507FJ-S photodiode receiver, with a 3dB bandwidth of 1.9GHz. The resulting frequency response was identical to that of the first fibre, as predicted from a Fourier analysis of the system. Using the switches, a null at ~309MHz was tracked by the lock-in system, with the two interrogation frequencies separated by 4MHz. With a constant strain applied to the fibre, and a frequency count period of 0.255, a standard deviation of 20μm was obtained in the measured length. As the fibre was strained in 0.5mm steps, the system successfully tracked the changes in optical path length (Fig. 3).

Discussion: The system functioned correctly and with low levels of noise. The system has an unambiguous dynamic range of ±15cm, corresponding to 3% strain in the fibre sections between reflectors. At the leading and falling edges of the pulse of subcarrier modula-

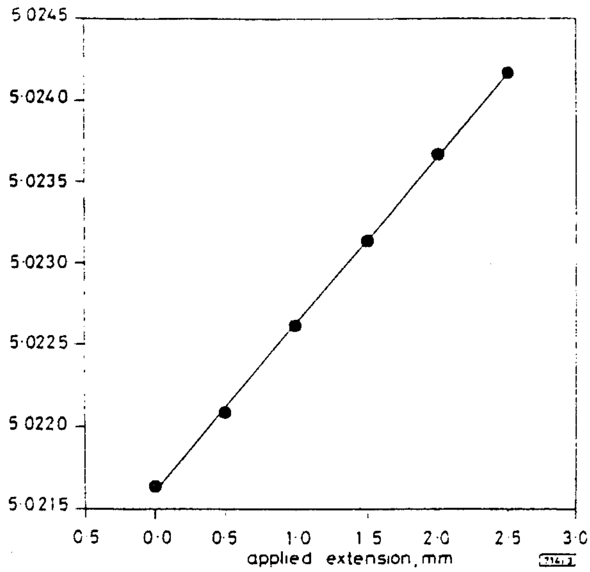

Fig. 3 *Performance of lock-in system*

tion, unwanted reflections from undesired adjacent mirrors may affect the feedback electronics. The unwanted signal is caused by the use of maximum width gate pulses and the mirror separations not being exactly 5m. The integrating action of the feedback system reduces the effect of these reflections and thus the system crosstalk. This crosstalk may be further reduced by slightly shortening the timing control signal to the receiving switch, while maintaining the same central time of the pulse.

Conclusions: A high resolution multiplexed strain-sensing system has been demonstrated using subcarrier interferometry and time division multiplexing. This method of selecting adjacent reflectors has the potential for low levels of crosstalk with high accuracy measurement using a simple optical system. Initial measurements have demonstrated a resolution of 20µm.

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