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Simultaneous spatial, time and wavelength division multiplexed in-fibre grating sensing network

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Abstract

A simultaneous spatial, time and wavelength division multiplexing topology, with combination of a tunable wavelength filter and an interferometric wavelength scanner, is proposed to interrogate a range of in-fibre Bragg grating (FBG) sensors. An eleven-element FBG sensor network based upon this topology is demonstrated for quasi-static strain sensing. Preliminary experimental results show that a strain resolution of ~ 7 $\mu\epsilon$ with a ~ 30 Hz bandwidth (~ 1.3 $\mu\epsilon/\sqrt{\mathrm{Hz}}$) for quasi-static strain measurement has been obtained.

1. Introduction

In-fibre Bragg grating (FBG) sensors appear to be ideally suited for structural health monitoring of modern composite materials and civil engineering-based applications as they have the potential of offering many distinct advantages over conventional electrical sensors: (i) immunity to electromagnetic interference; (ii) integration into composite materials or concrete without degration or significantly compromising the strength of the host material; (iii) significant advantages in cabling compared with electrical cables, such as smaller dimensions, low weight and cost; (iv) capacity of multiplexing many sensors in a single fibre lead, allowing quasi-distributed measurement; (v) capacity of mass-production with good repeatability, making them potentially competitive with conventional electrical sensors [1]. In order to monitor the induced strain in smart structures and skins with FBG, efficient quasi-distributed multiplexing networks are required. In principle, most multiplexing schemes developed for fibre-optic sensors, such as wavelength-division multiplexing (WDM), time-division multiplexing (TDM), and spatial-division multiplexing (SDM) [2–5], could be applied for FBG sensors. The series multiplexing topologies, such as WDM and TDM, which are based on a single fibre link arrangement, are very efficient in power usage. The parallel topologies, such as SDM, allow each FBG sensor in the network to be operated independently, interchangeable and replaceable in the event of damage. For practical applications, it is ideal to combine both series and parallel topologies to create a powerful two-dimensional quasi-distributed FBG sensor network.

Another key issue with FBG sensors is the high resolution required to detect the relatively small wavelength-shift of the FBG induced by strain or temperature (typically a few picometres for static measurement). Conventional optical spectrometers of monochromators cannot achieve the necessary high

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resolution hence new techniques have been introduced. These new techniques for high resolution wavelength-shift detection, include the use of matched filters [2,3], tunable filters [4], edge filters [6] and interferometric demodulation [7]. The interferometric approach can achieve very high resolution with a specified absolute measurement range mainly determined by the optical path difference (OPD) in the interferometer. In this paper, we propose and demonstrate a simultaneous SDM, TDM and WDM topology combined with a tunable wavelength filter (TWF) and an interferometric wavelength scanner (IWS). This (SDM+TDM+WDM) topology combines the advantages of both the series and parallel topologies creating an efficient 2-D quasi-distributed FBG sensor network which can be applied to many applications. Both the TWF and the IWS are combined to act as a tunable IWS which is located immediately after the broadband source rather than in front of the detector to allow all the FBG elements with similar wavelengths and positions on all the fibre sensing channels to be interrogated simultaneously. In operation, the TWF is used to select specified FBG elements with different centre wavelengths along a single sensing fibre, whereas the IWS, arranged after the TWF, is used to achieve high resolution and high speed wavelength-shift measurement by precisely detecting the phase change induced by the wavelength-shift of the FBG. An eleven-element FBG sensor system based upon this topology has been demonstrated for quasi-static strain sensing.

2. Topology

Fig. 1 shows the general concept of this (SDM+TDM+WDM) topology proposed. Light from a broadband source is launched into the network. Each grating element along a single fibre channel is written at a different centre wavelength which is chosen such that under maximum strain conditions, none of the grating wavelengths overlap. The TWF is used for wavelength-division addressing of individual FBG's in the system and hence its bandwidth normally determines the overall measurement range of each FBG sen-

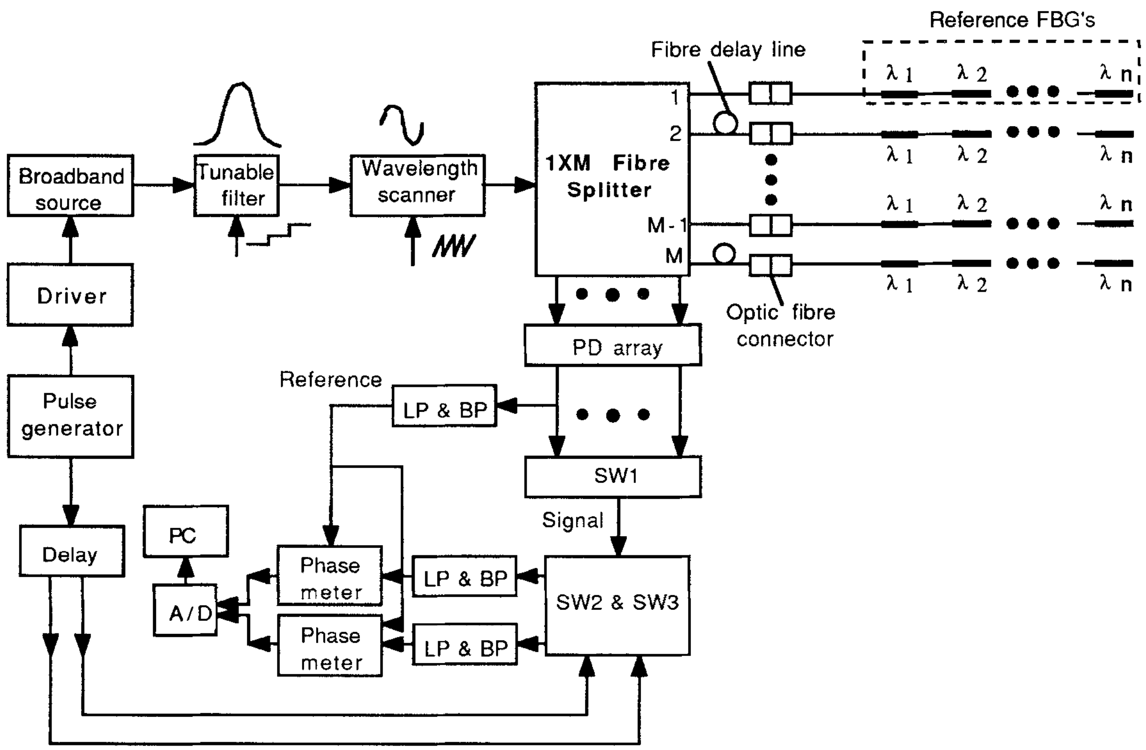

Fig. 1. Proposed high-resolution SDM, TDM and WDM system.

sor. However, the absolute measurement range of each FBG is also determined by the free spectral range (FSR) of the IWS which is based on an unbalanced interferometer with signal processing under a pseudo-heterodyne technique [8]. Ideally, the bandwidth of the TWF can be arranged to be identical with the FSR of the IWS. With the TWF tuned to match the centre wavelength of the sensing FBG, the maximum interference signal occurs. The amplitude of the interference signal decreases when a strain is applied to the FBG. This amplitude change is determined by the spectral envelope of the TWF and it should not have an influence on the measurement accuracy as only the phase change induced by the wavelength-shift of the FBG is detected. The IWS is modulated by using a ramp (serrodyne) function. By detecting the differential phase between the sensing FBG and the reference FBG with similar centre wavelength, the thermal drift of the TWF and the IWS can be eliminated [7]. This is achieved by bandpass filtering at the fundamental frequency of the serrodyne signal; the relative phases of the sinusoidal outputs corresponding to each sensing FBG and reference FBG are then detected with a phase meter. The output signals from the phase meter are sent to a PC via an analogue-to-digital converter (A/D). The TWF is then tuned to next sensing FBG and a phase reading is again obtained. This process is repeated for other subsequent FBG's in the network.

In order to achieve 2-D quasi-distributed strain measurement, the SDM topology described in reference [5] is combined with TDM and WDM topologies. At each output port of the fibre splitter, the FBG's can be arranged to be multiplexed in time or in wavelength or their combinations. Also, the centre wavelengths of the FBG's at corresponding locations on each single fibre channel can be arranged to be identical with each other, permitting each single fibre channel to be interchangeable or replaceable in the event of damage. TDM is incorporated in the network in order to separate the return pulse signals from the FBG's along the two adjacent output ports, where each port contains two fibre transmission lines with a differential delay length with connection to a specially-designed 1XM fibre splitter as shown in Fig. 2. The return pulse signals reflected by the FBG sensors are directed via the fibre splitter to an array of photodetectors (PD). The signals from the PD array are selected by using a switch (SW1). Thus each PD receives the returned signals from two fibre channels both containing N FBG's, where the signals from channel i and $i+1$ are separated in time (here $i=1, \ldots, M$ and M is the number of channels). These signals are demultiplexed using two high speed switches (SW2 and SW3) controlled by the delayed electric pulses produced by the pulse generator as shown in Fig. 1. The output signals of all the FBG's ($\lambda_1, \ldots, \lambda_n$) along each single fibre channel are demultiplexed sequentially in wavelength by setting the TWF at the mean wavelengths of the 1 to N FBG's by applying a stepping voltage to the TWF.

3. Experiment

The schematic diagram of the (SDM+TDM+WDM) system demonstrated is shown in Fig. 3. The light source used was a pigtailed temperature-stabilized superluminescent diode (SLD) with a bandwidth of ~18.5 nm (818–836.5 nm), supplied by Superlum Ltd (Russia). It was pulsed at a frequency of ~1.1 MHz with a pulse width of ~300 ns (duty cycle: ~1/3); an average output optical power of ~2 mW was launched into the network. The TWF used here was a Fabry–Pérot filter (FPF) (Queensgate Instruments QF100) with a free spectral range of 40 nm, a bandwidth of ~0.65 nm and a scale factor of 11.43 nm/V. The IWS was a bulk Michelson interferometer also developed by Queensgate Instruments Ltd., in which the piezoelectrical transducer (PZT) in one of the arms of the IWS was driven by a ramp (serrodyne) modulation function at a frequency of 300 Hz. The OPD of the IWS used here was set at ~0.7 mm (equal to a FSR of ~0.98 nm). As the bandwidth of the FPF is smaller than the FSR of the IWS, the absolute measurement range of this system is limited to ~0.65 nm. This range can be increased by altering the FSR of the FPF (not possible with the device used). The commercial 1 × 8 fibre-optic splitter shown in the inset of Fig. 3 was specially designed for this demonstration system. Although the total number of the FBG's which can be multiplexed in this network could be quite large in principle, only eleven FBG elements ($\lambda_1, \ldots, \lambda_{11}$) were deployed in this network as indicated in Fig. 3 due to limited number of FBG's available when the experiment was carried out (it would be straightforward to incorporate a further eleven FBG's by duplicating part of the network without any reduc-

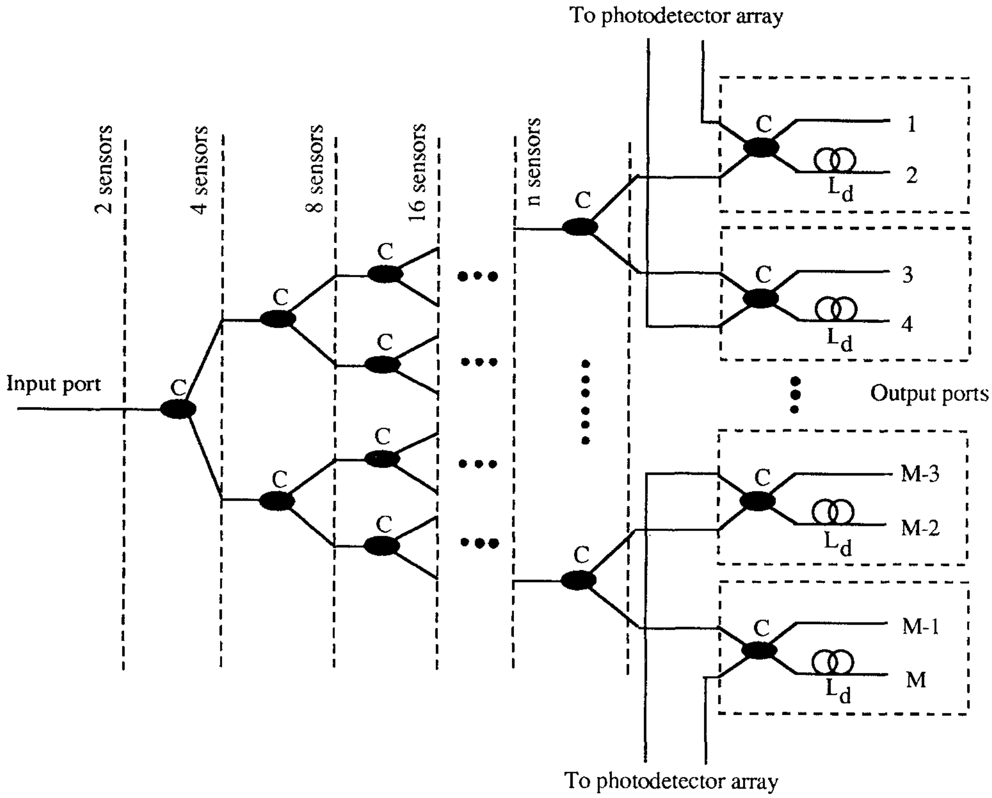

Fig. 2. Schematic diagram of the 1XM fibre splitter with fibre delay lines.

tion in SNR of each sensor as also indicated in Fig. 3). The return pulse signals from the FBG sensors were coupled back into the splitter and detected by an array of four avalanche photodetectors (APD) followed by integral separated high speed amplifiers (10 MHz). The nominal Bragg wavelengths (λ_1, ..., λ_{11}) of the eleven FBG elements were between ~825 nm and ~837 nm, with a spectral bandwidth of ~0.2 nm. The resolution of the phase meter was 0.1 degree, corresponding to a wavelength-shift detection resolution of $\sim 0.27\times10^{-3}$ nm for the FSR of the IWS (0.98 nm).

To show the operation of WDM, the detected wavelength distribution of three FBG's (λ_3, ..., λ_5) along a single fibre channel are shown in the upper trace in Fig. 4. The differences between the amplitudes of these reflection spectra are mainly due to different peak-reflectivities of these FBG's and different locations in the spectral envelope of the source. It was found that $\lambda_3 = 825.8$ nm, $\lambda_4 = 830.5$ nm and $\lambda_5 = 836.8$ nm. The length of the fibre delay lines shown in Fig. 3 was ~40 m, corresponding a time delay of ~400 ns. The detected pulse signals reflected from FBG's 3 to 7 are shown in the upper trace in Fig. 5a and those from FBG's 8 to 11 are also shown in the lower trace. In addition, the demultiplexed signals (after low-pass filtering), corresponding to FBG's 3 and 4, obtained by tuning the FPF to match FBG's 3 and 4 in turn are shown in Fig. 5b. This verifies that with TDM and WDM the phase changes of FBG's at each output port of the splitter can be recovered. Crosstalk between two adjacent TDM channels was measured to be < -36 dB.

To investigate the resolution of this system for quasi-static strain measurement, several ~0.5 Hz strain steps of ~28 $\mu\epsilon$ peak-to-peak amplitude were applied to one of the sensing FBG's ($\lambda_4 = 830.5$ nm), using three-point bending. The experimental results are shown in Fig. 6 (here the strain-to-phase shift responsivity of these FBG's has been precisely measured to be ~237 degree/mϵ [9]). As can be seen from these results, a

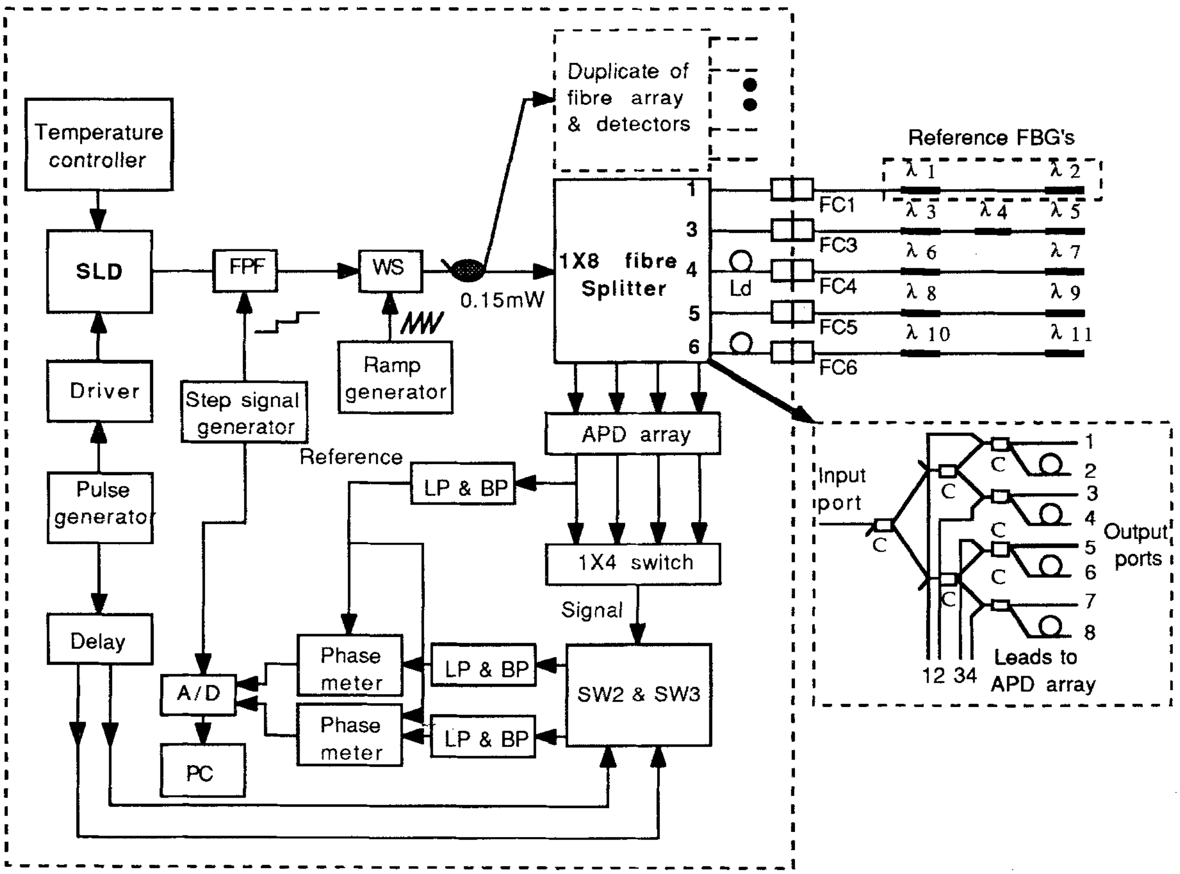

Fig. 3. Schematic diagram of the demonstration system.

resolution of ~7 $\mu\epsilon$ was achieved with a 30 Hz measurement bandwidth.

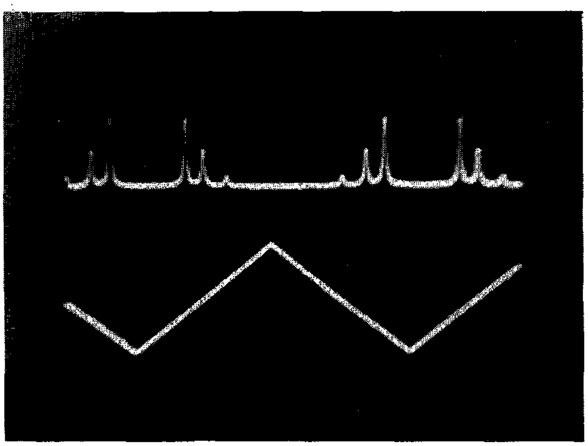

Fig. 4. Detected reflection spectra from grating 3 to 5.

4. Conclusion

In summary, we have described a simultaneous spatial, time and wavelength division multiplexing topology with a combination of a tunable wavelength filter and an interferometric wavelength scanner. An eleven-element grating sensor network is demonstrated based upon this topology. In principle, the network can be extended to support many more FBG sensors without effecting the SNR of each sensor. The preliminary experimental results show that a strain resolution of ~7 $\mu\epsilon$ with a ~30 Hz bandwidth (~1.3 $\mu\epsilon/\sqrt{\text{Hz}}$) for quasi-static strain measurement has been achieved. This multiplexing topology not only takes the advantages of SDM, TDM and WDM topologies, but also combines the advantages of the tunable filter used for selection of FBG sensors, and the interferometric wavelength scanner used to achieve high resolution and high

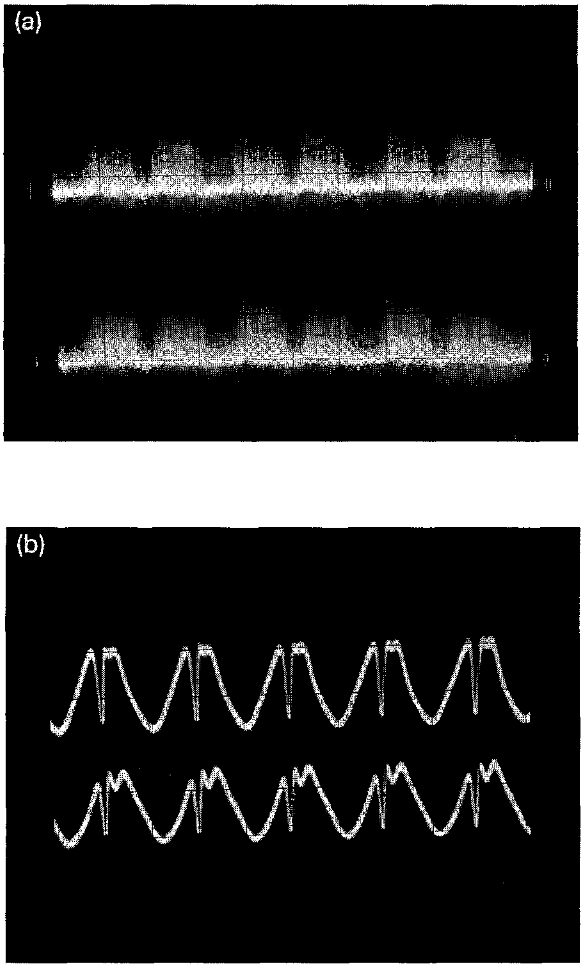

Fig. 5. Experimental waveforms. (a) Photodetected return pulse signals. The upper trace is pulses from grating 3 to 7 and the lower trace is pulses from gratings 8 to 11. (b) Demultiplexed signals (after low-pass filtering) for gratings 3 and 4 with WDM and TDM.

speed wavelength-shift detection, hence creating an efficient 2-D quasi-distributed network for FBG sensors. Furthermore, the centre wavelengths of the FBG's on each fibre channel could be arranged to be identical with those on other fibre lines in the network and this allows easy sensor array interchange and replacement in the event of damage, which is very important for those practical applications where safety is critical.

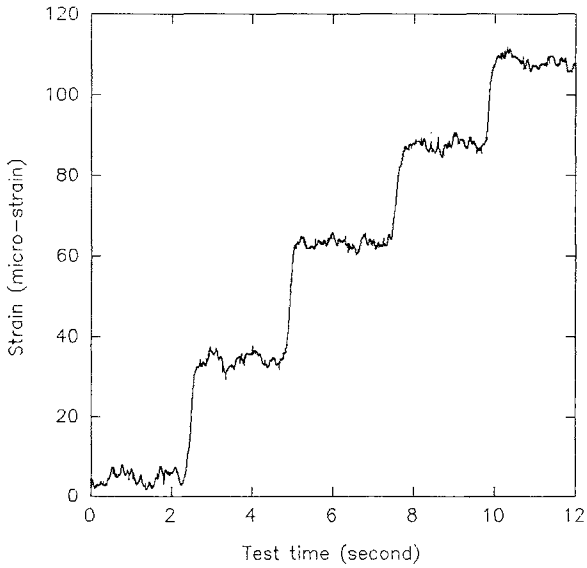

Fig. 6. Experimental results for the quasi-static strain measurement.

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