

SIMULTANEOUS INTERROGATION OF MULTIPLE FIBER BRAGG GRATING SENSORS FOR DYNAMIC STRAIN MEASUREMENTS

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A fiber Bragg grating (FBG) sensor system for multi point, dynamic strain or temperature measurement is reported. The system uses a combination of an unbalanced fiber interferometer and phase locked loops and is capable of measuring dynamic signals with frequencies ranging from 100 Hz to 10 kHz. Strain measurements with both serial and parallel FBG sensor arrays demonstrate strain resolution of better than $27.5 \text{ n}\epsilon/\sqrt{\text{Hz}}$ and measurement range of 0-3400 $\mu\epsilon$ at 10 kHz.

(Received October 27, 2002; accepted November 4, 2002)

Keywords: Fiber optic sensors, Fiber Bragg gratings, Strain measurements, Temperature measurements

1. Introduction

Fiber Bragg grating (FBG) sensors have been considered excellent sensing elements for both static and dynamic measurands such as temperature, strain and pressure [1]. The wavelength-encoded nature of FBG sensors make them independent of fluctuating light levels due to for example source power variations and/or connector losses, and being conveniently multiplexed using wavelength-division multiplexing (WDM). Numerous schemes have been proposed to interrogate FBG sensors. These include the use of edge filter, tunable filter, interferometric detection, tunable laser, CCD spectrometer, etc [1]. In this letter, we report the development of a multi-point, dynamic strain/temperature measurement system based on the interferometric principle [2] and phase locked loop (PLL) detection. The system is designed for the study of heat transfer in non-stationary flow field [3] and for flow-induced vibration measurements [4].

2. The interrogation system

A schematic of the multi point sensor system is shown in Fig. 1. Light from a superluminescent light emitting diode (SLED) with a spectral width of 50 nm is used to illuminate the FBG sensor array via a 50/50 coupler. The sensor array consists of up to 4 FBG sensors, each of a different wavelength. The FBGs can be connected in serial along the same fiber (Fig.1) or in parallel through the use of a star coupler. Light reflected from the sensor array passes through the same coupler and is fed into a fiber Mach-Zehnder interferometer (MZI). The optical path difference (OPD) of the MZI is 0.8 mm and much less the coherence length of the reflected light from the FBG sensors. Most of the FBGs for sensing applications are of spectral width from 0.1 to 0.3 nm, corresponding to coherence lengths of 2.4 cm to 0.8 cm. An integrated optical phase modulator (IOPM) is placed in one arm of the MZI and used

to produce a serrodyne phase modulation at a repetition frequency of 100 kHz. The peak-to-peak phase excursion of the serrodyne modulation is set to be 2π to facilitate heterodyne signal processing [5].

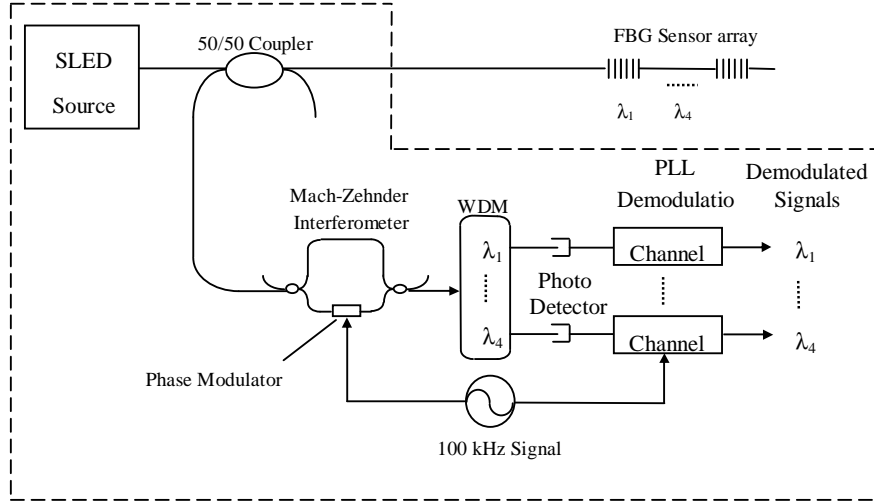
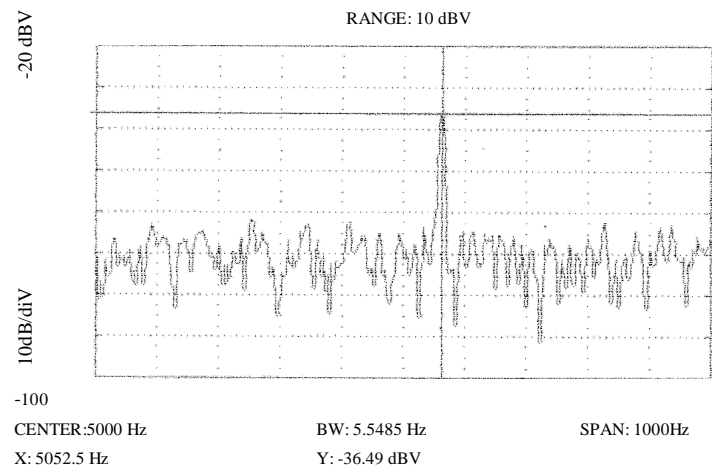


Fig. 1. The four channel dynamic strain/temperature system.

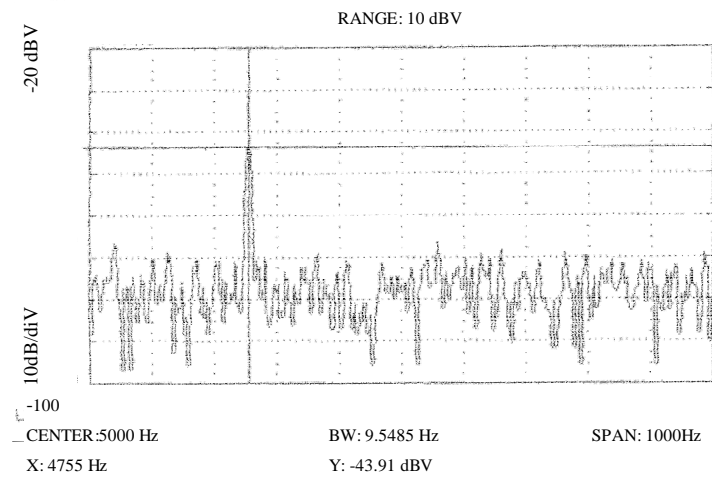
The serrodyne interferometric process simultaneously converts the measurand-induced Bragg wavelength shifts of all the FBG sensors in the array to phase difference variations between the two interferometer arms and further into phase shifts of the serrodyne signals at the interferometer output. The interferometer output is a composite signal consists of serrodyne signals from all the sensors within the array. All these signals are of the same frequency (i.e., 100 kHz) but with different optical wavelengths λ_{B1} , λ_{B2} , λ_{B3} , and λ_{B4} , corresponding to the four different sensors. The output from the MZI is coupled to a 4-channel WDM to separate the serrodyne signals from the four sensors, and output from each of the WDM channels was detected by an independent photodetector. The passing bands of the WDM were specified, by the manufacture, to be 1530–1534 nm, 1539–1543 nm, 1548–1552 nm and 1557–1561 nm, with inter-channel crosstalk of below -35 dB. Following each photodetector, a PLL is used to recover the measurand-induced Bragg wavelength shift of that particular channel from the corresponding serrodyne signal. The PLL circuits were designed to work around the serrodyne frequency (100 kHz). The performances of the PLLs were found to be dependent of the frequency of the measurand. The minimum detectable phase resolutions of the PLLs were measured to be ~ 0.003 degree/ $\sqrt{\text{Hz}}$ at 10 kHz, and reduced to ~ 0.025 degree/ $\sqrt{\text{Hz}}$ and ~ 0.56 degree/ $\sqrt{\text{Hz}}$ respectively at 1 kHz and 100 Hz. These phase resolutions correspond to strain resolutions of 20.3 $n\epsilon/\sqrt{\text{Hz}}$, 175 $n\epsilon/\sqrt{\text{Hz}}$ and 3.8 $\mu\epsilon/\sqrt{\text{Hz}}$, respectively. The measurement ranges of the four PLLs are all beyond 500 degrees within frequency range from 100 Hz to 10 kHz, corresponding to strain measurement range of over 3400 $\mu\epsilon$. This system can be used to interrogate 1 to 4 sensors, connected either in serial or parallel, with the aforementioned performance.

3. Dynamic strain measurements

Strain measurements were carried out with the system shown in Fig. 1. During measurements, only two sensors, FBG₁ and FBG₂, were connected. The nominal Bragg wavelengths of the two FBGs are 1531.6 nm and 1550.2 nm, respectively. The full-width at half-maximum (FWHM) and the reflectivities of the two FBGs are 0.2 nm and 90% respectively.



a



b

Fig. 2. Experimental results of a 2-sensor array. Output from channel 1 (a) and channel 2 (b) when dynamic strains of $\sim 3 \mu\epsilon$ peak to peak with frequencies of 5.06 kHz and 4.76 kHz were applied to FBG₁ and FBG₂, respectively.

The performance of the system was evaluated by applying the dynamic signals to each of the two sensors. Fig. 2 (a,b) show typical outputs from the two channels recorded using a dynamic signal analyzer, when dynamic strains of $3 \mu\epsilon$ peak-to-peak value at frequencies of 5.06 kHz and 4.76 kHz were applied respectively to FBG₁ and FBG₂. The noise limited strain resolution corresponding to signal to noise ratio of 1 were calculated to be $27.5 \text{ n}\epsilon/\sqrt{\text{Hz}}$ and $30.5 \text{ n}\epsilon/\sqrt{\text{Hz}}$ for FBG₁ and FBG₂, respectively.

Fig. 3 shows the output from the two channels when the two dynamic strains with $2 \mu\epsilon$ peak-to-peak at the frequencies of 9.22 kHz and 9.73 kHz were simultaneously applied to FBG₁ while a strain of the same amplitude ($2 \mu\epsilon$) at the frequencies of 9.455 kHz was applied to FBG₂. The noise limited strain resolutions for the two channels and for three frequencies are all better than $25.8 \text{ n}\epsilon/\sqrt{\text{Hz}}$. Experiments were also conducted with a 2-sensor parallel array, similar results were obtained.

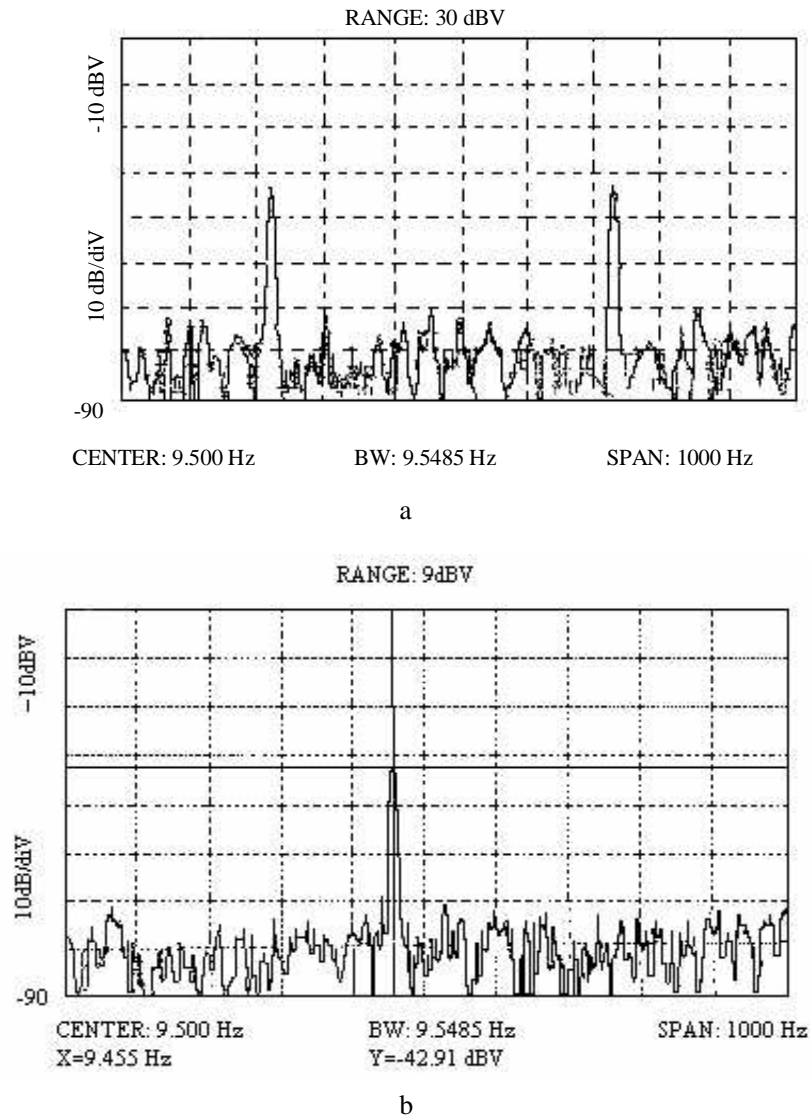


Fig. 3. Experimental results of a 2-sensor array. Output from channel 1 (a) and channel 2 (b) when dynamic strains of $\sim 2 \mu\epsilon$ peak to peak with frequencies of 9.22 kHz and 9.73 kHz were applied to FBG₁, and a dynamic strain of $\sim 2 \mu\epsilon$ peak to peak with frequencies of 9.455 kHz was applied to FBG₂.

4. Summary

We have demonstrated the simultaneous interrogation of FBG sensors using an unbalanced interferometer and PLL detection. Experiments with 2-sensor serial and parallel arrays connected in serial or parallel demonstrated noise limited strain resolution of better than $27.5 \text{ n}\epsilon/\sqrt{\text{Hz}}$ and measurement range of $3400 \mu\epsilon$ at 10 kHz. The system can be used to measure dynamic strains or temperature within 100 Hz to 10 kHz frequency range at up to 4 points. The system is currently used for the measurement of fluctuating strains and temperatures in the study of flow induced vibration around cylinders.

Acknowledgements

This work was supported by the Hong Kong SAR government through a CERG grant PolyU5105/99E and by the Hong Kong Polytechnic University through grant G-YW54.

References

- [1] A. Othonos, K. Kalli, Fiber Bragg Gratings: Fundamentals and Applications in Telecommunications and Sensing, Artech House Press, (1999).
- [2] A. D. Kersey, Journal of Lightwave Technology, **15**, 1442, (1997).
- [3] Y. Zhou, Z. J. Wang, R. M. C. So, S. J. Xu, W. Jin, Journal of Fluid Mechanics, **443**, 197, (2001).
- [4] Y. Zhou, R. M. C. So, W. Jin, H. G. Xu, P. K. C. Chan, Experiments in Fluid, **27**, 359, (1999).
- [5] D. A. Jackson, A. D. Kersey, M. Corke, J. D. C. Jones, Electronics Letters, **18**, 1081 (1982).