IEEE PHOTONICS TECHNOLOGY LETTERS, VOL. 8, NO. 5, MAY 1996

Photorefractive Volume Holographic Demodulation of In-Fiber Bragg Grating Sensors

Stephen W. James, Michael L. Dockney, and Ralph P. Tatam

***Abstract*—A demodulation scheme for an in-fiber Bragg grating sensor using a volume holographic filter formed in photorefractive $BaTiO_3$ is proposed and demonstrated. A strain range of 2500 μstrain, with minimum detectable strain of 4 μstrain/$\sqrt{\text{Hz}}$, is measured. Extension of the technique to allow demodulation of arrays of sensors is discussed.**

I. INTRODUCTION

THE potential of in-fiber Bragg gratings for use in quasidistributed fiber sensor systems is widely recognized. Large arrays of gratings may be written within a single length of fiber, with each grating acting as an independent point sensor for temperature and strain.

A number of techniques for the interrogation and demultiplexing of arrays of Bragg gratings have been proposed. Interrogation of the gratings involves the determination of the shift in Bragg wavelength induced by the measurand. This has been achieved using edge filters [1], matched receiving gratings [2], tunable filters [3], [4], and interferometric techniques [5]. Uniquely identifying the gratings within the array is generally achieved by wavelength division multiplexing. The grating array is addressed with a broad-band source with each grating assigned a wavelength region that allows the measurand to be demodulated with no crosstalk between sensor elements. The gratings may be addressed serially, using a scanning Fabry–Perot [3], or in parallel, using an array of matched receiving gratings [2], interference filters [1] or an acoustooptic tunable filter [4]. The serial techniques suffer from a limited bandwidth for detecting dynamic measurands. The use of matched receiving gratings or filters produces a complicated fiber network which makes inefficient use of the available reflected signal.

Volume holograms would appear to be attractive optical elements for demultiplexing Bragg grating arrays. They may be used to form spectral filters, the bandwidth of the filter depending upon the recording geometry [6], and large arrays of such filters may be multiplexed within a *single* optical component. In this letter a novel method for parallel interrogation and demultiplexing of an array of Bragg gratings using a volume holographic spectral filter bank is presented. The concept of the technique is illustrated in Fig. 1. An array of volume holograms is written using a combination of wavelength and angular multiplexing [7], as shown in Fig. 1(a). The reference beam direction for each of the holograms is identical, but a different angle of incidence is used for the object beams. The wavelength for each object beam is chosen to be related to the quiescent state of one of the Bragg gratings within the sensor array. The holograms are written such that their bandwidth exceeds the range of the Bragg wavelength shift to be induced by the measurand. The holograms may be permanently fixed within the material, such that once the spectral filter bank has been recorded there is no further requirement for the writing source. A broad-band source is used to address the Bragg gratings, and the reflected signals illuminate the volume hologram from the direction of the reference beam. The signal from each of the Bragg gratings is diffracted into a unique angle defined by angular-wavelength multiplexing of the holograms, with the diffraction efficiency being dependent

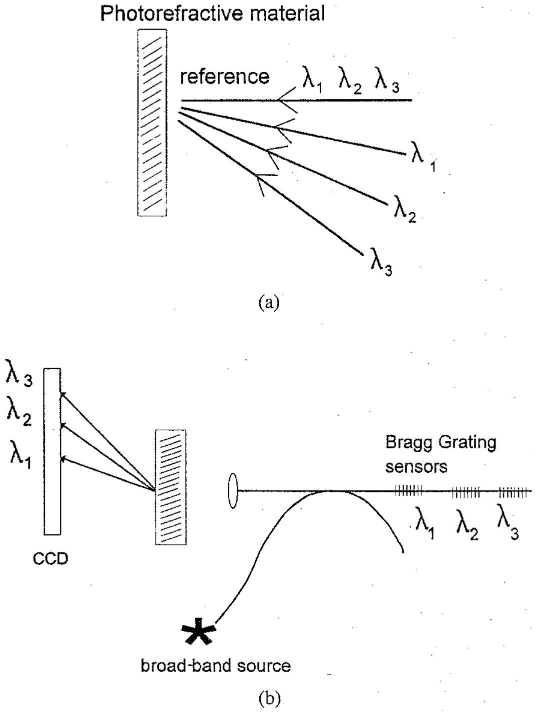

Fig. 1. Concept of the proposed Bragg grating sensor demultiplexing scheme. (a) Recording the holographic filter bank using wavelength-angular multiplexing. (b) Illuminating the filter bank with the reflected Bragg grating signals angularly separates the signals. The diffracted power depends upon the Bragg wavelength shift.

Manuscript received January 2, 1995; revised February 6, 1996. One of the authors, S. W. James, was supported by the Royal Society Grant RSRG 14170. One of the authors, M. L. Dockney, was supported by an Engineering and Physical Sciences Research Council CASE studentship in association with British Aerospace Ltd.

The authors are with the Optical Sensors Group, Center for Photonics and Optical Engineering, Cranfield University, Cranfield, Bedford, MK43 OAL, U.K.

Publisher Item Identifier S 1041-1135(96)03574-4.

1041–1135/96$05.00 © 1996 IEEE

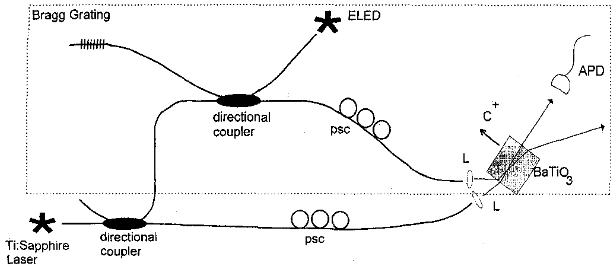

Fig. 2. Experimental Configuration. psc, polarization state controller; *L*, lens; APD, avalanche photodiode. c^+ indicates the orientation of the optical axis of the $BaTiO_3$ crystal. The sensor system comprises only the components within the box. The Ti : Sapphire laser source is required only during the recording of the hologram. In a practical system the hologram would be permanently fixed within the material, such that the tunable laser would not be required in the field.

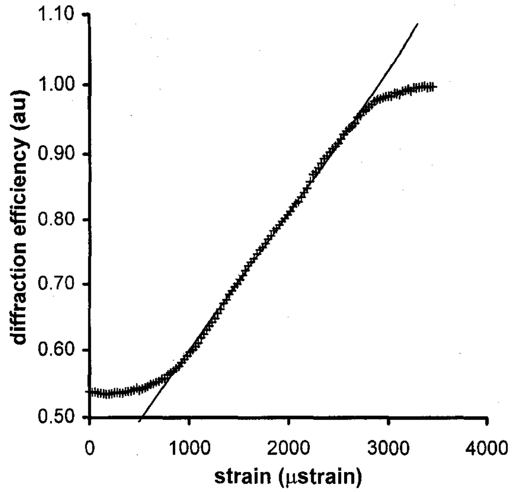

Fig. 3. DC strain response of the demodulation scheme. The solid line is a fit to the linear portion of the transfer function. The measurement range is 2500 μstrain, with 18 μstrain rms deviation.

upon the wavelength shift induced by the measurand. The Bragg grating wavelength shift is thus transduced into a change in diffracted power by the transfer function of the volume hologram, while the holographic filter bank angularly separates the signals from each of the sensors.

Recently there has been renewed interest in the use of photorefractive materials for volume holographic data storage. Photorefractive materials offer the ability to form read/write volatile memory systems, or permanent memories by fixing the holograms [8]. A number of multiplexing architectures have been proposed, including angular, spatial and wavelength, which use the high angular and wavelength selectivity of volume holograms to produce high density data storage systems [9].

For transmission volume holograms, the angular and wavelength selectivity (the separation of the first zeros in the diffraction efficiency with respect to the Bragg angle and wavelength, respectively), $\Delta\theta$ and $\Delta\lambda$, are given by [10]

$$\Delta\theta = \frac{n\lambda}{2d\sin\theta} \tag{1}$$

$$\Delta\lambda = \frac{\lambda^2\cos\theta}{2d\sin^2\theta}, \tag{2}$$

where n is the refractive index, d the length of the hologram, θ the half angle between object and reference beams, and λ the wavelength.

Thus, for a hologram of length 1 mm written in photorefractive $BaTiO_3$, $n = 2.424$, at an angle of 30°, and wavelength of 840 nm, the angular selectivity is 4 mrad, and the wavelength selectivity is 5 nm. The high angular selectivity of the holograms allows the construction of a compact detection system, possibly using a linear CCD array.

A Bragg grating was fabricated in hydrogen loaded Spectran fiber (FS SMC-AO780B) with 60% reflectivity at 840 nm, and 0.5 nm FWHM. The experimental configuration for writing the volume holographic database is shown in Fig. 2. The output from a Ti : Sapphire laser was divided at a 3 dB fiber coupler, with the outputs focused into a 5 mm × 5 mm × 5 mm crystal of Rhodium doped $BaTiO_3$ such that they crossed at an angle of 30°. The Ti : Sapphire was tuned to a wavelength chosen such that, in its quiescent state, the reflected signal from the fiber Bragg grating would lie midway up the positive slope of the hologram transfer function. The crystal was exposed for 30 s at an intensity of 0.1 W/cm^2, producing holograms with 10% diffraction efficiency and 2-nm FWHM. In this experiment the hologram was not fixed within the crystal, as the decay time of the hologram, when illuminated solely by the signal reflected from the Bragg grating, was in excess of three hours, sufficient to perform the measurements.

With the Ti : Sapphire beams blocked the fiber Bragg grating was addressed using an ELED, centered at 840 nm, with a bandwidth of 50 nm and output power of 0.5 mW, which was launched into the 3 dB coupler, as illustrated in Fig. 2. The power incident upon the Bragg grating was 1 μW, limited by the poor launch efficiency achieved form the highly divergent source. The signal reflected from the Bragg grating illuminated the hologram, and the diffracted light was observed on an appropriately positioned avalanche photodiode (APD).

Lock in detection was used by square wave modulating the ELED injection current at 1 kHz. Fig. 3 shows the variation of the diffracted power as a function of the strain applied to the fiber, illustrating a measurement range of 2500 μstrain with 18 μstrain rms deviation. The response of the system to dynamic strain was investigated by applying a sinusoidal signal to a piezoelectric stretcher, which was modulated at a frequency of 0.3 Hz. A typical spectrum analyzer trace is shown in Fig. 4. The minimum detectable strain was measured at 4 μstrain/$\sqrt{\text{Hz}}$. The response of the system is determined by the characteristics of the volume hologram, which may be written to meet a specific requirement.

The use of volume holograms as spectral filters for demodulating in-fiber Bragg grating sensors has a number of advantages over previously reported techniques. The properties of the hologram may be tailored to the application, allowing high sensitivity or large dynamic range. All of the filters required to demodulate an array of sensors may be stored within a single, passive, optical element. The Bragg gratings are interrogated in parallel, with no crosstalk. If photorefractive materials are used, the holograms may be

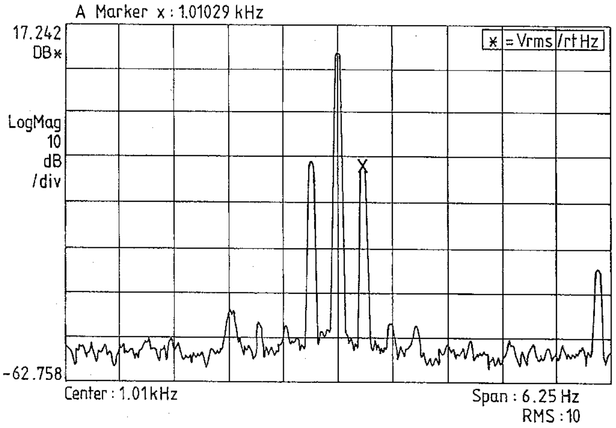

Fig. 4. Spectrum analyzer trace illustrating the response to dynamic strain. The ELED was modulated at 1 kHz. A peak strain modulation of 370 μstrain at 0.3 Hz was applied to the Bragg grating. The minimum detectable signal is 4 μstrain/$\sqrt{\text{Hz}}$.

fixed, or be updateable, and may also be tuned using electric fields. The use of photorefractive materials does present a number of issues. The diffraction efficiency is sensitive to the polarization of the reflected signal, although polarization changes were not observed in the laboratory. While, in this investigation, the hologram was not permanent, in a practical system the holographic spectral filter bank would be a array of permanent holograms, fixed within the material. Since diffraction efficiency of the photorefractive volume hologram is independent of the writing power [10], a low powered tunable laser diode could be used in place of the Ti : Sapphire laser. While, in many practical sensor systems, photorefractive materials may not be the optimum holographic medium, they are possibly the most flexible of holographic media, and have been used in this instance to demonstrate the potential of the use of volume holograms in demodulating in-fiber Bragg grating sensors.

Intensity referencing, to remove ambiguities arising from changes in source intensity, down lead losses and polarization, may be readily achieved using a second set of angular-wavelength multiplexed holograms written in the same crystal such the Bragg grating wavelengths sit on the negative slope of the holograms' transfer function. The signal from each sensor would then be diffracted in two directions, the ratio of the diffracted signals giving the measurand induced wavelength shift with double the sensitivity.

In summary, a novel fiber Bragg grating sensor demodulation scheme using a photorefractive hologram has been described. A strain measurement range of 2500 μstrain was achieved with resolution of 4 μstrain/$\sqrt{\text{Hz}}$. The resolution and measurement range may be tailored to the application by appropriate choice of hologram characteristics. The extension of the technique to allow demultiplexing of arrays of fiber Bragg grating sensors using a single optical component consisting of angular-wavelength multiplexed volume holograms, and an intensity referencing technique, have been proposed.

REFERENCES

[1] R. M. Measures, S. Melle, and K. Liu, "Wavelength demodulated Bragg grating fiber optic sensing systems for addressing smart structure critical issues," *Smart Mater. Structure,* vol. 1, pp. 36–44, 1992.

[2] D. A. Jackson, A. B. Lobo Ribeiro, L. Reekie, and J.-L. Archambault, "Simple multiplexing scheme for a fiber optic grating sensor network," *Opt. Lett.,* vol. 18, pp. 1192–1194, 1993.

[3] A. D. Kersey, T. A. Berkoff, and W. W. Morey, "Multiplexed fiber Bragg grating strain sensors system with a fiber Fabry–Perot wavelength filter," *Opt. Lett.,* vol. 18, pp. 1370–1372, 1993.

[4] M. G. Xu, H. Geiger, J.-L. Archambault, L. Reekie, and J. P. Dakin, "Novel interrogating system for fiber Bragg grating sensors using an acousto-optic tunable filter," *Electron. Lett.,* vol. 29, pp. 1510–1511, 1993.

[5] A. D. Kersey, T. A. Berkoff, and W. W. Morey, "High resolution fiber grating based strain sensor with interferometric wavelength shift detection," *Electron. Lett.,* vol. 28, pp. 236–238, 1992.

[6] G. A. Rakuliic and V. Leyva, "Volume holographic narrow band optical filter," *Opt. Lett.,* vol. 18, pp. 459–461, 1993.

[7] S. Campbell, X. Yi, and P. Yeh, "Hybrid-sparse wavelength angle multiplexed optical data storage system," *Opt. Lett.,* vol. 19, pp. 2161–2163, 1994.

[8] P. Gunter and J.-P. Huignard, Eds., "Photorefractive materials and their applications I: Fundamental phenomena,"*Topics in Applied Physics.* Berlin: Springer-Verlag, 1988, vol. 61.

[9] S. Tao, D. R. Seviah, and J. E. Midwinter, "Spatio-angular multiplexed storage of 750 holograms in an Fe-$LiNbO_3$ crystal," *Opt. Lett.,* vol. 18, pp. 912–914, 1993.

[10] P. Gunter, "Holography, coherent light amplification and optical phase conjugation," *Phys. Rep.,* vol. 93, pp. 199–299, 1982.