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A Wideband Interferometric Wavelength Shift Demodulator of Fiber Bragg Grating Strain Sensor

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The performance of a fiber Bragg grating strain sensor constructed with 3 × 3 coupler is investigated. A 3 × 3 coupler Mach-Zehnder (M/Z) interferometer is used as wavelength discriminator, interrogating strain-induced Bragg wavelength shifts. Two quadrature-phase-shifted intensities are synthesized from the ac-coupled interferometer outputs, and digital arctangent demodulation and phase unwrapping algorithm are applied to extract the phase information proportional to strain. Due to the linear relation between the input strain and the output of quadrature signal processing, signal-fading problems are eliminated. In the experiment, a fiber grating that was surface adhered on an aluminum beam was strained in different ways, and the photodetector signals were transferred and processed in a computer-controlled processing unit. A phase recovery of 7.8π *pk-pk* excursion, which corresponds to ~650 μstrain *pk-pk* of applied strain, was demonstrated. The sensor system was stable over the environmental intensity perturbations because of the self-referencing effect in the demodulation process.

I. INTRODUCTION

The fiber Bragg grating has attracted considerable interest in various sensing applications since the first demonstration of its easy fabrication method [1]. The physical quantities to be measured, such as strain or temperature, change the refractive index and/or physical dimension of a fiber grating, encoding the measurand to Bragg wavelength shifts. To decode this information effectively, a number of wavelength shift detection schemes have been developed [2–7]. Among the techniques, the interferometric systems have provided the highest sensitivity [3–5]. When the spectral width of the reflected Bragg spectrum is narrower than that of the interferometer's transmission band, the positive and negative slopes of the transfer function can be used as effective wavelength discriminators, converting wavelength deviations to variations of the transmitted optical intensity. The slopes can be adjusted to the optimum sensitivity by controlling interferometer parameters such as path length difference. However, the sensitivity of interferometric measurement fluctuates depending on the phase bias, which is easily influenced by environmental parameters such as temperature. Furthermore, there is a tradeoff between the sensitivity and the dynamic range of the measurement because of the interferometers' periodic transmission characteristic. By using wavelength filters [6,7] that have quasi-linear transmission characteristics with to wavelength variation, dynamic range can be substantially increased. However, their sensitivities cannot be comparable to those of interferometric sensors. Therefore, interferometer sensor systems without signal fading problems are desirable, and the solution can be found in quadrature signal processing.

Quadrature signal processing consists of two steps: getting quadrature-phase shifted signals and extracting the phase. Once quadrature signals are obtained, the phase extraction can be easily done by differentiate cross-multiply (DCM) [9] or arctangent demodulation, in analog and digitized signal processing schemes, respectively.

A number of quadrature signal generating techniques have been developed, and some of them can be used for fiber grating sensor demodulation. Koo *et al.* used a passive interferometer stabilization method using a 3 × 3 directional coupler and demonstrated an extended dynamic range of ~16 radian [8]. The phase generated carrier (PGC) demodulation proposed by Dandridge *et al.* [9] can be used in both quasi-static and dynamic sensing applications because the phase modulated intensity can be ac-coupled without affecting quasi-static phase variations. Recently Lo [5] proposed read-out Fabry-Perot cavities for Bragg wavelength shift interrogation. Two approximated quadrature signals were obtained from the cavity length matched Fabry-Perot interferometers. Although the technique demonstrated fairly high dynamic range as well as high sensitivity, quadrature condition mismatch occurs when a higher strain is loaded.

In this paper, we will describe and demonstrate a fiber grating strain sensor system that uses an unbalanced M/Z (Mach-Zehnder) wavelength discriminator in combination with quadrature signal processing. Koo's scheme of 3 × 3 directional coupler was selected as a quadrature signal generating technique and digitized arctangent demodulation was used for efficient data processing. Any electromechanical feedback to the optical circuitry or free space adjustment was not necessary because of the system's passive and all-fiber nature. Therefore, a simple, small size, rugged, all-fiber, and electrically isolated sensor system can be established for structural dynamic strain analyses. Also, this technique shows stable operation over the intensity perturbations of which effects are eliminated in the demodulation process.

II. QUADRATURE SIGNAL PROCESSING

The fiber Mach-Zehnder interferometer has been one of the most effective wavelength discriminators due to its simple and rugged configuration. When it is constructed with 2 × 2 couplers, the two outputs are precisely 180° out of phase; therefore, quadrature phase condition(90°) between two arms cannot be established. However, if the latter coupler is replaced with a 3 × 3 coupler as depicted in Fig. 1, the phase relations between the three outputs are determined by a set of differential equations as

$$\frac{dE_j}{dz} + iK_{j,j+1}E_{j+1} + iK_{j,j+2}E_{j+2} = 0, \qquad j = j+3,\ j = 1,2,3 \tag{1}$$

where E_j's are the input complex amplitudes, and $K_{ij}(= K_{ji})$ are the coupling coefficients between ith and jth arm. The general analysis of 3 × 3 coupler interferometers was performed by Sheem [10]. At first, he proposed to use a 3 × 3 coupler to obtain $\pi/2$ nonreciprocal phase bias in an optical gyroscope [11], and Koo *et al.* proposed a fiber interferometer stabilization method using this 3 × 3 coupler interferometer [8].

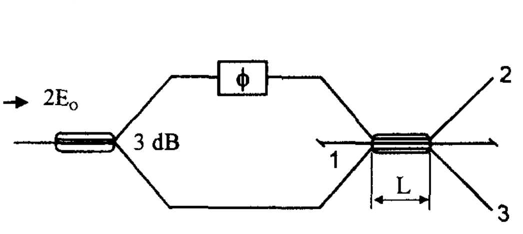

FIG. 1. Mach-Zehnder interferometer composed of a 1 × 2 input coupler and a 3 × 3 output coupler: L, coupling length; $2E_0$, input complex amplitude; ϕ, relative phase difference between two arms.

II. A. Generating Quadrature-Phase Shifted Signals

For simplicity, we assume the input coupler has 3 dB coupling loss and the K_{ij} of the 3 × 3 coupler are the same. When complex amplitude $2E_0$ is supplied to the input coupler, by solving Eq. (1), the output intensities of arm 2 and 3 will be

$$\begin{aligned} I_{2,3} = {} & (E_0^2/9) \times [7 + 2\cos(3KL) \\ & -2\cos\phi(1-\cos(3KL)) \mp 6\sin\phi\sin(3KL)] \end{aligned} \tag{2}$$

where L is the fused coupling length, and ϕ is the phase term that is modulated by the input light's wavelength variation and temperature drift. When $KL = 40°$, the three arms' coupling losses will be the same, and Eq. (2) can be simplified as

$$I_{2,3} = (E_0^2/3) \times \left(2 - \cos\phi \mp \sqrt{3}\sin\phi\right). \tag{3}$$

Then, adding and subtracting the photodetector outputs yields the sine and cosine terms. The dc terms in the quadrature signals should be removed before the signals are applied to arctangent demodulation. The dc biases can be set to zero in digital signal processing, but in that case, the bias setting should be updated to compensate the effects of possible input power fluctuations or environmental perturbations. Therefore, ac coupling of photodetector signals is desired, although this process disables quasi-static measurements by distorting the slowly varying phase information.

II. B. Arctangent Demodulation and Phase Unwrapping

The phase of quadrature signals is proportional to the strain-induced wavelength deviation as

$$\phi \approx (2\pi n d \Delta\lambda)/\lambda^2 + \phi_t = (2\pi n d \kappa_\epsilon \Delta\epsilon)/\lambda^2 + \phi_t, \tag{4}$$

where n is the refractive index of the fiber, d is the path length difference, λ is the Bragg wavelength, $\Delta\lambda$ is the Bragg wavelength shift by applied strain, ϕ_t is the drifting phase by ambient temperature variation, κ_ϵ is the wavelength shift per unit strain, and $\Delta\epsilon$ is the applied strain. To obtain the strain information, the phase should be demodulated. The digital arctangent demodulation can be easily implemented when the data acquisition and subsequent signal processing are done by a computer-based, i.e. programmable, processing unit. The sampled data array is transferred to the computer and generates two quadrature signals by adding and subtracting the photodetector raw sig-

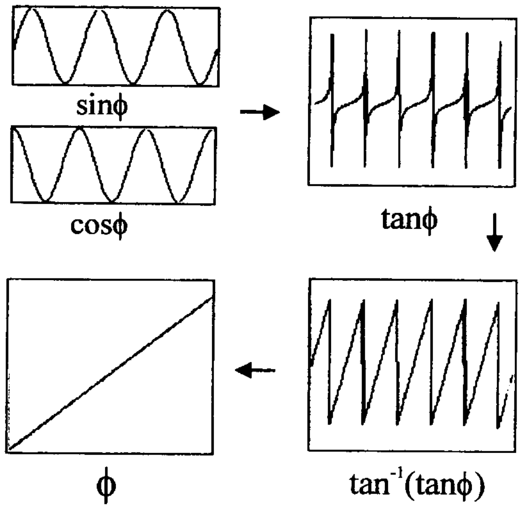

FIG. 2. Arctangent phase unwrapping procedure. A monotonic increasing phase was applied to the developed phase unwrapping algorithm.

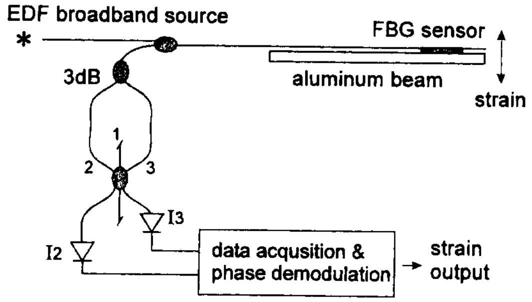

FIG. 3. Experimental setup: EDF, erbium-doped fiber; FBG, fiber Bragg grating.

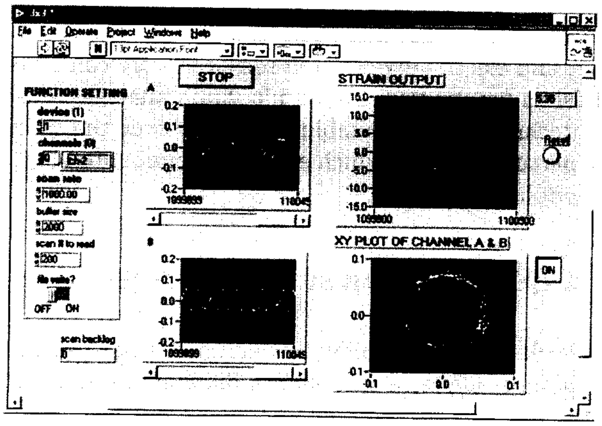

FIG. 4. User friendly developed strain sensor software.

nals. Then, one of the quadrature signal streams is divided by the other, generating tangent data. The tangent data stream is applied to arctangent function algorithm to extract the phase, and then the obtained phase is linearly proportional to the applied strain as in Eq. (4); therefore, signal fading problems are eliminated. However, the arctangent function output is confined in range of $\pm\pi/2$, limiting the unambiguous measurement range by π. A simple phase unwrapping technique can be applied to solve the problem: $\mp\pi$ are added to the extracted phase when it reaches $\pm\pi/2$ and changes abruptly in the amount of $\pm\pi$. This simple phase unwrapping is valid only when the phase jumps are confined to the adjacent level, which is true in most dynamic strain analyses. Fig. 2 shows the simulated phase extraction procedure when monotonic phase increase is fed to the developed arctangent demodulation and phase unwrapping algorithm.

III. EXPERIMENTS AND RESULTS

Fig. 3 shows the experimental setup. A fiber Bragg grating (strain free wavelength λ_B = 1552.5 nm) is adhered on the surface of an aluminum beam. A length of erbium-doped fiber (Lucent MP980) pumped by a 980 nm laser diode (100 mW, SDL) was used as a powerful broadband source. A 3 x 3 coupler (5.1, 5.1, and 4.8 dB of coupling losses, Gould) was fusion spliced to a 3 dB 1 x 2 directional coupler, and the optical path length difference of the two arms was set to about 1 cm (7 mm in fiber length). The intensities of two arms (I_2, I_3) are detected by InGaAs pin detectors, and then they are ac-coupled to remove dc biases and amplified by transimpedance amplifiers to match the input range of a 12-bit analog-to-digital converter. The amplified signals are sampled and held at 1 kHz sampling frequency by a data-acquisition board, and the signals are transferred to a personal computer for further signal processing. The frequency response of this system is governed only by the sampling speed of data acquisition and subsequent processing time of the computer. Several hundred kHz ~ MHz can be easily accessed using commercial hardware. However, to avoid redundant sampling that costs large amounts of memory and limits a system's multiplexing capacity, the sampling frequency should be chosen according to the target frequencies in the monitoring signals.

The user-friendly developed strain monitoring software is shown in Fig. 4. Two quadrature signals, their Lissajous pattern, and resultant strain profile are graphically monitored and their data are written on the hard disk for further processing. It should be noted that in Fig. 4, the final phase output does not show the effect of noisy intensity variations observed in the Lissajous plot. This self-referencing effect due to the dividing step in the demodulation process is one of the most important advantages of digital arctangent demodulation. Fig. 5 shows detailed plots of quadrature signals and their Lissajous pattern (X-Y plot) when the grating was strained to induce about 2π phase excur-

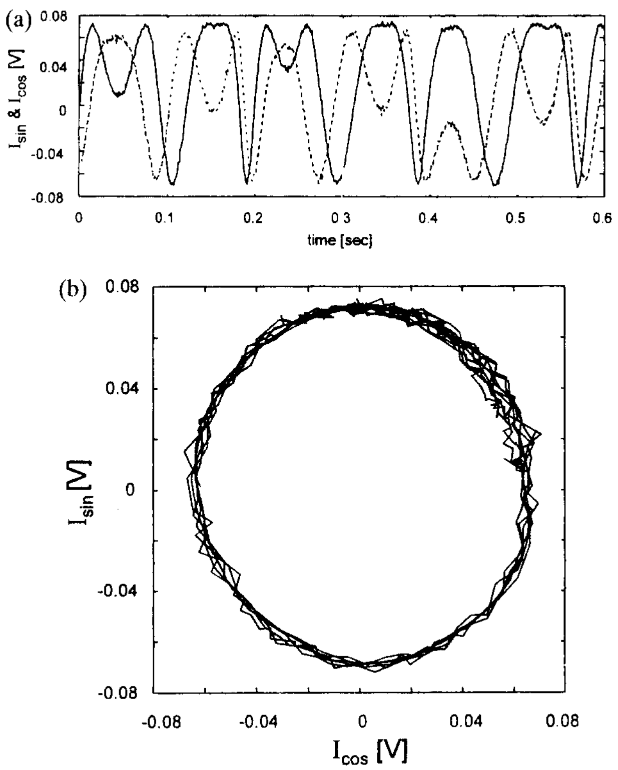

FIG. 5. Synthesized quadrature signals (a) and their Lissajous plot (b). About 2π phase modulation was loaded by bending the aluminum beam periodically.

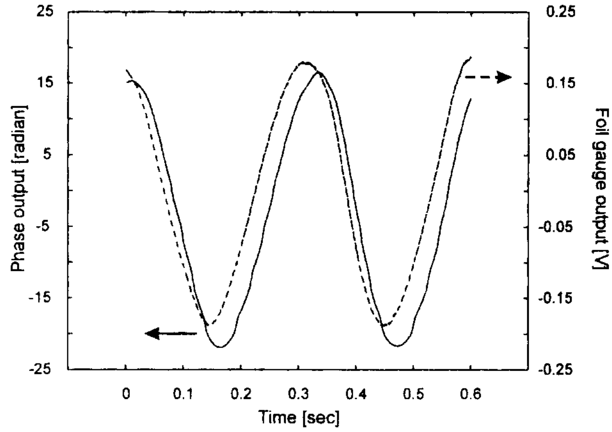

FIG. 6. Recovered phase modulation profile (7.8π *pk-pk*) when ~ 640 μstrain was loaded to the grating sensor. Broken line is foil strain gauge output.

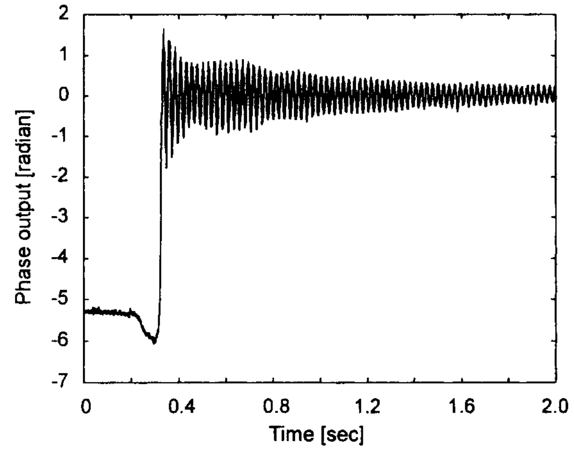

FIG. 7. Transient strain profile. The aluminum beam was pressed and released leading to transverse vibration.

sion. The quadrature phase condition is confirmed by the degree of Lissajou plot's circularity. Although gain or phase adjustments had not been used, quite stable quadrature condition was maintained throughout the experiments, and the polarization-induced quadrature condition mismatch reported by Dandridge *et al.* [12] was not noticeable, which can be attributed to the polarization independence of the input broadband source. Therefore, this combination of fiber grating sensor and 3 × 3 coupler interferometer system would be feasible for high dynamic strain measurement applications in harsh environments.

To demonstrate the broad input dynamic range of this quadrature signal processing approach, the aluminum beam was severely bent upward and downward to induce a large phase excursion. Fig. 6 shows the recovered phase. About 7.8π *pk-pk* phase (corresponding to ~650 μstrain *pk-pk*) was recovered, and the value was limited by the maximum strain that could be loaded on the beam. A foil strain gauge was mounted on the same aluminum beam to verify the fiber sensor signal. An amplified and low-pass filtered strain gauge output is plotted in a dotted line, which shows the same profile with the fiber sensor system.

The transient state of the vibrating beam was captured and shown in Fig. 7. The beam was pushed down and released to a free vibrating state in the transverse direction. This fast measuring capability (as aforementioned, the measurement bandwidth can be increased up to several MHz and more) will be useful in diagnosing transient strain phenomena of composite structures.

IV. CONCLUSIONS

A phase demodulation technique that uses a 3 × 3 coupler based M/Z interferometer and digital arctangent demodulation has been presented. The quadrature signal processing of the 3 × 3 coupler interferometer was successfully applied to interrogating the fiber grating strain sensor signal, and various dynamic strain analyses were demonstrated. In the measurements performed, the developed sensor system showed sensitive and fast operation in a very broad input range without signal fading effects.

The simple, rugged, all-fiber, and electricity-free configuration is the major advantage over conventional interferometric sensors in addition to the high-resolution and unlimited dynamic range. The system was stable over the environmental intensity and/or polarization perturbations, although the thermal phase drift limited quasi-static strain measurement. This technique may be a useful, cost-effective solution for dynamic strain measurements in which input wavelength dynamic range and fading effects are major concerns, while the quasi-static sensing is also possible with some increase of system complexity by implementing an interferometer stabilization technique [13].

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