Intrinsic fiber-optic ultrasonic sensor array using multiplexed two-wave mixing interferometry

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An intrinsic multiplexed laser interferometer is presented that allows for the simultaneous detection of acoustic waves by an array of fiber-optic sensors. The phase-modulated signals from each sensor are demodulated by use of an adaptive two-wave mixing setup. The light from each sensing fiber in the array is mixed with a reference beam in a single photorefractive crystal (PRC), and the output beams from the PRC are imaged onto separate photodetectors to create a multiplexed two-wave mixing (MTWM) system. The sensing fibers are embedded in graphite–epoxy composite panels, and detection of both acoustic emission and ultrasonic signals in these materials is demonstrated. The intrinsic MTWM system is an effective tool for the simultaneous demodulation of signals from a large fiber sensor array. Also, the adaptive nature of the MTWM setup obviates the need for active stabilization against ambient noise.

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1. Introduction

Fiber-optic sensors have been used to detect low-frequency variations of such phenomena as strain, temperature, and pressure.¹ Their primary advantage compared with conventional strain gauges and thermocouples is that they are nonelectrical devices that are also compact. A number of researchers have also developed fiber optic sensors that are capable of detecting high-frequency phenomena such as ultrasonic fields in a liquid²,³ and solid structure.⁴,⁵ Fiber-optic ultrasound sensors have potential applications in smart structure technology,⁶ composite materials,⁷ the materials processing industry,⁸ and medicine.⁹ Intrinsic fiber-optic Fabry–Perot¹⁰ and Sagnac¹¹ ultrasound sensors were described previously. The former is a localized sensor that requires active stabilization, whereas the latter is a nonlocal sensor that by virtue of its common-path interference is insensitive to low-frequency variations caused by thermal or vibration excitations and therefore requires no stabilization.

Any phase-encoded fiber-optic sensor (such as a sensor based on Michelson or Sagnac interferometry) requires a signal demodulation system. The major cost of many fiber-optic sensor networks arises from the fact that the signal from each sensor has to be extracted by a separate demodulation unit. For this reason, building extensive sensor array networks by use of Fabry–Perot or Sagnac sensors is not cost effective. In this paper we propose a fiber-optic ultrasonic sensor array that uses a multiplexed two-wave mixing (MTWM) device to provide simultaneous signal demodulation from a number of sensors at a relatively low cost per channel. Furthermore, the MTWM process is inherently adaptive, and therefore the system automatically compensates for any low-frequency ambient phase noise without the need for active feedback compensation.¹²

Two-wave mixing is essentially a dynamic holographic process in which two coherent optical beams interact within a photorefractive crystal (PRC).¹³,¹⁴ The process can be briefly summarized as (a) creation of intensity gratings as a result of coherent interference of the interacting beams, leading to (b) nonuniform photoexcitation of charges that then diffuse or drift to create (c) a space-charge field within the PRC, which in turn creates (d) a refractive-index grating by means of the electro-optical effect and causes (e) defraction of the interacting beams. This process of dynamic coupling is known as wave mixing, a phe-
nomenon that has been exploited over the years for a variety of applications, including optical interferometry. PRCs have the remarkable property that they can process multichannel optical information simultaneously in parallel. This property has been widely used in holographic memory storage and is being explored for add–drop optical telecommunication devices, but it has not received the attention that it deserves in optical metrology. Partly, this is due to the fact that in optical metrology we are actually interested in monitoring high-frequency time-varying analog signals in each channel.

We recently showed that it is possible to configure in one compact device MTWM interferometers with high sensitivity to monitor simultaneously temporally resolved subnanometer ultrasonic displacements at an array of points or lines on the test object. In this paper we present an intrinsic version of the MTWM system that is suitable for the simultaneous detection of acoustic waves detected by an array of intrinsic fiber-optic sensors. The intrinsic MTWM fiber array sensor has potential applications, for example, for process monitoring, biomedical ultrasonic imaging, acoustic emission detection, and health monitoring of smart structures.

2. Principle of Operation

The multiplexed interferometer is a homodyne scheme based on two-wave mixing in a bismuth silico oxide PRC. The interferometer uses a cw laser source (hereafter called the detection laser). The output beam from the detection laser is first split into N sampling beams and a single reference beam by a free-space 1 × N splitter made from polarizing beam splitters and wave plates. The sampling beams are coupled into polarization-maintaining fibers to form an array of intrinsic ultrasonic sensors that can be embedded in a test structure [see Fig. 1(a)]. The light beams from each element of the fiber sensor array (hereafter called signal beams because they contain the signal of interest) are collimated and mixed with the reference beam in the photorefractive crystal, as shown in Fig. 1(b). The collimated signal beams are aligned to be in the yz plane normal to the front surface of the PRC [Fig. 1(b)]. The reference beam is kept s polarized on incidence onto the PRC. The polarization of the signal beams is rotated approximately 45° with respect to the reference beam’s polarization by appropriate orientation of the fibers. The reference beam is incident upon the PRC along the xz plane at a slight angle to the yz plane. The s-polarized component of the reference beam interferes with the s-polarized sampling beams at the PRC, creating primary photorefractive gratings along the [001] crystal axis. The p-polarized components of the signal beams pass through the PRC essentially undisturbed, except for absorption.

It should be noted that multimode fibers can also be used for delivery of signal and reference beams to the MTWM demodulator. In this configuration, before coupling into fibers the linearly polarized beams from the 1 × N splitter are converted into circular polarized beams by passing through a λ/4 plate. At the output of the fibers two polarizers are used to extract the desired linear polarization components for the sampling and the reference beams.

A sinusoidal electric field of 6 kV/cm at 3000 Hz is applied along the x axis to enhance the diffraction efficiency. Optical activity in the bismuth silico oxide crystal is ignored in the following discussion for simplicity of explanation. The application of an ac field to the crystal leads to an index grating in the crystal that is π/2 shifted with respect to the intensity grating. The diffracted reference beams are thus in phase with the transmitted signal beams. At the output of the PRC, the diffracted reference beams (which are wave-front matched with the signal beams) and the transmitted signal beams are collected. The p-polarized components of the signal beams are then phase delayed 90° with respect to the s-polarized component of the diffracted reference beams by a Berek variable wave plate. The beams are then passed through a polarizer oriented at 45° to permit the appropriate polarization components of the diffracted reference and transmitted signal beams to be extracted for subsequent interference. The beams are then passed through another lens system and focused into a photodetector array. This optical arrangement forms a MTWM interferometer. The adaptive nature of the photorefractive process ensures that the MTWM interferometer is stabilized against low-frequency phase noise. The stabilization bandwidth depends on the photorefractive response time, which in turn depends on the crystal, the applied voltage, and the total optical power in the PRC. For the parameters used in our system the stabilization bandwidth was a few kilohertz.
In a general MTWM system the number of photorefractive gratings formed depends on the number of signal beams that are present as well as on the spatial distribution of the beams within the crystal. For best performance of the multiplexed interferometer it is important that two-wave photorefractive coupling occur primarily between the reference beam and each of the signal beams. We refer to the photorefractive gratings formed by the reference beam and the signal beams as the primary gratings. All other (secondary) photorefractive gratings that might form (between the signal beams or as a result of the presence of scattered beams in the PRC) are nuisance gratings and will lead to degradation of system performance through cross talk and reduced signal-to-noise ratios.

The reference beam makes a small (5°) angle with respect to the plane containing the signal beams. The primary gratings formed between the reference beam and all the signal beams therefore have their grating vectors ($\mathbf{k}_p$) essentially parallel to the applied field direction (see Fig. 2). The secondary gratings formed between all successive signal beams have their grating vectors ($\mathbf{k}_s$) normal to the direction of the applied field. In this configuration, coupling between the signal beams is significantly minimized, thereby reducing cross talk between them. This system has advantages compared with our earlier MTWM system in which all the signal beams and the reference beam were in one plane. It was shown that in that configuration coupling between the signal beams could occur unless the reference beam’s intensity were much higher than that of the signal beams. The configuration proposed in this paper obviates this requirement for higher intensity.

### 3. Experiment

A three-channel intrinsic acoustic sensor array based on the MTWM system described in Section 2 was developed. An argon laser source (514-nm wavelength; output power, 350 mW) was split into four beams, three of which were coupled into single-mode polarization maintaining-fibers to form a three-element array of intrinsic ultrasonic sensors. The fourth beam was used as the reference beam in the MTWM demodulator. The three sensing fibers were embedded in a multilayer composite test structure in the two configurations described below. Ultrasonic waves were generated in the composite structure by use of conventional piezoelectric transducers or by mechanical impact of the structure. The impinging ultrasound produces strains in the three sampling fibers. Consequently, the phase of the light beam in the sampling fibers is modulated because of the strain-optic effect. The output beams from the sampling fibers, which contain ultrasound-induced phase modulation, are sent to the MTWM demodulator unit to provide output signals that are proportional to the ultrasonic amplitude.

The sensitivity of detection of each of the three channels is affected by several factors, including the efficiency of two-wave mixing between the signal and the reference beams, and by possible variations in the optical intensity of the sampling beams. Therefore it is essential to calibrate the system before obtaining quantitative information. It should be noted that absolute measurements of acoustic pressure by use of fiber sensors is a difficult task because the actual amplitude of the detected signal depends on many factors, such as the angle of incidence of the acoustic wave, the length of interaction with the sensing fiber, and the acoustic frequency. However, one can perform a relative channel-to-channel calibration by introducing a phase shift into the reference beam and monitoring the output of all the channels. In our experiments we obtained the relative sensitivity of each channel by introducing a calibration signal into the reference beam (by use of a piezoelectric transducer mounted upon a mirror in the reference leg). Subsequent signals from each of the channels were normalized with respect to the calibration signal.

In a first experiment, the three sensing fibers were embedded in a four-layer composite structure, as shown in Fig. 3(a). Each layer was made from 37 graphite–epoxy plies and had a thickness of 3.6 mm. A 5-MHz contact transducer was used to launch bulk waves into the composite. The ultrasonic wave packet was detected by the sensing fibers, which were located at different depths within the composite. The normalized ultrasonic signals are shown in Fig. 3(b). From the measured signals it can be seen that the bulk longitudinal waves are clearly detected by all three channels with good sensitivity. The longitudinal wave arrives at different times at different sensor locations, providing information about the wave speed (related to material properties of the composite). The measured longitudinal velocity of 2480 m/s agrees well with data obtained for the same composite material by a different technique. Furthermore, the absence of any spurious signals in sensors 2 and 3 at the time of arrival of the ultrasonic wave packet at sensor 1 is an indication of the absence of cross talk in the MTWM system.
In a second experiment, a potential application of the MTWM sensing array for health monitoring of smart structures was evaluated. The three sensing fibers were embedded between two graphite-epoxy composite plates. Each plate had a thickness of 3.67 mm. The sensing fibers were aligned along the graphite-fiber direction, and the distance between them was kept at 10 mm. We generated an acoustical event by tapping the composite plate with a metal bar, 30 g at a point 35 mm away from the first fiber. The acoustic signals detected by the sensing fibers are shown in Fig. 4(b). The signals detected are quite complex in view of the multiple acoustic modes that can be sustained in such composite structures.

A complex network of intrinsic fiber sensors (demodulated by an N-channel MTWM system) can potentially provide information about the locations of impact damage or structural failures that generate acoustic emission. Because the sensitivity of interferometric detection depends on the optical power collected in the photodetector, the total number of channels is limited by the available optical laser source. To date, we have configured a free-space eight-channel MTWM system, using our 350-mW argon laser source. Compact MTWM systems can be configured by use of commercially available diode-pumped solid-state lasers. Such MTWM systems can be useful for monitoring of the structural integrity of the advanced smart structures that are increasingly used in advanced aircraft and civil applications.

4. Conclusions
A multiplexed two-wave mixing interferometer has been developed that allows for the simultaneous detection of acoustic signals from multiple intrinsic fiber-optic sensors embedded into a test structure. The intrinsic MTWM system has several advantages compared with conventional fiber sensor demodulators. It potentially allows for simultaneous demodulation of the signals from a large fiber sensor array. Also, the adaptive nature of the MTWM setup obviates the need for active stabilization against ambient noise. The intrinsic MTWM fiber array sensor can be used for process monitoring and biomedical ultrasonic imaging and for a number of nondestructive evaluation applications such as detection of acoustic emission and health monitoring of smart structures. Example applications for acoustic emission detection in composite panels have been presented.

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References