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Acousto-Ultrasonic Optical Fiber Sensors: Overview and State-of-the-Art

Graham Wild, *Member, IEEE*, and Steven Hinckley, *Member, IEEE*

Abstract—This paper gives a review of acoustic and ultrasonic optical fiber sensors (OFSs). The review covers optical fiber sensing methods for detecting dynamic strain signals, including general sound and acoustic signals, high-frequency signals, i.e., ultrasonic/ultrasound, and other signals such as acoustic emissions, and impact induced dynamic strain. Several optical fiber sensing methods are included, in an attempted to summarize the majority of optical fiber sensing methods used to date. The OFS include single fiber sensors and optical fiber devices, fiber-optic interferometers, and fiber Bragg gratings (FBGs). The single fiber and fiber device sensors include optical fiber couplers, microbend sensors, refraction-based sensors, and other extrinsic intensity sensors. The optical fiber interferometers include Michelson, Mach-Zehnder, Fabry-Perot, Sagnac interferometers, as well as polarization and model interference. The specific applications addressed in this review include optical fiber hydrophones, biomedical sensors, and sensors for nondestructive evaluation and structural health monitoring. Future directions are outlined and proposed for acousto-ultrasonic OFS.

Index Terms—Acoustic, fiber Bragg gratings (FBGs), interferometry, optical fiber sensing, ultrasound.

I. INTRODUCTION

SINCE the suggestion by Kao and Hockham [1] that optical fibers could be used in communication systems, methods of modulating the light within fibers have been investigated. These modulation methods form the basis for optical fiber sensors (OFSs). In 1967, the first “Fotonic” sensor was suggested [2] to measure position and spacing in the machine tool industry.

OFSs offer significant advantages over other sensing methodologies. The advantages of OFSs include [3]:

- greater sensitivity;
- reduced size;
- reduced weight;
- immunity to electromagnetic interference (EMI), since the fiber is not electrically conductive;
- reduced cost;
- versatility;
- reliability;
- compatibility to optical communication and telemetry.

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These advantages make OFSs ideal for sensing acoustic/ultrasonic signals in specific application areas, such as structural health monitoring.

Early reviews of acoustic OFSs are included in several general OFS review papers, including Giallorenzi [4], Giallorenzi *et al.* [5], [6], and Yao and Asawa [7]. *Fiber Optic Sensors*, edited by Udd [8], also includes a number of acoustic sensors and hydrophones. A more recent review for optical fiber ultrasonic sensing is given by Atique *et al.* [9], and to a lesser extent by Thursby *et al.* [10]. What follows is a broader review of the literature for optical fiber acoustic and ultrasonic sensing, summarizing the vast majority of sensing methods and techniques currently in the literature. This paper contains four sections, the relevant theory and the three major areas of optical fiber acoustic and ultrasonic sensing. The theory section covers strain-optics, and its application to interferometry and fiber Bragg gratings (FBGs). The three sensing areas are, single fiber intensimetric sensors, optical fiber interferometers, and FBGs. The intension is to flow chronologically through each section.

II. THEORY

A. Acoustic Emissions (AEs) and Ultrasound

Acoustic emissions (AEs) are elastic waves generated by a sudden release of energy within a solid [11]. For example, energy dissipated by the growth of a crack can be in the form of an elastic wave. An elastic wave describes a stress or strain wave, propagating through an elastic medium, typically a solid. In general, the amount of energy released as an elastic wave as apposed to other forms of energy, depends on the initial conditions of the source. Specifically, the initial conditions are how localized the release was, and the time period over which it takes place. That is, rapid localized releases of energy generated elastic waves, with frequencies in the ultrasonic range.

Examples of events that generate AEs are given below [11].

- Materials degradation—defect growth, crack advance, plastic deformation, inclusion or precipitate fracture, surface degradation including corrosion and disbonding of coatings.
- Reversible processes—crystallographic phase transformations, melting or solidification, thermoelastic effects, ferromagnetic and ferroelectric domain wall motion, friction between surfaces.
- Fabrication processes—welding noise, rolling, forging, machining, drilling, mixing, grinding, valve sequencing.
- Leak and flow—flow of single- and two-phase fluids and particles, leaks, gas evolution, boiling.

Elastic waves can also be actively generated by actuators. This is the case in ultrasonic-based nondestructive testing. Typically, piezoelectric transducers are used to generate ultrasonic

signals. Similar detection methods used for detecting AEs can be used to detect actively generated ultrasonic signals. Actively generated ultrasound can be used for defect detection, and thickness monitoring. Ultrasound has also been used as a wireless communications method, with applications to structural health monitoring [12].

B. Strain-Optics

The majority of optical fiber sensors to be discussed make use of a change in the refractive index. The change of refractive index in a material due to an applied strain is called the strain-optic effect.

From the strain-optic effect, the change in the optical indicatrix ($1/n^2$) due to an applied strain [13] is given by

$$\Delta \left(\frac{1}{n^2} \right)_i = \sum_{j=1}^6 p_{ij} S_j. \quad (1)$$

Here, p_{ij} is the strain-optic tensor. Since the fiber is isotropic and homogeneous, the strain-optic tensor is given as

$$p_{ij} = \begin{bmatrix} p_{11} & p_{12} & p_{12} & 0 & 0 & 0 \\ p_{12} & p_{11} & p_{12} & 0 & 0 & 0 \\ p_{12} & p_{12} & p_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & p_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & p_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & p_{44} \end{bmatrix}. \quad (2)$$

The strain vector S_j , for an applied longitudinal strain ϵ , is given as

$$S_j = \begin{bmatrix} \epsilon \\ -\nu\epsilon \\ -\nu\epsilon \\ 0 \\ 0 \\ 0 \end{bmatrix}. \quad (3)$$

Here, the strain in the two transverse directions (the diameter of the fiber), is related to the longitudinal strain by Poisson's ratio ν . Assuming there is no shear strain, solving (1) using (2) and (3) gives

$$\Delta \left(\frac{1}{n^2} \right)_{2,3} = \epsilon(1 - \nu)p_{12} - \nu\epsilon p_{11}. \quad (4)$$

The change in the indicatrix can be related to a change in the refractive index, Δn , by [13]

$$\Delta \left(\frac{1}{n^2} \right)_{2,3} = -2 \frac{\Delta n}{n^3}. \quad (5)$$

The change in refractive index due to an applied longitudinal strain can then be expressed as

$$\begin{aligned} \Delta n &= -\frac{1}{2} n^3 \Delta \left(\frac{1}{n^2} \right)_{2,3} \\ &= -\frac{1}{2} n^3 [\epsilon(1 - \nu)p_{12} - \nu\epsilon p_{11}]. \end{aligned} \quad (6)$$

C. Interferometry

For details on interference and interferometry see, for example, [14]. In interferometry the condition for interference is governed by the phase of the light interfering. In an optical fiber with length L , the phase of light (ϕ) passing through it is given by

$$\phi = \beta L. \quad (7)$$

Here, β is the propagation constant, given by

$$\beta = n_{\text{eff}} k_0 \quad (8)$$

where n_{eff} is the average refractive index of the fiber's core and cladding, and k_0 is the wavenumber $2\pi/\lambda$.

For use as a sensor, specifically for strain, there needs to be a change in phase to generate a change in the interference. From (7), the change in phase ($\Delta\phi$) can then be achieved by changing the length ΔL , or the propagation constant $\Delta\beta$. That is

$$\Delta\phi = \beta\Delta L + L\Delta\beta. \quad (9)$$

The change in length due to an applied strain is given simply by

$$\Delta L = \epsilon L. \quad (10)$$

The change in the propagation constant $\Delta\beta$ depends on a change in the refractive index Δn , and a change in the fiber's diameter ΔD . This is given as [13]

$$\Delta\beta = \frac{\partial\beta}{\partial n} \Delta n + \frac{\partial\beta}{\partial D} \Delta D. \quad (11)$$

The change in refractive index due to the applied longitudinal strain is given in (6). From (8), the derivative of β with respect to n is

$$\frac{\partial\beta}{\partial n} = k_0 = \frac{\beta}{n}. \quad (12)$$

The $d\beta/dD$ term is negligible [13], especially for a single-mode fiber at 1550 nm. Hence, it and the change in the diameter can be dropped. The final equation for the change in phase is then

$$\Delta\phi = \epsilon L \beta - \frac{\epsilon L n^3}{2} [(1 - \nu)p_{12} - \nu p_{11}]. \quad (13)$$

D. Fiber Bragg Grating (FBG)

A FBG [15], [16] is a spectrally reflective element written into the core of an optical fiber. The grating reflects a single wavelength of light, and transmits all others. The wavelength reflected, λ_B , called the Bragg wavelength, is determined by the gratings period Λ , and its effective refractive index n . The Bragg wavelength is given by

$$\lambda_B = 2n\Lambda. \quad (14)$$

As with the interferometer, to use the FBG as a sensor, a change in the Bragg wavelength is required. Using the same method applied to develop (9) from (7), the change in the Bragg wavelength ($\Delta\lambda_B$) can be achieved by either a change in the

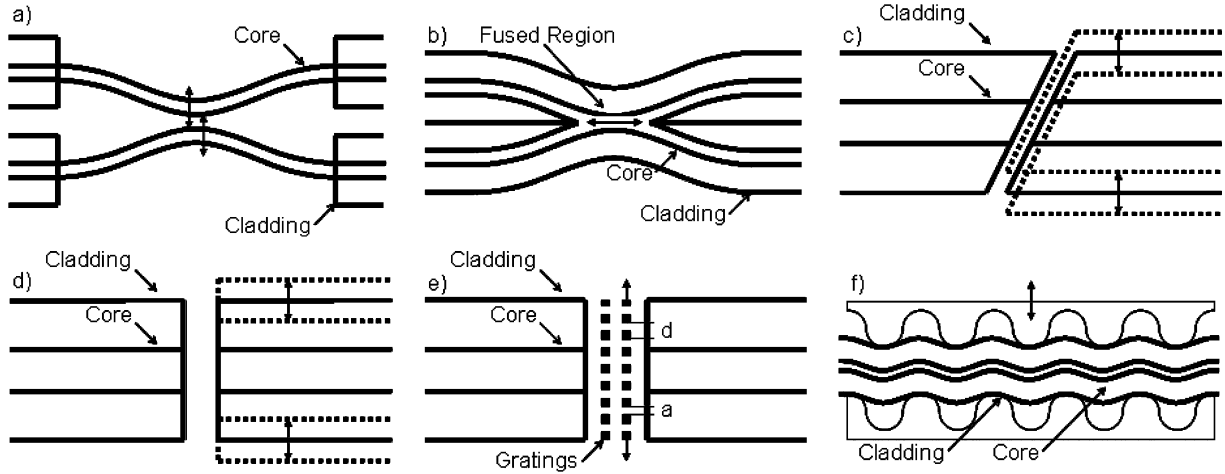


Fig. 1. Single fiber sensing methods using: (a) evanescent field coupler; (b) fused tapered coupler; (c) frustrated total internal reflection; (d) lateral misalignment; (e) two Ronchi gratings; and (f) microbending. The arrows indicated the direction of motion of the relative fiber. For the fused tapered coupler, the arrow shows the relative direction of the dynamic strain.

grating period $\Delta\Lambda$, or a change in the effective refractive index Δn . That is

$$\Delta\lambda_B = 2n\Delta\Lambda + 2\Lambda\Delta n. \quad (15)$$

The change in refractive index due to an applied longitudinal strain is given in (6). The change in grating period due to an applied longitudinal strain is given by

$$\Delta\Lambda = \varepsilon\Lambda. \quad (16)$$

The change in the Bragg wavelength can then be written as

$$\Delta\lambda_B = 2\varepsilon\Lambda n - \frac{2\varepsilon\Lambda n^3}{2} [(1-\nu)p_{12} - \nu p_{11}]. \quad (17)$$

Using (14), (17) can then be expressed as

$$\begin{aligned} \Delta\lambda_B &= \varepsilon\lambda_B - \frac{\varepsilon\lambda_B n^2}{2} [p_{12} - \nu(p_{12} + p_{11})] \\ &= \varepsilon\lambda_B \left(1 - \frac{n^2}{2} [p_{12} - \nu(p_{12} + p_{11})] \right). \end{aligned} \quad (18)$$

III. SINGLE FIBER SENSING METHODS

The first intrinsic optical fiber sensor for detecting dynamic strain was reported by Nelson *et al.* in 1977 [17]. The transduction mechanism of the OFS was the loss associated with fiber bending. The optical fiber was bent into a U-shape with its ends fixed, and the midpoint of the curve attached to a membrane which was acoustically driven to vary the bend radius. The sensor had a strong frequency dependence due to the length of fiber bending.

Sheem and Cole [18] reported on the sensitivity of single-mode optical power dividers (couplers) to acoustic signals. The evanescent field couplers used a twisted pair of fiber cores, enabling the light to be coupled from one core to the next via the evanescent field. The coupling ratio was found to be dependent on the separation of the cores, and the refractive index of the material separating them. Hence, anything that varies either the separation or the refractive index will vary the coupling ratio. The coupler was successfully implemented as an acoustic sensor. A simple schematic is shown in Fig. 1(a). This work

was similar to the coupled waveguide sensor presented by Fields [19]. A multimode twisted pair evanescent field coupler was also demonstrated as an acoustic sensor by Carome and Koo [20]. More recent work has been undertaken by Chen *et al.* [21]–[23] using fused-tapered fiber couplers as ultrasound and acoustic emission sensors. It was found that an incident strain field altered the length of the fused-tapered coupling region, resulting in a change in the coupling coefficient of the device. Fig. 1(b) shows the fused tapered coupler.

Spillman and McMahon [24] present an intensity-based acoustic sensor utilizing the principle of frustrated total internal reflection. The acoustic signal, down to static pressure, modulates the lateral separation between two angled fiber tips, resulting in a modulated intensity transmitted through the fiber gap. The sensor is illustrated in Fig. 1(c). Another approach using an angled fiber interface was proposed by Phillips [25]. The transmission and reflection at the interface of a single angled fiber depends on the refractive index outside the fiber. Hence, if an acoustic field is used to modulate the refractive index outside the fiber, the reflected intensity is also modulated.

Spillman and Gravel [26] present a moving fiber-optic hydrophone. The principle of operation is based on lateral misalignment. The impinging acoustic wave causes the free moving fiber end to oscillate, modulating the intensity of the light captured from the fixed end according to the equations which govern lateral misalignment. A similar sensor was also reported by Rines at the same time [27]. Fig. 1(d) shows the operation of the lateral misalignment sensor.

Spillman [29] and McMahon [28] also present a hydrophone based on Schlieren intensity modulation. Two Ronchi gratings (a standard diffraction grating, where $d = 2a$) are located perpendicular to the optical axis of two longitudinally separated fibers. One grating, attached to a diaphragm, is moved in the grating direction by the acoustic wave, resulting in an intensity modulation of the light captured from one fiber to the other. At the same time, a similar hydrophone was also presented by Tietjen [30]. The Schlieren sensor is shown in Fig. 1(e).

Fields *et al.* [31] present another novel intensity-based single fiber acoustic sensor. The sensing method uses microbend in-

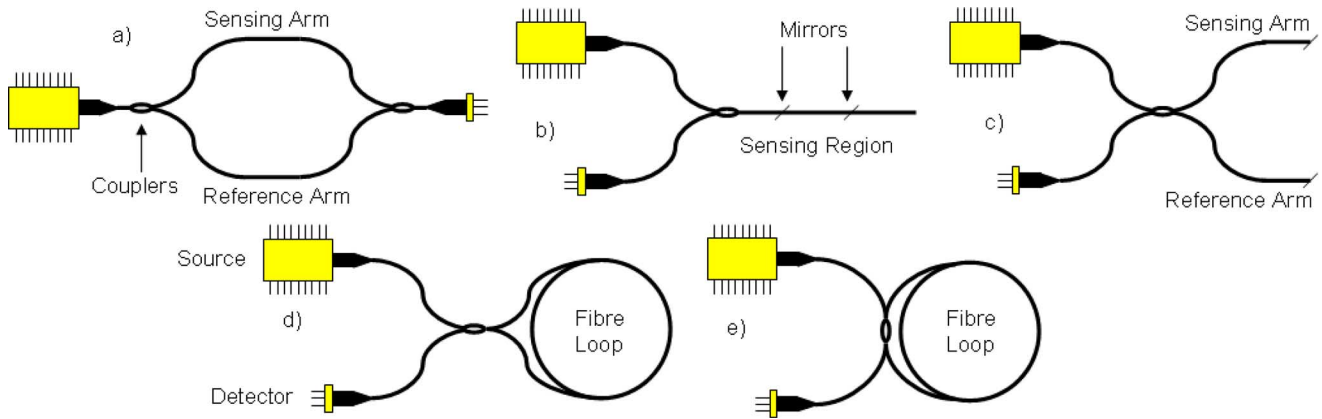


Fig. 2. Intrinsic optical fiber interferometers: (a) Mach-Zehnder; (b) Fabry-Perot; (c) Michelson; (d) Sagnac; and (e) ring resonator.

duced attenuation with an optical fiber to convert an applied force into an optical intensity. The multimode fiber is located within a bending loss modulator, which is comprised of two mating ridged plates. As the plates are forced together, the fiber is forced into smaller bend radii resulting in greater attenuation. Further work is presented by Fields and Cole [32]. A similar deformer is used by Lagakos *et al.* [33] in their displacement sensor, which can also be used as an acoustic sensor. The microbend sensor is illustrated in Fig. 1(f). Lagakos *et al.* [34] increased the sensitivity of the microbend sensor by using a deforming drum with the fiber wound around the outside.

Spillman and McMahon [35], [36] and McMahon *et al.* [37] report an extrinsic OFS based on the photoelastic effect. A birefringent transduction element was subject to stress from the acoustic pressure. The two components of the input circularly polarized light were modulated by the photoelastic effect. The two components are then split by a polarizing beam splitter. Since the two components are modulated in opposite directions, the difference on sum of the two intensity modulated signals was used to improve the sensitivity and signal-to-noise ratio.

Fuhr [38] gives a summary of some early work up to 1993. Fuhr states that early work utilized simple embedded fiber-optic grids to locate damage by a simple intensity method. The work referenced is that of Measures [39]. The principle behind this method is the use of the fiber to detect acoustic emissions via the phenomena of modal noise [40]. Light launched into a multimode fiber forms a speckle pattern at the output. This pattern is the result of modal interference and coupling along the fiber. When the fiber vibrates, the phase and intensity of each mode is modulated to varying degrees. This results in variations of the individual modal intensities, while the overall intensity is constant. If, however, the output is spatially filtered, then the overall intensity will be varied.

Williams and Dewhurst [41] report the implementation of an extrinsic differential fiber-optic sensor for the detection of surface acoustic waves. The sensor uses differential intensity sensing between adjacent fibers in a bundle.

Another microbending loss-based acoustic sensor is demonstrated by Tsutsui *et al.* [42] in an impact detection system. Nondestructive impact damage results in the deformation of the composite material. This deformation results in microbending of an embedded small diameter optical fiber, decreasing the

transmitted intensity. If destructive damage occurs above a specific level, this will result in the breakage of the fiber. In essence, this gives a digital output for the detection of destructive damage.

IV. OPTICAL FIBER INTERFEROMETERS

The literature on optical fiber interferometers of acoustic and ultrasonic sensing is extensive. What follows is a historical overview of the initial work, and the first reports of implementing the different interferometry configurations.

The first intrinsic optical fiber interferometric acoustic sensor was presented by Bucaro *et al.* [43] in July 1977. They used a Mach-Zehnder setup, shown in [44], to detect ultrasonic waves in water. They used frequencies of 40–400 kHz with no significant change in sensitivity. A similar setup was also presented by Cole *et al.* [45], [46]. Their limited experiments compared well with the theory, which suggests that the response of the sensors should be independent of the impinging frequency. They present results for 10–100 kHz. They were also able to obtain directivity measurements from -30° to 30° , which showed a strong directional dependence. Lower frequency operation of the in-fiber Mach-Zehnder interferometer was tested by Bucaro and Hickman [47]. The signals used were from 100 to 1200 Hz. The frequency was increased in work reported by Jarzynski *et al.* [48]. Experimental and theoretical results were presented for 100 Hz to 50 kHz. Fig. 2(a) shows an example of an in-fiber Mach-Zehnder interferometer.

Included in the initial work [43], [44] is mention of a single multimode fiber system based on intermodal interference, though little detail is given. Further work on this method is presented by Bucaro and Carome in [49], and by Layton and Bucaro in [50]. The detection method is similar; however, the technique was less sensitive than the two beam method, but much more simple to implement. The work in [49] also uses a single-mode fiber in a Fabry-Perot configuration. This method retained the high sensitivity, while having a simple configuration. However, the problem with the method was the “mirroring” of the end facets, with the need to make sure they were cut perpendicular to the fiber axis. Fig. 2(b) shows an in-fiber Fabry-Perot interferometer.

Shajenko *et al.* [51], [52] present work on the acousto-optic effect in the Mach-Zehnder optical fiber acoustic sensor. They

state that previous work (above) and theoretical analyses [53] assumed the delay in the sensing arm was a result of a variation in the refractive index of the fiber. That is, the first term of (13), $\epsilon L\beta$, was ignored. Their work shows that the delay is due to the dimensional changes of the fiber in response to the acoustic pressure, specifically, the change in length. They also state that the effect of the change in length is of opposite sign to the change of the refractive index. This is shown in (13). The work was performed at 60 kHz.

All of these early Mach–Zehnder interferometers made use of single-mode fibers. Culshaw *et al.* [53] point out some of the issues with using multimode fibers. Specifically, different modes in the fiber experience different phase modulation. This gives rise to intermodal interference. However, Hall [54] successfully demonstrated the use of a multimode fiber as a sensing element in a Mach–Zehnder interferometer. By ensuring that the fiber experienced a bulk change in pressure, such that the radial strain in the fiber was constant, the phase modulation of all the modes was found to have significantly less variation. Ueha *et al.* [55] previously demonstrated a similar vibration sensor using a multimode in-fiber Mach–Zehnder. The light was modulated external to the fiber, hence intermodal interference was not a problem. Further work on using multimode fiber as sensing elements, within a Mach–Zehnder interferometer, was presented by Shajenko [56].

Cielo [57] presents work that states that longitudinal compression produces much higher sensitivity than uniform 3-D compression in those hydrophones previously reported. Hence, modifications to the sensor design are proposed. The configuration suggested is similar to [48], but utilizes a double cavity configuration. The length of fiber between the reflective elements is then coiled around a compliant cylinder to increase the sensitivity to the acoustic field.

Hocker [58], [59] presents a Mach–Zehnder acoustic sensor with improved sensitivity. The improvement in sensitivity, two orders of magnitude, is achieved by placing the sensing arm into a composite structure with a lower elastic modulus. This increases the stress, and hence the optical phase shift, in the fiber for a given pressure. This is also suggested in the work performed by Hughes and Jarzynski [60], where it was found that fibers with plastic jackets had a significant improvement over bare fibers in static strain analysis and experiments. Further work on optimizing fiber coatings was carried out by Lagakos *et al.* [61], [62].

Rashleigh [63] proposed single fiber acoustic sensor. An acoustic wave differential changes the phase velocities of the polarization modes in a tension-coiled fiber. This results in the polarization rotation of the transmitted light. This is the first account of a polarimetric optical fiber acoustic sensor. Further work on polarimetric optical fiber sensors has been undertaken by dePaula *et al.* [64]–[66], and also by Chan *et al.* [67], [70] with Price [68], and Brinch [69]. The work of Chan *et al.* [67] describes a polarimetric optical fiber sensor based on acoustically induced birefringence in a polarization maintaining fiber. Further work [70] explains the acoustically induced birefringence occurs at higher frequencies (> 1 MHz) due to anisotropic strain distribution. At lower frequencies, the birefringence is a result of the inhomogeneous elastic properties of the fiber.

The first in-fiber Michelson interferometer for detecting vibration was demonstrated by Imai *et al.* in 1980 [71], [72]. Initial work used single-mode fibers. However, a multimode version of the Michelson interferometer was also reported [73]. Fig. 2(c) shows an in-fiber Michelson interferometer.

The first report of embedding optical fibers in solids to detect acoustic emissions is by Claus and Cantrell [74]. The sensing arm of a Mach–Zehnder interferometer was embedded in plastic resin. Further work by Wade *et al.* [75] looked at embedding fiber sensors in composites.

Udd [76] presents a series of fiber-optic acoustic sensors based on Sagnac interferometers. These represent the first implementation of Sagnac interferometers for acoustic detection. An in-fiber Sagnac interferometer is shown in Fig. 2(d).

Alcoz *et al.* [77] demonstrate a short gauge length (5–13mm) intrinsic Fabry–Perot interferometer. The sensor was used to detect ultrasonic longitudinal waves between 0.1 and 5 MHz.

Lui *et al.* [78] reported the use of a Michelson interferometer as an acoustic emission sensor. The sensor was embedded in a composite material, and had broadband response of 0.1–1 MHz.

Murphy *et al.* [79] present the first report using an Extrinsic Fabry–Perot Interferometer (EFPI) to detect dynamic strain. They state that the frequency limit is imposed by the signal processing electronics at the output.

Beard and Mills [80]–[83] report an EFPI for the detection of ultrasound. The geometry is an external Fabry–Perot etalon. The etalon is a transparent polymer film that varies in thickness with an incident ultrasonic wave. The application is for the *in vivo* detection of laser generator.

Sirkis *et al.* [84] present the in-line fiber etalon (ILFE). Dynamic strain measurements were reported, the minimum detectable strain was given for 0.5–2.5 kHz. No suggestion is given to the overall bandwidth.

This overview accounts for the historical development of all the major types of optical fiber interferometers sensors for acoustic and ultrasonic sensing. A summary of optical fiber interferometric sensing is given by Kersey [85]. Also, Nash [86] gives a review of interferometric optical fiber hydrophones.

One of the limitations of some interferometric OFS for ultrasound is the gauge length of the sensors. Although only a small section of the fiber can be bonded to, or embedded in, the structure for the dynamic strain sensing, the entire length of the sensing fiber is still sensitive. This can lead to cross sensitivity problems with other measurands, such as static strain or temperature. Point sensing is the ideal solution to this problem. Short length Fabry–Perot interferometers such as EFPI and ILFE offer a significantly reduced gauge length. Shorter gauge lengths can also be demonstrated with various intensimetric devices described in the single fiber sensing methods, or with FBGs.

V. FIBER BRAGG GRATING (FBG) SENSORS

Work on FBGs for ultrasonic measurements began with Webb *et al.* [87] in 1996. This work, and further work [88], looked at FBGs for the sensing of ultrasonic fields for medical applications. Specifically, the use of the sensors was for distributed *in vivo* sensing of ultrasound. Additional work [89]–[92] investigated the interaction of the FBG with the ultrasonic field. It was found that the upper limit on the incident

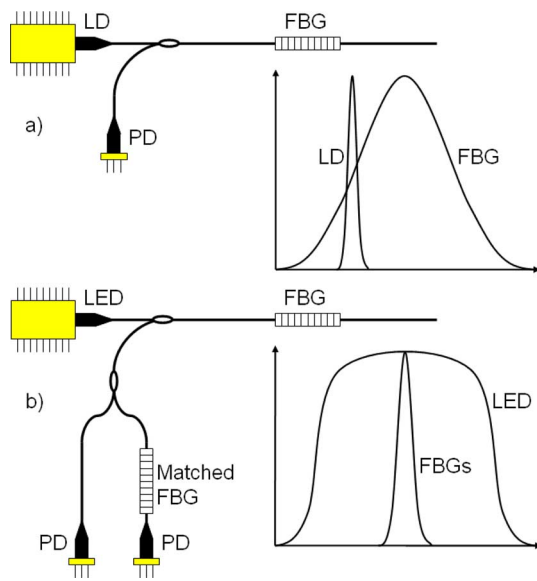


Fig. 3. FBG detection systems using: (a) a narrow line-width laser diode (LD), or (b) a broadband light emitting diode (LED) and photodiodes (PD). The insets show the spectra of the optical components.

acoustic frequency is set by the length of the grating. Specifically, the grating length should be less than half the acoustic wavelength in the fiber core. The setup used was similar to Fig. 3(a).

Around the same time, similar work was also being performed in Japan by Takahashi *et al.* [93]. They proposed an underwater acoustic sensor using a FBG. The setup was similar to the homodyne detection method proposed by Webb *et al.* [87], however, the signal transmitted through the grating was detected. Results, using only 20 kHz signals, show a linear relationship between the incident sound pressure and the signal intensity in dB. Results from tuning the laser show the maximum signal intensity is achieved at around the FWHM points of the FBG spectral response. Further work [94] includes the addition of a second FBG via wavelength division multiplexing. It was found that the sensors worked independently of each other even though located along the same length of fiber. The two fibers were then used to determine a bearing to the source. Next, they successfully determined the spatial distribution of the acoustic field generated by the PZT transducer [95]. Here, the FBG was used as a reflective element. The FBG hydrophone results were compared with the distribution as measured by a PZT hydrophone. The next stage of their development looked at detecting vibrations with the FBG sensor. Two reports were made, one [96] using a tunable laser as before. The second [97], [98] involved the use of a second FBG to select a narrow linewidth from a broadband source. The light was then sent to the sensing FBG, which was bonded to the PZT transducer, again they both used a reflective mode. Other work has also looked at both removing [99]–[101], and detecting [102] the effect of temperature.

Perez *et al.* [103], [104] used FBGs to detect acoustic emissions. Their setup using a matched FBG is shown in Fig. 3(b). The FBG was bonded to the surface of an aluminum panel, and they successfully detected acoustic emissions generated by both

a piezoceramic resonator and an ultrasonic transducer. The signals were detected at transmitter-receiver separation distances up to 30 cm. They also successfully detected the acoustic emission generated by a pencil lead breaking on the panel, albeit with significant amplification.

Coppola *et al.* [105] undertook a numerical analysis of FBG response to ultrasonic waves. As established by the preceding literature, it was found possible to characterize ultrasonic waves, but only if the ratio between the ultrasonic wavelength and the length of the grating used exceeded an established value, depending on the characteristics of the FBG and the ultrasonic amplitude. This revealed an insight into the conclusions reached by Webb *et al.* [87].

Fomitchov and Krishnaswamy [106], [107], also proposed the use of a FBG for the detection of ultrasonic waves in liquids and solid structures. Again, the implementation is the same as that initially used by Webb *et al.* [87]. The system makes use of a tunable laser tuned to the operating point of the FBG, and a photodetector to measure the returned intensity. They report sensitivity over a broad frequency range from 10 kHz to 5 MHz.

A similar FBG sensing method was also presented by Betz *et al.* [108], [109], [110]. Their system is intended to monitor and detect Lamb waves, and was implemented in a Perspex plate.

Wierzba and Karioja [111] present an active FBG underwater acoustic sensor. The sensor is active in the sense that the grating is written into a rare-earth doped fiber. The fiber then acts as an optically pumped distributed feedback (DFB) laser. The most significant aspect of their work is that they present some conditions for the effective operation of a FBG acoustic sensor. It is noted that for correct operation, the strain state along the grating should be a constant; hence, the wavelength reflected along the grating is a constant. This is similar to the constraint observed by Webb *et al.* [87], that the acoustic wavelength must be at least twice the grating length.

In addition to their microbend acoustic sensor, Tsutsui *et al.* [42] demonstrate the use of FBGs for impact detection in composites. FBGs were used to locate the impact, and hence damage associated with it.

Cusano *et al.* [112], Minardo *et al.* [113], and Italia *et al.* [114] have investigated FBGs for sensing dynamic strain. The initial work [112] used a FBG to measure dynamic strain up to 50 kHz. Theoretical and numerical modeling were then undertaken [113] to determine the response of the FBG to longitudinal ultrasonic waves. As with previous research [87], the same conclusion was reached, relating the acoustic wavelength to the grating length. Further work [114] analyzed the phase response of the FBG to longitudinal ultrasonic waves. They conclude by suggesting FBGs for detecting high frequency ultrasound would benefit from looking at time delay induced into the grating to detect the impinging wave.

A significant recent development has been presented by Fujisue *et al.* [115]. They present the demodulation of acoustic signals from FBG ultrasonic sensors using an arrayed waveguide grating (AWG). The basic system still uses the homodyne method initially proposed by Webb *et al.* [87]. The AWG enables a large number of multiplexed FBG sensors to be simultaneously monitored. The number is determined by the number of channels in the AWG minus one. This represents a

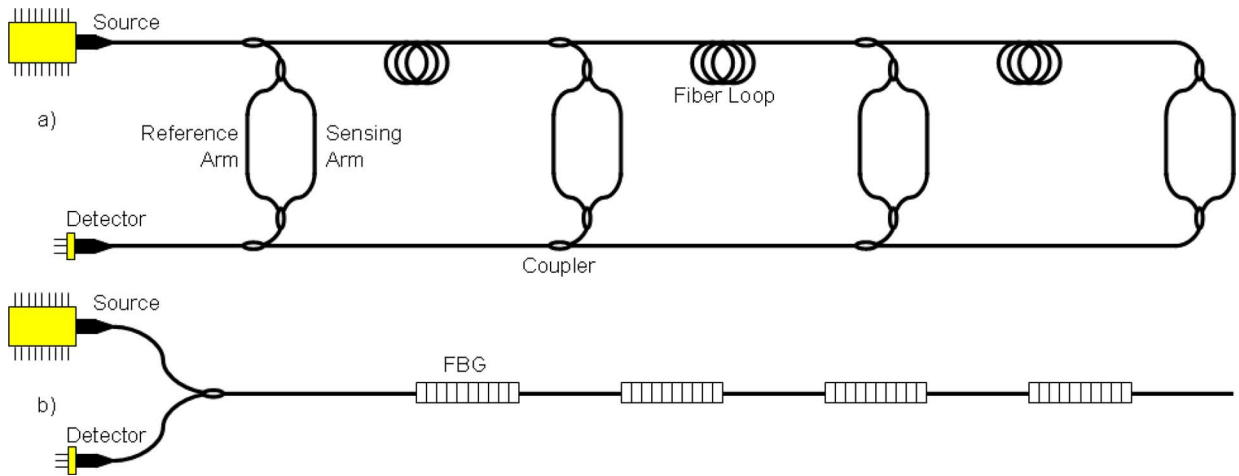


Fig. 4. Multiplexed OFS: (a) time-division multiplexed Mach-Zehnder interferometers and (b) wavelength division multiplexed FBGs using a tunable laser source.

simple implementation of multiplexing intensity sensors using FBGs.

Work by Lee and Tsuda [116], suggests that a FBG in a resonant structure has improved performance over conventional FBGs. They used a strain isolated FBG temperature sensor, bonded to a structure as an improved ultrasonic receiver. A 200 kHz Lamb wave was successfully received by various FBG sensor head configurations. The capillary tube in which the FBG is isolated, means the FBG is not directly affected by the strain from a passing wave. However, the wave is coupled into the fiber due to the fact that the fiber is bonded to the panel. This results in a more sensitive FBG acoustic sensor configuration in a direct comparison.

Although FBGs offer a shorter gauge length and improved spectral characteristics over interferometric optical fiber sensors, they are less sensitive. The other advantage of FBGs over optical fiber interferometers is their ease of multiplexing. Multiplexed optical fiber Mach-Zehnder interferometers can be complicated [85], requiring delay lengths for time division multiplexing. This can lead to attenuation losses, and losses due to the large number of couplers and splitters required. Conversely, the wavelength division multiplexing of FBGs [94], [95] uses a single fiber length. Since FBGs are only reflective to a single wavelength (in the band of interest) and the light does not have to leave the core of the fiber, FBGs are more efficient to multiplex than Fabry-Perot interferometers. A comparison between multiplexed Mach-Zehnder interferometers and FBGs is shown in Fig. 4.

Temperature and static strain signals detected by FBG intensimetric sensors are very low-frequency signals. The standard technique for removing the cross sensitivity signal is to simply filter out the low-frequency components. FBG detection systems can be characterized by the use of a narrow line-width light source [87] [Fig. 3(a)], or a broadband light source [103] [Fig. 3(b)]. Shifts in the spectrum of the sensing FBG due to large variations in quasi-static measurands, will result in changes to the sensitivity of the detection system. More work is required to stabilize the sensitivity of FBG systems over large temperature ranges, specifically for the intended applications areas such as Structural Health Monitoring.

VI. FUTURE WORK

The authors have identified two primary areas that will provide significant opportunity for improvement and advancement in acousto-ultrasonic optical fiber sensing. The two areas are microphotonics, and passive fiber sensors based on active materials.

Microphotonics has the ability to greatly improve current sensing techniques, and being at a micron scale, it also has the ability to greatly increase the upper frequency limit of current sensors. An optical fiber interferometric ultrasound sensor using a fiber coil [117] has an upper frequency limit of 50 kilohertz. The frequency limit of the sensor is due to the minimum bend radius of the fiber coil. Microphotonic fibers have no loss associated with bending [118]. The minimum bend radius reported before breakage was $100\ \mu\text{m}$. The authors, therefore, propose the use of a microphotonic fiber as an acousto-ultrasonic sensing element in an interferometric sensor. The result of using a microphotonic fiber would be a significantly greater frequency response. For example, in Aluminum with a longitudinal acoustic velocity of over $6000\ \text{ms}^{-1}$, a wavelength of $200\ \mu\text{m}$ (twice the bend radius) would correspond to a frequency of 30 GHz.

The physical properties of microphotonic fibers will also improve the ability to embed very large numbers of fibers into composite lay-ups with almost no affect on their structural properties [119]. The bending properties will also enable the fibers to form tighter meshes, without requiring fiber loops with large radii to turn a corner.

One of the current limitations of OFS methods is their active nature. Light must be supplied to be modulated; this is similar to a resistive strain gauge, as opposed to a passive sensor, such as a piezoelectric transducer, where the measurand generates an electric signal. Similar materials are required in photonics for OFS to truly surpass electronic sensors. Active materials represent the solution in photonics. Here, the term active materials, specifically refers to luminescent materials. Luminescent sensors have already been employed in optical fiber chemical sensors, based on chemoluminescence [120]. More applicable to the context of this review is the report of triboluminescence

or fractoluminescent fiber sensors [121], [122] used to detect damage in composites. Along this thought, the authors propose the use of sonoluminescence, acoustoluminescence [123], and mechanoluminescence [124], [125], as possible sources of active materials to make truly passive acousto-ultrasonic optical fiber sensors. This follows the idea of photon emission NDT, which was first proposed by Chandra [126].

VII. CONCLUSION

A review of optical fiber sensing methods for detecting acoustic, ultrasonic, and other dynamic strain signals has been given. The major types of optical fiber sensors discussed included FBGs, optical fiber interferometers, and various intensimetric optical fiber sensors. The theory of strain-optics, and its applications to interferometry and FBG sensors, was also summarized. In addition, two main future research directions are proposed. These were microphotonics, and passive optical fiber sensors, based on various luminescent mechanisms.

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