Fast and Distributed Brillouin Sensing for Dynamic SHM

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ABSTRACT

We report a fast and distributed Brillouin measurement technique suitable for dynamic SHM applications. Having the capabilities of sensing strains at high sampling rates (~a few KHz) over hundreds of meters of optical fiber, the technique could prove useful in a range of SHM scenarios. An application of the technique to the measurement of flexural waves in a composite strip is demonstrated.

INTRODUCTION

Following the immense impact they had on telecommunications, optical fibers have finally established their advantageous value also in the field of sensing. Recently, security applications from border fences to oil and gas pipes, as well as the need to monitor the health of structures, such as bridges, airplanes, train tracks, tall buildings etc., have called upon the unique properties of fiber-optic sensors: (*i*) they can both sense and transmit the sensed information by the same waveguide; (ii) they are dielectric; and finally, (iii) they are easily embedded in graphite-fiber based composites, or, alternatively, bonded to the surface of almost any material. In structural health monitoring applications, use is made of the intrinsic sensitivities of single mode optical fibers to two important measurands: strain and temperature. Many other parameters of importance (e.g., humidity) can be sensed by proper translation of variations of the parameter of interest into changes of either strain or temperature. Consequently, a variety of linear and non-linear optical transduction mechanisms have been studied in the last 30 years, dealing with the conversion of these measurands into measurable optical effects [1].

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The most successful strain/temperature fiber-optic sensor today is the fiber Bragg grating (FBG). Here, a few millimeters of the fiber core are exposed to a spatially periodic UV radiation, which writes there a permanent refractive index grating. The FBG acts as a narrow reflective filter (or, equivalently as a transmitting notch), where the location of the peak in the spectral domain is sensitive to both measurands. FBGs have many obvious advantages: (i) they can be multiplexed, i.e., many (up to thousands, at the expense of reading speed) FBGs can be written on the same fiber at different locations; (ii) modern interrogators can read them at high speeds (kHz), allowing dynamic measurements of strain; (iii) they can also sense ultrasonic waves; and (iv) they can be imprinted on the fiber while on the drawing tower, promising low prices. Their main disadvantages: they must be imprinted on the fiber and they populate the fiber in a *discrete* manner.

There has been, therefore, a trend to move to *distributed* sensing on standard fibers, where, without any special preparation, the whole length of the fiber serves as a sensor, assuming it is also possible to selectively read the measurand of interest at any arbitrary point along the fiber. A linear mechanism that has been pursued is the Rayleigh backscattering from the intrinsically inhomogeneous glassy fiber core. Viewed as nature-written random Bragg gratings, Rayleigh backscattering has been recently used to measure both measurands with sub-millimeter spatial resolution. While this technology is making progress, the weakness of the Rayleigh signal currently limits both the range, and more importantly, the measurement speed to tens of meters and a few Hz, respectively. In Raman non-linear sensing, an intense pulse is sent into the fiber, locally exciting Stokes and anti-Stokes backscattering waves, whose ratio depends on the local temperature. Timing this measured ratio with respect to the instant the pulse was launched, a Raman interrogator can sense the local temperatures along more than a 10km standard fiber with a spatial resolution of 1m and an accuracy of better than 0.5^0C. But the Raman distributed sensor is *insensitive* to strain, which is of extreme importance to a wide range of structural health monitoring applications.

For at least two decades, the interaction between acoustic and light waves, observed through the optical process called Brillouin scattering [2], has attracted substantial attention in the fiber sensing community, since it turns out that Brillouin scattering is particularly efficient and attractive for the implementation of strain and temperature distributed sensing in optical fibers [3,4]. In Stimulated Brillouin Scattering (SBS) a counter-propagating pump and probe waves, spectrally separated by the Brillouin shift frequency ν_B, interfere and produce through electrostriction an acoustic field, which in turn initiates a power transfer between the two optical waves. One of the more common approaches for implementing such an SBS sensor, use Brillouin Optical time Domain Analysis (BOTDA). Here, a pump pulse wave, which is launched into one end of the sensing fiber, nonlinearly interacts with a counter-propagating CW probe wave. This Brillouin-based interaction, which involves both the two counter-propagating optical fields and the excited acoustic field, attains its maximum efficiency when optical frequency difference between the pump and probe waves equals $\nu_B = 2nV_a/\lambda_p$. For standard single mode fibers at 1550nm, where $\nu_B \sim 11\text{GHz}$, and the Brillouin Gain Spectrum (BGS) is pretty much Lorentzian with a narrow linewidth of ~30MHz [5]. For a given fiber the exact value of the Brillouin Frequency Shift (BFS), ν_B, is sensitive to both the strain ($50\text{MHz}/1000\mu\varepsilon$) and temperature ($1\text{MHz}/1^0\text{C}$) at the interaction position.

In the BOTDA technique the optical frequency of either the pump or probe waves is swept across a range of frequencies as wide as dictated by the variability of ν_B along the fiber. Together with position information, which is resolved from a classical time-of-flight conversion from the temporal traces of the probe wave, the above-mentioned frequency scanning measures ν_B at each point along the sensing fiber. Spatial resolution is determined by the pump pulse width. BOTDA systems have been commercialized and proved to be very efficient for long range distributed sensing.

Classical BOTDA, however, has also its limitations. Due to the finite time required for the acoustic field to be excited by the interacting pump pulse and CW probe (~10ns 2), the spatial resolution is limited to ~1m. Recently, several time domain techniques [6-8], as well as a correlation domain method (BOCDA) [9] have been developed, improving the spatial resolution down to the order of cm and mm, respectively. But measurement speed is also a concern with BOTDA: To achieve high strain/temperature resolution over a wide dynamic range of these two measurands, the scanned frequency range must be wide and of high granularity, resulting in a fairly slow procedure, which together with the need for averaging, limits the BOTDA method to the quasi-static domain. Using a correlation domain technique, 200 Hz distributed sensing (at 1kHz sampling rate) was demonstrated at a *single* fiber location, with 10-cm spatial resolution and 20-m measurement range. A variant of the correlation technique [10] achieved strain distribution along the entire length of a 100-m fiber with 80-cm spatial resolution and 20-Hz sampling rate. While impressive, it has been argued that the number of spatially resolvable points for the correlation technique is limited to ~600, which is an order of magnitude smaller than the number achieved using pulse based techniques. Another attempt to perform dynamic Brillouin sensing employs the dependence of the efficiency of SBS on the relative states of polarization of the pump and probe waves [11]. Thus, the application of stress to a fiber segment will change the polarization states of the two interacting waves, thereby affecting the strength of the Brillouin signal, although not in a way directly traceable to the magnitude of the applied strain. Still, vibration frequencies of up to 5 kHz were demonstrated in a 1km fiber link. Another approach [12-14] proposes to use multiple pumps and multiple probes to avoid the time consuming frequency sweeping required by the classical BOTDA technique. Measurement speed will potentially increase but at the expense of frequency granularity.

It turns out, though, that a small modification of the classical BOTDA setup can achieve very fast sensing, albeit with a limited dynamic range. Using the BOCDA technique and working at a fixed pump-probe frequency difference on the slope of the Brillouin gain spectrum (BGS), Hotate and Ong [15], have measured 50Hz vibrations at 2kHz sampling rate (single fiber location). More recently, by tuning the probe frequency to the center of the rising/falling slopes of the Brillouin gain spectrum (BGS), Romeo et al. [16] utilized the SBS interaction between two counter-propagating pump and probe pulses, meeting at a selected spatial location, to demonstrate fast strain-induced variations of the intensity of amplified probe wave with a sampling rate of 200Hz. The interrogated location was determined by the relative delay between the counter-propagating pulses. The main problem with these slope-based techniques is that at each interrogated location the optical frequency of the probe must be adjusted to properly sit at (or near) the center of the slope of the local BGS, whose peak is likely to vary along the sensing fiber according to the local average strain/temperature and/or fiber properties.

In [17, 18] we presented a new method, named SA-BOTDA (for Slope-Assisted BOTDA), overcoming this issue by using a pump pulse of a fixed optical frequency and a *variable* optical frequency CW probe wave. The frequency of CW probe is tailored in such a way that when the probe meets the counter-propagating pump pulse at location z along the fiber, the frequency offset between these two waves sits as close as possible to the middle of the BGS slope. The tailoring of the probe wave is based on a prior measurement of the fiber Brillouin profile, using the classical BOTDA technique. Using the AWG, it is possible to create a long probe wave comprised of many different frequencies.

In this paper we present this dynamic and distributed SA-BOTDA technique and demonstrate its capabilities. Then, we show its application to the measurement of dynamic strain along a 20m Carbon-fiber-reinforced polymer strip, and, finally, discuss its advantages and limitations for structural health monitoring applications.

METHOD

In the SA-BOTDA technique [18], the optical frequency difference between the pump and the probe waves should sit as close as possible to the most linear part of the slope of the Brillouin Gain Spectrum (BGS). Dynamic strain changes along the fiber spectrally shift the local BGS to higher or lower frequencies (by 50MHz/1000μS for standard single mode fibers at 1550nm). The probe wave, meeting the pump pulse at any vibrating point along the fiber, will no longer experience the –3dB Brillouin gain; instead, the gain will be higher or lower, depending on the direction of the BGS shift, Fig. 1. Consequently, the changes in the local BGS will translate into gain variations of the recorded probe wave intensity.

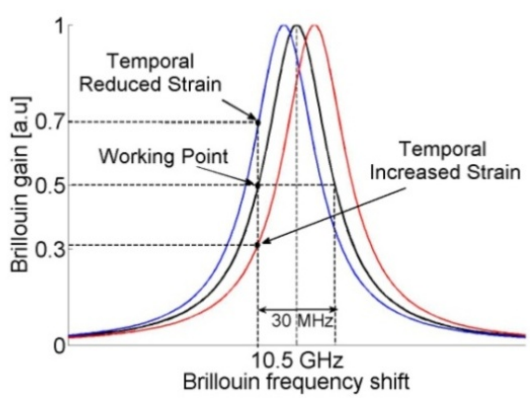

Figure 1. A Brillouin gain spectrum (BGS), originally centered around 10.5GHz, will move under strain either to the left or to the right according to the sign of the strain. When the probe frequency is tuned to coincide with the left -3dB point of the BGS (the 'working point'), an increased strain will be translated to a lower Brillouin gain of the probe and vice versa.

Due to the fact that there is no need to sweep the frequency of either wave, as in classical BOTDA measurement, the whole length of the fiber can be interrogated with a single pulse. Thus, the sampling rate of the strain changes is limited only by the fiber length and the need for averaging, to a value bounded $\left[2N_{avg}L/V_g\right]^{-1}$, where N_{avg} the number of averages, L is is the length of the fiber and V_g is the fiber group velocity.

EXPERIMENT

A detailed description of the experimental setup and data processing techniques appear in Ref. [18]. Here we report measurements of mechanical waves along a 20m long, 50mm wide, and 1mm thick high modulus reinforced composite strip. An 85m single-mode fiber was used in the experiment, dictating a maximum repetition rate of 1.17MHz for the pump pulses. In the experiment reported below, 13ns wide pump pulses were used. Every 10msec a train of 250 pump pulses were launched at a repetition rate of 1MHz.

Twenty meters of the fiber were glued to the composite strip under mild tension. A Brillouin frequency shift of 10.887MHz was measured on the loose fiber, while the BFS of the glued fiber was pretty uniform along the tape at 10.942GHz, corresponding to a static tension of 700με.

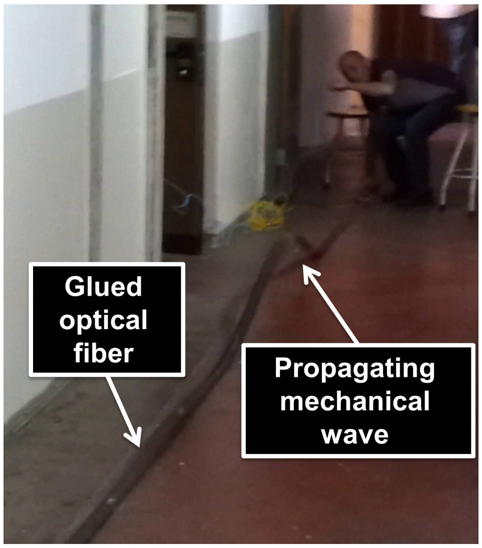

Figure 2. The experiment: Initially, the strip lied on the floor. A flexural bell-shaped wave was then manually excited at the far end of the picture, leading to its propagation towards the front part of the picture.

RESULTS

Figure 3 shows a top view of the Brillouin gain (scaled into color from blue (low) to red (high)) as a function of both time and distance. Each vertical cut through the plot at time t is obtained from the averaging of 250 probe traces (taken from the 250μsec-long pump pulse train, sent starting at time t), where each probe trace conveys information about the Brillouin gain along the fiber distance coordinate.

This represents an effective sampling rate of 100Hz. The plot describes a wave, propagating at almost constant speed of 9m/sec, slightly accelerating towards the tape end. A typical vertical cut, describing a snapshot of the propagating wave along the tape, is shown in Fig. 4 together with a schematic of the shape of the wave. In our slope-assisted Brillouin interrogation method the strength of the Brillouin gain, described by the ordinate of the top figure in Fig. 4, measures the local *strain* of the tape, adjusted so that away from the wave the strain is approximately zero. This strain is known to be proportional to the curvature of the shape of the mechanical wave, as is indeed the case: The maximum strain of ~250$\mu\varepsilon$ was measured at the wave peak (point *b* on the figure: maximum extension of the upper side of the tape), while the maximum negative strain was measured at points *a* and *c*, where the upper side of the tape experiences maximum contraction.

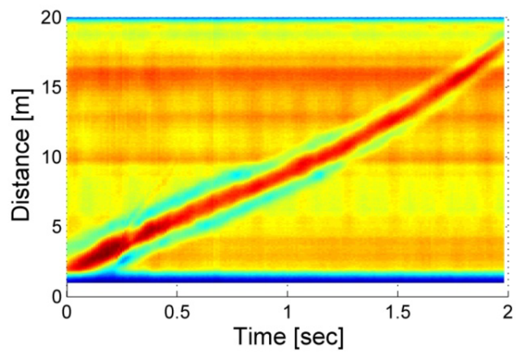

Figure 3. A top view of a 3D plot of the Brillouin gain (which is proportional to the probe intensity. Red is high, Blue is low) as a function of both distance and time, clearly showing a wave propagating at 9m/sec.

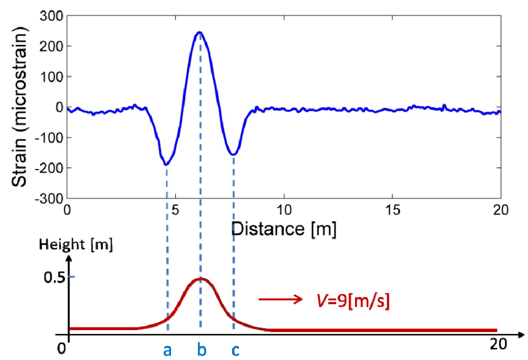

Figure 4. Top: A vertical cut through Fig. 3, showing a snapshot of the strain distribution along the tape at t=0.6sec (the ordinate is really the measured Brillouin gain scaled to express strain). Bottom: A schematic of the shape of the wave, see Fig. 2.

CONCLUSIONS

A novel method, SA-BOTDA, for distributed and dynamic sensing, based on a regular optical fiber, was demonstrated on a composite strip, measuring the strain induced by a propagating flexural wave. The method, which is based on the non-linear Brillouin effect, can monitor fast strain variations of up to many hundreds of Hertz along small and large structures up to hundreds of meters. A drawback of the method is its limited dynamic range of only a few hundred micro-strains. In [19] we utilized the same instrumentation to perform a Fast BOTDA (F-BOTDA) measurement, where the whole Brillouin gain spectrum is scanned thereby eliminating the dynamic range limitation of the SA-BOTDA technique at the expense of a slower sampling rate. Yet, a distributed measurement of 100Hz vibrations at 8.33kHz sampling rate was demonstrated [19]. Spatial resolution of both techniques is currently at the level of a few tens of centimeters and could go down to below 10cm, thereby making these methods attractive for many SHM applications.

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