Distributed Acoustic Impedance Measurement Based On Forward Stimulated Brillouin Scattering

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Abstract: A technique to measure the local spectrum of forward stimulated Brillouin scattering (FSBS) along a standard optical fiber is proposed. The local acoustic impedance of surrounding material is retrieved from the measured FSBS resonance linewidth.
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1. Introduction

Forward stimulated Brillouin scattering (FSBS), also known as guided acoustic wave Brillouin scattering (GAWBS) [1], is an optoacoustic interaction in an optical fiber, in which the participating transverse acoustic waves are stimulated through electrostriction. Because of the bounded cross-section of the optical fiber, the transverse acoustic waves are confined into eigenmodes. The quality factors of these resonances depend on the acoustic impedance mismatch at the cladding-surrounding interface. Thus, by measuring the acoustic decay rate or the spectral linewidth of a selected resonance, the acoustic impedance of an external material can be retrieved [2-4]. The reported measurements of polarized FSBS relied on a pump and probe technique [1-2]. The pump stimulates the transverse acoustic waves in the fiber whereas the probe, which is in a different wavelength range, is configured into an interferometer to convert phase changes induced by radial transverse acoustic waves into intensity changes detectable by a photodetector. However, such measurements give responses that are integrated over the entire fiber length. As FSBS process scatters light in forward direction [1, 5], time-of-flight information cannot be obtained directly from the scattered light, hence the local FSBS measurement becomes challenging.

In this work, we report a distributed FSBS spectrum measurement for the first time through recovering the longitudinal phase change of a guided reading light that is perturbed by the FSBS-induced transverse acoustic wave. The transverse acoustic waves in the optical fiber are first stimulated by a long optical pulse, which is intensity-modulated at a FSBS resonance frequency. Subsequently, a reading optical pulse (in another wavelength range) is introduced just after the FSBS activating pulse to be phase modulated by the transverse acoustic wave, thus generating multiple sidebands on the reading pulse spectrum. As the phase shifts experienced by the reading pulse accumulates along the fiber, the intensity of each sideband changes, following the corresponding order of Bessel functions. The intensity progression of several reading pulse sidebands are independently selected and measured as a function of distance over the fiber using Brillouin optical time-domain analysis (BOTDA) [6-7]. Thus, the longitudinal phase information of the reading pulse is retrieved mathematically from the measured intensity progressions of three reading pulse sidebands. The local response of FSBS is then obtained from numerical differentiation of the phase evolution. The eventual full distributed FSBS resonance spectrum is obtained by detuning the FSBS activating frequency around a selected FSBS resonant frequency. Here, we achieve distributed measurements of the FSBS resonance spectrum along a 730 m single-mode fiber (SMF) with a spatial resolution of 15 m.

2. FSBS Activation

Firstly, the FSBS activation process is implemented by using a long optical pulse with superimposed sine intensity modulation, which originates a pulse spectrum containing a central and sideband components co-propagating along the sensing fiber. The beating among the pulse spectral components can induce resonant transversal acoustic waves through FSBS at specific modulating frequencies ν_F. The resonant conditions are dictated by the boundary condition in a cylindrical structure. Thus, by launching an optical pulse that is intensity modulated at one of the FSBS resonance frequencies (see Fig. 1(a), red trace), a particular transversal FSBS-induced acoustic mode can be stimulated inside the optical fiber (see Fig. 1(a), blue trace). These FSBS-induced acoustic waves propagate radially from the fiber core towards the optical fiber cladding boundary. Depending on the acoustic impedance of the outer material, the transversal acoustic wave resonating inside the optical fiber experiences a partial reflection at the optical fiber boundary due to the acoustic impedance mismatch with silica, affecting the decay time of the acoustic field and thus the spectral linewidth of the FSBS resonances. When the modulation frequency ν_F matches one of the resonance frequencies, efficient FSBS is activated, resulting in a resonating transversal density acoustic wave that periodically modifies the local refractive index of the fiber core, expressed as in Eq. (1), where $A_n(z)$ is the amplitude of refractive index perturbation.

$$\Delta n(z) = A_n(z)\cos(2\pi\nu_F t) \tag{1}$$

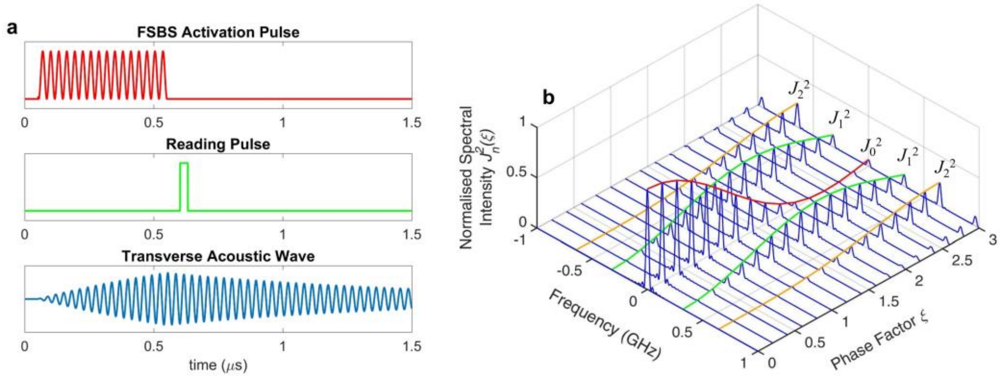

Fig. 1. (a) The participating light and acoustic waves in the distributed FSBS spectrum measurement. (b) The simulated longitudinal spectrum evolution of the reading pulse that is perturbed by the transverse acoustic waves.

3. Reading Pulse

The FSBS-induced refractive index changes can in turn modulate the phase of any light propagating inside the fiber core through photoelastic effect and generates new co-propagating spectral sidebands. Therefore, by launching another optical signal (see Fig. 1(a), green trace) at a distinct wavelength into the sensing fiber and measuring the longitudinal evolution of the newly generated spectral sidebands, local information of the FSBS-induced phase shift can be recovered along the entire sensing fiber. However, the intense FSBS activation pulse simultaneously generates an additional phase modulation in the reading pulse due to Kerr cross-phase modulation thus disturbing the measurement of the FSBS-induced phase shift. Hence, to avoid this unwanted effect, the reading optical pulse is launched into the sensing fiber immediately after the FSBS activating pulse, so that it only interacts with the decay tail of the FSBS acoustic wave [4].

As the reading pulse propagates in the presence of the transversal acoustic resonance only, it experiences a phase shift $\phi(z)$ that accumulates over distance, expressed in Eq. (2), where $\xi(z)$ is a quantity defining the accumulated phase amplitude over distance and is referred as phase factor.

$$\phi(z) = \frac{2\pi}{\lambda}\int_0^L \Delta n(z)dz = \frac{2\pi}{\lambda}\cos(2\pi\nu_F t)\int_0^L A_n(z)dz = \cos(2\pi\nu_F t)\xi(z) \quad (2)$$

Consequently, the input reading pulse spectrum will gradually degenerate during propagation into a series of spectral sidebands (see Fig. 1(b)). For a given $\xi(z)$, the amplitude of the optical field associated to the n^{th} order spectral sideband is defined by the amplitude of the ordinary Bessel function of order n, $J_n(\xi)$. As the reading pulse propagates along the fiber, $\xi(z)$ is monotonically increasing with z, therefore the peak intensity of the n^{th} spectral sideband evolves along the sensing fiber according to the n order Bessel function. In other words, the local intensity of each spectral sideband is given by $J_n^2(\xi)$, which in turn is determined by $\xi(z)$ experienced by the reading pulse between the fiber input at $z = 0$ and each local position z in the optical fiber.

4. Sidebands Mapping

Each sideband progression $J_n^2(\xi)$ can be retrieved using BOTDA because the Brillouin gain spectrum (BGS) width (~30 MHz) is much narrower than the separation between spectral sidebands ν_F [6-7]. For this, a continuous-wave (CW) BSBS probe signal is launched into the sensing fiber in the opposite direction compared to the pulse propagation, thus interacting with one of the reading pulse's modulation sidebands by BSBS. Knowing the resonance frequency of the BSBS in the fiber, commonly called Brillouin frequency shift ν_B (BFS), the CW probe wave can be spectrally positioned at an optical frequency that is red-shifted by $\nu_B - n\nu_F$ from the pump frequency, where n is the order of spectral sideband. As a result, the intensity progression of the n^{th} forward-moving spectral sideband $J_n^2(\xi)$ can be retrieved as a function of distance over the sensing fiber. The principle of this local light intensity interrogating technique in the proposed FSBS local phase recovery analysis is comparable to the one previously used in the literature to monitor 4-wave mixing signals with the aim of obtaining the position-resolved value of chromatic dispersion [8].

5. Recovery of phase information

The recurrence properties of Bessel functions is used here to recover ξ from the measured $J_n^2(\xi)$ from three consecutive spectral sidebands. This way, ξ can be robustly determined independent of the power loss of the reading pulse. A simple form of the Bessel recurrence relation can be written as,

$$J_{(n-1)}(\xi) + J_{(n+1)}(\xi) = \frac{2n}{\xi} J_n(\xi) \quad (3)$$

where n is the Bessel function order. The 0^{th}, 1^{st} and 2^{nd} order spectral sidebands can be selected to maximize the signal-to-noise ratio (SNR) of the detected traces as they have the highest intensities as compared to the other higher-order $J_n^2(\xi)$. $\xi(z)$ is yielded by solving ξ in Eq. 4 with $n = 1$,

$$\xi = 2\left(\frac{J_1(\xi)}{J_0(\xi)+J_2(\xi)}\right) \tag{4}$$

Since the detected BSBS traces map the optical intensity rather than the field amplitude of the spectral sidebands of the phase-modulated reading pulse, the square root values of the acquired J_0, J_1 and J_2 sideband traces must be calculated for retrieving $\xi(z)$.

6. Local FSBS response

From the acquisition, the intensity progression $J_n^2(\xi)$ around the FSBS resonant frequency for the first three orders sidebands are stored and processed. The data are processed trace by trace for each scanned frequency ν_F in the entire FSBS scanning range. For better understanding, the data processing steps are here detailed only for the traces measured at the selected resonant frequency (322 MHz). The intensity traces of the 0^{th}, 1^{st} and 2^{nd} order spectral sidebands, which have been obtained from their respective BGS peak amplitudes, are plotted in Fig. 2(a). The $\xi(z)$ trace is retrieved by applying the Bessel function recurrence relation in Eq. (4) pointwise at each spatial location (see Fig. 2(b)).

Subsequently, $A_n(z)$ - the amplitude of refractive index perturbation, along the optical fiber is computed by numerical differentiation. To mitigate the impact of the measurement noise on the numerical differentiation, the process is carried out by segmenting the data points of the trace and calculating their respective average value in the segment. The segment length defines the spatial resolution of the final measurements. Differentiation is then performed by subtracting the average value of each segment with that of the segment before. The result is shown in Fig. 2(c). The spatial resolution of each segment is set as 15 m in this experiment to achieve a good balance between the number of resolved points and the SNR of the retrieved $\xi(z)$. The noise source of $\xi(z)$ is mainly attributed to the inhomogeneity of the BGS peak frequency that could arise from several factors including strain variations along the optical fiber due to coiling and an imperfect compensation of the BSBS probe light polarization fading in the traces.

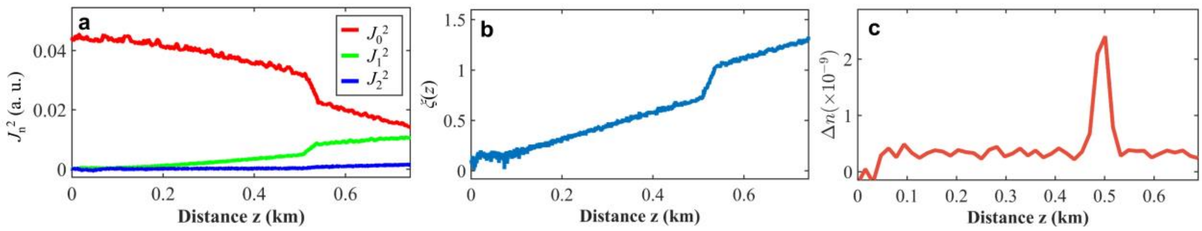

Fig. 2. (a) The experimentally obtained longitudinal intensity progression of reading pulse sidebands. (b) The phase factor $\xi(z)$ recovered using Bessel recurrence relation. (c) The FSBS response after differentiating the phase factor $\xi(z)$.

7. Sensing demonstration

A segment of 30 m uncoated optical fiber is exposed to three different outer environments (air, ethanol and water). The experimentally obtained distributed FSBS spectra is shown in Fig. 3. The exposed region could be clearly identified in the FSBS distributed spectra maps thanks to the strong resonance obtained by the efficient acoustic wave reflection at the fiber boundary. The rest of the sensing fiber keeps its original acrylate coating, which reduces significantly the acoustic wave reflection. The local FSBS spectral response in the coated segments can be nevertheless observed, though with a much reduced amplitude contrast.

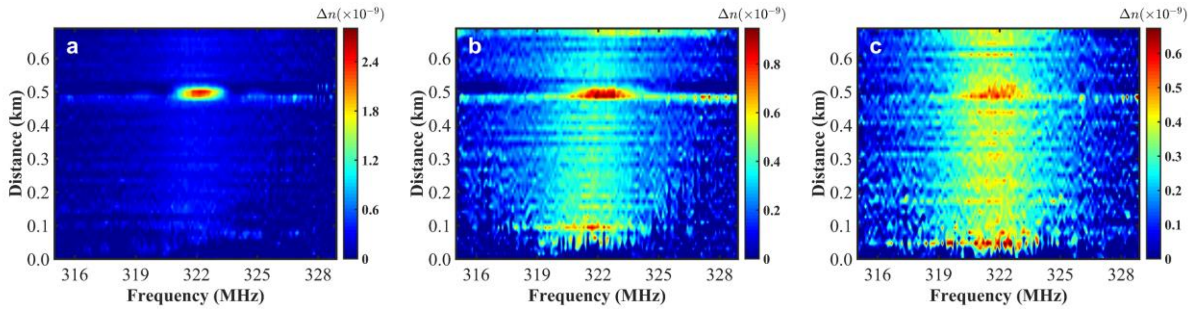

Fig. 3. Measured distributed FSBS spectra when the 30 m exposed fiber segment is surrounded by (a) air, (b) ethanol and (c) water.

The FSBS resonance spectra at the exposed fiber segment are shown in Fig. 4. In the presence of different outer media, the FSBS resonance linewidth changes in an inverse proportion to the resonance peak intensity; i.e. as the resonance linewidth broadens, the resonance peak intensity decreases. The FSBS spectrum of the normal uncoated fiber segment with acrylate polymer coating (Fig. 4, blue) are plotted alongside as reference for comparison. The FSBS linewidth of each liquid sample is related to the acoustic impedances Z_o of the outer material and Z_f of the fiber material by [4],

$$\delta\nu_m - \delta\nu_s = \frac{\Delta\nu_m}{\pi}\ln\left(\left|\frac{Z_o + Z_f}{Z_o - Z_f}\right|\right) \tag{5}$$

where $\delta\nu_\mathrm{m}$ is the measured FSBS linewidth, $\delta\nu_\mathrm{s}$ is the intrinsic FSBS linewidth of the silica fiber, and $\Delta\nu_\mathrm{m}$ = 48 MHz is the average frequency separation between the chosen resonant frequency (322 MHz) and the two adjacent FSBS spectral resonances. Z_f is the acoustic impedance of silica (13.19×10^6 kg/m^{2}s).

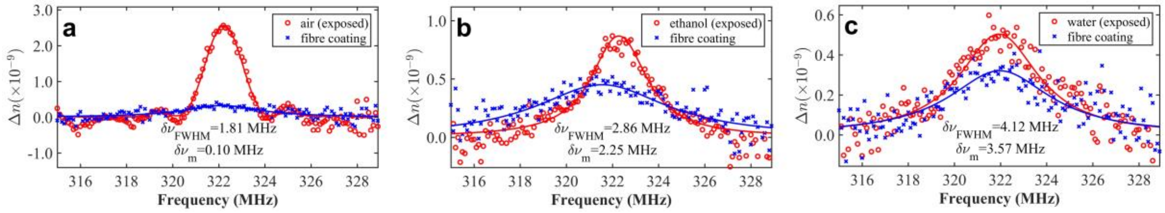

Fig. 4. The FSBS spectra in the 30 m exposed fiber segment when it is surrounded by (a) air, (b) ethanol and (c) water.

The intrinsic acoustic loss defining $\delta\nu_\mathrm{s}$ is estimated from the resonance linewidth when the uncoated fiber section is exposed to air, since under this condition nearly perfect acoustic reflection at the optical fiber boundary is obtained owing to the very large acoustic impedance mismatch. The intrinsic linewidth $\delta\nu_\mathrm{s}$ (~100 kHz) is considered in this case as solely due to the bulk viscous damping of silica. The measured FWHM $\delta\nu_\mathrm{FWHM}$ of the FSBS resonance spectrum for air, ethanol and water are respectively 1.81 MHz, 2.86 MHz and 4.12 MHz. However, because of the finite duration of the FSBS stimulating pulse, the measured FSBS spectrum indeed corresponds to a convolution of the pulse spectrum (sinc function) and the original FSBS resonance spectrum (Lorentzian function). Therefore, a full analytical expression of the broadened gain spectrum for a given stimulating pulse duration is used here to fit the measured FSBS spectrum. The original FSBS resonance linewidth $\delta\nu_\mathrm{m}$ successfully retrieved from the fittings are 0.10 MHz, 2.25 MHz and 3.57 MHz for air, ethanol and water exposures, respectively. The corresponding acoustic impedances of the outer materials at the exposed fiber segment are then calculated based on Eq. 5, resulting in 1.49×10^6 kg/m^{2}s for water, and 0.93×10^6 kg/m^{2}s for ethanol. These results agree well with the standard acoustic impedance values of water: 1.483×10^6 kg/m^{2}s, and ethanol: 0.93×10^6 kg/m^{2}s (published online by NDT Resource Center, http://www.nde-ed.org).

8. Conclusion

A technique to perform distributed FSBS spectrum measurements along a fiber is demonstrated for the first time where the local acoustic impedance of surrounding liquids can be accurately retrieved. The stripping of fiber coating in this work is to simplify the calculation of acoustic impedance. The practical handling issues can be simply overcome by using commercial fibers coated with a thin polymer layer, the same technique here applied.

9. Funding Information

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10. Reference

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