Polyimide Coated Fiber as Optomechanical Sensor

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Abstract: A commercially available optical fiber coated with 8 μm-thickness polyimide is used for measuring the acoustic impedance of the surrounding liquid materials, by means of the generation and detection of forward stimulated Brillouin scattering (FSBS). © 2018 The Author(s)
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1. Introduction

Opto-acoustic interactions in the optical fiber is a fascinating discipline that inspires a broad range of sensors, such as those based on stimulated Brillouin scattering (SBS), which has been widely used to perform distributed strain and temperature measurements [1-2]. Recently, another class of opto-acoustic interaction in optical fibers - forward stimulated Brillouin scattering (FSBS) - has been exploited to measure the acoustic impedance of liquid surrounding a standard optical fiber [3–5]. FSBS is also known as guided acoustic wave Brillouin scattering (GAWBS) [6]. This effect involves optically stimulating the transverse acoustic waves in an optical fiber through electrostriction. Because of the circular fiber's cross-section at the cladding-exterior boundary, the acoustic waves are reflected and confined inside the disc-shaped transversal cavity, giving rise to eigenmodes with resonant frequencies in the radio-frequency range. The difference of acoustic impedance between the fiber material and the external medium determines the acoustic reflectivity at the fiber's boundary and can be detected optically through measuring the decay rate [3] or linewidth [4] of the FSBS resonances.

However, all reported implementations of FSBS-based acoustic impedance sensors so far rely on stripping away the fiber's acrylate coating that shows high acoustic loss to facilitate direct contact between the cladding's boundary and its surroundings [3–5]. Although this approach greatly simplifies the retrieval of acoustic impedance, the mechanical strength of the sensing fiber is nonetheless compromised. In this work, we use a commercially available 20 m long 80 μm-diameter single-mode silica optical fiber coated with a 8 μm-thickness polyimide layer to demonstrate acoustic impedance sensing of ethanol and water. The thin polyimide layer allows the transverse acoustic waves to traverse between the cladding boundary and the coating boundary with much reduced loss, so that the acoustic waves keep sufficient energy to complete the transverse cavity roundtrip. In analysis, since the acoustic impedances of fiber material and polyimide are different, the polyimide coating is treated as a thin layer that is sandwiched between the fiber material and the surrounding material, in good analogy with an optical thin film. Besides, polyimide coated fiber shows excellent mechanical strength, known to sustain high temperature and has been deployed extensively as downhole sensors. As such, the demonstrated technique has strong potential to be adapted in the fiber optics sensing industry.

2. FSBS in polyimide coated 80 μm-diameter single-mode fiber

An optical fiber has cylindrical structure that supports longitudinal, radial, torsional, and flexural acoustic vibrations that can be stimulated through electrostriction [6]. The acoustic vibrations present in the forward scattered lights are the radial and torsional modes, which correspond to the acoustic waves that propagate transversally and circumferentially, respectively. We use the radial modes in this work as they provide the strongest response for detection. The eigenfrequencies of the radial modes for a 80 μm-diameter fiber can be calculated analytically by finding solutions satisfying the boundary conditions [6], tabulated in Fig. 1(a). In this work, we select one of the strongest modes (9th mode, ν_{res} = 636 MHz) for the sensing demonstration.

Through FSBS, two co-propagating lights of frequencies ω_1 and ω_2 couple to the transverse acoustic mode of frequency $\Omega = \Delta\omega = \omega_1 - \omega_2$. Conservation of momentum requires that the axial wavevector of the acoustic wave and the co-propagating lights satisfy the phase matching condition, $\mathbf{K}(\Omega) = \mathbf{k}_1(\omega_1) - \mathbf{k}_2(\omega_2)$. Since the transverse acoustic waves have negligible axial group velocity for a nearly zero axial wave vector, the phase matching condition is relaxed, thus the transverse acoustic waves can be stimulated over a broad range of optical wavelengths. Because of the photoelastic effect, the generated transverse acoustic waves in turn perturb the refractive index of the fiber core. A probe light at any wavelength that is introduced into the fiber will be phase modulated by the transverse acoustic waves. As such, the FSBS response impacts on the probe light as phase shifts, which can then be retrieved by using an interferometry setup that converts the induced phase shifts into intensity changes for detection [6-7]. Here, we use a Sagnac interferometer to probe the transverse acoustic waves that are stimulated by two co-propagating lightwaves with frequency separation given by the sweeping frequency ν_F [4]. The FSBS spectrum of the polyimide coated 80 μm-diameter fiber is shown in Fig. 1(b).

a

m	Calculation (MHz)	Measurement (MHz)
1	57	45
2	131	132
3	205	198
4	279	282
5	354	345
6	428	429
7	502	492
8	576	576
9	651	636
10	725	723
11	800	786
12	874	870

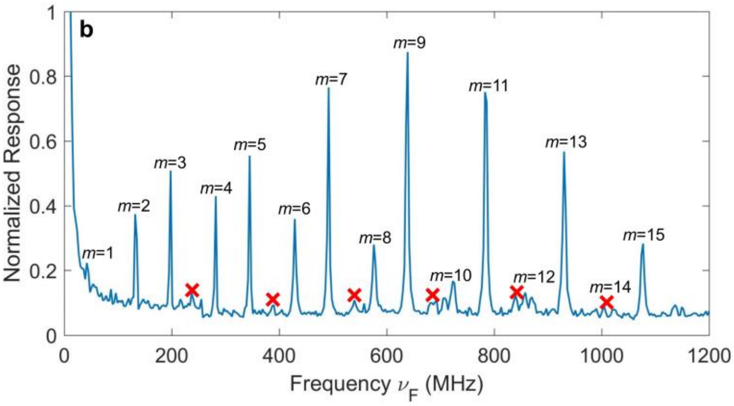

Fig. 1. FSBS spectrogram of the 80 µm-diameter polyimide coated fiber. (a) The frequencies of resonant modes from calculation and measurement. (b) The FSBS spectrum obtained using the frequency sweeping technique described in [4].

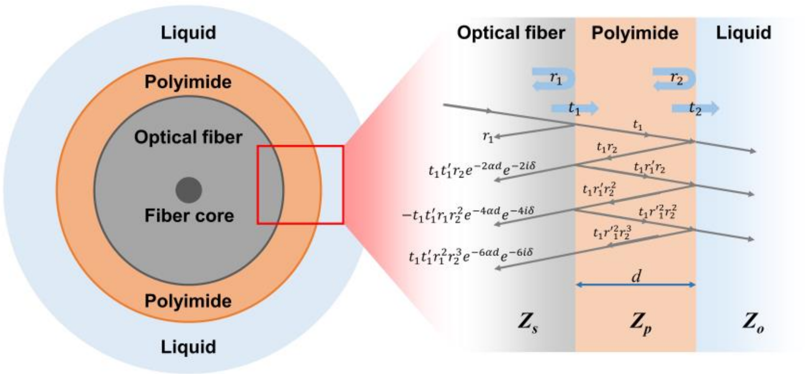

Fig. 2. Schematic diagram of the optical fiber with polyimide coating layer that acts as a 1D acoustic thin film. The reflection is angled for illustration purpose, transverse acoustic wave is assumed to be reflected normally from the surfaces.

The FSBS spectrum obtained from the experiment (Fig. 1(b)) exhibits multiple resonant peaks that could be individually associated to one of the calculated FSBS resonances in the 80 µm-diameter bulk fiber (Fig. 1(a)). This polyimide layer coating of the fiber turns out to show an acoustic roundtrip time through the layer which is approximately half of that through the silica bulk cross-section, causing the even order modes in the polyimide layer to interfere destructively with the acoustic resonances in the bulk fiber thus showing a reduced contrast.

The dynamics of transverse acoustic waves inside the polyimide coated fiber can be simplified as a two-tier process where the acoustic impedance of the external material first affects the global acoustic reflectance of the polyimide coating layer, which in turn changes the FSBS spectral linewidth in the silica fiber structure. In other words, the linewidth broadening of FSBS resonance $\Delta\nu_m$ is considered as due to the effective reflectance R at the silica-polyimide boundary as seen by the resonating acoustic waves inside the silica fiber, given as [4]:

$$\Delta\nu_m = \Delta\nu_s - \frac{\Delta\nu_{rt}}{\pi}\ln(R) \tag{1}$$

where $\Delta\nu_{rt}$ is the roundtrip frequency of the transverse acoustic wave, written as $\Delta\nu_{rt} = V_s/2a$, where V_s is the speed of sound in silica (~5950 m/s) and a is the fiber radius (40 µm), therefore $\Delta\nu_{rt}$ for this fiber is ~74 MHz. The broadening due to the intrinsic loss of the fiber material $\Delta\nu_s$ is a constant that is much smaller as compared to $\Delta\nu_m$, which can be deduced from [3] by assuming that silica has the same acoustic quality factors for the same frequency region, which gives $\Delta\nu_s \approx 0.35$ MHz at 636 MHz.

3. Polyimide coating acting as an acoustic thin film

The acoustic structure of the fiber and the polyimide coating can be approximated as a 1D acoustic layer in between two bulk materials (silica and the surrounding liquids), illustrated in Fig. 2. The mathematical description of this acoustic structure is similar to an optical thin film [8]. The acoustic impedance of the structure decreases successively following this order: silica-polyimide-exterior. The acoustic impedances of silica and polyimide are $Z_s = 13.1\times10^6$ kg/(m^{2}s) and $Z_p = 3.6\times10^6$ kg/(m^{2}s), respectively, whereas the acoustic impedance of most liquids-under-test Z_o fall below 2×10^6 kg/(m^{2}s). The acoustic field reflectance of silica-polyimide and polyimide-exterior boundaries, r_1 and r_2, respectively, are expressed as:

$$r_1 = \left|\frac{Z_s - Z_p}{Z_s + Z_p}\right|, \qquad r_2 = \left|\frac{Z_p - Z_o}{Z_p + Z_o}\right| \tag{2}$$

r_1 is calculated to be 0.5678. The total field reflectance R as seen by the acoustic waves at the silica-polyimide boundary can be derived from the superposition of successive reflected waves, the terms are in geometric series, expressed as

$$R = r_1 + t_1 t_1^{'} r_2 e^{-2\alpha d} e^{-2i\delta} - t_1 t_1^{'} r_1 r_2^2 e^{-4\alpha d} e^{-4i\delta} + t_1 t_1^{'} r_1^2 r_2^3 e^{-6\alpha d} e^{-6i\delta} \ldots \tag{3}$$

$$= \frac{r_1 + r_2 e^{-2\alpha d} e^{-2i\delta}}{1 + r_1 r_2 e^{-2\alpha d} e^{-2i\delta}}$$

Both t_1 and t_1' are the transmittances from silica to polyimide and vice versa, respectively, they are related by $t_1t_1' = 1 - r_1^2$. α is the acoustic attenuation constant of polyimide and δ is the phase delay as the acoustic waves propagate through the polyimide layer, given as:

$$\delta = \frac{2\pi \nu_{res}}{V_p} d \tag{4}$$

ν_{res} is the resonant frequency of the transverse acoustic mode (636 MHz), V_p is the speed of sound in polyimide (~2440 m/s) and d is the thickness of the polyimide layer, which can be retrieved accurately from the FSBS spectrum in Fig. 1(b) where the small peaks marked by red crosses are due to the leakages from the acoustic resonances inside the polyimide layer. The frequency separation between the peaks is ~151.7 MHz, which gives d = 8.04 µm. δ is then calculated to be ~13.17 rad. Since R is a complex quantity where its argument (phase) is absent in the linewidth $\Delta\nu_m$ measurement, the intensity reflectance R_P should be used in the following analysis:

$$R_P = R^2 = \frac{r_1^2 + 2\eta r_1 r_2 \cos(2\delta) + \eta^2 r_2^2}{1 + 2\eta r_1 r_2 \cos(2\delta) + \eta^2 r_1^2 r_2^2} \tag{5}$$

Here, the polyimide attenuation is written as a power ratio $\eta = \exp(-2\alpha d)$ for the ease of the subsequent algebraic manipulations.

4. Attenuation constant for polyimide coating

The polyimide layer acts as a buffer for a fraction of resonating transverse acoustic waves, thus its intrinsic acoustic loss becomes a significant factor that contributes to the FSBS linewidth broadening. The attenuation constant can nevertheless be determined in the condition where the polyimide coated fiber is surrounded by air. In this case, $r_2 \approx 1$, Eq. (5) can then be rewritten as:

$$\eta^2 (R_P r_1^2 - 1) + 2\eta r_1 (R_P - 1)\cos(2\delta) + R_P - r_1^2 = 0 \tag{6}$$

As R_P is obtained from Eq. (1) using the measured linewidth $\Delta\nu_m$ of air surroundings, η can be calculated by solving the quadratic equation Eq. (6) and consider only the positive solution. The measured FSBS spectrum around the resonant peak (636 MHz) with air as exterior is shown in Fig. 3(a), which is fitted with a Lorentzian function and gives $\Delta\nu_m$ = 2.825 MHz. Then, η, α and the quality factor are calculated to be 0.874, 8.34×10^3 m^{-1} and 196, respectively, which agree well with the reported loss characterization of polyimide [9].

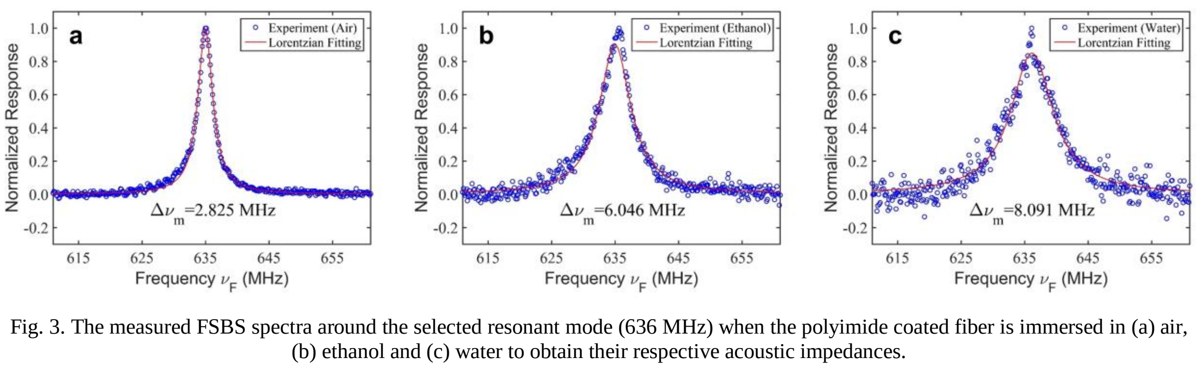

Fig. 3. The measured FSBS spectra around the selected resonant mode (636 MHz) when the polyimide coated fiber is immersed in (a) air, (b) ethanol and (c) water to obtain their respective acoustic impedances.

5. Measuring the acoustic impedance of the surrounding liquids

The measurement of acoustic impedance is demonstrated by immersing the polyimide coated fiber into the sample liquids. The FSBS spectra around the resonant peak (636 MHz) for ethanol and water surroundings are shown in Fig. 3(b) and (c), respectively. In the presence of liquids, the resonant linewidth $\Delta\nu_m$ broadens and the peak amplitude decreases. $\Delta\nu_m$ is retrieved through Lorentzian function fitting and used to calculate R_P by using Eq. (1). To obtain r_2, Eq. (5) should be rewritten as:

$$r_2^2\eta^2(R_P r_1^2-1)+2\eta r_1 r_2(R_P-1)\cos(2\delta)+R_P-r_1^2=0 \tag{7}$$

r_2 is obtained by solving the quadratic equation Eq. (7) and only the positive solution is considered. The acoustic impedance of the surrounding liquid Z_o is subsequently calculated from Eq. (2). The experimental results and calculations are listed in Table 1.

Table 1. Experimental results and calculations of acoustic impedances

Material	*Ethanol*	*Water*
$\boldsymbol{\Delta\nu_m}$	6.046 MHz	8.091 MHz
$\boldsymbol{R_P}$	0.6164	0.5182
$\boldsymbol{r_2}$	0.5915	0.4373
$\boldsymbol{Z_o}$	0.927×10^6 kg/(m^{2}s)	1.414×10^6 kg/(m^{2}s)
Standard Values [a]	0.93×10^6 kg/(m^{2}s)	1.483×10^6 kg/(m^{2}s)
Meas. Error, *e*	0.3 %	4.7 %

[a]From NDT Resource Center (www.nde-ed.org)

6. Conclusion

A technique to accurately retrieve the acoustic impedances of liquids surrounding a polyimide coated fiber is presented in this work, eliminating the need to strip away the protection coating so as to retain the mechanical strength of the sensing fiber. The measurements of liquid acoustic impedances have less than 5% error as compared to the standard values. Although polyimide is known to swell in the presence of water vapor, the results presented here are not affected as the humidity response time of polyimide is more than 15 minutes [10], whereas a typical full spectrum scan using this technique takes only a few seconds. The presented analysis is not limited to polyimide coating and can be used in the same way for optical fiber coated with other materials as a thin layer, ideally with an acoustic impedance matching that of silica, being poorly hydrophilic and with a much reduced acoustic loss. In addition, by carefully designing the polyimide layer thickness, certain acoustic modes could be suppressed or enhanced, in full analogy with quarter or half wave thin films in optics. In brief, this demonstration highlights the feasibility of using a thinly-coated optical fiber for acoustic impedance sensing, important for practical handling as well as for the implementation of long distance distributed measurement.

7. Funding Information

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8. References

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