Highly sensitive measurement of submicron waveguides based on Brillouin scattering

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ABSTRACT

Fabrication and characterization of submicron optical waveguides is one of the major challenges in modern photonics, as they find many applications from optical sensors to plasmonic devices. Here we report on a novel technique that allows for a complete and precise characterization of silica optical nanofibers. Our method relies on the Brillouin backscattering spectrum analysis that directly depends on the waveguide geometry. Our method was applied to several fiber tapers with diameter ranging from 500 nm to 3 µm. Results were compared to scanning electron microscopy (SEM) images and numerical simulations with very good agreement and similar sensitivity.

Keywords: Optical metrology, nonlinear optics, Brillouin scattering, tapered optical fibers, microwires.

1. INTRODUCTION

Subwavelength-diameter optical fibers, also known as optical micro and nanofibers, are the tiny cousins of standard optical fibers [1-3]. These hair-like slivers of glass, manufactured by tapering optical fibers down to a size hundred times smaller than a strand of hair, have a number of optical and mechanical properties that make them very attractive for both fundamental physics and technological applications. In addition to providing strong light confinement and enhanced nonlinear optical effects, optical microwires also exhibit a large evanescent field, enabling applications not currently possible with comparatively bulky optical fibers.

Although microfibers have extensively been investigated these last years, measuring their diameter remains a difficult challenge. Among the existing methods, the most common is the scanning electron microscopy (SEM) but it is often destructive. Another method based on optical imaging uses the scattered light from the microwire under laser illumination. Accuracy of 50 nm for the diameter has been reported [4]. A third approach is based on second- and third-harmonic light by inter-modal phase matching condition with a precision better than 2% [5]. Recently, a method using Rayleigh scattering has been proposed by controlling modal superposition with higher-order modes. The variation in the radius of the fiber waist was measured below 3 nm [6]. Forward Brillouin scattering has also been used to determine the microwire diameter by measuring the radial acoustic frequency [7].

In this work, we propose and describe a novel in-situ and non-destructive method to characterize optical nanofibers. It is based on Brillouin backscattering which relies on the interaction between light and acoustic waves [8-10]. In optical nanofibers, the backward Brillouin spectrum is fundamentally different from that of standard optical fibers. It exhibits several acoustic resonances due to shear and longitudinal hybrid acoustic waves (HAW) and surface acoustic waves (SAW) [11]. Here we take advantage of those new acoustic resonances to determine the fiber diameter from a comparison with numerical simulations. Using this technique, we achieve a sensitivity of 5 nm for wire diameter ranging from 500 nm to 3 µm.

The paper is organized as follows: First, we will introduce the theoretical background of our method and explain how the Brillouin spectrum from an optical microwire depends on the diameter. Then we will describe the experimental setup and shows the results.

2. THEORY AND NUMERICAL MODEL

2.1 Brillouin backscattering

When coherent laser light is coupled and guided into an optical fiber, as that shown schematically in Fig. 1, the light excites and feels several types of acoustic waves. In the standard description of Brillouin scattering, a pump wave (in red) generates via electrostriction an acoustic wave (green) that acts as a moving Bragg reflector. Light is thus scattered in the backward direction by this moving index grating, giving rise to a Stokes wave (blue) down frequency shifted by an amount that corresponds to the phonon frequency. Furthermore, the coherent interaction between the pump and Stokes waves generates an optical beating (purple) that propagates at the same speed as the phonon (3400 m.s^{-1} in silica).

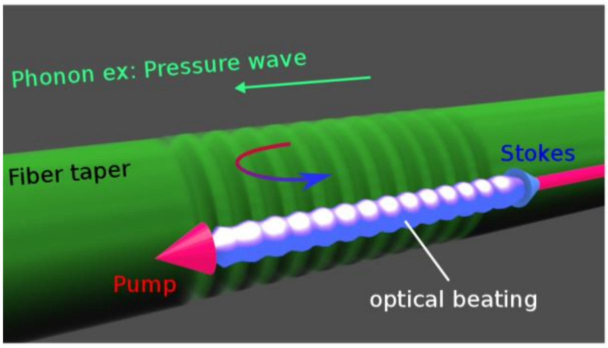

Fig. 1. Principle of Brillouin backscattering in an optical fiber taper

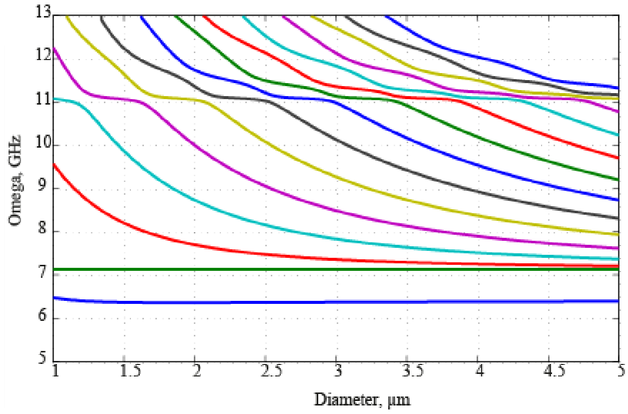

Fig. 2. Frequencies of the acoustic modes as a function of the microwire diameter without optical dispersion.

This acousto-optic interaction is governed by two relations, the energy conservation $\omega_p = \Omega + \omega_s$ and the phase matching condition $\beta_a = 2\beta$. ω_p, ω_s and Ω are frequencies of the pump photon, Stokes photon and acoustic phonon respectively. β_a is the acoustic wave vector and β is the optical wave vector. In the case of standard single-mode fiber (SMF), that are bulky compared to the acoustic wavelength (~ 0.5 µm), β_a has no specific relationship with the fiber geometry, so Brillouin backscattering does not provide direct information about the fiber dimension but rather about the effective index. For optical nanofibers, this is not the case because the acoustic resonances directly depend on the dimensions, as we will see thereafter.

2.2 Acoustic modes

The propagation of acoustic modes in a rod silica satisfies the following equation:

$$\frac{2p}{a}(q^2+\beta_a^2)J_1(qa) - (q^2-\beta_a^2)^2 J_0(pa)J_1(qa) = 4\beta_a^2 pq J_1(pa)J_0(qa) \quad (1)$$

with $p = \sqrt{\frac{\Omega^2}{V_L^2} - \beta_a^2}$ and $q = \sqrt{\frac{\Omega^2}{V_T^2} - \beta_a^2}$, where V_L and V_T are the longitudinal and shear acoustic velocities, respectively at *5900 m.s*$^{-1}$ and *3740 m.s*$^{-1}$, related to the longitudinal and shear components of the displacement. J_i are the Bessel functions and a is the fiber taper radius [12]. The above equation (1) is generally used to compute the propagation constant β_a as a function of the acoustic frequency Ω for a given radius a. However, in our case the propagation constant is determined by the phase-matching condition ($\beta_a = 2\beta$). As a result, solving the acoustic dispersion for a given diameter provides the Brillouin frequency. Figure 2 shows the acoustic frequencies versus the taper diameter given by Eq. (1). However, this figure does not straightforwardly depict the Brillouin spectrum because the optical propagation constant varies with the fiber diameter. Consequently, the optical dispersion must be included in the model.

2.3 Optical modes

The optical dispersion of a step index silica fiber provides the optical wave vector $\beta = k_0 n_{eff}$ solutions for a given integer m (azimuthal order of the mode) and fiber diameter a [13], as given by

$$\left\{\frac{J_m'(\gamma_1 a)}{\gamma_1 a J_m(\gamma_1 a)} + \frac{n_1^2}{n_2^2}\frac{K_m'(\gamma_2 a)}{\gamma_2 a K_m(\gamma_2 a)}\right\} = \frac{m}{a^2}\left(\frac{1}{\gamma_1^2}+\frac{1}{\gamma_2^2}\right)\left(\frac{1}{\gamma_1^2}+\frac{n_2^2}{n_1^2}\frac{1}{\gamma_2^2}\right) \qquad (2)$$

where $\gamma_1 = \sqrt{k_0^2 n_1^2 - \beta^2}$, $\gamma_2 = \sqrt{\beta^2 - k_0^2 n_2^2}$, and K_m denotes the modified Bessel function of the second order, with the prime denoting differentiation with respect to the argument. K_0 is the wave vector in vacuum. The resulting solutions are illustrated in Fig. 3 where we plotted the evolution of effective refractive index of each optical mode as a function of the microwire diameter.

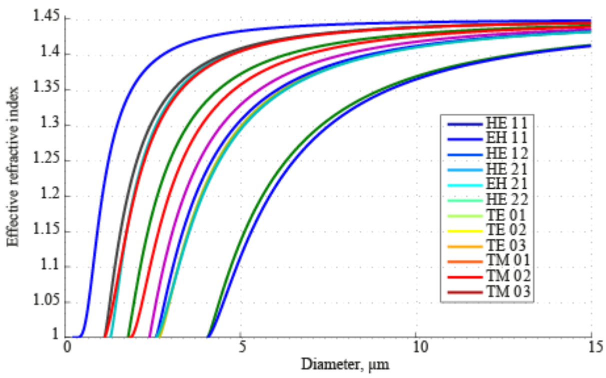

Fig. 3. Effective refractive index in optical fiber as a function of diameter for the fundamental mode (HE11) and higher-order HE, TE, TM modes.

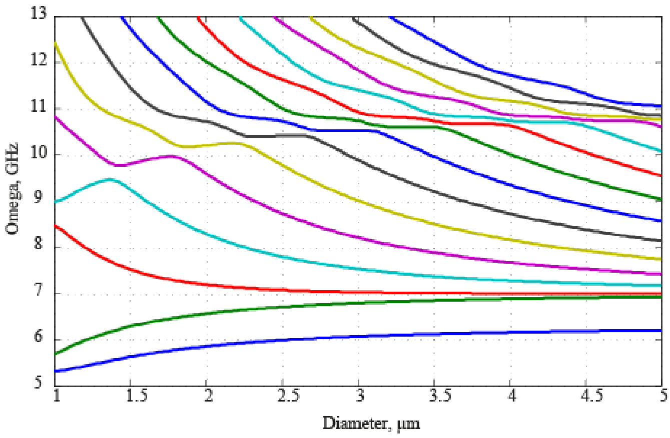

Fig. 4. Acoustic frequencies as a function of the microwire diameter including the optical dispersion of the fundamental mode HE11.

For large diameter (> 3 µm), the effective index of the fundamental mode HE11 reaches 1.445 but for thinner diameter it strongly drops from 1.445 to 1 in few micrometers of diameter. If we take into account the optical mode dispersion (equation 2) when solving equation (1), the Brillouin frequency spectrum depicted in Fig. 4 is different from Fig. 2. As it can be seen, the spectrum varies for diameter below 3 µm. In the following section, we will investigate how we can experimentally deduce the diameter of an optical microwire by fitting an experimentally measured Brillouin spectrum.

3. EXPERIMENTAL SETUP

3.1 Fabrication method

Optical microwires have been tapered from a standard telecom fiber (SMF-28) using the heat brush technique [11]. The tapering system is sketched in Fig. 5(a). The fiber is fixed on two translation stages and softened on its central part with a small butane flame. The flame (Fig. 5b) is regulated using a mass-flow controller and it is kept motionless while the two translation stages stretch the fiber. The microwire shape is fully controlled by the trajectories of the two stages.

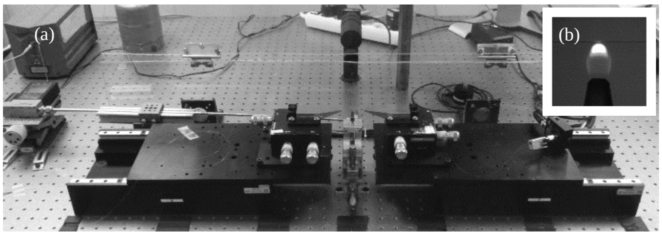

Fig. 5. (a) Pulling bench for fabrication of OMW. (b) View on the flame position in relation to the fiber position before stretching.

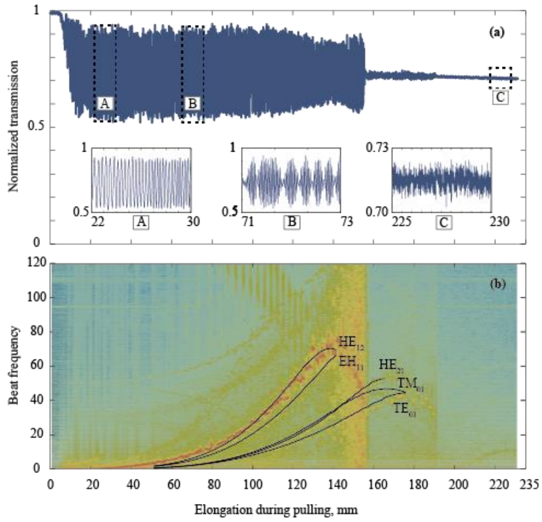

Fig. 6. (a) Transmitted optical power at the output of the OMW as a function of elongation during the pulling. (b) Related spectrogram of the transmission with visualization of higher mode excited.

We control the quality of the tapering process by measuring the optical transmission [13, 14]. The transmitted power is represented in Fig. 6(a) as a function of the stretching, which is related to the diameter of the fiber.

At the beginning of the pulling, the transmission remains stable until 5 mm of elongation (70 µm of diameter reached). This means that the light is still guided by the fundamental mode of the fiber. Beyond this elongation, the transmission is reduced and optical mode beating occurs, which reveals excitation of higher-order modes (A and B areas in Fig. 6(a). This beating is due to the between a core/clad guidance to a clad/air guidance. The core is vanished and the light is then guided by a large cladding waveguide, the fiber then becomes multimode as we can see in Fig. 3. We then observe a first cut-off at 155 mm of elongation (2.5 µm of diameter) where the beat amplitude is reduced and a second one at 190 mm of elongation (1.5 µm of diameter) from which the interferences disappear. Then the transmission turns back into stable (C area) that means the fiber is single-mode again. The average transmitted power at the end of the pulling is around 75 % or 1.2 dB of total loss.
Figure 6(b) shows a Fourier spectrogram related to the transmission signal (Fig. 6a). It reveals the excited higher-order modes during the pulling process as a function of the elongation. Each mode branch can be identified as the optical beating depends on the effective refractive index difference between the two beating modes [15]. Solving the optical dispersion equation of the optical microwire (Eq.2), we can compute the beat frequency with respect to the diameter. The black lines of Fig. 6(b) depict the beating between a given mode and the fundamental one. Here, the optical fiber was tapered until single-mode propagation was achieved. As shown in Fig. 3, single-mode operation typically appears for fiber taper below 1-µm diameter. In this case, the theoretical acoustic frequencies computed in Fig. 4 are valid.

3.2 Heterodyne detection setup

The experimental setup to measure the Brillouin spectrum is shown in Fig. 7(a) and the tapered optical fiber is schematically depicted in Fig. 7(b). A continuous-wave (CW) laser at λ = 1550 nm is first split into two beams using a fiber coupler. One beam is used as pump light and the other one is used as reference light. The pump light is then amplified by an erbium-doped fiber amplifier (EDFA) up to 33 dBm and injected into the microwire under test through an optical circulator. The backscattered Brillouin signal from the wire is mixed with the reference light, giving rise to an optical beat signal which is detected with a fast photodiode and analyzed with an electrical spectrum analyzer (ESA).

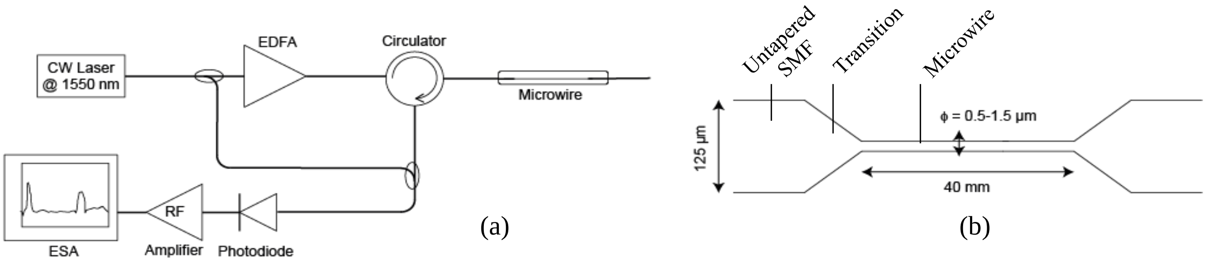

Fig. 7. (a) Heterodyne detection setup for measuring the backscattering Brillouin spectrum (b) Scheme of an optical microwire.

4. RESULTS

Figure 8 shows the experimental Brillouin spectrum (blue) for a microwire diameter lower than 1 µm. We observe many acoustic resonances, such as two surface acoustic waves (SAW) around 5.5 GHz, and hybrid acoustic waves (HAW) in the range 8-10.5 GHz. We can also see the resonances due to the taper transitions and the untapered optical fibers. The red dashed curve in Fig. 8 shows a theoretical fit obtained from our model with a diameter of ϕ=805 nm. A further comparison shows that the agreement is very good for SAWs and HAWs, only, as we did not take into account the transitions and un-tapered sections in our model.

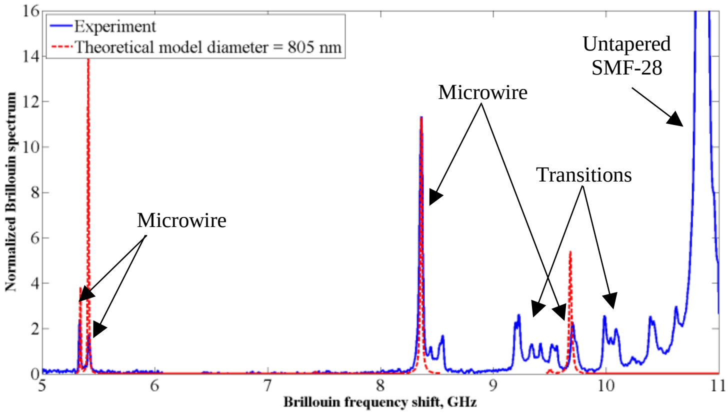

Fig. 8. Experimental Brillouin spectrum (blue) versus the theoretical one (red dashed curve) for a diameter ϕ= 805 nm.

In our model, the diameter step is 5 nm. For each step, the Brillouin spectrum is slightly frequency shifted by a few MHz. In most case, +/- 5 nm of margin error on the diameter is acceptable, because the theoretical spectrum is still verified with the experimental one. The sensitivity depends on the diameter because of different slopes between shear and compression branches, according to the map in Fig. 4. For a 10 nm diameter variation, the spectrum would shift by 50 MHz, which is visually perceptible owing to the experimental full width at half maximum, which is around 30 MHz for HAWs and 20

MHz for SAWs for microwire part. As a consequence, we can estimate the sensitivity of our diameter measurement to 5 nm. We checked this value by measuring with the Focused Ions Beam (FIB) a fiber taper diameter of ϕ=780 nm for this sample, that is only ~3% of variation.

Figure 9 shows another experimental Brillouin spectrum from a thinner fiber taper than Fig. 8. We evidence resonances from SAWs and HAWs in addition to transitions.

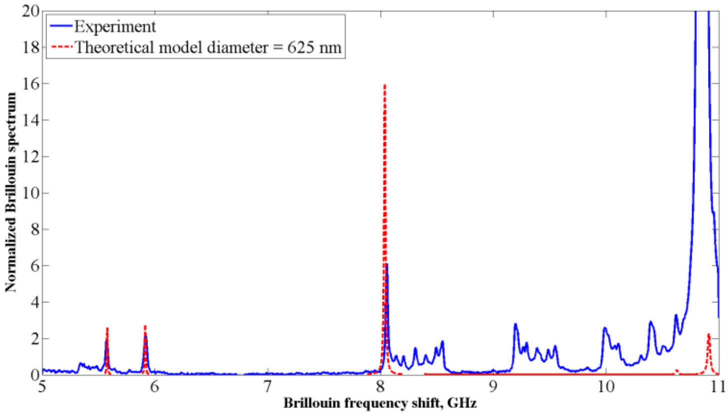

Fig. 9. Experimental Brillouin spectrum (blue) versus the simulated one (red dashed curve) for a diameter ϕ= 625 nm.

As the same method than the first sample, the red dashed theoretical plot shows that the diameter is 625 ±5 nm and the FIB measurement gives ϕ = 590 nm. The difference between Brillouin spectrum and FIB is 35 nm only (5.6% error). This result indicates that our technique is quite efficient to determine the diameter in a wide range from 500 nm up to 3 µm.

5. CONCLUSION

In this work, we proposed and demonstrated an original technique based on Brillouin backscattering that allows for the accurate diameter measurement of sub-micron optical fibers. Its advantages over other methods include a simple heterodyne setup, no need for optical alignment, and an excellent precision close to 5 nm.

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