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Intracavity Brillouin Gain Characterization

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Abstract—Brillouin gain coefficient is usually evaluated using well-established pump-probe technique. We report a technique based upon the cavity ringdown method that enables to characterize this fundamental parameter directly in a Brillouin laser cavity. Indeed, within a unique experimental setup, material gain, optical cavity parameters and laser properties can be extracted. This method would be particularly suitable for micro-resonator lasers intracavity material Brillouin gain determination.

Index Terms—Brillouin gain, Fiber ring laser, Cavity ringdown method

I. INTRODUCTION

Stimulated Brillouin scattering (SBS) initiated in an optical cavity is an attractive phenomenon to generate narrow linewidth lasers [1]. Stokes waves might even be generated in cascade reaching better coherence properties [2]. This ability can be used to produce a pure electrical signal by beating two Stokes waves separated of a multiple of the Brillouin Stokes shift (ν_B) for microwave generation [3]–[8]. To reach high performance Brillouin laser, the material gain coefficient (g_B) is a crucial parameters to evaluate.

Brillouin gain coefficient can be estimated by measuring gain bandwidth using usual pump-probe method [9] or threshold power determination [10]–[12]. In those methods, g_B can be infer at the expense of knowing material constants which are not always possible depending of the material used.

We propose to use the cavity ringdown spectroscopy (CRDS) to determine the Brillouin gain coefficient inside a laser cavity. CRDS have been successfully demonstrated in ring cavities to determine dispersive properties [13] and selective amplification [14]. This method applied to Brillouin ring-cavity fiber laser allow to determine, using a simple setup, the gain coefficient.

II. CAVITY RINGDOWN SPECTROSCOPY

Brillouin fiber lasers are based on Stimulated Brillouin Scattering (SBS), a nonlinear optical process involving two optical waves (Pump and Stokes signals) and an acoustic wave. For sufficiently high pump intensity, a Stokes signal can be efficiently created in the counter propagating direction of the incident pump. The Stokes frequency is downshifted from the pump frequency by the Stokes shift ν_B . The associated gain curve is described by:

$$g_B(\nu) = g_B \frac{(\Delta\nu_B/2)^2}{(\nu - \nu_B)^2 + (\Delta\nu_B/2)^2} \quad (1)$$

where $\Delta\nu_B$ is the Full Width at Half Maximum (FWHM) of the gain and g_B the Brillouin gain coefficient. The inset of Figure 1 displays the spectral repartition of the SBS when studied in a resonant cavity. The single pass gain experienced by the cavity mode is proportional to $e^{g_B(\nu)P_{in}L_{\text{eff}}/A_{\text{eff}}}$ where P_{in} is the incident pump power, A_{eff} the effective mode area and L_{eff} the usual effective interaction length. Maintaining the cavity mode (green color) in resonance with the maximum of the Brillouin gain (blue color), insures optimal Stokes signal generation with $g_B(\nu) = g_B$. Then the passive losses of the cavity mode might be compensated by Brillouin gain when pump intensity is increased.

Let's consider the temporal amplitude evolution $u(t)$ of the cavity mode located below the Brillouin gain (green color, inset of Fig.1). The total photon lifetime $\tau/2$ experienced by the cavity mode is:

$$\frac{1}{\tau} = \frac{1}{\tau_0} + \frac{1}{\tau_e} \quad (2)$$

where $\tau_0/2$ and $\tau_e/2$ are the intrinsic photon and the coupler lifetimes respectively. In the good finesse approximation the coupler lifetime can be related to the coupling coefficient by $|\kappa|^2 = 2\tau_L/\tau_e$ and the intrinsic photon lifetime τ_0 to the intensity round trip attenuation a^2 by:

$$a^2 = 1 - 2\tau_L/\tau_0 \quad (3)$$

where τ_L is the round trip time. Then $\tau_0 > 0$ corresponds to optical attenuation with $a^2 < 1$ when $\tau_0 < 0$ implies optical Brillouin gain $a^2 > 1$.

When SBS occurs in the probed cavity mode, the intensity round trip attenuation can be expressed as:

$$a^2 = \beta e^{-\alpha L} e^{g_B(\nu)P_{in}L_{\text{eff}}/A_{\text{eff}}} = a_{\text{op}}^2 e^{g_B(\nu)P_{in}L_{\text{eff}}/A_{\text{eff}}} \quad (4)$$

where β is the inner local losses (isolator transmission loss, fiber splice) and α the fiber loss coefficient. In the following we consider $L_{\text{eff}} \approx L$ and $g_B(\nu) = g_B$. Increasing the pump intensity P_{in} , allows to compensate the intensity round trip attenuation and then to tune the τ_0 value.

If one can evaluate experimentally τ_0 , and then a^2 , experimental estimation of the Brillouin gain coefficient can be obtain by using Eq. 3 together with Eq. 4:

$$g_B = \frac{A_{\text{eff}}}{P_{in}L} \ln \frac{a^2}{a_{\text{op}}^2} \quad (5)$$

A. Experimental setup

The experimental setup is presented on Figure 1. The fiber

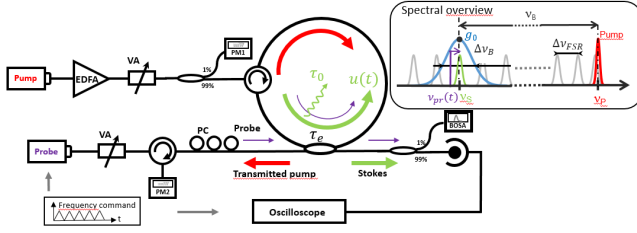


Fig. 1. Experimental setup. EDFA: Erbium-doped fiber amplifier, VA: variable attenuator, PC: polarization controller, BOSA: Brillouin optical spectrum analyzer.

cavity is composed of a 20 m polarization maintaining silica fiber giving a free spectral range (FSR) of $\Delta\nu_{FSR} = 10\text{MHz}$. The laser pump intensity of a single mode laser with 250 kHz linewidth centered at 1550 nm, is first amplified through and Erbium Doped Fiber Amplifier (EDFA) and then adjusted by a variable attenuator. 1% of the pump is extracted through a coupler for intensity power monitoring (PM1), the main part of the laser pump intensity being coupled in the cavity by a circulator. The circulator insures a single pass to the pump signal in the fiber loop preventing re-injection. For sufficiently intense pump intensity, stimulated Brillouin Stokes signal is generated in the opposite direction of the pump signal. Extracted Stokes signal is analyzed spectrally through a Spectrum Analyser (BOSA) and the intensity is recorded by a photodiode. The lasing threshold is determined when pump depletion starts corresponding to a pump power of $P_{th} = 65\text{mW}$.

The probe signal is provided from a tunable laser with 250 kHz linewidth. Before entering the cavity the signal intensity is controlled by a variable attenuator (VA) and its polarization adjusted through polarization controller (PC). The probe laser frequency is positioned close to the cavity mode experiencing Stokes amplification thanks to the 10 MHz resolution of the BOSA. The frequency of the probe signal is continuously swept across the resonant Stokes signal by a frequency command allowing to adjusted the sweeping speed and the scanned frequency range. The transmission of the cavity mode is then collected by a photodiode and observed on an oscilloscope triggered by the frequency command. The sweeping speed of the laser is tuned sufficiently fast to observed ringing phenomenon characteristic from the transient response of the cavity [13].

B. Measurements

Cavity ringdown signal are collected for various pump power ranging from 12 to 61 mW. It is important to notice that gain coefficient measurements are performed below the lasing threshold.

An example of transmission signal is shown on Fig. 2 (blue

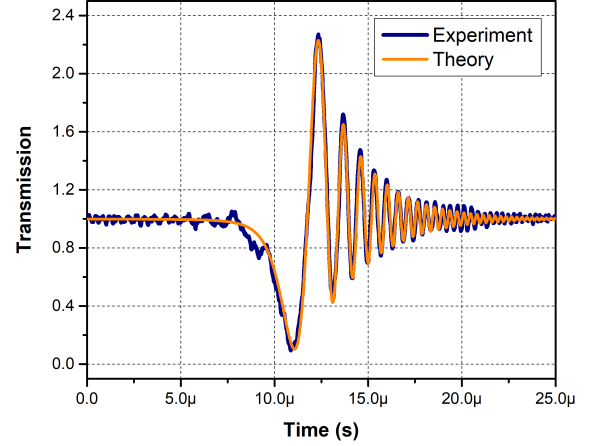


Fig. 2. Ringing profile recorded for Brillouin ring cavity with an input pump power of 45 mW. Theoretical fit gives $\tau_e = 3.8\mu\text{s}$, $\tau_0 = 33\mu\text{s}$ and $V = 20\text{MHz}/\mu\text{s}$ corresponding to a cavity in the overcoupling regime.

curve). Fitting the curve with an analytical model [13] gives τ_0 and τ_e from which we can extract a^2 ((4)) and finally g_B ((5)). Here, since the coupler coefficient is fixed (τ_e constant) and that the intrinsic photon lifetime τ_0 is tunable by adjusting the pump power, various coupling regime of the cavity can be investigated ranging from undercoupling to selective amplification. For each acquisition, an estimation of g_B can be obtained. Figure 3 summarized the extracted values in function of the pump power. The mean value is equal to $2.08 \times 10^{-11} \pm 1.1 \times 10^{-12}\text{m/W}$, being of the same order than usually reported value for Brillouin gain in silica fiber [7].

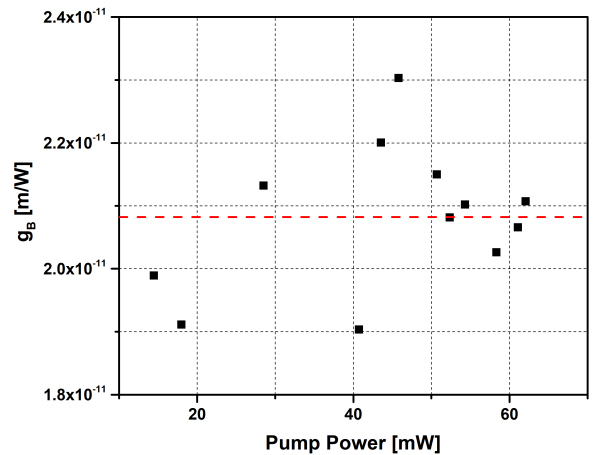


Fig. 3. Brillouin gain coefficient extracted from the CRDS signal for various input pump power. The mean value is equal to $g_B = 2.08 \times 10^{-11} \pm 1.1 \times 10^{-12}\text{m/W}$

III. CONCLUSION

A cavity ringdown method is applied to SBS in fiber cavity. Contrary to usual techniques, this new method gives access, through a simple measurement, as well to the Brillouin gain coefficient of the fiber material as to the cavity parameters. We have shown that the fast sweeping ringdown technique allows Brillouin gain characterization. The proof of concept has been experimentally demonstrated with silica fiber ring resonator. This allowed us to determine unambiguously the coupling regime and to estimate the Brillouin gain coefficient, which is similar to reported results and to our measurements using standard methods. This cavity ringdown method can be applied to any kind of resonators allowing for example, the determination of Brillouin gain coefficient in microresonators, chalcogenide fiber and Whispering Gallery Mode cavities.

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