Brillouin Optical Time-Domain Analysis of Fiber-Optic Parametric Amplifiers

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***Abstract*—We carried out distributed measurements of the longitudinal gain of fiber-optical parametric amplifiers using a novel sensing technique based on Brillouin optical time-domain analysis. Using this technique, we successfully characterized different gain behaviors in the linear and the saturation regimes. In addition, we demonstrated the recently predicted gain reciprocity at opposite ends of the amplifier span.**

***Index Terms*—Brillouin sensing, fiber-optical parametric amplifier (FOPA), four-wave mixing (FWM).**

I. Introduction

RECENT advances in fiber-based optic parametric amplifiers (FOPAs) have shown their tremendous potential applications for future ultrahigh bandwidth all-optical technologies [1], [2]. FOPAs are based on an efficient four-wave-mixing (FWM) process involving one- or two-pump waves and frequency-detuned signal and idler waves. Because the efficiency of the FWM process relies on the phase-matching condition between these four waves, it is fundamental to tune the pump wavelength near the zero-dispersion wavelength (λ_0), so as to reach ultrahigh gain bandwidth. When phase-matching is fully satisfied, both FWM or modulation instability theories predict an exponential-like growth for the signal and idler waves. In practice, however, a FOPA is strongly phase-sensitive once the idler is efficiently generated. Therefore, phase-matching is hardly satisfied all along the amplifier fiber span for two main reasons. First, longitudinal random fluctuations in λ_0 alter the phase-matching, leading to a reduction of both the achievable parametric gain and bandwidth [3], [4]. Second, a tiny pump depletion may lead to drastic variations of phase-matching as well, leading to saturation of the FOPA and, in the worst case, to signal depletion [5]. In both cases, we can expect that the parametric gain is no longer rigourously exponential. It is thus crucial to perform a distributed measurement of the FOPA gain along the amplifier span, for optimizing the full initial parameters, and possibly for mapping the underlying λ_0 fluctuations. Recently, a technique based on optical time-domain reflectometry has been applied for the characterization of a FOPA [6]. This method is suitable for analyzing the exponential gain, however, it only allows the measurement of the accumulated parametric gain from randomly distributed Rayleigh sources along the fiber and is, therefore, not phase-sensitive. In this work, we propose and demonstrate another approach to probe the local parametric gain by using Brillouin optical time-domain analysis (BOTDA) [7], in a novel scheme where the studied phenomenon (parametric amplification) acts on the BOTDA pump. In particular, this technique enables us to show different gain behaviors such as the parabolic and exponential regimes generated in a long dispersion-shifted fiber (DSF). We also observe the impact of longitudinal dispersion fluctuations and pump depletion on the distributed gain. Finally, measurements performed in highly nonlinear fiber (HNLF) demonstrate the gain reciprocity at opposite ends of the fiber, an interesting behavior recently predicted by Marhic *et al.* [8].

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II. Principle

In a single-mode fiber, the small-signal parametric gain reads as

$$G(z) = 1 + \left(\frac{\gamma P}{g}\sinh(gz)\right)^2 \tag{1}$$

where P is the parametric pump power, γ the nonlinear coefficient, $g^2 = (\gamma P)^2 - (\kappa/2)^2$, g the gain per unit length, and κ the phase-mismatch which is expressed as

$$\kappa = 2\gamma P + \Delta\beta_L \tag{2}$$

where $\Delta\beta_L$ is the linear phase mismatch between the parametric pump, the signal, and the generated idler wave. When the parametric pump wavelength is tuned close to λ_0, it is useful to expand $\Delta\beta_L$ as

$$\Delta\beta_L = \beta_2 \Delta{\omega_P}^2 + \frac{\beta_4}{12}\Delta{\omega_P}^4 \tag{3}$$

with β_2 and β_4, the second- and fourth-order dispersion coefficients at the pump frequency, respectively, and $\Delta\omega_P$ the frequency detuning between the pump and the signal. Note that, as κ depends on the dispersion and on the pump power, (2) and (3) together highlight the vulnerability of the phase matching on pump depletion and fluctuating λ_0.

BOTDA makes possible the distributed measurement of the stimulated Brillouin scattering (SBS) interaction along an optical fiber. It manifests through the coupling between two counterpropagating waves showing a well defined frequency difference. The amplitude of the SBS interaction depends essentially

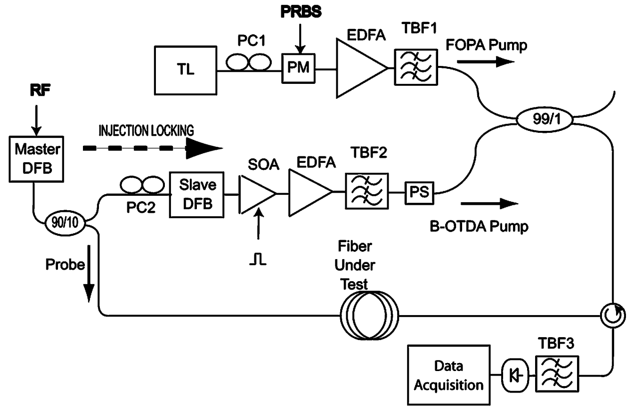

Fig. 1. Experimental setup. TBF: tunable Bragg filter. PM: phase modulator. PC: polarization controller.

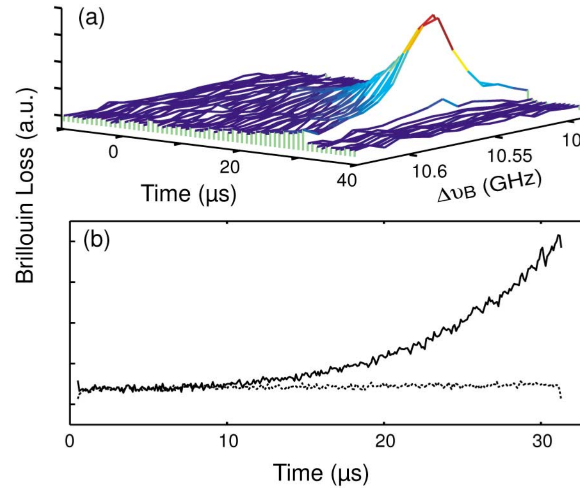

Fig. 2. (a) Brillouin loss spectra of the pump pulse. (b) Distribution of the peak probe Brillouin loss when the parametric pump is ON (solid curve) and OFF (dashed curve).

on the amplitude of the interacting waves. For distributed measurement, one of these waves is a pump nanosecond pulse and the local information is retrieved in the time domain [7]. In our method, this pulse at frequency ν_B acts as the signal to be amplified in a single-pump FOPA and its local power inside the FOPA is measured through local Brillouin interaction with a counterpropagating continuous-wave (CW) probe. Indeed, the threshold for Brillouin interaction is well below the one for parametric interaction in most fibers. For this reason, one can use the BOTDA pump as a small signal in the FOPA. Note also that parametric amplification only occurs on the BOTDA pump which copropagates with the parametric pump and does not affect the counterpropagating CW-probe. When the CW probe beam at frequency ν_A is tuned so that $\nu_A = \nu_B \pm \Delta\nu_B$, where $\Delta\nu_B$ is the Brillouin shift, the interaction with the BOTDA pump pulse leads to a change in the CW-probe power by an amount ΔP_A, which can be expressed at a first approximation, as

$$\Delta P_A = \frac{g_B}{A_{\text{eff}}} P_A(z) \times P_B(z)\Delta z \tag{4}$$

where g_B is the Brillouin gain coefficient ($g_B \approx 5 \times 10^{-11}$ $\text{m}\cdot\text{W}^{-1}$ in bulk silica), A_{eff} is the fiber effective area and Δz is the BOTDA pump pulse length [7]. More precisely, when the probe is on the anti-Stokes side, it undergoes Brillouin loss while when it is on the Stokes side, it experiences Brillouin gain. Using Brillouin loss ensures that no BOTDA pump depletion takes place so that any saturation would come from the parametric pump. In addition, thanks to both the high sensitivity and the high spatial resolution of the BOTDA technique, one can use relatively low BOTDA pump power so as to study the FOPA in the nonsaturation regime. Through an optical time-domain analysis of the probe, one can readily obtain the longitudinal distribution of $P_B(z)$, which in turn is related to the parametric gain as $P_B(z) = P_B(0) \times G(z)$.

III. Experimental Setup

Fig. 1 depicts the experimental scheme. As a parametric pump, we use a CW tunable laser which is phase-modulated by a pseudorandom binary sequence generator at 3.5 GHz in order to suppress Brillouin back-scattering from the parametric pump. The output is amplified using a 33-dBm erbium-doped fiber amplifier and filtered by a 1-nm bandpass filter to remove amplified spontaneous emission. The Brillouin pump frequency needs to be precisely stabilized so that the detuning with probe frequency remains equal to the Brillouin shift. To achieve this condition, the probe is intensity modulated by an RF signal to produce two symmetrical sidebands separated from the carrier by $\Delta\nu_B$. Most of the probe is then directly injected at the end of the fiber under test, while a small part is launched into the cavity of a slave distributed feedback laser diode. Through injection locking, the frequency of the slave cavity locks on the desired probe sideband [9]. The BOTDA pump is then pulsed using a semiconductor optical amplifier whose gain was gated using an electric pulse train. The parametric pump and the BOTDA pump are then combined using a 99/1 coupler and the counterpropagating probe is extracted using an optical circulator. Note that the probe is filtered before detection to avoid interference with Rayleigh backscattering from the FOPA pump. A polarization scrambler is also used to avoid any polarization-dependent Brillouin interaction. Two different fibers were tested: a 3.1-km DSF with $\gamma = 2\ \text{W}^{-1}\cdot\text{km}^{-1}$, $\lambda_0 = 1549.5$ nm and a 490-m-long HNLF with $\gamma = 11.2\ \text{W}^{-1}\cdot\text{km}^{-1}$, $\lambda_0 = 1553$ nm. For all experiments, the probe wavelength was fixed to 1550.8 nm. The BOTDA pump frequency was swept over 200 MHz around the Brillouin shift of the tested fiber, while the pulsewidth was set to 100 ns, leading to a 10-m resolution. The parametric pump power was measured at 400 mW and the BOTDA pump wavelength was tuned so that the probe is on the anti-Stokes side.

IV. Results

Fig. 2(a) shows a typical evolution of the Brillouin loss spectra along the DSF fiber when the BOTDA pump is parametrically amplified. These spectra are well fitted by the following Lorentzian function [10]:

$$f_B(\nu) = G_B \frac{\delta\nu^2}{(\nu - \Delta\nu_B)^2 + \delta\nu^2} + C_{\text{ref}} \tag{5}$$

with $\delta\nu$ the full-width at half-maximum of the Brillouin loss spectrum and G_B the net Brillouin loss, which is proportional

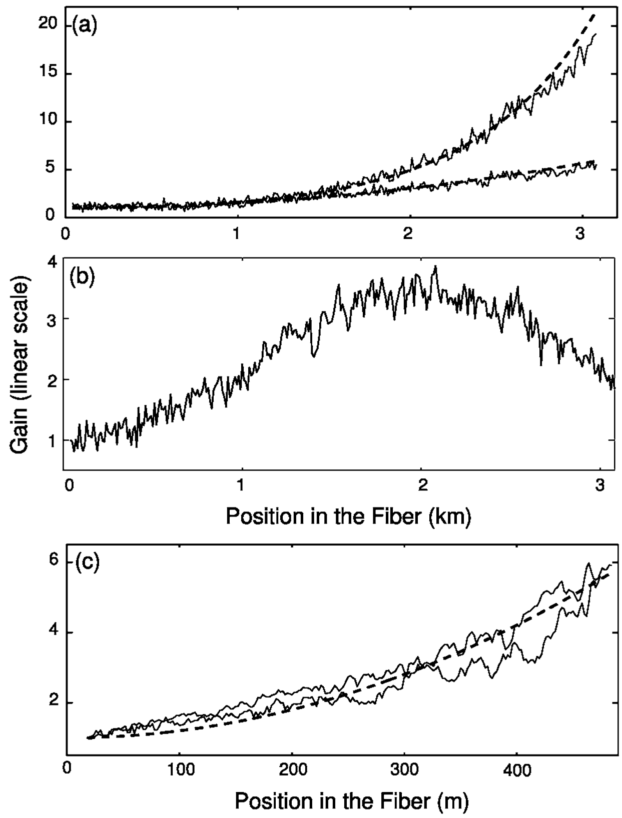

Fig. 3. (a) Distributed measurement of the FOPA gain in the DSF for two gain regimes. (b) Distributed measurement of the DSF FOPA gain in the saturation regime. (c) FOPA gains in the HNLF for the two opposite directions.

to the amount ΔP_A of (4). C_{ref} is a fitting parameter that accounts for the background DC level of the probe. Using (5), the net Brillouin loss for the cases where the parametric pump is switched ON and OFF are depicted on Fig. 2(b) that clearly shows the parametric amplification of the BOTDA pump. Then, to obtain the net FOPA gain, we simply divided the solid trace by the dashed trace. Note that we assumed only half of the polarization-scrambled BOTDA pump is parametrically amplified. Fig. 3(a)–(c) shows the derived FOPA local gain in linear scale, using the HNLF and DSF fibers in different experimental conditions. For instance, Fig. 3(a) illustrates the situation of the exponential ($\kappa = 0$) and parabolic ($g \approx 0$) gain regimes, simply measured by tuning the FOPA pump wavelength at 1553.3 and 1550 nm, respectively. Using (4), we evaluated the injected polarization scrambled BOTDA pump peak power to be less than 4 mW. We also plotted in dashed lines the parametric gain as given by (1) assuming no λ_0 fluctuation nor parametric pump depletion. We can see a fairly good agreement between the standard theory and experimental results. The slight difference seen in the exponential regime is due to residual pump depletion. We also studied the FOPA in the saturation regime. For this purpose, we tuned the FOPA pump frequency far from the pulse frequency so as to get a negative phase-mismatch ($\kappa < 0$) and thus saturate the parametric gain more quickly [5]. We also increased the Brillouin pump amplitude while the resolution was set to 300 ns. Fig. 3(b) depicts the FOPA gain distributed measurement that reveals two stages. At the beginning of the fiber, the Brillouin pump is amplified until saturation of the FOPA takes place. Then the power is transferred from the BOTDA pump to the parametric pump and its generated idler, leading to the observed power decrease. Finally, Fig. 3(c) reports the distributed FOPA gain at opposite ends of the HNLF, with a pump wavelength close to λ_0. As can be seen, both traces exhibit the same output gains but with fairly different long scale longitudinal fluctuations, that can be probably attributed to longitudinal λ_0 fluctuations along the fiber [4]. These measurements are in agreement with the gain reciprocity recently demonstrated theoretically by Marhic *et al.* [8], though the assumption on the wave polarization states is not clearly fulfilled. This latter point deserves further study.

V. CONCLUSION

Using a time domain analysis based on the Brillouin backscattering technique in a novel configuration, we have performed a distributed measurement of the parametric gain in FOPA, with an unprecedented sensitivity and spatial resolution thanks to the high efficiency of SBS. We clearly observed and identified different parametric gain regimes, in good agreement with theoretical predictions. This useful technique setup could be easily extended to study other configurations such as two-pump FOPAs. Parametric gain distributed measurement opens up new ways for the accurate mapping of the random dispersion fluctuations, which is currently under development.

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