View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by Infoscience - École polytechnique fédérale de Lausanne

Brillouin Optical Time Domain Analysis of Fiber Optic Parametric Amplifiers

A. Vedadi(1), D. Alasia(2), E. Lantz(1), H. Maillotte(1), L. Thévenaz(2), M. González-Herráez(3), T. Sylvestre(1)
1 : Département d'Optique P.M. Duffieux, Institut FEMTO-ST, Université de Franche-Comté, CNRS UMR 6174, 25030 Besancon, France, armand.vedadi@univ-fcomte.fr
2 : Laboratoire de Nanophotonique et Métrologie, Ecole Polytechnique Fédérale de Lausanne, Lausanne CH-1015, Switzerland
3 : Departamento de Electronica, Universidad de Alcala. Edificio Politecnico, Campus Universitario. 28871 Alcala de Henares, Madrid, Spain.

Abstract *We carried out, for the first time to our knowledge, distributed measurements of the small-signal gain of fiber-based parametric amplifiers by using a novel technique based on Brillouin optical time domain analysis.*

Introduction

Numerous recent studies have shown the tremendous potential of fiber optic parametric amplifiers (FOPAs) for future ultra-high bandwidth optical communication devices [1]. FOPAs are based on an efficient four-wave mixing (FWM) process between one (or two) pump waves and co-propagating signal and idler waves. Because the efficiency of the FWM process relies on the phase-matching condition κ between these four interacting waves, it is fundamental to tune the pump wavelength near the zero-dispersion wavelength (λ_0) of the amplifying fiber, so as to maximize the gain bandwidth. In such conditions, usual FWM or modulation instability theories predict an exponential-like amplification for FOPA gain when phase-matching is satisfied. In practice, however, λ_0 randomly fluctuates along the fiber and therefore makes the FOPA strongly phase-sensitive once the idler wave is generated, leading to a reduction of both the achievable parametric gain and bandwidth [2,3]. It is thus useful to perform a distributed measurement of FOPA along the fiber. OTDR was recently applied for characterization of FOPA [4]. This technique only measures the accumulated gain from randomly distributed Rayleigh sources within the FOPA. In this communication, we propose and demonstrate another approach based on Brillouin-optical-time-domain analysis (B-OTDA) [5] to probe the local small-signal parametric gain. In particular, our distributed measurement technique allowed us to identify the parabolic and exponential gain regimes and their longitudinal variations.

Principle

The B-OTDA method is useful for distributed measurement of a probe beam by the stimulated Brillouin scattering (SBS) interaction with a counter-propagating nanosecond pump pulse. In our method, the B-OTDA pump pulse is amplified in a single-pump FOPA and its local power is measured through a counter-propagating CW anti-Stokes probe, which in turn is subject to local Brillouin loss from the B-OTDA pump. When the B-OTDA pump pulse at frequency ν_B co-propagates with the FOPA pump at frequency ν_P in a single-mode fiber, the parametric gain reads as:

$$G = \frac{P_B(z)}{P_B(0)} = 1 + \left(\frac{\gamma P_P}{g}\sinh(g \times z)\right)^2 \qquad (1)$$

where P_B is the B-OTDA pump power, P_P is the FOPA pump power, γ is the nonlinear coefficient, and g is the gain per unit length, which depends on κ. When the CW probe beam at frequency $\nu_A=\nu_B+\Delta\nu_B$, with $\Delta\nu_B$ the Brillouin shift, counter-propagates with the B-OTDA pump, it loses power according to the following relation:

$$\Delta P_A = \frac{g_B}{A_{eff}} P_A(z) \times P_B(z) \Delta z \qquad (2)$$

with g_B the Brillouin linear peak gain, A_{eff} the fiber effective area and Δz the B-OTDA pump pulse width. Through an optical time domain analysis of the probe, one can easily obtain the longitudinal distribution $P_B(z)$, which in turn is related to the parametric gain as shown in Eq. (1). Note that combining the high-sensitivity of B-OTDA technique and the use of Brillouin loss avoids saturation of both the B-OTDA and FOPA pumps, as the results below will show.

Experimental Setup

Fig. 1 shows the experimental setup. The FOPA pump is a tunable laser (TL), phase-modulated by a Pseudo Random Binary Sequence (PRBS) generator at 3.5 GHz in order to suppress SBS in the FOPA.

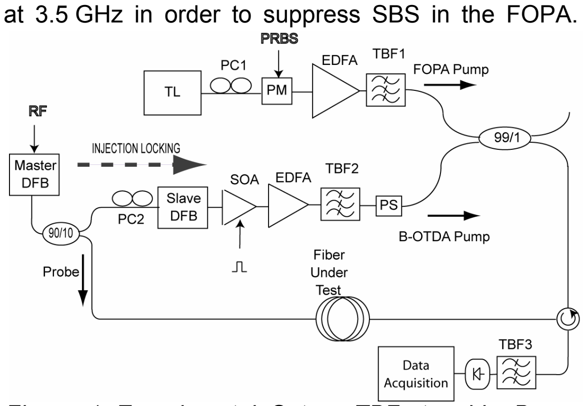

Figure 1 Experimental Setup. TBF: tunable Bragg filter, PM: phase modulator, PC: polarization controller

The output is amplified by a 33dBm-EDFA and filtered by a 1 nm bandpass filter. The B-OTDA pump frequency needs to be precisely stabilized so that the detuning with ν_A remains equal to $\Delta\nu_B$. To achieve this, the probe is intensity modulated by a RF signal to produce two sidebands frequency-shifted 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 in a slave DFB cavity. By injection locking, the frequency of the slave cavity tunes to the probe sideband at $\nu_A-\Delta\nu_B$ [6]. The B-OTDA pump pulses are then generated by a SOA which gain was gated using an electric pulse train. A polarization scrambler (PS) avoids any polarization-dependent Brillouin interaction. The FOPA and B-OTDA pumps are combined using a 99/1 coupler and the counter-propagating probe is extracted using an optical circulator. To avoid interference with Rayleigh backscattering of the FOPA-pump, the probe is filtered before acquisition.

Results

Two fibers were tested: a 490-meter long highly non linear fiber (HNLF) with γ=11.2 $W^{-1}km^{-1}$, λ_0=1553nm and a 3.1-km dispersion shifted fiber (DSF) with γ=2 $W^{-1}km^{-1}$, λ_0=1549.5nm. For all experiments, the probe wavelength was fixed to 1550.8nm. The B-OTDA pump frequency was swept over 200MHz around $\Delta\nu_B$ of the tested fiber, while the pulse width was set to 100ns, leading to a 10m resolution. The FOPA pump power was measured at 400mW. Fig. 2(a) shows a typical evolution of the Brillouin loss spectra along the DSF fiber during parametric amplification. The net Brillouin losses for the cases where the FOPA-pump is switched on and off are depicted on Fig. 2(b), which clearly shows the parametric amplification of the B-OTDA pump. Fig. 3(a-b) shows the derived FOPA local gain in linear unit. In particular, Fig. 3(a) clearly shows both exponential gain ($\kappa\approx0$) and small-gain parabolic ($g\approx0$)

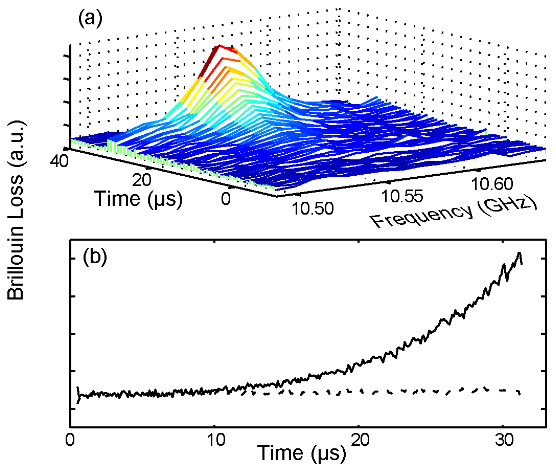

Figure 2 a) Brillouin loss spectra of the B-OTDA pump amplified in a FOPA. b) Traces of the probe Brillouin loss when the FOPA pump is ON (solid curve) and OFF (dashed curve)

regimes, simply by tuning the FOPA pump wavelength. Fig. 3(b) reports the distributed FOPA gain for the two directions of the HNLF, with FOPA pump wavelength close to λ_0, showing a similar gain but with different longitudinal fluctuations. We must stress we assumed that only half of the polarization-scrambled B-OTDA pump power is parametrically amplified. We also plotted in dashed lines the parametric gain as given by Eq. (1). We can see a fairly good agreement between usual theory and experimental results, without saturation. We can infer that the long scale (tens of meters) gain variations are due to the small κ or λ_0 fluctuations [3] and are the signature of the phase-sensitive nature of FOPA.

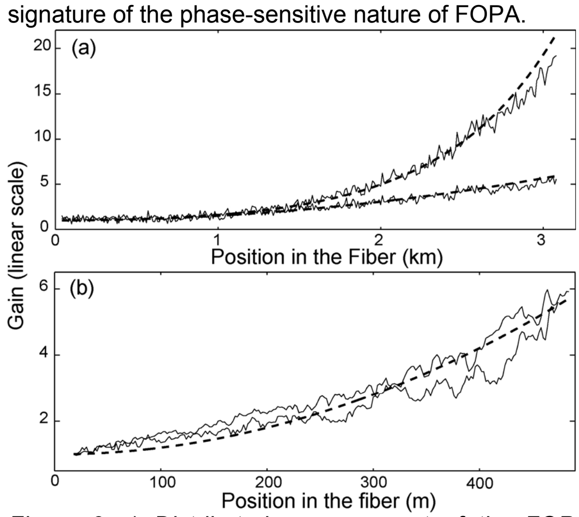

Figure 3 a) Distributed measurement of the FOPA gain in the DSF for two gain regimes. b) FOPA gains in the HNLF for the two directions.

Conclusions

Using B-OTDA technique in a novel configuration, we have been able, for the first time to our knowledge, to perform a distributed measurement of the parametric gain in a single-pump FOPA. The setup can be easily extended to study other configurations such as two-pumps FOPAs. Parametric gain distributed measurement also opens up new means for the accurate mapping of λ_0 fluctuations, which is currently under development.

Acknowledgement

This work was supported by the Conseil Régional de Franche-Comté and European COST Action Number 299. We gratefully thank Sumitomo and Alcatel R&I for the disposal of the HNLF fiber.

References

1 J. Hansryd et al IEEE. JSTQE. 8 (2002), 506.
2 M. Karlsson, J. Opt. Soc. Am. B 15 (1998), 2269.
3 A. Mussot et al., IEEE Photon. Tech. Lett. 18 (2006) 22.
4 B-E. Olsson et al., OFC, OWT3 (2006).
5 K.-Y Song et al IEEE J. Lightwave Tech. 23 (2005), 4140
6 L Thévenaz et al, Meas. Sci. Tech. 15 (2004), 1519