ELectronics EXpress

LETTER

IEICE Electronics Express, Vol.11, No.18, 1–5

Brillouin signal amplification in pumped erbium-doped optical fiber

Mingjie Ding[a], Neisei Hayashi, Yosuke Mizuno, and Kentaro Nakamura

Precision and Intelligence Laboratory, Tokyo Institute of Technology, Yokohama 226–8503, Japan

a) *ding@sonic.pi.titech.ac.jp*

Abstract: Amplification of Brillouin scattering signal extends the measurement range and improves the signal-to-noise ratio of fiber-optic distributed Brillouin sensors. Here, we investigate the amplification effect of a 980-nm pump laser on Brillouin gain spectrum in an erbium-doped optical fiber. The Brillouin-scattered Stokes power increased exponentially with increasing pump power, exhibiting approximately 87% enhancement at 252 mW compared with the Stokes power obtained without the pump. This suggests that a more significant increase in the Stokes power is feasible with a higher-power 980-nm pump laser.

Keywords: erbium-doped optical fibers, Brillouin scattering, optical fiber sensors

Classification: Fiber optics, Microwave photonics, Optical interconnection, Photonic signal processing, Photonic integration and systems

References

[1] G. P. Agrawal: *Nonlinear Fiber Optics* (Academic Press, San Diego, 2001).

[2] T. Horiguchi, T. Kurashima and M. Tateda: IEEE Photon. Technol. Lett. **1** (1989) 107. DOI:10.1109/68.34756

[3] T. Kurashima, T. Horiguchi and M. Tateda: Appl. Opt. **29** (1990) 2219. DOI:10.1364/AO.29.002219

[4] T. Horiguchi and M. Tateda: J. Lightwave Technol. **7** (1989) 1170. DOI:10.1109/50.32378

[5] T. Kurashima, T. Horiguchi, H. Izumita, S. Furukawa and Y. Koyamada: IEICE Trans. Commun. **E76-B** (1993) 382.

[6] X. H. Jia, Y. J. Rao, L. Chang, C. Zhang and Z. L. Ran: J. Lightwave Technol. **28** (2010) 1624. DOI:10.1109/JLT.2010.2046719

[7] M. A. Soto, G. Bolognini and F. D. Pasquale: Opt. Express **19** (2011) 4444. DOI:10.1364/OE.19.004444

[8] S. Martin-Lopez, M. Alcon-Camas, F. Rodriguez, P. Corredera, J. D. Ania-Castañon, L. Thévenaz and M. Gonzalez-Herraez: Opt. Express **18** (2010) 18769. DOI:10.1364/OE.18.018769

[9] K. Hotate and T. Hasegawa: IEICE Trans. Electron. **E83-C** (2000) 405.

[10] Y. Mizuno, W. Zou, Z. He and K. Hotate: Opt. Express **16** (2008) 12148. DOI:10.1364/OE.16.012148

[11] Y. Mizuno, W. Zou, Z. He and K. Hotate: J. Lightwave Technol. **28** (2010) 3300. DOI:10.1109/JLT.2010.2081348

DOI: 10.1587/elex.11.20140627
Received June 30, 2014
Accepted August 11, 2014
Publicized August 27, 2014
Copyedited September 25, 2014

[12] Y. Mizuno, N. Hayashi and K. Nakamura: J. Appl. Phys. **112** (2012) 043109. DOI:10.1063/1.4747926
[13] M. Ding, N. Hayashi, Y. Mizuno and K. Nakamura: Appl. Phys. Lett. **102** (2013) 191906. DOI:10.1063/1.4806986
[14] M. C. Farries, M. E. Fermann, R. I. Laming, S. B. Poole, D. N. Payne and A. P. Leach: Electron. Lett. **22** (1986) 418. DOI:10.1049/el:19860285
[15] K. T. V. Grattan, A. W. Palmer and C. A. Willson: J. Phys. E: Sci. Instrum. **20** (1987) 1201. DOI:10.1088/0022-3735/20/10/010
[16] Y. Mizuno and K. Nakamura: Appl. Phys. Lett. **97** (2010) 021103. DOI:10.1063/1.3463038

1 Introduction

Brillouin scattering in optical fibers is caused by acoustic-optical interaction, generating backscattered Stokes light, the spectrum of which is known as Brillouin gain spectrum (BGS) [1]. The center frequency of BGS is shifted downward relative to that of the incident light by the amount termed the Brillouin frequency shift (BFS). Because BFS linearly depends on strain and temperature [2, 3], Brillouin-distributed strain and temperature sensing has been extensively studied for monitoring large-scale civil structures, such as buildings, bridges, dams, pipelines, and aircraft wings.

Various sensing schemes have been developed, such as time-, frequency-, and correlation-domain techniques [4, 5, 6, 7, 8, 9, 10, 11]. Among them, time-domain techniques have been reported to have the widest measurement range, which is limited by optical attenuation. To date, many methods have been implemented to extend the measurement range further by using Raman-based signal amplification [6, 7, 8]; as a result of these efforts, the measurement range is now well over 100 km and the spatial resolution is on the order of several meters. Another approach utilizes pumped rare-earth-doped fibers (REDFs) with amplification capability, such as neodymium-, thulium-, ytterbium-, and erbium-doped fibers (EDFs). Although the Brillouin properties of un-pumped REDFs have been already clarified [12, 13], the effects of pumping have not been reported yet. Note that the fluorescence spectra and decay times of such REDFs are temperature-dependent [14, 15], and a novel discriminative measurement method of strain and temperature will be feasible by combining these features with the BGS dependence.

In this paper, we investigate the effect of a 980-nm pump laser on the BGS in an EDF, which is the REDF most commonly used as a key component of optical amplifiers. The Brillouin-scattered Stokes power increases exponentially with increasing 980-nm pump laser power.

2 Experimental setup

The EDF used as a fiber under test (FUT) had a length of 17.8 m, mode-field diameter of 7.2 µm, core refractive index of ~1.47, peak absorption of 18 dB/km at 1530 nm, and erbium concentration of 720 wtppm. Both ends of the FUT were spliced to 1-m-long silica single-mode fibers (SMFs) by using a fusion splicer

DOI: 10.1587/elex.11.20140627
Received June 30, 2014
Accepted August 11, 2014
Publicized August 27, 2014
Copyedited September 25, 2014

IEICE Electronics Express, Vol.11, No.18, 1–5

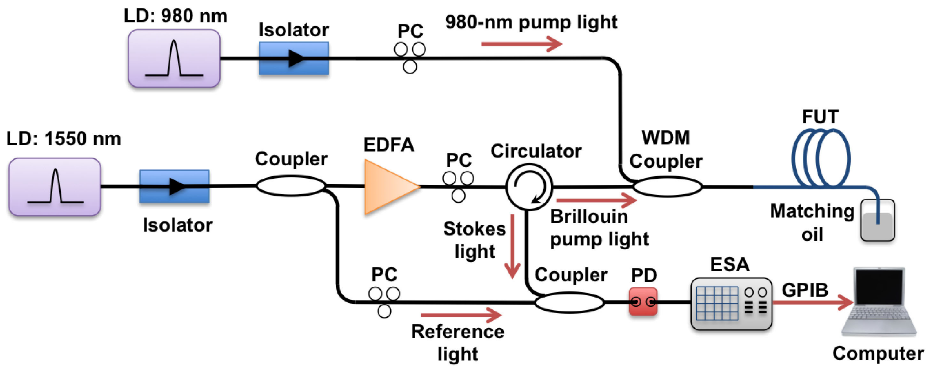

Fig. 1. Experimental setup. EDFA: erbium-doped fiber amplifier, ESA: electrical spectrum analyzer, FUT: fiber under test, GPIB: general-purpose interface bus, LD: laser-diode, PC: polarization controller, PD: photo-diode, WDM: wavelength division multiplexing.

(FSM-50S, Fujikura), where the splicing loss was suppressed to < 0.1 dB by optimizing the arc duration.

The experimental setup for investigating the BGS in the pumped EDF is depicted in Fig. 1, and is based on self-heterodyne detection with a high frequency resolution [16]. The output light of a laser diode (LD) at 1550 nm was divided into two beams by an optical coupler. One beam was used as a reference light for heterodyne detection. The other beam was amplified by using an EDF amplifier (EDFA), and was injected into the FUT (incident power: 100 mW) after propagating through a circulator and a 1550/980-nm wavelength-division-multiplexing (WDM) coupler. The output of another LD at 980 nm was injected into the FUT as a pump light, via the WDM coupler. The open end of the 1-m long SMF spliced to the FUT was immersed into matching oil ($n = 1.46$) to suppress the Fresnel reflection. The polarization states of each beam were optimized by using polarization controllers (PCs), thus maximizing the Brillouin signal. The Stokes light that backscattered from the FUT was coupled with the reference light, was converted to an electrical signal by using a photo-diode (PD), and was observed by using an electrical spectrum analyzer (ESA).

3 Experimental results

Fig. 2 shows the measured BGS dependence on the power of the 980-nm pump in the EDF. Since it is the net amplification effect of the Stokes power that is important in Brillouin sensing, we adjusted the noise floor of the BGS measured with pump light (pump power = 16, 40, 100, and 252 mW) to the noise floor of the BGS measured without pump light (~0.8 nW); thus, the amplification effect of the Stokes power, i.e. the relative power between the peak and the noise floor of the BGS, can be easily compared. The BFS obtained without the pump was 11.42 GHz, which agrees with the previously reported result [13]. Although the BFS was not changed by EDF pumping, the Stokes power increased with increasing pump power. With the maximal pump power at 252 mW, the Stokes power increased by 0.36 nW. This amplification is attributed not only to the amplified Brillouin-scattered light itself but also to the amplified incident light. Note that the tail of the Rayleigh scattering

DOI: 10.1587/elex.11.20140627
Received June 30, 2014
Accepted August 11, 2014
Publicized August 27, 2014
Copyedited September 25, 2014

IEICE Electronics Express, Vol.11, No.18, 1–5

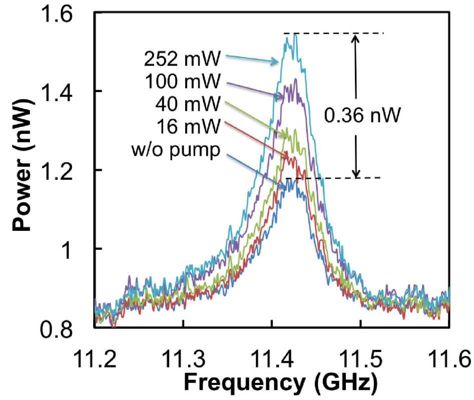

Fig. 2. Measured BGS dependence on the 980-nm pump power in the EDF.

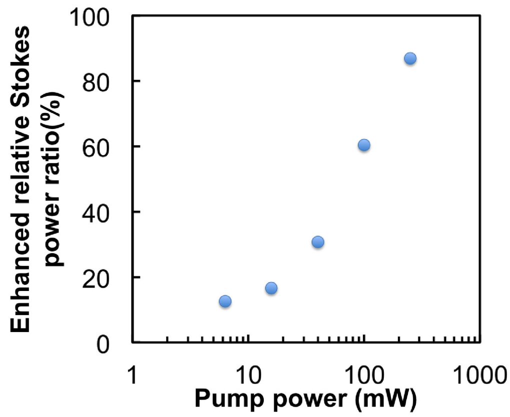

Fig. 3. Relative enhancement of the Stokes power *vs.* the 980-nm pump power.

spectrum was also amplified and overlapped with the BGS, resulting in the elevated noise floor.

The relative enhancement of the Stokes power was plotted as a function of the 980-nm pump power, and is shown in Fig. 3. When the EDF was pumped with the power of 252 mW, the relative enhancement reached ~87%. Furthermore, the relative enhancement of the Stokes power dramatically increased for pump power above ~40 mW, indicating that, if a 980-nm pump laser with an output power ≫252 mW is employed, more significant enhancement of the Stokes signal is likely to be achieved.

4 Conclusion

We investigated the pumping effect of the 980-nm pump on the Brillouin Stokes power in an EDF. As the pump power increased, the Stokes power increased as well, even after the influence of the enhanced noise floor was subtracted. The relative enhancement of the Stokes power reached ~87%. These results indicate that significant Brillouin amplification might be achievable by employing higher-power pumps. We believe that these results will be important in the near future for implementing distributed strain and temperature sensors based on Brillouin scattering in EDFs.

DOI: 10.1587/elex.11.20140627
Received June 30, 2014
Accepted August 11, 2014
Publicized August 27, 2014
Copyedited September 25, 2014

Acknowledgments

We are indebted to Fujikura Ltd., Japan, for providing us with the EDF sample. This work was partially supported by Grants-in-Aid for Young Scientists (A) (no. 25709032) and for Challenging Exploratory Research (no. 26630180) from the Japan Society for the Promotion of Science (JSPS) and by research grants from the General Sekiyu Foundation, the Iwatani Naoji Foundation, and the SCAT Foundation. N. H. acknowledges a Grant-in-Aid for JSPS Fellows (no. 25007652).

DOI: 10.1587/elex.11.20140627
Received June 30, 2014
Accepted August 11, 2014
Publicized August 27, 2014
Copyedited September 25, 2014