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Brillouin suppression in a fiber optical parametric amplifier by combining temperature distribution and phase modulation

Michael Lorenzen,[1,*] **Danny Noordegraaf,**[1] **Carsten Vandel Nielsen,**[1]
Ole Odgaard,[1] **Lars Grüner-Nielsen,**[2] **and Karsten Rottwitt**[1]

[1] *COM•DTU Department of Communications, Optics and Materials, Technical University of Denmark, DK-2800, Denmark*
[2] *OFS Fitel Denmark ApS, Priorparken 680, DK-2605 Brøndby, Denmark*
[*] *Corresponding author:s011767@com.dtu.dk*

Abstract: We demonstrate an increased gain in a fiber optical parametric amplifier through suppression of stimulated Brillouin scattering by applying a temperature distribution along the fiber, resulting in a reduction of the required phase modulation.

OCIS codes: (190.4970) Parametric oscillators and amplifiers; (290.5900) Scattering, stimulated Brillouin

1. Introduction

During recent years, fiber optical parametric amplifiers (FOPA's) have attracted large interest. Both high bandwidth of up to 208 nm [1] and also high gain of up to 70 dB [2] have been demonstrated. Furthermore, the FOPA has additional functionalities such as wavelength conversion [3], demultiplexing [4] and signal regeneration [5]. In this work, a single pump FOPA is described where only one strong pump amplifies a weak signal in a highly nonlinear fiber (HNLF). Optical power from the pump is coupled to the signal due to degenerate four wave mixing. In the process an idler is generated at a wavelength determined by energy conservation: $2\omega_p = \omega_s + \omega_i$, where ω_p, ω_s and ω_i is the frequency of the pump, signal and idler, respectively. The parametric amplification is maximized at phase matching between the three optical waves. This phase match is expressed as $\Delta\beta = \beta(\omega_s) + \beta(\omega_i) - 2\beta(\omega_p)$, where $\Delta\beta$ is the propagation mismatch and $\beta(\omega_p)$, $\beta(\omega_s)$ and $\beta(\omega_i)$ is the propagation constant of the pump, signal and idler, respectively.

When a strong pump beam is sent into an optical fiber, stimulated Brillouin scattering (SBS) results in backscattering of the optical power. The scattering occurs due to coupling between the optical mode and acoustic vibrations in the fiber. A simple way of suppressing SBS is by broadening the pump spectrum by applying a phase modulation to the pump [6]. When the pump spectrum is much broader than the Brillouin gain bandwidth of the HNLF ($\sim$20 MHz [7]) SBS is suppressed. The drawback is that a wide pump spectrum results in a spectral broadening of the amplified signal and also in a spectrally broad generated idler. Another method to suppress SBS is by applying a temperature distribution along the fiber [8]. This was investigated for a FOPA in [9], where a 4.8 dB increase in the SBS threshold was demonstrated for a fiber length of 100 m.

In this paper, we show how an applied temperature distribution increases the SBS threshold by 4 dB in a 500 m long fiber. We also show that such a temperature distribution together with a phase modulation of the pump can be used in a FOPA to increase the gain by 8 dB, even when the spectral width of the pump is reduced by a factor of 3 compared to an uncooled fiber. Also, an increased gain of 5.9 dB can be achieved, with an even further reduction of the spectral width of the pump by a factor of 9 compared to the uncooled fiber. Therefore, such a combined phase modulation and temperature distribution is an advantage when using the FOPA for wavelength conversion.

2. SBS suppression

When a temperature distribution is applied to an optical fiber the Brillouin frequency is shifted. Figure 1(a) shows the measured backscattered light spectrum obtained using a photo detector and an electrical spectrum analyzer. The figure also shows the measured Brillouin frequency shift at different temperatures. The solid line is at -178°C, the dashed line is at -45°C, the dash dotted line is at 0°C and the dotted line is at 90°C. If the fiber is divided into sections that are kept at different temperatures, the SBS builds up at different Brillouin frequency shifts in the different sections of the fiber. The result is that SBS is not amplified in the entire length of the fiber and the Brillouin threshold is therefore increased. Figure 1(a) also shows the spectrum of the backscattered light when the fiber is divided into

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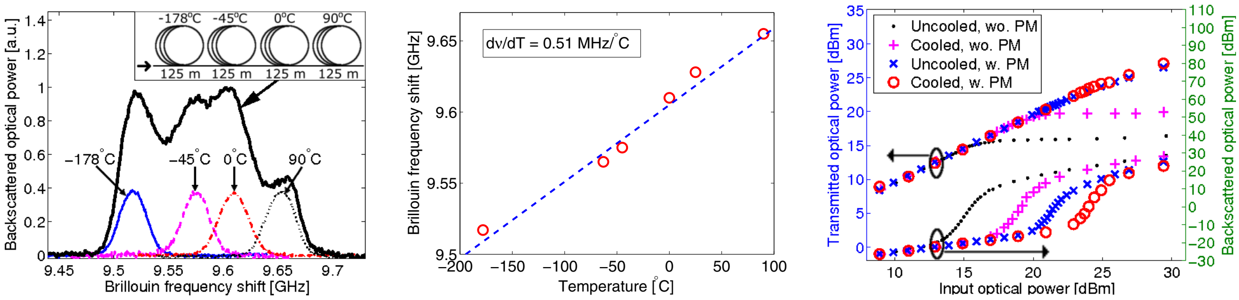


(a) (b) (c)

Fig. 1. (a) Measured backscattered light spectra. The solid line, the dashed line, the dash dotted line and the dotted line show the spectra when the entire fiber length of 500 m is at -178°C, -45°C, 0°C and 90°C, respectively. The thick solid line shows the spectra when the temperature distribution shown in the inset is applied to the fiber. (b) Measured Brillouin frequency shift as a function of temperature. The frequency is shifted 0.51 MHz/°C. (c) Measured transmitted and backscattered optical power as a function of optical input power.

four sections each of 125 m. The first section is kept at -178°C, the second at -45°C, the third at 0°C and the fourth at 90°C (See inset of the figure). The figure shows a wide spectrum of the backscattered light, with partially separated peaks resulting from the different temperatures. Figure 1(b) shows the measured Brillouin frequency shift as a function of temperature. A linear shift of 0.51 MHz/°C is observed.

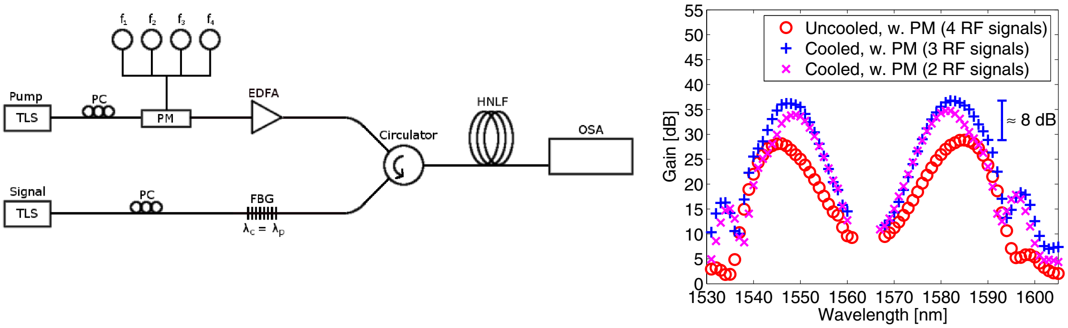
In order to measure the increase in the Brillouin threshold, we measured the backscattered and transmitted light as a function of optical input power. This is shown in Fig. 1(c). The result for the uncooled fiber is shown as dots and the result for the cooled fiber is shown as pluses. In this paper, the cooled fiber refers to the fiber with the applied temperature distribution along the fiber seen in the inset of Fig. 1(a). The Brillouin threshold, here defined as the optical input power where the backscattered Brillouin power equals the backscattered Rayleigh power, is 13.1 dBm for the uncooled fiber and 17.2 dBm for the cooled fiber. When only phase modulation is applied to the pump with four RF frequencies of 100 Mhz, 300 MHz, 900 MHz and 2.7 GHz, the SBS threshold is even further increased to 19.9 dBm, as shown with crosses. By combining both phase modulation and applying a temperature distribution the threshold is even further increased to 22.6 dBm, seen in Fig. 1(c) as circles.

3. Fiber optical parametric amplifier

The setup of a single pump FOPA is seen in Fig. 2(a). An optical spectrum analyzer (OSA) is used to measure the output of the amplifier. A tunable laser source (TLS) is used as pump and another TLS is used as the signal. The pump is fixed at a wavelength of λ_p = 1564.8 nm. Light from the pump is amplified by an erbium doped fiber amplifier (EDFA) with 30.5 dBm of maximum output power, and coupled into the HNLF using a circulator and a fiber Bragg grating. The grating is centered at λ_c = 1564.8 nm and therefore reflects the pump back into the circulator and into the HNLF. The grating, which has a 3 dB width of 2 nm, removes the amplified spontaneous emission (ASE) from the EDFA. The signal is coupled through a polarization controller (PC), used to match the polarization of the signal and the pump, and coupled into the HNLF using the circulator. The length of the HNLF is 500 m, it has a nonlinear coefficient of $\gamma = 11.4\ \mathrm{W}^{-1}\mathrm{km}^{-1}$ and a loss of $\alpha = 0.76$ dB/km. The zero dispersion wavelength is $\lambda_0 = 1560.5$ nm.

Using the setup shown in Fig. 2(a), the gain of the amplifier is measured, when only phase modulation of the pump is used to suppress SBS (four RF signals at 100 MHz, 300 MHz, 900 MHz and 2.7 GHz). This is shown in Fig. 2(b) as circles. The measurement shows that the maximum gain is 28.8 dB. The figure also shows the measured gain when both phase modulation of the pump and the temperature distribution seen in the inset of Fig. 1(a), is applied along the HNLF (pluses and crosses). For the pluses, three RF signals are used to phase modulate the pump (100 MHz, 300 MHz and 900 MHz) and for the crosses two RF signals are used (100 MHz and 300 MHz). The measured gain curves show an increase in the gain compared to the uncooled fiber, even when the width of the phase modulated pump beam is decreased. The measurement shows an increase in the gain of 8 dB at a reduced spectral width of the pump by a factor of 3 compared to the uncooled fiber, and an increase in gain of 5.9 dB at a reduced spectral width of the pump by a factor of 9 compared to the uncooled fiber.

Figure 2(b) also shows that the gain spectrum is more narrow for the cooled fiber. The reason for this is that the zero dispersion wavelength moves towards shorter wavelengths as the temperature is decreased [10], i.e. the zero-dispersion moves further away from the pump wavelength in the cooled sections of the fiber. This results in a more narrow spectrum. The reason for the increase in the gain is partly due to an increase in the nonlinear coefficient when



(a) (b)

Fig. 2. (a) Illustration of the FOPA setup. TLS: Tunable laser source. PC: Polarization controller. PM: Phase modulator. EDFA: Erbium doped fiber amplifier. HNLF: Highly nonlinear fiber. OSA: Optical spectrum analyzer. (b) Measured internal fiber gain as a function of signal wavelength. The circles show the gain when only phase modulation is used to suppress SBS. The pluses and the crosses show the gain when both phase modulation and temperature distribution are applied. For the pluses a phase modulation of 100 MHz, 300 MHz and 900 MHz is applied and for the crosses a phase modulation of 100 MHz and 300 MHz is applied. All gain spectra are measured at a pump power into the fiber of 29 dBm.

the temperature is decreased [11] and due to the suppression of SBS caused by the applied temperature distribution.

When the number of RF signals is further reduced to one RF signal, the gain of the cooled fiber is significantly reduced due to the fact that SBS is not sufficiently suppressed. A further reduction of the number of RF signals might be possible, if the fiber is divided into more sections and creating a more linear temperature gradient along the fiber.

4. Conclusion

We have demonstrated that by applying a temperature distribution to the HNLF of the FOPA, together with a phase modulation of the pump, the gain is increased by 8 dB. We also demonstrate that the number of RF signals needed to phase modulate the pump is reduced from four to three compared to the uncooled fiber, thereby reducing the spectral width of the pump by a factor of 3. An increased gain of 5.9 dB is also demonstrated for the cooled fiber compared to the uncooled fiber, when reducing the number of RF signals from four to two. This reduced the spectral width of the pump by a factor of 9. By applying a temperature distribution along the fiber, the required phase modulation of the pump is decreased, thereby resulting in a spectrally narrower signal and idler.

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