Novel suppression scheme for Brillouin scattering

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Abstract: We demonstrate a new scheme for the efficient suppression of Brillouin scattering of a single-frequency laser source in a 72 m-long Neodymium-doped fiber amplifier by simultaneous amplification of two seed lasers separated in wavelength by two times the Brillouin-shift. This scheme can be independently employed in addition to conventional methods of suppressing stimulated Brillouin scattering enabling further power scaling of existing systems.

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1. Introduction

Fiber-based systems offer a variety of advantages in comparison to bulk laser systems like their very high efficiency and excellent beam quality independent of the output power. The mode confinement in the fiber core results in a high power density and a long interaction length. On the one hand, this results in the high efficiency, but favors also the onset of nonlinear stimulated scattering processes. In particular, if single-mode, ultra-narrow linewidth or even single-frequency sources are employed, stimulated Brillouin scattering (SBS)

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becomes the dominant nonlinear scattering process limiting the output power and the amplitude stability [1–4], especially, as this scattering takes place into the backward direction.

However, the use of multi-mode fibers led to the generation of several Watts of output power [5], and lately the single-frequency amplification above the 100 W level in a large-mode-area fiber with a core diameter of 28 µm has been reported [6]. Nevertheless, in both cases the systems were merely limited by the onset of SBS and not by the available pump power. In order to overcome this limit, several schemes have been proposed and experimentally demonstrated. These schemes include the use of fibers with a Brillouin frequency shift distribution [7], Bragg gratings, which are used for reflection of the scattered signal [8], and the simultaneous amplification of more than one laser frequency [9–11].

Particularly, in the simultaneous amplification of two single-frequency laser sources, the effective Brillouin gain is partially reduced if the frequency difference is within the Brillouin bandwidth. If the laser frequencies are separated by more than the Brillouin bandwidth, both lasers are scattered independently causing an effective reduction of the Brillouin gain of a factor of 2 and a doubling of the overall power. However, if only one of the single-frequency signals will be used after the transmission or amplification e.g. due to application restrictions, no power enhancement can be gained by this method.

In this contribution we present a new scheme for the effective suppression of SBS which can be employed in addition to the schemes mentioned above. Our scheme is based on the simultaneous amplification of two independent single-frequency sources, of which the frequency separation is well adjusted to twice the Brillouin frequency shift and causing thereby an effective suppression of the stimulated scattering process.

2. Theory and concept

The following system of differential equations describes the generation of a Brillouin-scattered signal generated by a single-frequency signal propagating in +z-direction [12]:

$$\frac{dI_L(z)}{dz} = -\frac{\lambda_B}{\lambda_L} g_B I_B(z) I_L(z) - \beta_B I_L(z) - \alpha_B I_L(z) \tag{1}$$

$$-\frac{dI_B(z)}{dz} = g_B I_L(z) I_B(z) + \beta_B I_L(z) - \alpha_B I_B(z) \tag{2}$$

Here, I_L is the intensity of the single-frequency seed-signal at a wavelength λ_L, I_B is the intensity of the backward-scattered Brillouin-signal at the wavelength λ_B, g_B is the Brillouin gain, β_B is the coefficient for spontaneous Brillouin scattering and α_B is the attenuation coefficient in the optical fiber.

In Fig. 1, the scheme used in our experiments leading to the suppression of the SBS is depicted. It is based on the simultaneous propagation and amplification of a second single-frequency signal which is separated by twice the Brillouin frequency shift Δf_{BS} from the first signal. Hence, for the description of all contributing factors, the above system of differential equations has to be extended by two additional scattering processes. At first, the Brillouin-scattered signal from the first laser experiences stimulated scattering into the second laser and at second, the second laser causes an additional Brillouin line analogous to the first laser.

If the difference in wavelengths is neglected ($\Delta f_{BS} \approx 16$ GHz), i.e. $\lambda_B \cong \lambda_L$, and the fiber attenuation and the spontaneous terms are neglected as well, the equation for the first Brillouin signal results in

$$-\frac{dI_{B1}(z)}{dz} = g_B I_{B1}(z)\left(I_{L1}(z) - I_{L2}(z)\right) \tag{3}$$

Here I_{L1} is the intensity of the first laser and I_{L2} is the intensity of the second laser. Hence, for the stimulated scattering process only the difference of both laser powers is relevant as any

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power scattered into the first Brillouin line will be reduced by the second SBS-interaction with the second laser. It can be easily seen, that if the seed power of the second laser is chosen to $P_2 = 0.5\,P_1$, the first laser power can be doubled before SBS occurs. This leads to an increase of a factor of 3 in Brillouin threshold regarding the overall transmitted laser power and a factor of 2 if only the main single-frequency signal is considered. In addition, this scheme can easily be extended to more seed frequencies. If a constant power difference between adjacent seed frequencies is maintained, a linear power increase of the main signal can be gained by adding more seed lasers.

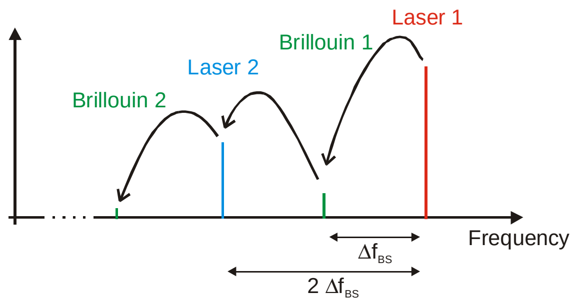

Fig. 1. Brillouin-scattering scheme with two single-frequency lasers separated by twice the Brillouin frequency shift Δf_{BS}.

Strictly speaking, Eq. (3) is only valid, if the two lasers are separated by exactly twice the Brillouin frequency shift. However, due to the finite Brillouin bandwidth of the order of some 10 MHz [12], there will be a frequency range, in which the SBS will be suppressed with a decreasing strength if the deviation from twice the Brillouin frequency shift is increased.

In addition to the Brillouin scattering, the effect of four-wave mixing (FWM) has to be taken into account as well [12]. If Brillouin scattering is suppressed, the two incident laser frequencies can serve as strong parametric pump sources for each other. On the one hand this leads to a power transfer between the two frequencies causing an equalization of the respective powers and thus alters the power ratio from its initial value. In addition, FWM will lead to the generation of additional Stokes and Anti-Stokes frequency components ω_3 and ω_4:

$$\omega_3 = 2\omega_1 - \omega_2 \tag{4}$$

$$\omega_4 = 2\omega_2 - \omega_1 \tag{5}$$

Significant FWM can only occur, if the fiber is significantly shorter than the coherence length, which is $L_{coh} \approx 6.5$ km for a typical frequency separation of 32 GHz corresponding to twice the Brillouin frequency shift [12]. Assuming perfect phase matching and non-depletion of the pump wave, FWM causes a parametric gain G of

$$G = \exp(g_{max} l) \quad \text{with} \quad g_{max} = g_p \left(\frac{P_0}{A_{eff}} \right) \tag{6}$$

Here, P_0 is the pump power, A_{eff} the effective mode area, l the fiber length and g_p the parametric gain factor of $g_p = 2 \times 10^{-13}$ m/W for a wavelength of 1 µm [12].

3. Experimental setup

In our setup, see Fig. 2, the beams of two independent 1064 nm-Nd:YAG single-frequency nonplanar ring oscillators (NPRO) were combined by a 50/50-beamsplitter. Both NPROs were protected against backreflections with Faraday isolators. The combined radiation of the NPROs was focused into the active core of a single-mode 72 m long Nd-doped double clad

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fiber. The core diameter of the fiber was 6 μm with a numerical aperture (N.A.) of 0.16 and the doping concentration was 1300 mol ppm Nd_2O_3. The amplifier was pumped counterdirectionally by a fiber-coupled diode laser at 808 nm. The inner cladding, which served as the pump core was D-shaped for maximum pump light absorption and had a diameter of 400 μm with a N.A. of 0.38. On the pump side of the fiber the amplified signal was separated from the pump light by a dichroic mirror. It was then imaged onto an iris aperture to cut off radiation from the pump core. Both fiber ends were polished at an angle of about 8° to avoid Fresnel backreflections and lasing oscillation of the amplifier. For all experiments, the seed power of the NPROs was chosen to P_1 = 100 mW and $P_2 = 0.5\,P_1$ = 50 mW.

A small fraction of the backward traveling signal was picked off with a glass plate. Both the forward and the backward propagating signals were monitored with respect to the output power and the optical spectrum.

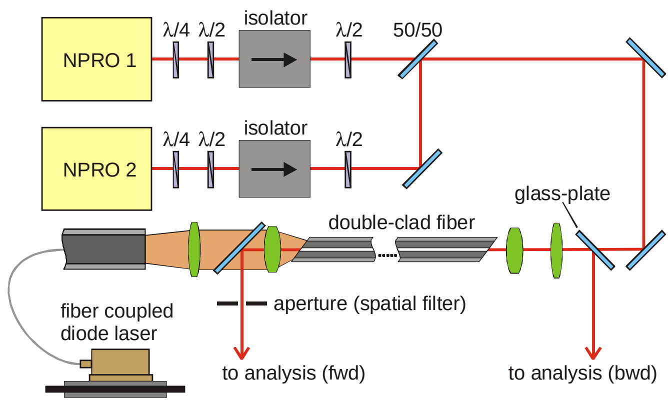

Fig. 2. Experimental setup for the evaluation of the SBS-suppression.

The NPRO wavelengths and hence the frequency separation were tuned by means of crystal temperature. Single-frequency operation of both NPROs was verified under all operating conditions applying a confocal scanning Fabry-Perot interferometer with a free spectral range of 10 GHz. In order to investigate the frequency acceptance-range of the proposed scheme, the frequency of NPRO 2 was tuned slowly by linearly ramping its crystal temperature.

4. Results and discussion

The experimental results regarding the output power of the amplifier are depicted in Fig. 3(a) for three different seed power configurations. It can be seen (black squares), that in the amplification of NPRO 1 without the presence of the second NPRO, the output power starts to increase linearly up to an output power of about 2 W. From this power level, SBS starts to transfer power into a backward scattered Brillouin signal. If the second NPRO is amplified along with the first NPRO with arbitrary frequency difference, the two laser signals are amplified independently (red circles). In this case, SBS was observed starting at an output power of about 4.5 W. If the wavelength of the second NPRO was then tuned to exactly twice the Brillouin shift (blue triangles), SBS was suppressed and the forward output power could be increased further up to 6.3 W, before SBS started again.

Thus, it was demonstrated, that SBS can be suppressed effectively by the presence of a second, frequency-adjusted signal. By this method, a power increase of about 3 could be achieved in comparison to the amplification of only one single-frequency laser.

The suppression of SBS was measured by the reduction of the backscattered power when the second NPRO was tuned over the optimum frequency difference, see Fig. 3(b) for a typical tuning curve. The acceptance-bandwidth of the SBS suppression was defined as FWHM of the measured trace.

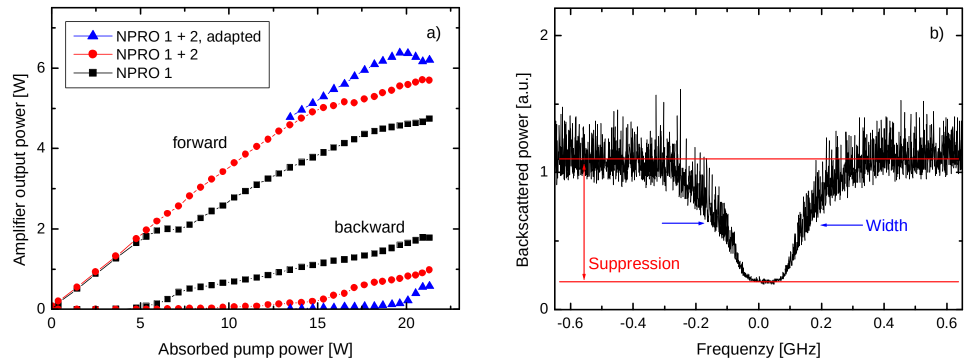

Fig. 3. (a) Output power of the amplifier for three different seed configurations, see text for explanation. (b) Typical tuning curve of the backscattered power.

Both the acceptance-bandwidth and the SBS suppression depended on the amplifier power, see Fig. 4. It can be seen, that the acceptance-bandwidth decreased with increasing pump power. At the same time, the suppression of the SBS decreased as well. Both effects can easily be understood, if one considers, that our scheme is based on an effective reduction of the laser power relevant for the first Brillouin process. Both a frequency deviation from the optimum separation as well as an increased overall power level increase the effective laser power for the Brillouin process leading to the observed behavior. The rather large measurement error observed in the measurement (20-30%) can be attributed to the noise properties of the nonlinear backscattering process causing large variations in the measured traces of the backscattered power.

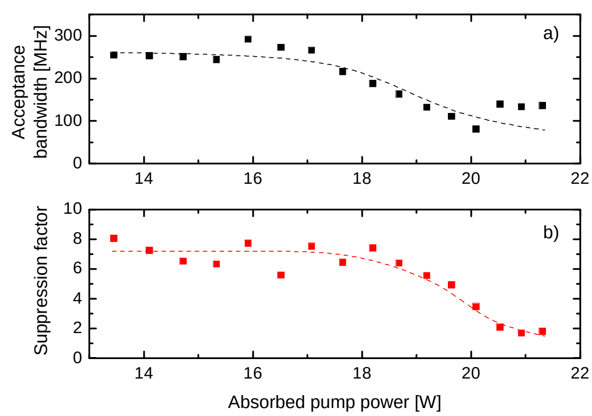

Fig. 4. Dependency of (a) the acceptance-bandwidth and (b) the SBS-suppression factor on the absorbed pump power.

In Fig. 5, typical output spectra of the amplifier both for the amplification of one and two single-frequency sources are shown. If only NPRO 1 was amplified, several SBS frequencies could be identified in the optical spectrum (Fig. 5(a)) above an output power of 2 W. In addition to the Stokes lines at the long-wavelength side of the seed frequency, several anti-Stokes lines were apparent as well. Most probably, these lines were generated by partly degenerated FWM of the Stokes-lines with the unscattered carrier wave.

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Similarly, FWM was observed in the simultaneous amplification of both NPROs, if SBS was not present, see Fig. 5(b) for a typical output spectrum. The depicted lineshape of the individual frequencies corresponds to the apparatus function of the optical spectrum analyzer set to a nominal resolution bandwidth of 0.01 nm. It can be seen, that up to six additional frequency-sidebands were generated with identical frequency spacing. Furthermore, the power ratio of the amplified NPROs was equalized from an initial value of 3 dB to less than 0.02 dB. This equalization is a direct result of the parametric gain caused by the strong incident seed sources. According to Eq. (6) and assuming a gain of 1, an input power of P_1 = 100 mW of NPRO 1 will already cause a parametric gain of 1.05 for the second NPRO. Although this seems to be a low gain value, the power of NPRO 1 will significantly be reduced by 5 % due to the presence of NPRO 2 and $P_2 = 0.5\,P_1$. From this 5 % power loss, one half will be transferred into the NPRO 2 frequency and the other half will generate a corresponding anti-Stokes line containing 2.5 mW of power. With increasing gain and thus increasing intensity, the parametric gain increases and the power transfer in-between the seed sources leads to the power equalization.

In addition to the suppression of the SBS, the generation of the FWM-sidebands could be suppressed in principle as well. For this purpose, the use of highly dispersive fibers would decrease the coherence length and thus largely reduce the effect of FWM. Another possibility would be the periodic use of fiber Bragg gratings which introduce large phase shifts between the FWM-sidebands and thus disturb their coherence as well.

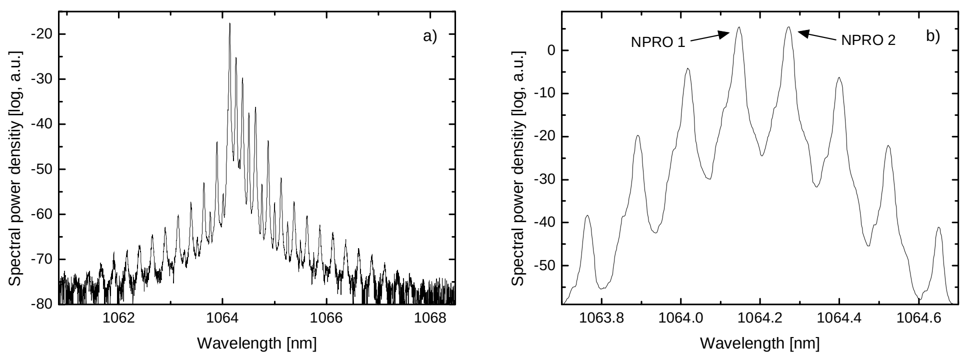

Fig. 5. Typical optical output spectra of the amplifier for (a) only NPRO 1 incident on the amplifier causing cascaded Brillouin scattering and (b) two seed laser frequencies being amplified simultaneously without SBS.

In summary, we have demonstrated an effective new scheme for the suppression of stimulated Brillouin scattering which can be used in extension to conventional methods of suppressing SBS. By the simultaneous amplification of a second frequency-tuned laser, a power enhancement of 3 was achieved. In the absence of Brillouin scattering, we observed strong FWM. However, in contrast to the Brillouin-scattered signal, the power transferred into the FWM-sidebands propagates in forward direction and, thus, can be used along with the amplified carrier waves.

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