

Observation of a comb-like spectrum with a passively self-Q-switched Er-doped fiber laser

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We report on the generation of a stable comb-like spectrum with a passively self-Q-switched Er-doped fiber laser pumped by a ~160mW diode. More than ~25 Stokes and anti-Stokes Brillouin components were observed when a 34-GHz-reflection-width cavity mirror was incorporated in the laser cavity. The spectral width of the cavity mirror was only ~3 times broader than the SBS shift (~11 GHz). However, the total width of the generated spectrum was about ~8 times broader than the spectrum of the cavity mirror. We show that this effect is caused by the SBS four-wave mixing in a fiber configuration.

Introduction

Fiber lasers have found many applications in different areas. Typically these devices operate in CW regime. A realization of pulsed fiber lasers extends the area of possible applications of fiber lasers due to a large scale of a peak power. An original passive Q-switching mechanism has been reported [1-4] for fiber lasers. The principal scheme of a Q-switched fiber laser is similar to shown in Figure 1. In order to provide Q-switching a fiber laser cavity incorporates a fiber ring interferometer that operates as a passive nonlinear mirror. Backreflection from the interferometer is provided by backward light scattering in the ring fiber. At the beginning of every cycle, the population inversion in the rare-earth doped fiber builds up and lasing in the fiber cavity (at frequency ν_A) occurs due to reflection from the cavity mirror and reflection caused by linear Rayleigh backscattering (RS) in the fiber ring resonator. RS feedback provides a very effective linewidth narrowing of growing laser radiation thus creating the conditions for stimulated Brillouin scattering (SBS) in the fiber. The growth of SBS in the ring (at a Stokes shifted frequency $\nu_B \approx \nu_A - \Delta\nu_{SBS}$, where $\Delta\nu_{SBS}$ is SBS shift) then causes a series of avalanche processes in the laser cavity leading to Q-switching.

Passive Q-switching in rare-earth-doped fiber lasers has been observed experimentally both with high-power (>500 mW) [1] and lower-power (~20 - 160 mW) [2 - 4] fiber lasers. At the low pump power level, no additional nonlinear effect influences the laser behavior and the laser dynamics is well described by the RS-SBS model. Two pulses are usually emitted by the laser during one generation cycle: a small pulse with a duration of 50 - 200 ns (a peak power of 0.5 - 5 W) followed by a gigantic Q-pulse with a duration of 10 - 50 ns (a peak power of 50 - 200W) [2 - 4].

Here we present new experiments with low-power passively self-Q-switched fiber lasers. We report on the generation of a comb-like spectrum with an Er-doped fiber laser pumped by a ~160mW diode. More than ~25 Stokes and anti-Stokes Brillouin components were observed when a 34-GHz-reflection-width cavity mirror was incorporated in the laser cavity. We show that this effect is caused by the SBS related four-wave mixing mechanism a fiber configuration.

Experiment

The studied configuration is shown in Figure 1. The experimental laser cavity with a total length has been built by splicing of standard telecom components: a fiber Bragg grating (FBG), WDM, an Er-doped fiber, a single-mode fiber, and a fiber coupler (insertion losses, $k_{13}/k_{14} = 0.05/0.95$). Having two free arms spliced together the coupler has been transmuted to a ring interferometer that operates as second laser mirror, while reflections from the output fiber face are prohibited by an optical isolator. The laser is pumped through WDM by a 980 nm laser diode with a maximal output power of 160 mW. The radiation from the laser output is monitored by an optical spectrum analyzer with resolution of ~ 2.5 GHz and simultaneously detected by photodiode to be digitized and recorded by an oscilloscope with the resolution of ~ 1 ns.

In order to force the laser to operate in mentioned manner, a FBG with a bandwidth of ~ 34 GHz (FWHM) has been employed in the laser configuration. It allowed us to localize the frequency ν_A near maximum of FBG reflectivity ($\lambda_M \sim 1533.6$ nm) and also admitted an effective growth of SBS components during lasing (up to third order since FBG bandwidth is about three times of $\Delta\nu_{SBS} \approx 11$ GHz). The length of the ring was chosen to be as low as ~ 1.5 m, thus the free spectral range of the ring interferometer $\Delta\nu_R \approx 130$ MHz was much broader than the bandwidth of SBS amplification line $\delta\nu_{SBS} = 1/\pi T_2 \approx 15$ MHz, where $T_2 \approx 20$ ns [5] is a hypersound decay rate (for $\lambda \sim 1.5$ μ m). We were adjusting our scheme by heating the FBG in order to find a optimal overlap between the SBS gain spectrum provided by the laser field at ν_A and the ring's modes.

A Q-switched operational mode has been successfully obtained with this configuration at pump power levels of 80–160 mW. Self-starting pulsation occurred at a repetition rate in the range of 100–500 μ s. Gigantic Q-pulses with a peak power of 40–300 W and a duration of 10–40 ns (FWHM) has been recorded. Figure 2(a) shows a typical oscilloscope trace obtained at the pump power level of ~ 130 mW. The fine structure of the first smaller pulse differs from the previous observations [4] by the presence of a high narrow peak.

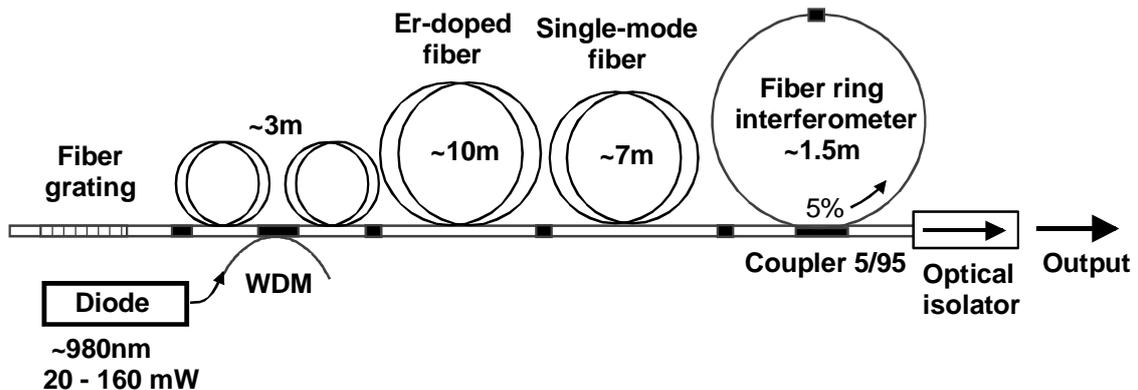


Figure 1. The experimental setup.

The laser exhibited a specific spectral behavior. At low pump power level ($\sim 80 - 100 \text{ mW}$) the laser optical spectrum contains three-four Stokes components as it may be expected from the bandwidth of the FBG. The shift between components is exactly the SBS shift for the laser wavelength of $\sim 1.5 \mu\text{m}$, $\Delta\nu_{\text{SBS}} \approx 11 \text{ GHz}$. However, increasing of the pump power leads to the appearance of new Stokes and anti-Stokes SBS components. Simultaneously, the shift between components decreases down to $\sim 10 \text{ GHz}$. Figure 2(b) presents a typical laser optical spectrum recorded at the pump power level of $\sim 130 \text{ mW}$. Seventeen Stokes and anti-Stokes SBS components are well resolved in the spectrum. One can see that the bandwidth of each component is as narrow as $\sim 2.5 \text{ GHz}$ (what is limited by the resolution of the optical spectrum analyzer). More than ~ 25 SBS components were observed at the pump power level of $\sim 160 \text{ mW}$.

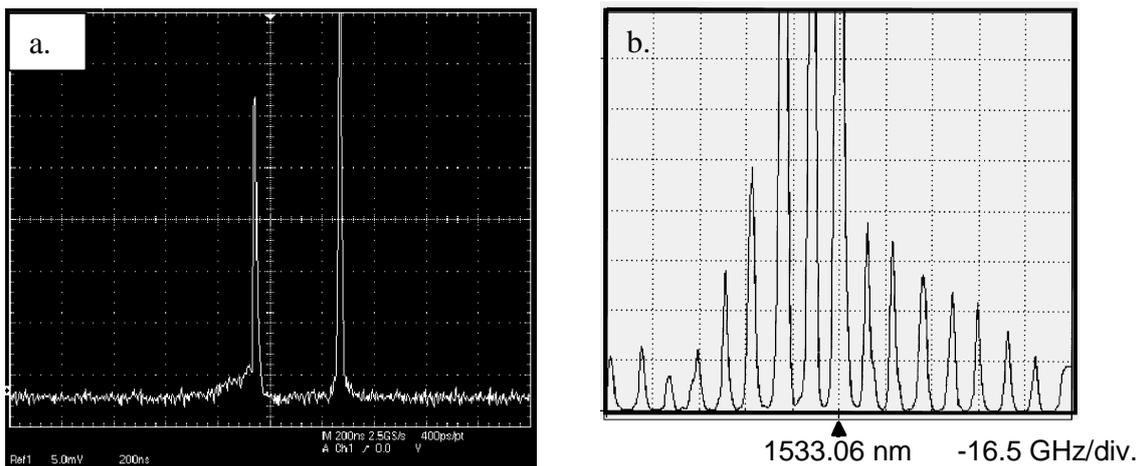


Figure 2. A typical oscilloscope trace (200 ns/div.) (a) and an optical spectrum (b) recorded at pump power level of $\sim 130 \text{ mW}$.

Discussion

Presented results can be explained in terms of the RS-SBS model [1- 4]. Q-switching in the fiber laser occurs due to RS-SBS cascade mechanism. Generation of first two cascades of SBS is usually considered as a process initiating Q-switching [3, 4]. Specifically in our case, the effective growth of three-order SBS components is supported by the spectrum of FBG reflectivity. These growing Stokes waves propagate in the fiber configuration in both directions leading to a formation of a powerful hypersound wave in the fiber. New Stokes and anti-Stokes SBS components could be born inside the fiber configuration as a result of a parametric interaction between existing SBS waves and the hypersound wave. The schemes of a four-wave mixing process leading to parametric generation of new SBS components is shown in Figures 3 (a, b). The frequencies of fields 1, 2 and 4 are SBS shifted: $\nu_2 = \nu_1 - \Delta\nu_{\text{SBS}}^{12}$, $\nu_4 = \nu_3 - \Delta\nu_{\text{SBS}}^{34}$. The fields 2 and 3 are considered to be at the same frequency $\nu_3 = \nu_2$.

The pairs of fields forms two hypersound waves (HS_{12} , HS_{34}). These hypersound waves have approximately equal frequencies $\Omega_{12} \approx \Omega_{34}$ and correspondingly wave-vectors $q_{12} \approx q_{34}$. However, there is a difference between the frequencies (as well as between Δv_{SBS}^{12} and Δv_{SBS}^{34}). It is well known that for SBS interaction between coplanar plane waves in a bulk medium this difference is estimated to be about ~ 0.5 MHz and could not be vanished. In contrast, for SBS in optical fibers the resonance conditions could be matched and thereat the fields 1 - 4 interacts each to other through the same hypersound wave. If one of four fields is primarily absent it would be generated from the noise parametrically by others fields. Thus a new Stokes (see, Figure 3(a)) or anti-Stokes (see, Figure 3(b)) SBS component is born.

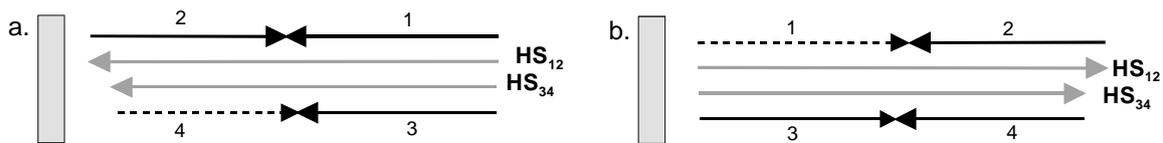


Figure 3. Schemes of a SBS four-wave mixing process. Parametric generation of Stokes (a) and anti-Stokes (b) components.

Conclusion and acknowledgment

In conclusion we have successfully demonstrated a new operating regime for the low-power Er-doped laser. In this regime the cascaded SBS process leading to Q-switching takes place as usual. However, specifically for the configuration under consideration, the effective lasing of three SBS cascades is primarily supported by the FBG bandwidth. As a result, the parametric generation of new SBS components occurs due to the SBS related four-wave mixing process in the fiber. More than ~ 25 Stokes and anti-Stokes Brillouin components were observed with the laser at the pump power level of ~ 160 mW. Such a unique source has a considerable potential for many applications.

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References

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