

Generation of gigantic nanosecond pulses through Raman-Brillouin-Rayleigh cooperative process in single-mode optical fiber

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ABSTRACT

We report a self-starting gigantic pulse generation observed during steady state stimulated Raman scattering (SRS) process in 10 km long telecom fiber. In our rather specific experimental configuration, the fiber was pumped by radiation from a 2.4 W continuous wave (CW) fiber laser source operating at 1455 nm. This pump provided the generation of light at Raman shifted wavelength around 1555 nm. At pumping face, the fiber was spliced with a broadband fiber loop mirror that reflected ~80% of Stokes power back into the fiber. Reflection from the far fiber end face was strongly prevented by the use of an optical isolator. The configuration provided ~30% power conversion from pump to Stokes radiation. Pulsations were observed from both ends of the fiber and occurred in rather stochastic manner with repetition rates in the range from hundreds kilohertz to several megahertz. Gigantic pulses with duration down to ~1 ns and peak power estimated to be above ~1 kW were recorded from the far fiber end. Smaller pulses with duration down to ~50 ns were observed from the pumping side of the fiber. Using a digital oscilloscope we investigated the fine structures of the pulses and determined some consistent patterns of their mutual dynamics. The RF spectrum measurements highlighted the stimulated Brillouin scattering that is suspected to be a main dynamical mechanism initiating pulsations. We observed also other different nonlinear effects caused by propagation of the intensive pulses through the fiber. Corresponding optical spectra were recorded and interpreted. Reported experimental data indicate that Rayleigh, Brillouin and Raman scatterings are all involved in the process of gigantic pulse generation in the fiber.

Keywords: Nonlinear fiber optics, stimulated Raman scattering, stimulated Brillouin scattering, Rayleigh scattering, Q-switching

1. INTRODUCTION

High peak power pulsed single mode fiber lasers are very attractive sources because of their compact size, air-cooled scheme and very good output beam quality. They found applications in many technological areas such as telecommunication, material processing, medicine, range finding and remote sensing. Pulsed Raman fiber lasers (RFL) are of a great interest because of the versatility in the wavelength choice and the possibility to tune their wavelength over a wide range. ¹ RFL are usually implemented with a high power ytterbium doped fiber lasers used as pump source. A cascaded Raman resonator converts initial pump wavelength to any desired wavelength above ~ 1 μm with very good efficiency. ² The upper limit of the emission wavelength is only determined by the available pump power. To our knowledge, the only pulsed RFL that have been reported until now are based on synchronous pumping, ³ which requires very complex implementation.

Traditional Q-switching techniques have not proven to be efficiently applicable to RFL, in particular because of the long length of the cavity required for effective Raman process. Here, we demonstrate for the first time a pulsed RFL based on specific fiber approach. The principle of operation exploits dynamical properties of several nonlinear phenomena realized in the laser cavity with high efficiency. Among the different types of nonlinearities, the stimulated Brillouin scattering (SBS) is the lowest threshold nonlinear phenomena in the fiber. It plays probably dominant role in the Q-switching mechanism providing initial formation of the gigantic pulses through cascaded Stokes-frequency generation process. The growth of cascaded SBS is supported by the distributed Rayleigh backscattering (RS) that provide effective spectral narrowing of lasing radiation. ^{4, 5} Specific features of Raman amplification in the fiber add complexity to dynamical process of the pulse formation.

We report the first experimental observation of short duration and high peak power pulses in a passively self-Q-switched Raman fiber laser. Generation of pulses with peak power about 1 kW and average power up to 700 mW has been achieved in our experiment.

2. EXPERIMENTAL SETUP

Our experimental setup is shown in Fig. 1. A 10-km-long single mode optical fiber is pumped by radiation from a CW unpolarized Raman fiber laser source operating at 1455 nm with a linewidth of ~ 1 nm. The laser provides effective Raman process inside the fiber resulting in generation of light at Stokes wavelength around 1555 nm. The difference in the pump and Stokes wavelengths corresponds to a SRS shift in silica (~ 13 THz). Pumping light is introduced into the fiber through a wavelength division multiplexer (WDM) and filtered at the end of the fiber by another WDM used as a demultiplexer. At pumping face, the fiber is spliced to a broadband fiber loop mirror that reflects $\sim 80\%$ of Stokes power back into the fiber. Reflection from the far fiber end is strongly prevented by the use of an optical isolator. A 1% tap coupler installed between the mirror and the fiber is used to monitor the radiation reflected from the mirror. The output Stokes radiation from both fiber ends (from the 1% tap coupler and from the isolator indicated in Fig.1 as “monitoring” and “output”, respectively) is detected simultaneously by two photodiodes. The signals from photodiodes are digitized and recorded by an oscilloscope for further comparison and analysis. The temporal resolution of the detection system is less than ~ 1 ns. An optical power meter, a 15 pm-resolution optical spectrum analyzer and a 22 GHz-bandwidth electrical spectrum analyzer have also been used for monitoring of the Stokes and pump radiations from both fiber ends.

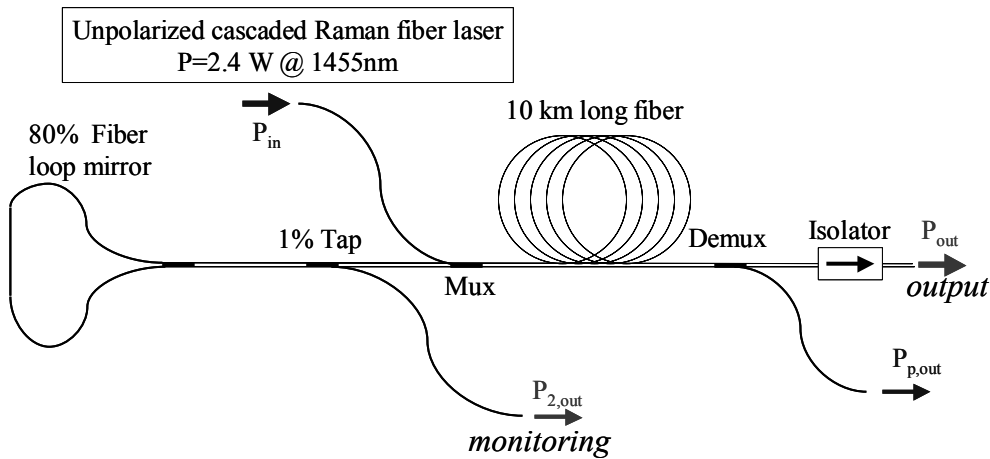


Fig. 1. Experimental set-up with pump multiplexer (Mux) and demultiplexer (Demux).

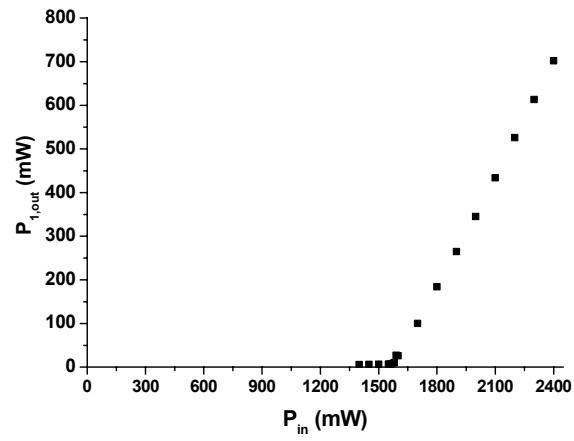
3. RESULTS

3.1. Output power measurements

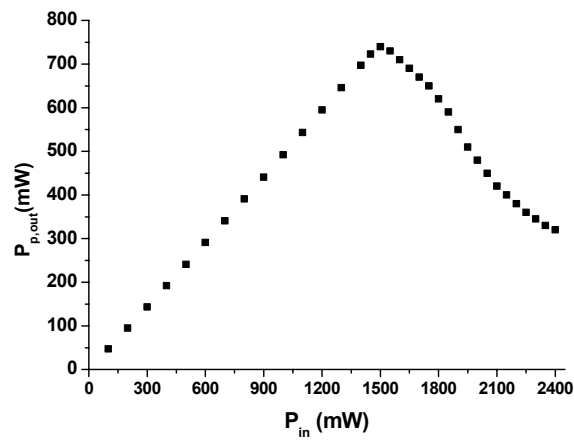
In the first experiment, power characteristics of the Raman process in the fiber configuration shown in Fig. 1 have been investigated. The results of power measurements are shown on Fig. 2. Output power, residual pump power and power at mirror side are presented versus input pump power P_{in} that varies between 0 and 2.4 W.

At low pump power level, the nonlinearities of the fiber are too small to affect propagation of the pumping light through the fiber. Propagating light just exhibits linear losses (~ 0.2 dB/km) associated mainly with Rayleigh scattering process. SBS, the lowest threshold nonlinear phenomenon in optical fibers, is strongly prohibited in this case, because the linewidth of the pump source is too large in comparison with the SBS gain spectrum width. As a result, the output pump power linearly depends on the input pump power until some threshold input power is reached. Indeed, when $P_{in} \sim 1.6$ W, the generation of Raman Stokes radiation begins abruptly.

(a)



(b)



(c)

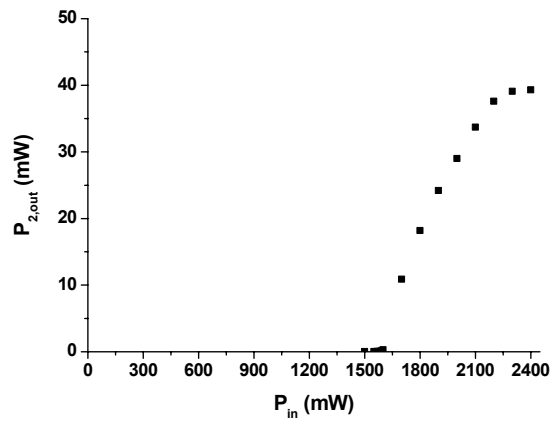


Fig. 2 : (a) Output power (b), residual pump power and (c) Power at mirror side

The growth of the Stokes power in the fiber leads to effective depletion of the pump power as it is shown on Fig. 2 (b). Note that the Stokes signals, observed from two different fiber ends, do not rise in the same manner. The signal recorded from the 1% tap coupler exhibited an obvious saturation when the pump power level exceeded 2.0 W. A similar feature is observed on the curve describing the residual pump power. It means that the pump-power-to-Stokes-power conversion efficiency in the fiber decreases when the pump power increases above 2.0 W. However, this decrease does not affect the output Stokes power observed from the other fiber end, which remains in linear dependence on input pump power. The growth is not either following an exponential law as it could be expected from SRS process.

Let us estimate the threshold power for classical SRS⁶ in the configuration shown in Fig. 1. The threshold of SRS in the fiber is considered to be achieved when the output Stokes power exceeds the noise power level with the factor $\sim \exp(16)$. Taking into account a double pass SRS amplification in the fiber we can express the threshold as:

$$P_{in}^{th} \approx \frac{K \cdot A_{eff}}{2g_R L_{eff}} [16 - \ln R] \quad (1)$$

where P_{in}^{th} is the threshold input pump power, $L_{eff} = (1 - \exp(-\alpha_p L)) / \alpha_p$ is the effective length of the fiber, g_R is the Raman gain coefficient, A_{eff} is the effective core area, $K \approx 2$ is the depolarization factor, R is reflection coefficient of the mirror. With the parameters corresponding to our experiment ($L_{eff} \approx 8 \text{ km}$, $g_R \sim 6 \cdot 10^{-10} \text{ cm/W}$, $A_{eff} \sim 80 \mu\text{m}^2$, $R \approx 80\%$) the threshold power is estimated from (1) as $P_{in}^{th} \approx 2.4 \text{ W}$.

One can see that range of input powers used in the experiment is lower than the threshold power of classical SRS. The decrease of the threshold is associated with distributed Rayleigh scattering in the fiber. RS provides a feedback to the SRS leading to effective generation of the Stokes radiation through RS-SRS lasing process. Note, that the linear dependence of the output power on the input pump power shown in Fig. 2 is also a specific feature of such lasing.

At maximum input output power of $\sim 2.4 \text{ W}$ the output power reaches $\sim 700 \text{ mW}$ demonstrating $\sim 30\%$ conversion efficiency for our laser.

3.2. Pulse shape measurements

At pump power above 1.6 W the fiber configuration generates pulsations that can be observed from both fiber ends. The typical pulses recorded from both fiber ends are shown in Fig. 3. They have different duration and pulse shape. The pulse recorded from the mirror side is $\sim 50 \text{ ns}$ wide. It exhibits a $\sim 20 \text{ ns}$ -width hill followed by a plateau. The pulse recorded from the main output is only 1 ns wide. Its right edge is more abrupt than the left one. One can see also a plateau attached to this pulse from the left, however its amplitude rather small in comparison with the pulse peak. Specifically, the pulses shown in Fig.3 were recorded with the delay of 50 μs that corresponds to the time that light takes to travel through the fiber. So, one can see how propagating through the fiber the wide pulse transforms to the narrow. During this process the 20 ns-width hill narrows down to 1 ns-width pulse, while the plateau is suppressed.

3.3. Radio-frequency measurements

In order to identify the physical origin of the pulsation, we performed radio-frequency (RF) spectrum measurement of the output light. On Fig. 4, we can see that the RF spectrum exhibits a strong peak at $\sim 11 \text{ GHz}$, which corresponds to Brillouin shift in silica optical fiber. This peak is originated from beating between Brillouin-Stokes and RS-SBS lasing lines. RS support multi-cascaded SBS generation in the optical fiber providing very effective line narrowing of laser radiation. Essentially, an interferometer employing at least one distributed Rayleigh mirror is formed in the fiber. Although the reflection coefficient associated with RS in single-mode optical fiber is rather small, the SBS amplification in an optical fiber is high enough to compensate such low feedback. The feedback caused by RS demonstrates strong spectral selectivity and can provide primary SBS amplification and lasing for some spectral components inside the SBS line.⁷ We support that namely SBS cascaded process is a mechanism initiating Q-switching in our RFL as it has been demonstrated in Brillouin fiber lasers.⁸

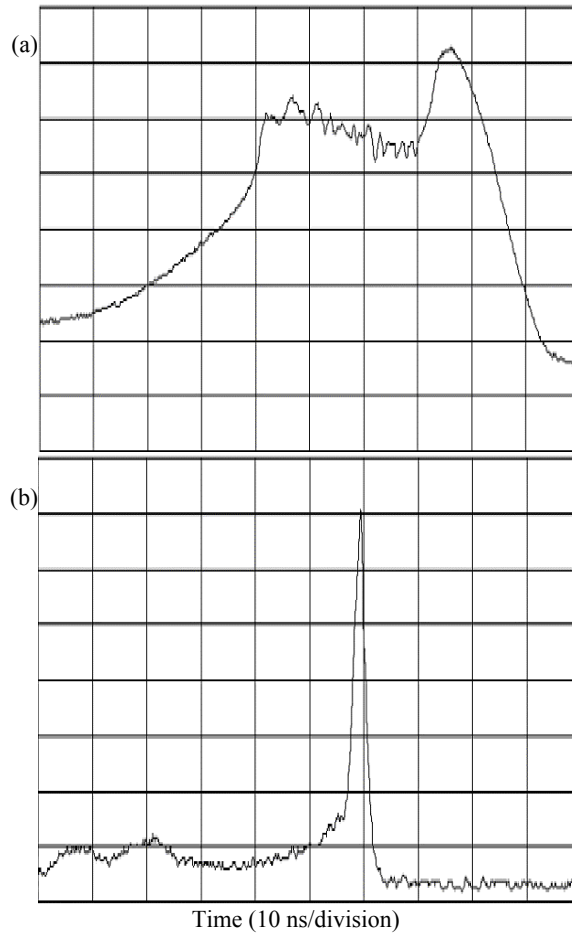


Fig. 3 : (a) wide pulse shape at mirror side and (b) narrow pulse shape at output of the Raman fiber laser (arbitrary units).

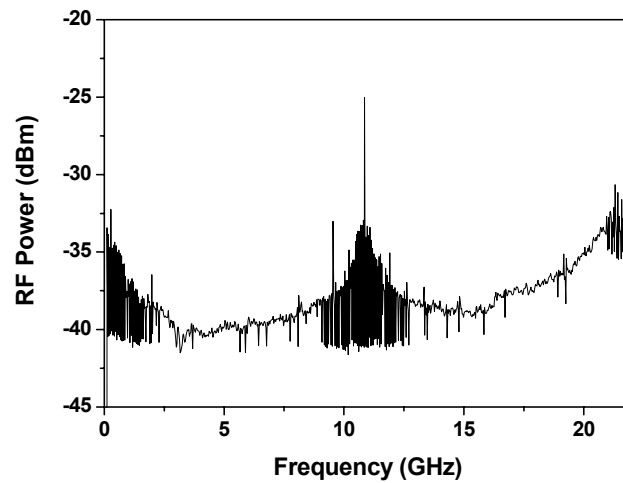


Fig. 4: radio-frequency spectrum of the output radiation exhibits strong 11 GHz Brillouin line due to beating between Brillouin pump and Stokes

3.4. Pulses statistics

In order to make an estimation of the peak power of the pulses, we performed statistical measurements of their width and repetition rate. Fig. 5 presents statistics of 200 samples of the pulses at the output. The average pulse duration is 4 ns but histogram presents clear maximum under 1 ns, which is the limit of our oscilloscope. The average repetition rate is around 180 kHz. The knowledge of those values enables a rough estimation of the peak power to be around 1 kW. Single pulse energy is estimated around $\sim 1 \mu\text{J}$. The repetition rate of pulses train was very unstable due to the stochastic nature of the Rayleigh backscattering process, which is the initial cause of the pulsations. At mirror side the same kind of estimation gives a peak power of 7 W.

3.5. Output optical spectra

To complete the characterization of our laser, we present on Fig. 6 the output spectrum below and above threshold for different wavelength ranges. We can see the numerous Brillouin lines filling all the Raman bandwidth. All these lines can be interpreted as the superposition of several Brillouin cascaded processes, which are able to generate the pulsation behavior that we have reported. The high peak power of the pulses generates other nonlinear effects; comparison of optical spectra below and above threshold indicate that there is generation of second Raman order Stokes lines around 1680 nm. Four wave-mixing (FWM) lines are also generated with respect to the zero-dispersion wavelength of the fiber around 1310 nm.

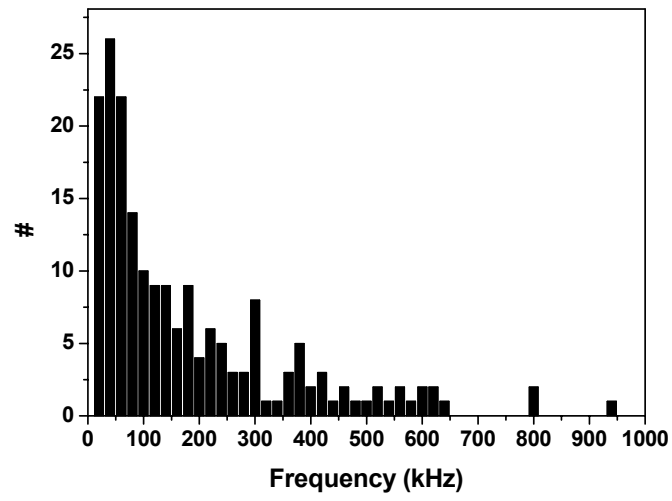
4. CONCLUSIONS

In conclusions, we have experimentally demonstrated for the first time, the passive Q-switching operation of a Raman fiber laser thanks to cooperative lasing process between Rayleigh and stimulated Brillouin backscatterings. RS provides feedback and spectrum narrowing leading to SBS cascaded process. Double-pass SRS gain supplies amplification and pulse narrowing through pulse steepening. We could record pulsation generated around 1550 nm through 2.4W pumping of a standard single mode fiber. Measurements showed duration shorter than 1 ns, repetition rate in the 100 kHz range and peak power above 1 kW. Such high power enables the generation of numerous other nonlinear effects.

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(a)



(b)

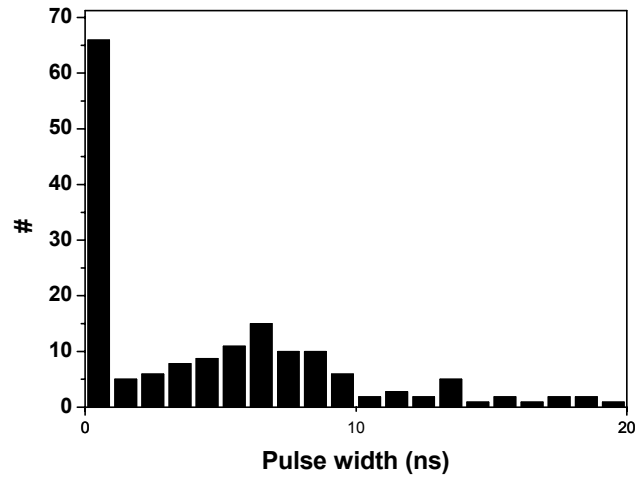


Fig. 5 : histograms of the pulsation characteristics for 200 samples : (a) repetition rate and (b) pulse width.

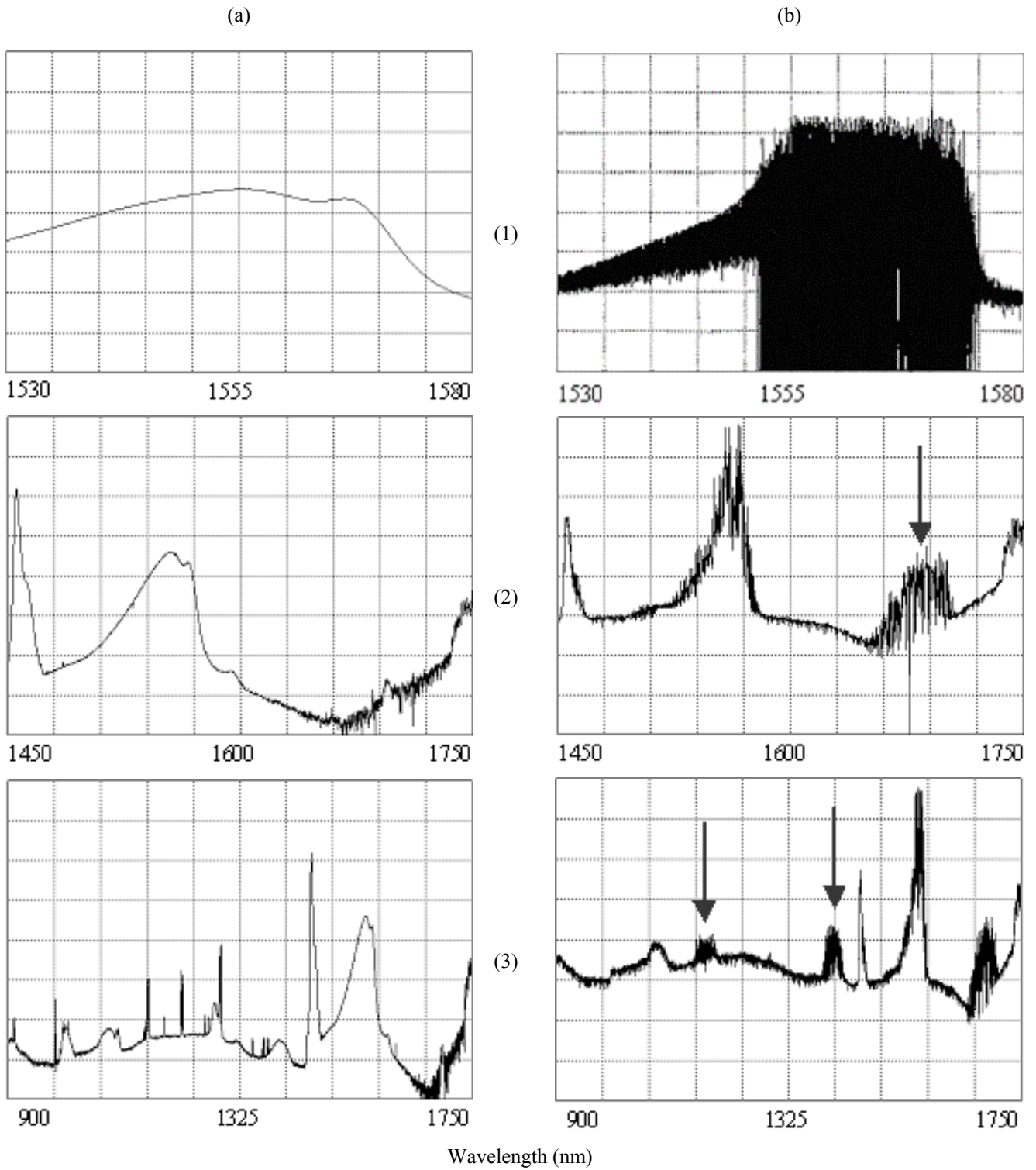


Fig. 6 : output optical spectra (10 dB/division) below threshold (a) and above threshold (b). (1) shows the Brillouin components that are generated through RS-SBS lasing process with 20 pm resolution. Peak power is so important that it generates second order SRS (2) (30 nm/division and 1 nm resolution) and four-wave mixing (3) (85 nm/division and 1 nm resolution).

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