High-brightness, pulsed, cladding-pumped Raman fiber source at 1660 nm

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We report the first demonstration of a pulsed single-stage cladding-pumped Raman fiber source which is capable of delivering up to 10µJ diffraction-limited pulses at 1660 nm. The pulses are 620 ns long with a peak power near 16 W and the pump to signal conversion efficiency is about 36 %.

Introduction:

Single-mode, high-energy pulses are required in many applications, for example, in micro-fabrication [1]. These pulses are commonly produced by rare-earth doped fiber devices. Often these are configured as master oscillator – power amplifier (MOPA) systems. These take advantage of the combination of high gain, high power, and high efficiency offered by fiber amplifiers. Thus, high power and energy output can be reached even when starting from a low-power seed, e.g., as provided by laser diodes for pulse on demand and electronic pulse shaping applications. The energy from the seed laser is often on the nanojoule level, which underlines the requirement for high-gain amplification to reach high output pulse energies. However, in practice, the gain, per amplification stage, is limited to 30 dB because amplified spontaneous emission (ASE) produced by the high gain limits the energy storage and reduces the energy extractable by the signal. Hence, several amplification stages are required which, generally, need intermediate optical isolation and time gating elements to prevent any ASE propagation and amplification in the cascade. These additional components lead to further extra losses and complex set-up, and are also prone to optical damage.

The attainable energy is still limited by the intrinsic saturation energy of a rare-earth doped fiber. Large cores are often used to increase the saturation energy. However, as the core becomes larger, it also becomes multimoded and the signal beam quality is degraded. Thus, so far, the highest energy reported from single-mode fibers has been with large-core Yb-doped fibers. However, for other rare-earths at other wavelength, in particular Er:Yb co-doped fibers operating in the "eye-safe" 1550 nm wavelength range, large-core single mode fiber are considerably more challenging and this limits the pulse energy.

Here, we use another approach based on the concept of cladding-pumped Raman fiber amplification [2] to amplify the pulse seed to higher energy. Previously, we demonstrated the capability to achieve high gain in a single amplification stage [3] in a double-clad Raman fiber (DCRF) with a single-mode output. By contrast to rare-earth doped fibers, in a pulsed Raman amplifier, SRS is a nearly instantaneous process and no energy is stored in the gain medium. For pulse amplification, the most interesting scheme is when the amplifier is co-directionally pumped with optical pulses. Then, signal (Stokes) and pump light must temporally coincide in the fiber to achieve the maximum gain, because the SRS gain is only available to the signal during the pump pulse. Therefore, the gain created by a short pump pulse automatically forms its own time-gate. This negates the effects ASE build-up as well as of spurious feedback, and also allow us to use cw seed lasers.

Experimental set-up:

The experimental set-up shown in Fig. 1 consists of three sections: a DCRF amplifier (DCRFA), a seed source at the Stokes wavelength and a high-peak power high-energy pulsed pump source.

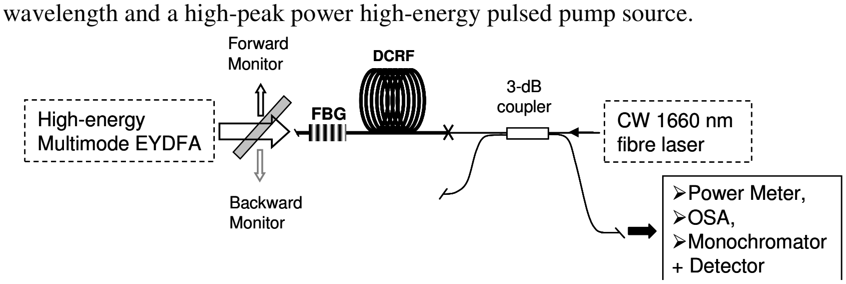

Figure 1: Experimental set-up of the high-energy high-brightness converter

The pump source, formed by a cascade of Er:Yb co-doped fiber amplifiers, is described elsewhere [4]. It produces 700 ns long pulses at a 25 kHz repetition rate with a beam propagation factor (M^2) of about 4 at 1542 nm. Electronic pulse shaping is used to compensate for gain-shaping in the amplifiers, to yield rectangular output pulses. Rectangular pulses help to improve the conversion efficiency in nonlinear fiber devices, but severe gain shaping at high peak powers and the speed of electronics limits the pulse durations and peak powers that are attainable. These pulses are free-space launched into the DCRF (details in [2, 3]) with a launch efficiency of about 70%. The launched peak power is 40 W and the pulse energy 28 µJ. The input DCRF end face is angle cleaved to avoid any back reflection into the pump source. To ensure an adequate seeding of the core mode, the seed signal is core-launched from the pump output end using a broadband single-mode 3 dB coupler spliced to the DCRF. The seed is then reflected at the pump launch end by a fiber grating (FBG) written in the core of the DCRF. The FBG reflectivity is about 83% at 1661 nm. Thus, following reflection of the signal, the signal and pump are co-propagating in the DCRF, with the seed in the core only. This ensemble forms the DCRFA. The output of the DCRFA is then analyzed using a thermal power-meter, an optical spectrum analyzer, a monochromator, and a fast detector. The seed signal is generated by a counter-pumped fiber Raman ring-laser (see [3]) emitting at 1661 nm with an output power of 32 mW.
In the results presented here, the pump power is always the same. The DCRF is 850 m long because, from previous experiments, it yields the best performance given the pump peak power and the fiber background loss.

Results:
The output energy and peak power is shown in Fig. 2 for seed powers between 0.016 mW and 16 mW. The seed energies within a pump pulse become 0.01 – 10 nJ. At the maximum input seed power, the Stokes pulse energy reaches the level of 9.9 µJ in a 620 ns pulse corresponding to a peak power of nearly 16 W and a saturated energy gain of 30 dB. For lower energies, the gain exceeds 30 dB. As the seed power is increased more power is transferred from the pump into the signal until the output energy rolls off indicating that nearly all the pump power is transferred into the single mode. Indeed, the output spectrum at the maximum output (Fig.2. inset), clearly shows that the pump is nearly depleted **.** Here, the signal linewidth is 1.85 nm

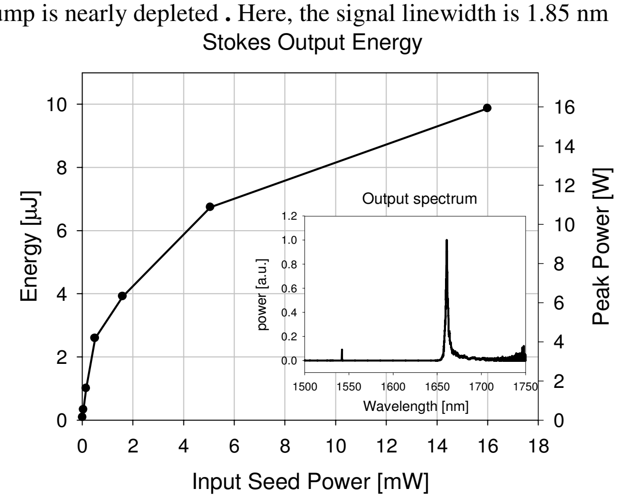

Figure 2: Stokes output energy vs. input seed power. Inset: output spectrum of high-energy Stokes pulse (optical resolution 0.5 nm)

The overall energy conversion efficiency is 36% which quite remarkable considering the various excess loss mechanism such as the background loss of the fiber. This result shows the amplification of pulses in a cladding-pumped Raman fiber to higher energy. This approach could easily be scale up to generate larger energy pulses. Furthermore, electronic shaping of the pump pulses was successfully applied to improve the conversion efficiency and indirectly shape the signal output pulses.

References:
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