BRIGHTNESS ENHANCEMENT LIMITS IN CLADDING-PUMPED FIBER RAMAN AMPLIFIERS

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ABSTRACT

We analyze theoretically limitations on the brightness enhancement of a multimode pump beam, to be efficiently converted into a diffraction-limited Stokes beam in a cladding-pumped fiber Raman amplifier. For a given minimum Raman pump absorption, parasitic 2nd Stokes generation limits the cladding-to-core area ratio, and thus the brightness enhancement. A W-type fiber acting as a spectral waveguide filter allows for nearly five times larger inner-cladding areas by suppressing the 2nd Stokes. We further analyze limits set by glass damage and indirectly propagation loss, as well as pulse walk-off. A well-designed fiber with 3.5 dB/km propagation loss allows for a pump-to-signal brightness improvement of up to 3600 times both in the pulsed and the cw regime.

INTRODUCTION

In recent years we have demonstrated and analyzed cw and pulsed cladding pumped fiber Raman amplification (CPFRA) at 1.66 μm and 1.1 μm [1 – 5]. In this novel approach, a low-brightness pump which is propagating in a passive double-clad fiber is converted through stimulated Raman scattering (SRS) into a diffraction-limited core mode at the Stokes wavelength. The operation of CPFRAs is similar to that of rare-earth doped double-clad fibers, with the advantage that this scheme is wavelength-flexible, limited only by the transparency range of the fiber. Other advantages are that it is possible to reach very high gain in the pulsed regime [2, 4] without being limited by ASE since there is no energy storage involved in the amplification process, and a low relative quantum defect, in particular at shorter wavelengths.

LIMITATIONS ON BRIGHTNESS ENHANCEMENT

We have shown in [2] the design requirements for efficient power conversion in a cladding-pumped Raman fiber amplifier, in a basic double clad fiber design with step-index core and cladding. We showed that a 2 Np (= 8.9 dB) pump depletion by the signal as required for efficient operation imposes a restriction on the cladding-to-core area ratio of approximately ~8. Otherwise, the 2nd Stokes will inevitably build up, which depletes the power in the 1st Stokes and limits the brightness enhancement (BE) process. This is a first limitation. However, more sophisticated fiber designs allow for higher BE whilst maintaining high conversion efficiency. We have found that with a W-type core [6] design, it is possible to achieve a cladding-to-core area ratio (CCAR) of about 34 with large core areas. This design is such that the SRS from the 1st to the 2nd Stokes is reduced, allowing for a larger cladding and therefore relaxing the limit on the area ratio set by the 2nd Stokes.

A second limitation on the CCAR is set by optical damage in the core. A high pump intensity combined with a large CCAR may well lead to 1st Stokes intensities in the core that exceed the damage threshold. The area ratio limitation from material damage will depend on the pulse duration because of its influence on the damage threshold. Here, we assume that the damage intensity is proportional to the inverse of the square-root of the pulse duration [7], and reaches the cw damage threshold for a duration of 625 ns. Thus, data for 625 ns pulses are valid for the cw regime. Note also that although a lower pump intensity allows for a higher degree of BE, the propagation loss and thus the useable fiber length limits the use of low pump intensities.

Finally, we find that the pulse walk-off that takes place in any multimode fiber limits the BE, too. In a CPRFA, this is important since the energy is directly transferred from the pump to the Stokes waves, so these must overlap temporally for efficient operation. In addition, the pump and signal pulses can experience temporal broadening. These effects limit the interaction length over which Raman amplification occurs. Specifically, we find that pulse walk-off limits the cladding NA and the fiber length, which also in this case is related to the pump intensity.

We can combine these limitations to determine the maximum BE that is possible to achieve in a CPRFA. Figure 1 and 2 show the maximum BE that can be reached for various pump intensities in a double-clad fiber with an all-glass outer cladding and for a jacketed air-clad fiber. Here, the pump and Stokes wavelength are 1.55 μm and 1.66 μm; the damage threshold is assumed to be 500 W/μm^2 for a 1 ns pulse with an inverse square-root dependence of the damage threshold on the pulse duration. The core radius is fixed at 9 μm, which allows for a cladding-to-core area ratio of 34 in an optimized W-type fiber.

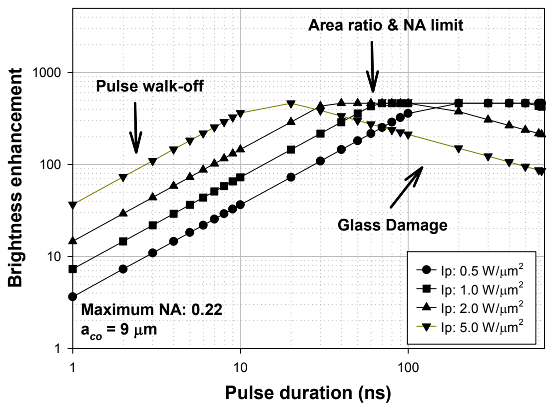

Fig. 1: Brightness enhancement limits in a cladding-pumped solid all-glass fiber.

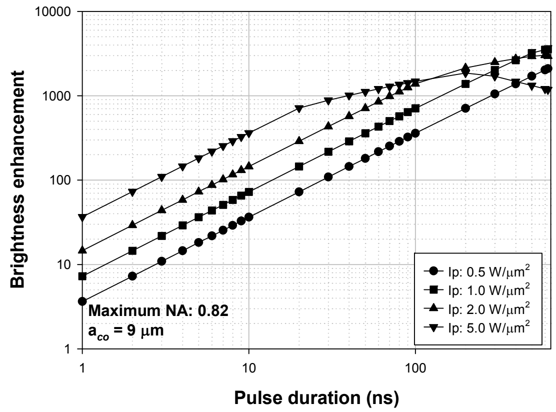

Fig. 2: Brightness enhancement limits in a cladding-pumped jacketed air-clad fiber.

In Fig. 1, in a fiber with a 0.22 inner cladding NA, the BE is limited by the pulse walk-off for short pump pulses, then the 2nd Stokes and the NA of the fiber limit any further BE for longer pulses. For even longer pulses, the glass damage reduces the BE that can be achieved. By contrast, with a high-NA inner cladding such as in the jacketed air-clad fiber, the BE is not limited by the inner cladding NA as shown in Fig. 2. In this case, a BE factor of ~ 3600 is possible. The highest BE-factor can be achieved with pump pulses longer than 100 ns, as well as cw. In the all-glass fiber, the maximum brightness enhancement is constant, ~500 over a range of pulse durations.

CONCLUSIONS

We have shown that core damage and pump pulse walk-off can limit the brightness enhancement in cladding-pumped Raman fiber. An analytical expression of the optimum pump pulse parameters will be given in the manuscript. For an air-clad fiber, the brightness enhancement can be about 400 to 3600 for pump pulses longer than 100 ns.

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