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Self-pulsing in a double-clad ytterbium fiber laser induced by high scattering loss

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Abstract

The characteristics of self-pulsing behavior in a double-clad ytterbium-doped fiber laser are presented. The self-pulsing generates a supercontinuum spectrum that mostly propagates through the multimode structure of the fiber. In fact, 90% of the total power, including the fundamental laser wavelength and the generated supercontinuum spectrum, propagates trough the first cladding. The experimental evidence indicates that the main mechanism for the self-pulsing is the high scattering loss in the double-clad fiber.

Keywords: Fiber laser; Double-clad; Self-pulsing; Ytterbium; Scattering; Supercontinuum

1. Introduction

Generation of high peak power pulses in double-clad fiber lasers is recognized as a desirable alternative to solid-state pulsed laser sources [1]. The most common approach to obtain a pulsed regime in fiber lasers is based on external bulk elements, such as acousto-optic or electro-optic modulators, that are inserted into the cavity to form an actively Q-switched fiber laser [2]. In contrast with solid-state lasers, fiber lasers require longer interaction lengths, which in conjunction with the high powers sometimes favors the onset of nonlinear effects such as stimulated Brillouin scattering (SBS), stimulated Raman scattering (SRS), self-phase modulation (SPM), cross-phase modulation (XPM), and four-wave mixing (FWM) [3,4]. In this case, a direct coupling between the stimulated emission and the nonlinear effects is observed, which result in instabilities and the generation of unwanted Stokes waves that are detrimental for the laser performance [4,5].

On the other hand, to obtain higher pulse energies it is necessary to increase the gain volume of the active medium, which in the case of Q-switched double-clad fiber lasers results in an increase of the fiber length or larger doped core. The increase of fiber length instead, limits the minimum pulse width that can be obtained in the fiber laser, i.e., the longer the cavity length, the broader the pulse. A different approach to obtain Q-switched operation of fiber lasers exploit the fiber nonlinearities and their dynamics, allowing the generation of pulses in the order of a few nanoseconds and high peak powers [6,7]. Recently, the operation of a double-clad fiber laser with 10 kW peak power and pulse width of the order of 2 ns has been demonstrated [6]. In this case, several dynamic mechanisms contribute to the generation of the pulses, namely, distributed Rayleigh scattering, cascaded stimulated Brillouin scattering (SBS), SBS amplification and noise [8]. It is clear that in this case the main mechanism for the passive Q-switching is based on the cascaded Rayleigh scattering and SBS that acts as a dynamic feedback element enhanced by the addition of few meters of standard single-mode fiber. The high peak power and short pulses generated through SBS initiate a cascade of nonlinear processes

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(SRS, SPM, XPM, and FWM) which results in the generation of a supercontinuum spectrum.

There exist other mechanisms that can be responsible for the self-pulsing behavior of fiber lasers. As shown by Hideur et al. [4,5], near threshold Yb^{3+}-doped fiber lasers exhibits irregular self-pulsing behavior that tends to disappear as the pump power is increased. This chaotic self-pulsing regime is attributed to the reabsorption of laser photons in the unpumped length of the fiber or to the quenching effect due to a high concentration of Yb^{3+}-ions. The quenching effect is also given as a possible reason for self-pulsing in experiments where the pump light is injected into the active core [9]. However, even in that case some abnormal effects are observed, such as the high scattering loss for the pump light that is coupled into the fiber core [9]. Since, in principle, the concentration quenching is precluded by the high energy gap between the ground and upper manifolds of Yb^{3+}-ions, the laser dynamics and performance can be mainly determined by the fiber quality. The effect of the fabrication parameters has been shown to be a factor that severely affects the performance of Yb-doped fiber lasers [10]. Some parameters than can influence the final fiber quality are the composition of co-dopants in the fiber core, the uniformity of the outer polymer cladding, and the drawing temperatures.

In this work we describe the operation of a self-pulsed double-clad ytterbium-doped fiber laser. The self-pulsed operation is obtained by the use of a square double-clad fiber with the following composition 0.2 mol% Yb_2O_3, ~1.1 mol% Al_2O_3, 0.65 mol% GeO_2, ~3.0 mol% P_2O_5. The fiber shows a high and non-homogeneous scattering loss that favors strong Brillouin and Rayleigh backscattering, distributed along the whole fiber length. Thus, a bad quality active fiber used as gain element in a bad cavity configuration can be used as a way to obtain strong self-pulsing and supercontinuum. In our case, the generated supercontinuum spans from 1100 nm to 1700 nm and a considerable part (~90%) of this spectrum propagates through cladding, probably due to the coupling to radiation modes induced by the non-homogeneous doping and frozen-in stresses in the fiber. It is worth to mention that the bad cavity configuration refers to the fact that we used a fiber length at least three times longer than the length needed to obtain 12 dB of pump absorption, which favors nonlinear effects and hence enhances the self-pulsing of the fiber laser. In addition, we compare the performance of this fiber with a good quality fiber with composition 0.3 mol% Yb_2O_3, ~1.8 mol% Al_2O_3, 0.4 mol% GeO_2, ~0.1 mol% P_2O_5. This composition is used with a virtual-square inner cladding geometry[10]. In this case the self-pulsing behavior is only observed under three particular conditions: (a) near the laser threshold; (b) if there are two well separated laser wavelengths competing for the same gain; and (c) if some length of the fiber is vibrating due to some air flux or similar. Out of these cases the fiber is under a continuous regime, despite the fact that the concentration of Yb^{3+}-ions is higher than that of the square fiber.

2. Experimental results

Fig. 1 shows the setup of the self-Q-switched fiber laser. It consists of a double-clad ytterbium-doped fiber laser, end pumped by a diode laser pump module delivering up to 4.8 W at 915 nm. The double-clad fiber showed a 0.9 dB/m of measured pump absorption, cladding dimensions of 123 × 123 μm, and 6 μm core diameter. This fiber was designed to match the core diameter and numerical aperture of the fiber Bragg grating fiber at the input side (~6 μm diameter and 0.14 NA). On the input pump side, a high reflection fiber Bragg grating (FBG) with a Bragg wavelength of 1085 nm is spliced to the double-clad fiber. The FBG is written in a standard single-mode fiber, where the original polymer was removed and substituted by a low index material to support the propagation of the pump modes. The output reflector is provided by the 4% Fresnel reflection from the perpendicularly cleaved end of the double-clad fiber.

For the 40 m fiber length the calculated total pump absorption is 36 dB, which means that the residual pump is negligible. This value of pump absorption is extremely high since only 12 dB of pump absorption are enough to obtain efficient laser emission. We implemented the laser using the 40 m fiber and observed high output laser power, which lead us to suspect that the fiber was self-pulsing. To determine the pulsed nature of the output light, a small

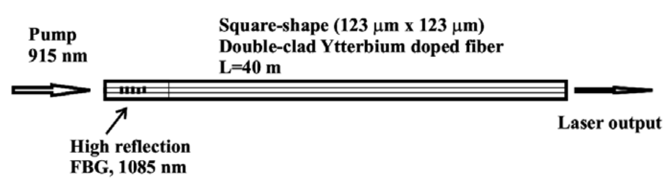

Fig. 1. Sketch of the self-Q-switched double-clad fiber laser.

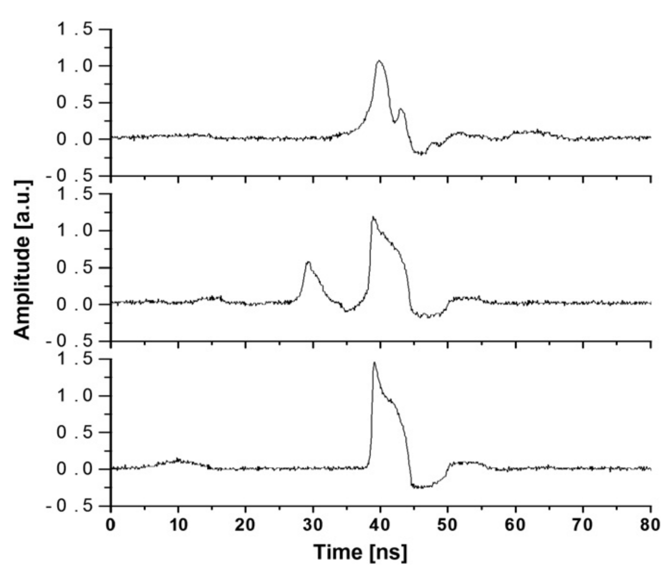

Fig. 2. Snapshot of the chaotic pulses generated by the self-pulsing of the double-clad fiber.