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High performance pulsed coherent fiber laser emitting >1.7kW at 1060nm in ns regime

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Fiber lasers and amplifiers are used in a variety of applications either for scientific (spectroscopy, medicine ...) or industrial applications (free space communications, laser marking and drilling ...). The combination of doped double clad fibers (DCF) and high power multimode semiconductor laser diodes technologies allows to achieve very high output power in very compact, robust and maintenance free systems. Yb³⁺ doped DCF are well suited for 1 μ m wavelength amplification. In pulsed regime, achievable peak power can be strongly limited by nonlinear effects such as Kerr effect, Stimulated Raman Scattering (SRS) or Stimulated Brillouin Scattering (SBS). Consequently, the optimisation of optical amplifier architecture is required. In this paper, we demonstrate performances obtained for the generation of 2ns optical pulses up to >1.7kW peak power in a Master Oscillator Power Fiber Amplifier (MOPFA) configuration. The laser seed signal at 1060nm is emitted out of a single longitudinal mode source with spectral linewidth <0.2nm. The pulse repetition rate can be changed between 3 and 30MHz. The high power stage, based on a 2-stages architecture, allows to deliver >10W average output power with a good beam quality ($M^2 < 1.2$). No significant limitation due to nonlinear effects of the type of the Kerr effect or SRS appears by means of the optimisation of the final stage's fiber parameters. Results, such as a concentration of more than 80% of the total output power in a 1nm window around the central wavelength and above all an excellent conservation of the spectral properties of the seed source are demonstrated for a peak power of >1.7kW. These high performances are obtained in a fully-integrated device.

1-INTRODUCTION

The combination of the DCF technology with high power semiconductor laser diodes allows to develop high power optical fiber sources in the 1-100W range. Yb³⁺ doped DCF are very efficient to develop lasers and amplifiers in the 1 μ m wavelength range [1, 2]. Intrinsic properties of DCF authorize a good coupling efficiency of the light emitted out of multimode high power laser diodes. Pulsed regime allows generation of peak power >1kW. One of the most important limitation concerns nonlinear effects [3]. To achieve high energy extraction and increase the nonlinear effects threshold the use of large mode area (LMA) fibers are required. In this paper, we present results obtained while amplifying a very narrow laser signal up to >1.7kW in 2ns pulses. The most difficult here was to achieve such high peak power while maintaining the spectral source properties (linewidth <0.2nm) and spatial properties ($M^2 < 1.2$).

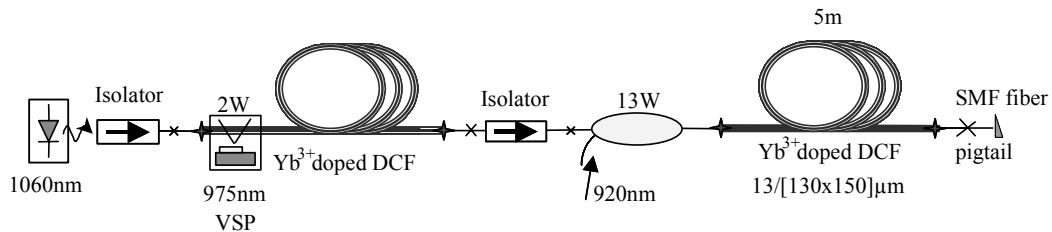


Figure 1: Architecture of the MOPFA fiber laser designed to achieve >10W average output power in 2ns pulses at 3-30MHz repetition rate

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2-POWER FIBER AMPLIFIER OPTIMISATION

The architecture of the device is presented on fig. 1. To achieve output power higher than few watts average, a 2-stages amplifier is required. The preamplifier stage is pumped by a broad stripe laser diode at 975nm using the V-groove side pumping technique [4]. The output power of the preamplifier stage ($\sim 200\text{mW}$), corresponding to $\sim 33\text{W}$ peak power, is high enough to efficiently saturate the power amplifier stage. To increase the nonlinear effects threshold, we have retained a slightly multimode Yb^{3+} doped fiber for the booster stage. This DCF has a core diameter of $13\mu\text{m}$ and a numerical aperture of 0.13. The length of DCF used is 5m and corresponds to a pump power absorption $>10\text{dB}$ (absorption $\sim 2.5\text{dB/m}$ at 920nm). A fiber pigtail of quasi single mode fiber at the signal wavelength (short piece of SMF28, mode field diameter $<9\mu\text{m}$) is used to preserve the beam quality parameter ($M^2 < 1.2$).

The source generates 2ns pulses at a repetition rate adjustable between 3 and 30MHz. The limitation due to nonlinear effects can appear for peak power higher than few watts/m at $1\mu\text{m}$ (for fibers of $\sim 20\text{-}40\mu\text{m}^2$ effective mode area). For optical pulses >10 ns, the Stimulated Brillouin Scattering (SBS) effect is the most important non linear effect [5,6]. In our case, the dominant non linear effects are Kerr effect and SRS respectively. Even if there is a penalty in terms of non linear effects, we had to consider the use of commercially available 920nm high power fiber pigtailed laser diodes. The penalty in terms of non linear effects threshold is balanced by the possibility of using uncooled laser diodes with no wavelength stabilization. The booster stage is pumped by a combination of high power laser diodes using a fiber bundle for a total pump power budget of 13W. A contra-pumping scheme allows increasing non linear effects threshold [7]. However, we have retained a co-pumping scheme to avoid the penalty of the insertion loss of the fiber bundle at the output of the booster amplifier. This configuration allows to reduce pump power budget.

3- SPECTRAL BROADENING AND OPTIMISATION OF THE SOURCE PARAMETERS

In pulsed regime, for peak powers higher than a few watts/m, an optical spectrum broadening can occur due to Kerr effect. This nonlinear effect results in a spectral broadening of the seed source in dependence with output peak power. The seed source is an external cavity laser with a linewidth $<0.2\text{nm}$. The most important contribution to linewidth broadening is the SPM effect (Fig. 2).

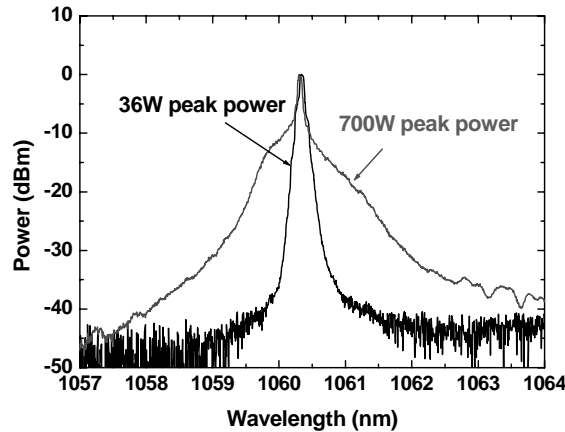


Figure 2: Spectral broadening due to SPM

The spectrum broadening can be estimated using the expression [8]

$$\Delta\omega_{SPM} \cong \gamma_{Yb} \frac{\partial P_{peak}}{\partial t} L_{eff} \quad (1)$$

where γ_{Yb} is the nonlinear Kerr parameter and L_{eff} the effective length. The nonlinear Kerr parameter $\gamma_{Yb} \sim 10 \text{ W}^{-1} \cdot \text{km}^{-1}$ has been determined using by the measurement of the four-wave mixing (FWM) efficiency between two co-propagating signals with co-linear polarization. The FWM phase matching condition is realized for $<1\text{nm}$ wavelength spacing. Assuming an uniform amplifier gain distribution along the Yb^{3+} doped fiber length ($L=5\text{m}$), the effective length is $L_{eff} \sim 1.3\text{m}$ [6]. A $\sim 0.08 \text{ nm}$ spectral broadening corresponds to an output peak power of 1.7 kW . In practise more than 80% of the overall power at 1.7kW is contained in a 1nm window around the central wavelength and even more than 90% in 5nm around it. In the meantime, the laser linewidth and spectral purity of the source are preserved (Fig. 3).

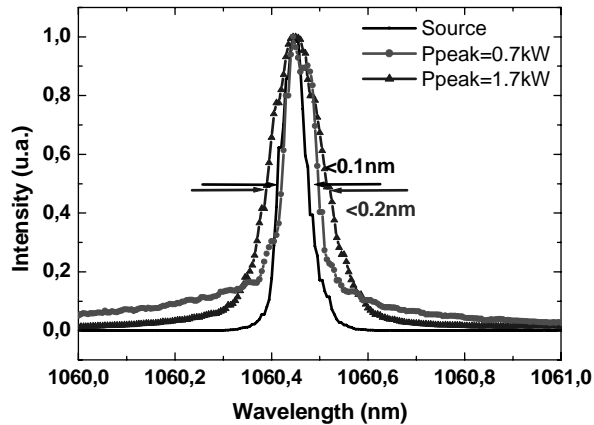


Figure 3: Optical spectra of the external cavity laser diode before and after amplification

CONVERSION EFFICIENCY AND PEAK POWER

The booster amplifier stage architecture has been designed to maximize power conversion efficiency. We have measured better than 75% efficiency: 10W output power at 1060nm is obtained for a pump power of 13W (Fig. 4). Peak power is higher than 1.7kW in 2ns pulses at a repetition rate of 3MHz (Fig 5). Thanks to the geometry of the 2nd clad of the DCF and its numerical aperture, we have achieved a quasi-conservation of the fundamental mode propagation throughout the booster. The signal to noise ratio is not limited by SRS and remains $>28\text{dB}$ even when peak power is $>1.7\text{kW}$. It is only limited by the amplified spontaneous emission around 1075nm .

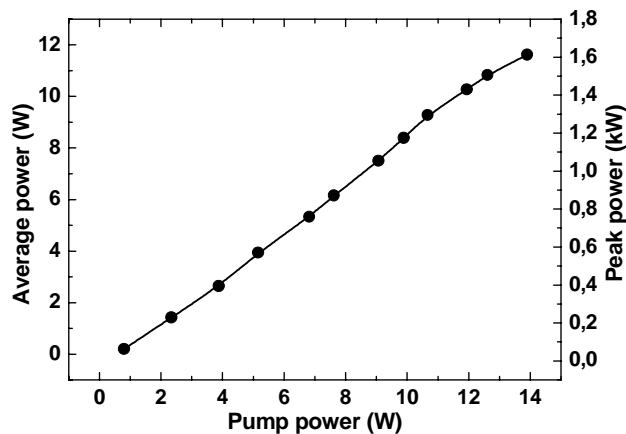


Figure 4: Average output power and peak power over $\pm 0.5\text{nm}$ around central wavelength versus injected pump power

At such a high level of peak power, SRS nonlinear effect appears. In case of standard Yb^{3+} -doped DCF (i.e. mode field diameter of $\sim 6\mu\text{m}$) are used, this phenomenon is visible at peak powers as low as few hundreds of watts [3, 10]. The large mode area fiber used in this power amplifier allows to increase the SRS power threshold up to 1.5kW. Even at 1.7kW most of the total average power is contained in a 1nm window around the central wavelength. At 30MHz repetition rate, SRS disappears as peak power is $<160\text{W}$.

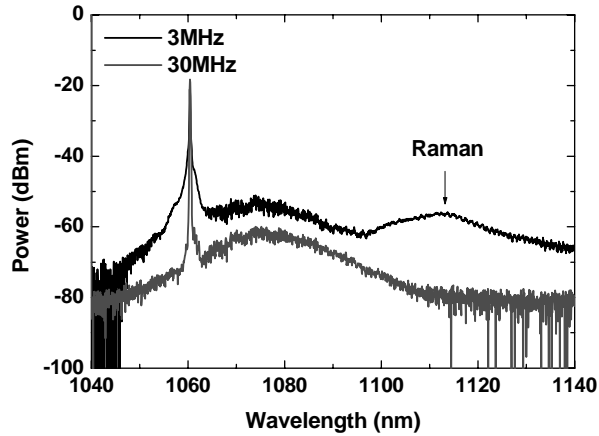


Figure 5: Optical spectra obtained at 10W average output power at 3 and 30MHz repetition rate.

CONCLUSION

We have demonstrated the feasibility of a high power pulsed Yb^{3+} doped double-clad fiber laser in a MOPFA configuration capable of delivering $>10\text{W}$ average power in 2ns pulses. Booster stage fiber parameters optimization allows to achieve $>1.7\text{kW}$ at a repetition rate of 3MHz. No pulse distortion in temporal domain is observed even at this level of peak power. The beam quality ($M^2 < 1.2$) proves that the preservation of the propagation of a quasi-gaussian mode is achieved. The performance also results in the preservation of the spectral purity of the source even at high peak power. To our knowledge, these good specifications constitute the best performances with the constraints of the 920nm pumping wavelength and co-pumping scheme of the booster stage and are achieved in a fully integrated device.

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