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High power fiber lasers and amplifiers/Lasers et amplificateurs à fibre de puissance

Millijoule, high-peak power, narrow-linewidth, sub-hundred nanosecond pulsed fibre Master-Oscillator Power-Amplifier at 1.55 μm

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Abstract

In the first part of this article we review the challenges associated with erbium–ytterbium doped fibre amplifiers and the design considerations to scale-up the output power and energy using cladding-pumped large-core fibre amplifiers in master-oscillator power-amplifier (MOPA) configuration. Previous results are also given to illustrate this rather successful approach. The second part consists of our latest experimental results with improvements in terms of linewidth and peak power using shorter pulses. Sub-hundred nanosecond pulses with millijoule energy and narrow linewidth were obtained using cascaded fibre amplifiers with large-core fibres. The energy level obtained with such short pulse duration and narrow spectral linewidth is the highest ever reported. System limitations and potential routes for further improvement are also discussed. ***To cite this article: C. Codemard et al., C. R. Physique 7 (2006).***

Résumé

Source MOPA à fibre générant des impulsions brèves de faible largeur spectrale avec une énergie de l'ordre du millijoule et une forte puissance crête à 1,55 μm. Dans la première partie de cet article, les difficultés associés à l'utilisation d'amplificateurs optiques à fibre dopée Er:Yb ainsi que les paramètres de conception pour augmenter la puissance et l'énergie des pulses en utilisant des amplificateurs optiques à fibres à cœur larges, pompées par la gaine, en configuration master-oscillator power-amplifier (MOPA) sont revus. Cette approche est illustrée par des résultats obtenus précédemment par notre groupe. Dans la deuxième partie de l'article les résultats les plus récents sont donnés avec une nette amélioration en ce qui concerne la largeur spectrale de la puissance crête des impulsions obtenues. Les limitations et les différentes techniques pour améliorer ces résultats sont aussi décrites. ***Pour citer cet article : C. Codemard et al., C. R. Physique 7 (2006).***

Keywords: MOPA; Doped fiber; Erbium; Ytterbium; Pulsed laser; High energy

Mots-clés : MOPA ; Fibre dopée ; Erbium ; Ytterbium ; Laser impulsionnel ; Haute énergie

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1. Introduction

Narrow-linewidth, high-energy, high-power fibre pulsed sources in the 'eye-safe' 1.5–1.6 μm wavelength range have numerous applications in the domains of defence and aerospace, from remote sensing and coherent LIDAR systems to range-finding and free-space communications to name a few. In addition, there are many more uses in medical sciences (e.g., laser surgery and imaging) and for scientific research (e.g., non-linear optical conversion). The interest in fibre based sources owes to the fact that they can be made into compact devices with small foot print and low weight while maintaining the versatility and the optical performance required for many applications. Therefore pulsed fibre sources are potentially well-suited for airborne system such as LIDAR detection.

Recently high power fibre laser and amplifiers have seen their output power increased [1,2] thanks to the advances in diode pump technology such as diode stacks and with improved double-clad fibre designs. Nonetheless the scaling of the energy and peak power of pulses in fibres has been much slower [3] at 1550 nm than in the 1050–1080 nm wavelength region where ytterbium-doped fibre sources [4] perform well. Operation in the 1.5–1.6 μm spectral range is possible by doping the core of double-clad fibre with erbium ions. However the low absorption of erbium at the pump wavelength requires the fibre co-doping with Yb ions to increase the pump absorption [5]. Consequently widely available high-power pump sources operating from 910 to 1100 nm become suitable for pumping erbium–ytterbium (Er:Yb) doped fibre. In addition double-clad Er:Yb doped fibres (EYDF) are compatible with existing components developed originally for telecommunications, which make them good candidates to design complex fibre sources that need to be tailored to produce high-energy, narrow-linewidth pulses.

In the first part of this article we review the challenges associated with power-scaling of Er:Yb doped fibre amplifiers and the necessary design considerations for high-energy, narrow-linewidth fibre amplifiers in a master-oscillator power-amplifier (MOPA) configuration.

In the second part of the article we present our fibre MOPA based on large-core EYDFs and some experimental results. The MOPA delivers millijoule, narrow-linewidth, sub-hundred nanosecond pulses. These energy levels are among the highest ever reported from EYDF. Finally, systems limitations and potential routes for further improvement are also discussed and the results summarized.

2. Challenges and design considerations

Although cladding-pumped Er:Yb fibre sources were demonstrated in the early 1990s, e.g., [5] their output powers have remained at a much lower level than of Yb-doped fibre source. It is only recently that the power has risen to the 200 W level [6]. Indeed practical power scaling of EYDF remains challenging and even more so for energy-scaling of narrow-linewidth sources.

2.1. Challenges in power scaling cladding-pumped Er:Yb co-doped fiber source

Challenges to power scale the output from cladding-pumped Er:Yb co-doped fibres are linked to the intrinsic nature of the dopant ionic system. In order to enhance the pump absorption required for a high output power source, ytterbium co-doping is utilized, allowing EYDF devices to be pumped at 915 or 980 nm where Yb ions absorb. Photon energy is then transferred to the Er ions which emit light between 1.53 and 1.62 μm. The insertion of large quantities of Yb into the glass host requires the addition of co-dopants like phosphorous to improve the energy transfer between ions [7]. Such a composition leads to an increase of the core numerical aperture (NA) of the fibre core. Therefore the core dimension should be of a small dimension in order to be single-moded at the operating wavelength. On the other hand larger-cores are often required to increase the stored energy in the fibre which associated with high NA leads to undesirably multimoded core.

A consequence of the presence of the large quantities of Yb ions and of high-pump intensity is the parasitic emission at 1–1.1 μm from the Yb ions. It has been shown in [8] that this emission causes the output power from the erbium ions to rollover at the 100-W level as the energy transfer is bottlenecked. More dramatically spurious lasing and self-pulsing can occur when a large fraction of ytterbium ions are excited, which as a consequence can damage or even destroy fibre end facets as consequence.

By contrast to Yb-doped fibre, the large pump-signal wavelength difference increases the quantum defect which leads to considerable heat generation in EYDF. This large quantum defect combined with high active ions concentration leads to high thermal loading density. Hence damage can occur in Er:Yb doped fibre as experimentally shown in [9]. Therefore, special active cooling methods near the pump injection points such as water-cooled V-grooves [6] are used to prevent thermal loading.

Despite these difficulties, we have recently demonstrated power-scaling of continuous-wave (cw) EYDF amplifiers and lasers from a 40 W [10] to 100 W [8] and to nearly 200 W [6]. Also with a more advanced configuration and employing large-core fibre, a 150 W CW fibre MOPA with single-mode and single-frequency output has been demonstrated [11].

2.2. Design considerations for narrow-linewidth pulsed fibre MOPA

The general configuration of a pulsed narrow-linewidth source uses a MOPA architecture which allows for temporal control (e.g., pulse shape, pulse duration and repetition rate) and spectral control (e.g., linewidth and wavelength tunability) of the pulsed light. An all-fibre MOPA benefits from the versatility of the configuration while retaining the advantages of fibre based sources such as compactness and good efficiency. Thus fibre MOPAs provide a unique combination of high power and flexibility which suits a number of applications. A number of design parameters that must be considered in order to reach high energy levels and obtain a narrow-linewidth output from a fibre MOPA will now be discussed.

High average power: High average power is sometimes required from pulsed MOPA. In that case, larger amount of pump power must be launched into the double-clad EYDF amplifier. Higher power pump sources such as diodes stack or diode bars can be used. However, the increase in amount of output power is accompanied with a degradation of brightness from the pump sources. Thus larger inner-cladding are required to accommodate the pump power into the EYDF. For example in [11] we used fibres with a 650 μm diameter inner-cladding. However, operating at higher repetition rate increases the average power but at the detriment of pulse energy.

High energy: In an ideal system, higher energy can be obtained when more energy is stored in the active medium. Therefore fibres with large-core and high concentrations are utilized [12] to increase the energy storage. However, it has always been more difficult to extract a lot of energy from EYDF than pure erbium doped fibres [13]. This is may be explained by the various energy transfer processes which take place in EYDF, specifically backward energy transfer to Yb ions, e.g., [14]. Still, in practice it is difficult to power-scale erbium-doped only fibre due to the lack of adequate high-power pump sources operating in the necessary absorption bands. On the hand, the abundance of high power pump source for EYDF makes it a more attractive solution.

High peak power and narrow-linewidth signal: High energy, short duration pulses are associated with high peak power. Therefore, non-linear effects can become significant inside the MOPA. Self-phase modulation, four-wave-mixing and stimulated Raman scattering can deteriorate the temporal and spectral properties of the pulse. As non-linear effects scale with the intensity-length product [15], they can be avoided by using larger core and/or shorter fibre lengths. In the case of a narrow-linewidth source, stimulated Brillouin scattering (SBS) is the major non-linear impediment. Although some SBS suppression schemes have been proposed at low power (e.g., [16]), the cumbersome and complex arrangements make them unsuitable for high peak power level. In our MOPA, non-linear effects are managed by using short length EYDF with high concentration and large core.

Beam quality: Diffraction-limited output beams are often desired. Hence single mode fibre cores are preferably used. However, as discussed above, it is somehow a contradiction with the requirement of large-core fibre for energy-scaling and to avoid undesirable non-linear effects. Normally, low NA cores are used to expand the core dimension while preserving a diffraction limited output beam. Nevertheless, this approach is difficult to implement as efficient Er:Yb fibres require co-dopants to enhance the energy-transfer between ions. This ultimately leads to doped cores with typical NA ~ 0.2. Hence fibres with core diameters of 30 μm are highly multimode with large V number (~ 12). Still, large and multimoded fibre cores can be made to operate on the fundamental mode with the appropriate modal excitation and by suppressing higher-order mode coupling [17]. Therefore the active fibres must be carefully fabricated, and uniformed large-core fibres to reduced the mode coupling. In addition, large-core fibres require a good refractive index profile such as where the fundamental mode is diffraction limited (i.e., no central dip is present). Then it is possible to achieve single-mode excitation and power scaling [11]. However, the drawback of using multimode fibre is that amplified spontaneous emission (ASE) which is proportional to the number of modes sustained by the fibre core, can become strong and limits further energy extraction.

Thus large-core EYDF fibres seem the best compromise to reach high-energy in a narrow-linewidth fibre MOPA in the "eye-safe" wavelength range. With this approach a high-coherence fibre MOPA with energy of 0.4 mJ has been demonstrated [18], and also a millijoule single-stage MOPA with good beam quality and 575 ns long pulse [19]. Still in [19], the output linewidth was rather large ∼7.3 nm. In this work, we present a high-energy EYDF MOPA where we improve on the results of [19] with narrow-linewidth and shorter pulse duration.

3. Experimental set-up

Our fibre MOPA consisted of four cascaded fibre amplifiers (Fig. 1). Monitoring taps were introduced to monitor spectral and temporal evolution of the pulse along the MOPA. The master source was a directly modulated external-cavity tuneable laser (TLS) source (TUNICS-Plus) operating at 1535 nm. The pulse duration was 250 ns and the repetition rate was set at 1 kHz. Though the precise linewidth is unknown, it is sufficiently narrow to generate SBS in the cascade. Direct measurements with an optical spectrum analyser showed a linewidth of less than 0.05 nm (resolution-limited). The oscillator output was amplified in a core-pumped erbium-doped fibre (EDF) amplifier (length ∼3 m, core diameter ∼12 μm) whose output was time-gated with a synchronized acousto-optic modulator (AOM). The signal was then further amplified in a cladding-pumped Er:Yb co-doped fibre (CP EYDF) amplifier (length ∼2.5 m, core diameter ∼18 μm) whose output was spectrally filtered with a narrow-band fibre-Bragg grating (FBG) at the signal wavelength. The third amplifier consisted of a 2.5 m long double-clad EYDF with a core diameter of 50 μm. The signal is injected through a taper (see Fig. 1 inset) and spliced to the previous stage. A polarization controller (PC) is used to optimise the modal excitation. The signal is then free space launched through coupling optics into the final large-core (length 2 m, core diameter ∼90 μm) amplifier. Both final stages were end-pumped with multimode pumps sources at 915 and 960 nm respectively, using dichroic mirrors to separate the signal and pump wavelengths.

Time gating by the AOM and spectral filtering with the FBG reduced any forward propagating ASE which limits the energy extraction in the amplifier cascade. Furthermore optical isolation between the amplifications stages where possible was used to prevent the leakage of backward ASE and to protect upstream amplifiers from potential backward high-peak power pulses induced by SBS. Finally the overall length of the MOPA was reduced to a minimum (<12 m) and the powers from different amplifiers were adjusted to avoid any SBS or strong ASE saturation. Without proper power adjustment of the amplification stages, SBS arose in the second stage indicating a "single-frequency" nature of at least a part of the energy in the optical pulse.

The output pulses were characterized with a thermal power-meter, an energy-meter (OPHIR), a fast detector (Thorlabs DT310) and an optical spectrum analyser (AQ-6315E).

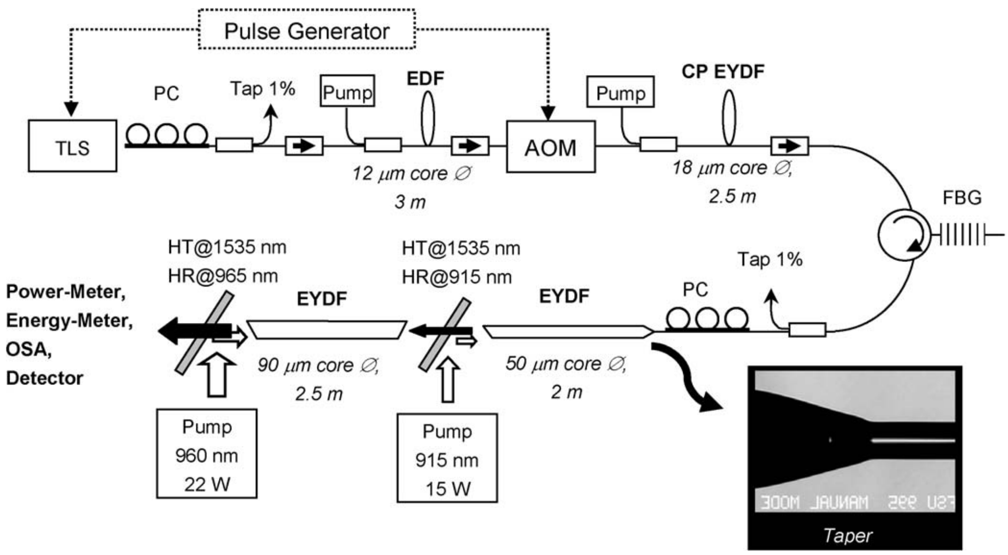

Fig. 1. Experimental set-up of high-energy, narrow-linewidth erbium–ytterbium large-core fibre MOPA. Inset: large-core fibre taper.

Fig. 1. Dispositif MOPA à fibre à large cœur erbium–ytterbium, faible largeur spectrale et haute énergie. Insert : fibre à large cœur évasé.

4. Results

The performance of MOPAs similar to this one, without the fourth stage, has been reported before [20], so here we concentrate on the behaviour of the fourth-stage amplifier. The average input power of the fourth amplification stage was 233 mW at 1 kHz repetition rate. The pulse energy was measured to be 179 µJ. This was then amplified to 1.011 mJ pulse at maximum pump power (Fig. 2). This corresponds to a peak power of 6.6 kW for a pulse duration (FWHM) of 88 ns (Fig. 2 insets). We observed pulse compression from the original 250 ns to 88 ns FWHM pulse duration due to the differential gain between the leading and the trailing edge of the pulse edges. Despite the high-peak power, no non-linear effects were observed thanks to the large-core fibre.

The average output power (ASE included) was more than 1.5 W. The energy extraction was limited by ASE saturation which represents about 30% of the total output power. The ASE can be suppressed, and the average power in the pulses can be improved, at higher repetition rates, however, this is at the expense of pulse energy and peak power.

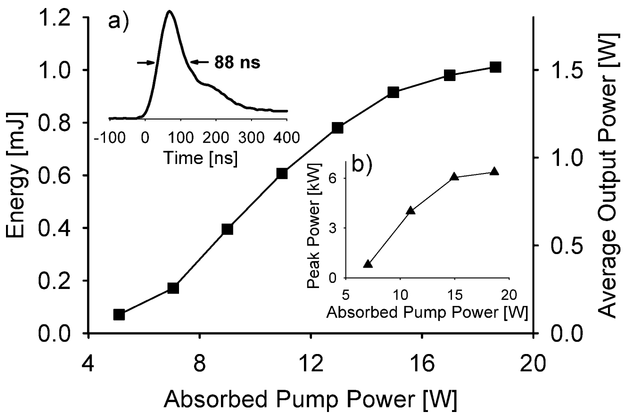

Fig. 2. Output energy and average output power versus absorbed pump power in the final stage. Insets: (a) temporal trace of the pulse, (b) peak power versus absorbed pump power.

Fig. 2. Evolution de l'énergie et de la puissance de sortie en fonction de la puissance de pompe absorbée dans l'étage final. Inserts : (a) évolution temporelle de l'impulsion, (b) puissance crête en fonction de la puissance de pompe absorbée.

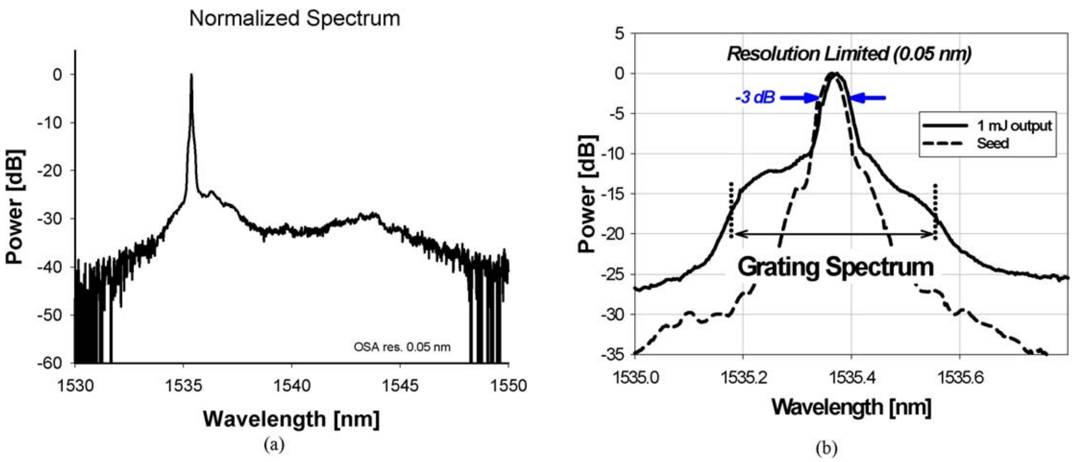

Fig. 3. (a) Normalized output optical spectrum (resolution 0.05 nm) at the maximum energy output, (b) enlarged spectra from: output (solid line), input diode (dashed line).

Fig. 3. (a) Spectre optique de sortie normalisé (résolution 0,05 nm) pour l'énergie de sortie maximum (b) détails des spectres : sortie (traits pleins), diode d'entrée (pointillés).

The normalized output optical spectrum at the maximum output energy is shown in Fig. 3(a). The ASE level is 25 dB below the signal wavelength. However a closer look in Fig. 3(b) shows a spectral pedestal due to the cw ASE leaked from the FBG and amplified in the amplifier cascade. Comparison with the seed spectrum shows that the amplified linewidth remains unchanged and resolution-limited below 0.05 nm (Fig. 3(b)).

Our experience with this fibre suggests that the beam is not diffraction-limited, but may have an M^2-value of 5. Direct measurements of beam-quality of the pulses, is difficult when there is a significant ASE-background. While the launch of the signal pulses can be adjusted for best beam quality, the ASE cannot be controlled in that way and can therefore have a worse beam quality. A more advanced setup that could distinguish the beam quality of the pulses from the ASE was not available.

5. Improvements

Despite the relative good performance of our fibre MOPA, improvements can be realized to further improve on the energy and the beam quality. Firstly, ASE which reduces the performance of the last amplification stage can be mitigated by simply introducing time-gates in between all stages. For example a free-space high-power AOM could be used between the two final stages. An alternative solution is it to modulate the pump power [4] so that ASE does not have time to build up inside the amplifiers in-between pulses. This approach would require a careful consideration into the choice of pump sources and of the adequate driving electronics. Still, it is potentially the best solution as ASE is then nearly completely suppressed.

In the case, where ASE is not a bottleneck, the pulse high-peak power caused by the gain compression can induce SBS. The pulse shaping technique at the input could allow control of the peak power by compensating for the differential gain between the pulse edges so that the peak power remains below the SBS threshold. As a result further increase in output energy can be expected. Otherwise the SBS threshold can be raised to unreachable level in the fibre MOPA for example by enhancing the longitudinal variation of the SBS frequency shift which can be practically implemented with a temperature gradient along the fibre.

Finally, the beam quality can be considerably improved with a better control of the refractive index of the core during fabrication and by reducing the core numerical aperture.

6. Conclusions

A high-energy, high-peak power, narrow-linewidth cascaded fibre MOPA is presented. Up to 1 mJ and 6.6 kW peak power pulses with a 88 ns FWHM, are obtained at 1 kHz repetition rate. The main limiting factor in this configuration is ASE saturation due to the large-core fibre used. However, no SBS or any other non-linear effects have been observed which indicates that even higher energies are possible with improved fibre design.

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