Low-noise single-frequency 50 W fiber laser operating at 1013 nm

Benoît Gouhier¹, Sergio Rota-Rodrigo¹, Germain Guiraud², Nicholas Traynor² and Giorgio Santarelli¹

¹ Laboratoire Photonique, Numérique et Nanosciences, Institut d’Optique Graduate School, CNRS, Université de Bordeaux, Talence, France
² Azur Light Systems, Avenue de la Canteranne, Pessac, France

E-mail: giorgio.santarelli@institutoptique.fr

Received 16 November 2018, revised 17 December 2018
Accepted for publication 18 December 2018
Published 12 March 2019

Abstract
We have developed a 50 W all-fiber, single-frequency (SF), low-noise master oscillator power amplifier laser operating at 1013 nm, with an efficiency of 67%. The output signal shows an optical signal-to-noise ratio of 50 dB and excellent noise properties. These are to date and to the best of our knowledge, the highest reported figures of merit for a SF laser at this wavelength. The relative intensity noise of the laser is analyzed and is shown to follow the theoretical behavior for fiber amplifier.

Keywords: laser, fiber amplifier, low noise, Ytterbium

(Some figures may appear in colour only in the online journal)

1. Introduction

Ytterbium (Yb) -doped fiber lasers have proved a very competitive solution for generating high powers in the 1 µm region. Because of their simple architecture compared to crystal-based lasers such as Nd:YAG or Ti:sapphire, they exhibit great stability and often reach efficiencies of 70% [1, 2]. The spatial quality of the output signal, which is often close to diffraction-limited, is also a key advantage over other technologies. Combining the all-fiber approach with the master oscillator power amplifier (MOPA) architecture, it is possible to obtain very high powers while retaining the spectral qualities of a single-frequency (SF) seed. Such lasers are forecast to be the new standard in demanding applications such as next-generation gravitational-wave detectors [3]. In SF regime however, the main issue is stimulated Brillouin scattering (SBS), which thrives when intensity is high and interaction length is significant. This is indeed often the case for doped-fiber amplifiers where the light is tightly confined within several meters of gain medium. Recent progress in large mode area (LMA) fiber manufacturing, together with strain or temperature gradients, have helped to push back the SBS threshold while retaining single-mode operation [4, 5].

Despite their remarkable performances in the 1020–1090 nm region, high power, low-noise MOPAs operating outside of this conventional band remain scarce. For L-band (>1100 nm), the weak emission cross-section can be balanced with long fibers, but SBS then quickly becomes the limiting factor [6]. For S-band (<1020 nm), the main issue is the strong signal re-absorption. This has two perverse effects: first, ASE around 1030 nm sees a much higher gain, and eventually triggers parasitic lasing. Second, strong pump intensity is needed to prevent signal reabsorption. The solution is to use short fibers, to limit ASE gain and ensure strong pump intensity all along the fiber. This usually impairs efficiency, as pump light does not get fully absorbed, and leaves a strong residual pump, which can be difficult to deal with. Fibers with a large core-clad ratio are also useful to enhance emission at short wavelengths [7]. Cryogenically-cooled rod-type fiber have also proved efficient to reduce reabsorption but remains
unpractical [8]. Another approach involves using phosphate fibers [9]. These fibers are however difficult to splice with standard silica fibers, and their use remains experimental.

Some notable results below 1015 nm include a Yb-based laser tunable from 976 nm to 1100 nm, albeit not in SF regime [10]. The highest reported power at 1015 nm is a bit more than 30 W [11]. However, this system relies on a 1.4 m fiber with a relatively small core diameter (10 µm) which means the power will be limited by SBS in SF regime. Indeed, injecting a SF seed in a similar system, the same group could only reach 19 W before being limited by SBS [7]. Albeit this is a notable performance, the forward ASE is close to 10 W at full power. A few other moderate power SF amplifiers below 1015 nm have also been reported, in particular at 1014.8 nm for frequency quadrupling to 254 nm for cooling of mercury atoms [8, 12]. However, they either rely on cryogenic cooling [8], exhibit strong ASE, or have limited power. MOPAs based or rods have also been demonstrated at 1009 nm, but they remain cumbersome and require optical alignment [13].

The most convincing laser reported to-date delivers 8 W of narrow-linewidth 1015 nm radiation with an OSNR of 45 dB [14]. Shorter wavelengths are much more challenging: the same group have succeeded in realizing a narrow linewidth, 10 W fiber laser tunable down to 1010 nm, but with mediocre OSNR and no characterization of intensity noise [11]. These recent developments highlight the growing demand for low-noise, robust lasers delivering shorter wavelengths. Of particular interest is the study of cold Rb atoms in Rydberg state, which require a low-noise, high power laser at 1013 nm [15, 16].

In this paper, we report on the realization of a SF, low-noise 50 W all-fiber laser operating at 1013 nm. The output signal shows outstanding spectral properties (OSNR of 50 dB) and excellent noise properties, while retaining the robustness and ease of use of a fiber laser.

2. Experimental setup

The schematic of the MOPA is shown in figure 1. The seed laser is an external cavity tunable laser (Toptica DL-pro) able to deliver up to 120 mW of power at 1013 nm. The fast linewidth of the laser has been estimated to be around 30 kHz by the heterodyne beat-note method with an independent laser at 1025 nm. It is spliced to a filter which cuts wavelengths between 1020 and 1060 nm. Although the ASE from the seed is weak, these wavelengths see maximum gain in the gain fiber; by attenuating them before amplification, we minimize gain competition within the pre-amplifier. An isolator is also spliced just behind to protect the seed and the filter from back-reflections. The output is the injected to a first stage of amplification, able to deliver up to 2.5 W of power, with less than 0.2% of ASE (see figure 3). Nevertheless, this residual ASE is removed by a filter before being injected to the booster stage. This is to ensure the performance of the main amplifier is optimum as ASE around 1030 nm encounters a much stronger gain than the 1013 nm signal. After the filter and the isolator, about 1.5 W of power is available to seed the booster stage, which is clad-pumped at 976 nm. The main amplifier is based on a custom 1.4 m of polarization-maintaining LMA active fiber with a mode field diameter (MFD) of 15 µm and clad absorption of about 6 dB m⁻¹ at 920 nm (28 dB m⁻¹@976 nm). As usual, such large core diameters require the fiber to be coiled to ensure single-mode operation. A mode stripper is placed at the end of the amplifier to remove all residual pump light. A fraction of the output signal is sent to a photodiode and an optical spectrum analyzer (OSA) for diagnostics.

3. Results

The power at the output of the MOPA is plotted against pump power in figure 2. The maximum of 50.2 W of output power is reached for a pump power of 76 W, with an optical-to-optical efficiency of 67%. To the best of our knowledge, these are the highest reported values to-date for a SF Yb fiber laser below 1015 nm. The slope remains linear up to 50 W, showing no sign of saturation due to ASE or SBS.

3.1 Spectrum

The spectrum of the output signal is plotted in figure 3, together with the seed and pre-amp spectra before filtering. The shape of the pre-amp spectrum is due to the notch filter at the output of the seed. The optical signal-to-noise ratio (OSNR) of the
amplifier output reaches 50 dB (with a resolution bandwidth of 0.07 nm), which corresponds after integration over the full ASE span to a total ASE power of 140 mW (i.e. less than 0.3%). To the best of our knowledge, this is again the highest reported OSNR for an Yb fiber laser below 1015 nm. This result demonstrates that Yb fiber MOPAs can also be considered serious candidates for applications demanding low noise and high power at these wavelengths.

The small pedestal below the 1013 nm peak is residual ASE from the pre-amplifier passing through the filter. This level of spectral quality can be obtained because we have a strong seed power and a relatively short gain fiber (1.4 m). Indeed, seeding strongly at 1013 nm inhibits the onset of ASE at the beginning of the fiber, while the short fiber limits the maximum gain of the ASE around 1030 nm. With a stronger seed power, we could in principle afford a longer fiber which would further improve the efficiency. In the current setup, we are limited by the maximum input power of the filter. We have found that decreasing the seed power to 1 W already degrades the OSNR by about 3 dB (not shown), so it is crucial to obtain a strong signal from the pre-amplifier.

### 3.2. Relative intensity noise measurements

The relative intensity noise (RIN) of the laser was also measured by detecting part of the output power on a photodiode. The output signal (after low-noise amplification) was then detected on a RF spectrum analyzer. The RINs for the seed laser, pre-amplifier and amplifier are plotted in figure 4. The relative intensity noise (RIN) of the laser was also measured by detecting part of the output power on a photodiode. The RIN of output signal at 50 W (blue), pre-amplifier (orange) and seed laser (green). Pump RIN is also plotted (in red).

### 3.3. Noise dynamics

The transfer functions (TF) of the amplifier regarding pump and seed noise can be computed from the system parameters such as output power, emission and absorption cross-sections, fiber parameters etc [21–23]. For amplifiers in C-band, (e.g. at 1064 nm or 1030 nm), these models can be simplified as assumptions such as low ASE, low residual pump, negligible reabsorption are valid. In our case however, we need to consider that (i) there is a strong reabsorption of the signal and (ii) the short fiber leads to significant residual pump. The low ASE assumption is still valid in our case. The general equation for the corner angular frequency is:

\[
\omega_{\text{eff}} = \frac{P_{\text{out}} \Gamma_s (\sigma_s^a + \sigma_s^e)}{\hbar \nu_s A} + \frac{P_{\text{p,res}} \Gamma_p \sigma_p^a}{\hbar \nu_p A} + \frac{1}{\tau}
\]

where \(P_{\text{out}}, P_{\text{p,res}}\) respectively the signal output power and residual pump power (in W), \(\nu_s, \nu_p, \Gamma_s, \Gamma_p, \sigma_s^a, \sigma_p^a\) respectively the optical frequency (in Hz), doped region overlap factor and absorption cross section (in m²) for signal (s) and pump (p). \(\sigma_s^e\) is the emission cross section of the signal, and \(A\) is the effective area of the fiber core (in m²). \(\tau\) is the Yb ion lifetime. The last term is negligible given the rather long lifetime \(\tau\). The second term is usually ignored as residual pump is supposed to be weak. For short wavelengths however, we have
seen that a rather strong pump intensity is required all along the fiber, yielding a significant residual pump. Regardless, the very low overlap between the pump light and the doped region \((\Gamma_p = (15/125)^2 = 0.0144)\) means the second term remains about two orders of magnitude below the first one. In this remaining term, both absorption and emission cross sections at signal wavelength contribute \(\left(\sigma_e^{*}\right)^{\text{p}}\). Again, at 1064 nm, the absorption is usually ignored, being more than two orders of magnitude weaker than the emission term. At 1013 nm, this ratio decreases to 1/10 [24], which is still weak but means the re-absorption starts to have a notable effect on the corner frequency. For shorter wavelengths, the ratio keeps growing to reach 1/3 at 1000 nm where it cannot be ignored anymore. Note that in this spectral region, the nature of the host glass (germanosilicate or aluminosilicate) have little incidence on the cross sections [24].

Figure 5 shows a comparison of the predicted RIN either ignoring or considering these assumptions. As expected, there is little difference between the two cases, and both describe rather accurately the observed behavior. The effect of re-absorption is to raise the corner frequency of the pump transfer function by about 10% (which corresponds to the ratio of absorption and emission cross sections at 1013 nm). As it will keep increasing with shorter wavelength, we can expect the corner frequency to be slightly higher for amplifiers closer to 1000 nm (for the same output power). This will eventually limit the noise level of such devices, as pump noise will be more and more significant over the output RIN. This will be rather challenging for several reasons. First, the increasing signal re-absorption leading to stronger gain competition with ASE means gain will be limited to a few dBs per stage. Then, the strong pump intensities required lead to a very high residual pump which can be challenging to dispose of. Finally, low-noise operation will be challenging because of the increasing contribution of signal re-absorption to the corner frequency of the TF. Finally, the ASE will also degrade the output noise. Despite these hurdles, we are confident that a goal of a few watts of low-noise signal at 1000 nm is attainable, up to a few tens of watts at 1010 nm.

In summary, we have developed a 50 W, all-fiber, SF, low-noise Yb MOPA operating at 1013 nm, with an efficiency of 67%. The output signal OSNR is 50 dB and shows excellent noise properties. Although PD is noticeable at this wavelength, it was not found to impede performances other than efficiency. Study of the output RIN and pump noise transfer function have shown that Yb MOPAs operating at these short wavelengths will exhibit a higher noise due to stronger signal re-absorption and lower OSNR. In addition to demonstrating Yb fiber laser are suitable for generation of high power, low noise signals below 1015 nm, this result paves the way for further studies below 1010 nm.

4. Perspectives and conclusion

Further power scaling would most likely be limited by the onset of parasitic lasing around 1030 nm. Another issue would be the design of a robust clad mode stripper able to manage a rather high residual pump. An promising follow-up is the investigation of high power amplification towards 1000 nm, as there is no currently commercial offer able to provide a few watts of SF, low noise radiation at these wavelengths. This will be rather challenging for several reasons. First, the increasing signal re-absorption leading to stronger gain competition with ASE means gain will be limited to a few dBs per stage. Then, the strong pump intensities required lead to a very high residual pump which can be challenging to dispose of. Finally, low-noise operation will be challenging because of the increasing contribution of signal re-absorption to the corner frequency of the TF. Finally, the ASE will also degrade the output noise. Despite these hurdles, we are confident that a goal of a few watts of low-noise signal at 1000 nm is attainable, up to a few tens of watts at 1010 nm.

In summary, we have developed a 50 W, all-fiber, SF, low-noise Yb MOPA operating at 1013 nm, with an efficiency of 67%. The output signal OSNR is 50 dB and shows excellent noise properties. Although PD is noticeable at this wavelength, it was not found to impede performances other than efficiency. Study of the output RIN and pump noise transfer function have shown that Yb MOPAs operating at these short wavelengths will exhibit a higher noise due to stronger signal re-absorption and lower OSNR. In addition to demonstrating Yb fiber laser are suitable for generation of high power, low noise signals below 1015 nm, this result paves the way for further studies below 1010 nm.

Funding

Agence Nationale de la Recherche (ANR) (ANR14 LAB05 0002 01); Conseil Régional d’Aquitaine (2017-IR50302-00013493); LAPHIA (Lasers and Photonics in Aquitaine); Marie Sklodowska-Curie grant agreement No 748839.

References

[1] Fu S, Shi W, Feng Y, Zhang L, Yang Z, Xu S, Zhu X, Norwood R A and Peyghambarian N 2017 J. Opt. Soc. Am. B 34 A49–62
[2] Zhao J, Guiraud G, Pierre C, Chaibi O, Floissat F, Traynor N, Boulet J and Santarelli G 2018 Appl. Phys. B 124 114
[3] Varona O D, Fittkau W, Booker P, Theeg T, Steinke M, Kracht D, Neumann J and Wessels P 2017 Opt. Express 25 24880–92
[4] Huang L, Wu H, Li R, Li L, Ma P, Wang X, Leng J and Zhou P 2017 Opt. Lett. 42 1–4
[5] Ma P, Zhou P, Ma Y, Su R, Xu X and Liu Z 2013 Appl. Opt. 52 4854–7
[6] Gouhier B, Guiraud G, Rota-Rodrigo S, Zhao J, Traynor N and Santarelli G 2018 Opt. Lett. 43 308–11
[7] Hu J, Zhang L, Liu H, Liu K, Xu Z and Feng Y 2014 Appl. Opt. 53 4972–7
[8] Steinborn R, Koglauer A, Bachor P, Diehl T, Kolbe D, Stappel M and Walz J 2013 Opt. Express 21 22693–8
[9] Yang C, Xu S, Yang Q, Lin W, Mo S, Li C, Feng Z, Chen D, Yang Z and Jiang Z 2014 Appl. Phys. Express 7 062702
[10] Royon R, Lhermite J, Sarger L and Cormier E 2013 Opt. Express 21 13818
[11] Hu J, Zhang L and Feng Y 2015 IEEE Photonics Technol. Lett. 27 2559–62
[12] Sarlo L D, Favier M, Tyumenev R and Bize S 2016 J. Phys. Conf. Ser. 723 012017
[13] Beier F, Otto H-J, Jauregui C, de Vries O, Schreiber T, Limpert J, Eberhardt R and Tünnermann A 2014 Opt. Lett. 39 3725–7
[14] Zhao R, Fu X, Zhang L, Fang S, Sun J, Feng Y, Xu Z and Wang Y 2017 Appl. Opt. 56 8973–7
[15] Bernien H et al 2017 Nature 551 579–84
[16] Simonelli C, Archimi M, Asteria L, Capecci D, Masella G, Arimondo E, Ciampini D and Morsch O 2017 Phys. Rev. A 96 043411
[17] Hildebrandt M, Büsche S, Weßels P, Frede M and Kracht D 2008 Opt. Express 16 15970–9
[18] Kablukov S I, Zlobina E A, Podivilov E V and Babin S A 2012 Opt. Lett. 37 2508–10
[19] Ricciardi I, Mosca S, Maddaloni P, Santamaria L, Rosa M D and Natale P D 2013 Opt. Express 21 14618–26
[20] Chiodo N, Djerroud K, Acet O, Clairon A and Wolf P 2013 Appl. Opt. 52 7342–51
[21] Tünnermann H, Neumann J, Kracht D and Weßels P 2012 Opt. Express 20 13539
[22] Novak S and Moesle A 2002 J. Light. Technol. 20 975
[23] Zhao J, Guiraud G, Floissat F, Gouhier B, Rota-Rodrigo S, Traynor N and Santarelli G 2017 Opt. Express 25 357–66
[24] Kurkov A S 2007 Laser Phys. Lett. 4 93–102
[25] Koponen J J, Söderlund M J, Hoffman H J and Tam-mela S K T 2006 Opt. Express 14 11539–44
[26] Manek-Hönninger I, Bouillet J, Cardinal T, Guillen F, Erneneux S, Podgorski M, Doua R B and Salin F 2007 Opt. Express 15 1606–11