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Dia Darwich, Yves-Vincent Bardin, Mathieu Goepner, Clément Dixneuf, Germain Guiraud, et al.. Ultralow-intensity noise, 10 W all-fiber single-frequency tunable laser system around 1550 nm. Applied optics, 2021, 60 (27), pp.8550-8555. 10.1364/AO.435274 . hal-04690841

HAL Id: hal-04690841

<https://hal.science/hal-04690841v1>

Submitted on 10 Sep 2024

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Ultra low-intensity noise, 10 W all-fiber single-frequency tunable laser system around 1550 nm

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Received XX Month XXXX; revised XX Month, XXXX; accepted XX Month XXXX; posted XX Month XXXX (Doc. ID XXXXX); published XX Month XXXX

We report herein on the development of a linearly polarized, single-frequency tunable laser system producing more than 10 W in the 1550 nm range, using a two-stage Erbium/Ytterbium co-doped fibers-based master oscillator power amplifier (MOPA) architecture. The all fibered MOPA provides an ultra-low intensity noise of -160 dBc/Hz beyond 200 kHz between 1533 nm and 1571 nm ($\Delta\lambda=38$ nm) at full output power and a minimum optical signal to noise ratio of 38 dB. A good stability is obtained over four hours at maximum power for several wavelengths with peak-to-peak fluctuation less than 3 % and rms below 0.5 %. © 2020 Optical Society of America

1. Introduction

Due to their compactness, excellent beam quality, narrow linewidth and low noise, linearly polarized high power single frequency master oscillator power amplifiers (MOPA) using Erbium-doped fibers have attracted much attention in several application fields such as nonlinear conversion, molecular spectroscopy, atomic physics, and LIDAR [1–3]. However, the power scaling in these amplifiers has been limited by the low absorption of Erbium ions, making practical double clad geometries difficult to realize. In order to overcome this limitation, Erbium/Ytterbium (Er/Yb) co-doped double-cladding fibers represent an excellent alternative due to the high absorption of Yb ions at pump wavelength compared to Erbium ions. Using Er/Yb co-doped fibers, several high power, all-fiber single-frequency MOPA emitting at fixed wavelength in the C [1,4–7] or L-band [8,9] and the highest power were reached with large mode area fibers injected in free space [10].

Tunable Er/Yb MOPA have also been investigated in free space [11,12], reaching up to 43 W. Tunable all-fiber configurations have been realized [13] reaches between 1 and 2W from 1535 to 1620 nm with 35dB of optical signal to noise ratio (OSNR), and [14] produces up to 7W between 1534 and 1568 nm (no information on OSNR but 1 μ m colasing). In 2018, Tang *et al.* have demonstrated in [15] a two-stage tunable MOPA

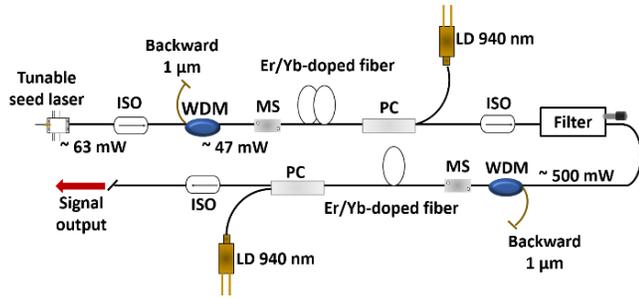
with an output power higher than 10 W over 35 nm (from 1535 nm to 1570 nm) with a maximum efficiency of 30 % but with a minimum OSNR of 20 dB for a resolution bandwidth of 0.05 nm with a broad ASE spectrum, leaving only 30 % of power in the laser peak at short wavelength. None of these sources have been investigated in terms of intensity noise, while it becomes essential for several applications such as the generation of watt level tunable laser in the orange and mid-infrared spectral ranges via sum and difference frequency generation by mixing it with well-established high power laser emitting at 1 μ m [16]. In this work, besides the tunability and the power scaling, special attention is given to the laser intensity noise investigation and characterization. The two-stage MOPA developed here provides a linearly polarized output power higher than 10 W tuned over 38 nm at 1.55 μ m with a minimum efficiency of 33 % and an OSNR greater than 38 dB (using a resolution bandwidth of 0.1 nm). Moreover, an ultra-low relative intensity noise (RIN) floor of -160 dBc/Hz beyond 200 kHz at full output power and over the whole tuning range is demonstrated. To our knowledge, this is the first demonstration of such ultra-low intensity noise in 10 W level widely tunable lasers at 1.55 μ m.

2. Experimental setup description

Our two stage MOPA architecture, represented in Fig.1, consists of a seed laser, a pre-amplifier, and a main amplifier. Our two stage MOPA architecture, represented in Fig. 1, consists of a seed laser, a

pre-amplifier, and a main amplifier. The seed laser is a tunable single-frequency laser with a linewidth of about 18 kHz (Pure photonics PPCL300, 1525 nm – 1580 nm) which can deliver up to 63 mW of output power. The signal reduced to 47 mW after an isolator and a Wavelength Division Multiplexer (WDM), is pre-amplified up to 1 W through a 10.5 m Er/Yb-doped double cladding fiber with a core diameter of 6 μm providing a cladding absorption of 0.73 dB/m at 915 nm. This fiber is pumped at 940 nm in counter-propagative direction using a (1+1) \times 1 combiner. Then, a high-power tunable filter (Agiltron FOTF 1520 nm – 1580 nm) is added to suppress the amplified spontaneous emission (ASE) present in the signal. Thereafter the filtered signal is amplified using 12 μm core diameter Er/Yb-doped double cladding fiber providing cladding absorption of 2.58 dB/m at 915 nm which is also pumped in counter propagation direction at 940 nm via (2+1) \times 1 combiner (the unused combiner port is angle-cleaved). Thereafter, the combiner output is spliced to a high-power polarization-dependent isolator, which provides a polarization extinction ratio higher than 20 dB, with an angle-cleaved output to avoid any parasitic reflection on the fiber facet.

In both stages, the residual pump light is suppressed via mode-strippers (MS in Fig. 1) and two 1 μm /1.55 μm WDM were added to monitor the parasitic counter propagated emission at 1 μm . Furthermore, it is worth noting that all the fibers used here, active



and passives ones, are polarization-maintaining (PM) fibers.

3. Pre-amplifier 1 μm band ASE emission mitigation strategy

In order to reach a broad range of tunability at high power, it is essential to saturate the amplifier fiber, especially at the most extreme wavelengths. Thus, the first stage represents a key element of our architecture, and a thorough experimental study was conducted to select the optimal pumping scheme to ensure an emission of hundreds of milliwatts over a wide spectral range, while maintaining excellent intensity noise and mitigating the

Fig. 1. Schematic representation of the high power tunable MOPA. ISO: isolator, MS: mode stripper, LD: laser diode, PC: pump combiner, WDM: wave division multiplexer, Er: Erbium ions, Yb: Ytterbium ions. All the fibers used in our experiment are PM.

emission at 1 μm . First, the co-propagation configuration was tested by pumping the active fiber in forward direction using laser diodes at 976 nm and 940 nm separately. Using this architecture, we observed a parasitic backward emission at 1 μm of few milliwatts at 976 nm and hundreds of microwatts at 940 nm. At the extreme wavelength range of 1575 nm, a laser emission at 1060 nm was observed for around 500 mW of 1575 nm useful signal as depicted on Fig. 2 (a). The 1 μm -ASE lasing could have been recycled to serve as in-band pumping, as realized in [17], but

for scientific applications, low intensity noise lasers are required. Therefore, we studied the impact of the ASE measuring the relative intensity noise power spectral density (RIN PSD) using the same method as described in [18]. This measurement is highly sensitive and widely used to assess single frequency laser quality due to its capability to detect stimulated Brillouin scattering (SBS) and any generation of high level of ASE in our case [19,20]. It has been demonstrated that for Yb doped fiber amplifiers, the pump has a major impact at low frequencies, while the intensity noise at high frequencies depends on the seed laser and the MOPA properties, the transition between the two regimes follows a smooth decay described by a first order transfer function [19].

There are very few reports of RIN studies of 1550 nm MOPA, the only study reported was mainly focused on high frequency noise which transcribes the seed laser noise [21] and was limited by its detection noise at -150dB/Hz. Our study is the first reported thorough RIN study at 1550nm. Fig. 2.(b) depicts the 1 μm - ASE of the seed laser, and the pre-amplifier outputs for co-and counter-propagative pumping configurations. The seed laser has the lowest RIN, always below -150dBc/Hz and reaching our detection limit of -163dBc/Hz below 50kHz. The noise increase at low frequency of the counter-propagative pumping scheme (orange curve) is thus expected [19], but we reach the detection floor at 50kHz. The co-propagative configuration on the other hand shows a bump with a

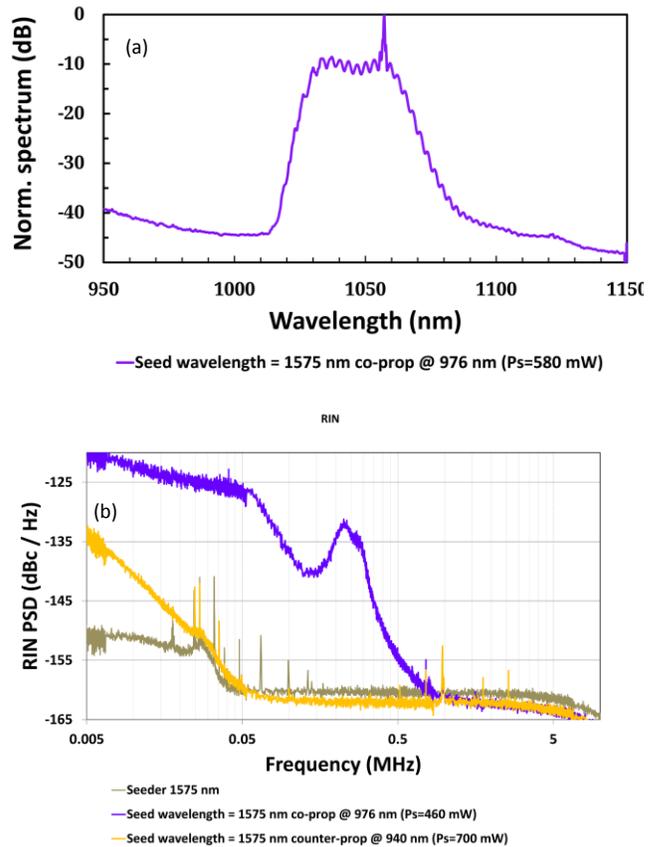


Fig. 2 (a) 1 μm ASE spectrum of the pre-amplifier for a seed wavelength of 1575 nm and a power of 580mW when pumping at 976nm in co-propagation configuration (0.1 nm resolution bandwidth of 0.1 nm of an Advantest 8384 spectrum analyser). (b) RIN measurements of in grey, the seed laser, in blue, the pre-amplifier pumped in co-propagative configuration at 976 nm, in orange pumped in counter-propagative direction at 940 nm.

30dB increase of noise with a bump at 100 kHz, indicating an excess of noise. As the appearance of this peak is congruous with the 1 μm -ASE lasing, we believe that this peak is a signature of the 1 μm -ASE spurious lasing, although it may also be linked to a backward 1.5 μm -ASE lasing, that we could not monitor. Our conclusion is that any spurious lasing effect or ASE increase leads to a RIN deterioration. This detrimental effect led us to choose the counter-propagative pumping as the best 1 μm -ASE mitigation strategy. We were able to enhance our laser efficiency and reduce the 1 μm emission to few tens of microwatts at both wavelengths (940 nm and 976 nm). The experimental measurement showed that pumping in counter propagation direction at 976 nm increases the 1.5 μm -ASE level and complicates the thermal management because of the high absorption of the active fiber at this wavelength compared to 940 nm, where the population inversion is more homogenous along the fiber length.

The cut-back method was used to identify the optimal fiber length which can ensure high power emission over wide tuning range while maintaining an excellent intensity noise. A wide tuning range of 42 nm has been achieved using a 10.5 m long fiber. An

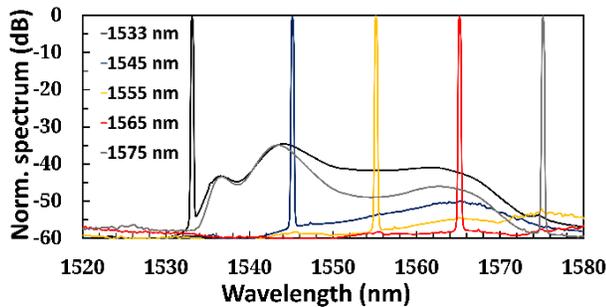


Fig. 3. Pre-amplifier spectrum at 1 W output power at 1533 nm (black), 1545 nm (Brown), 1555 nm (blue), 1565 nm (Gray) and 1575 nm (red) wavelengths. (0.1 nm optical resolution bandwidth of Advantest 8384).

output power of 1 W is obtained from 1533 nm to 1575 nm with an efficiency (η) between 25 % and 30 % depending on the operating wavelength. The emitted spectrum at 1 W output level is depicted in Fig. 3. We can note a significant level of 1.5 μm -ASE when we operate at 1533 nm and 1575 nm wavelengths which is still acceptable as its power remains below 34 mW (< 3.5 %) over the entire emission band with an OSNR greater than 30 dB (0.1 nm resolution bandwidth).

Despite the low 1.5 μm -ASE level, a tunable filter has been added to enhance the OSNR up to 55 dB at the entire tuning range. Unfortunately, the filter loss is measured to be around 3 dB and the signal power at the input of the amplifier is reduced to 0.5 W.

4. Amplifier optimization

Given the experience gained in the pre-amplifier investigation, we opted for the same pumping configuration in the amplifier stage. The cut-back method was used to measure the laser efficiency at different wavelengths for several fiber lengths and the results are shown in Fig. 4(a). We should note here that the values showed in Fig. 4 are obtained without adding the second isolator (cf. Fig. 1) in order to estimate the real efficiency of our fiber. As results, an efficiency between 34 % and 41 % is obtained for wavelengths ranging from 1535 nm to 1575 nm using a length of 9.5 m (red curve). However, the efficiency drops off down to 14 %

at 1533 nm which means that the gain of the fiber is shifted to high wavelengths due to reabsorption process. We can clearly observe that when we shorten the fiber to 6.7 m (red curve), the efficiency at 1533 nm is enhanced up to 36 % and then it increases up to 40 % at 1535 nm, and it remains almost constant until it decreases down to 32 % at 1575 nm. Furthermore, when the fiber length is reduced to 5.2 m, the efficiency of the amplifier becomes limited to 27.5 % at 1575 nm, because of lack of gain at long wavelengths. During the power scaling, we have noticed that for a fixed fiber length, when the efficiency starts to lose more than 15 % of its maximum value at extreme wavelengths, the maximum output power at these wavelengths cannot reach 10 W because of the appearance of laser effects in the 1.5 μm -ASE band. As a result, a 10 W emission over a tuning range around 38 nm can be achieved using the three fiber lengths, but the central wavelength of this spectral band shifts towards high or short wavelengths when we use longer or shorter fiber.

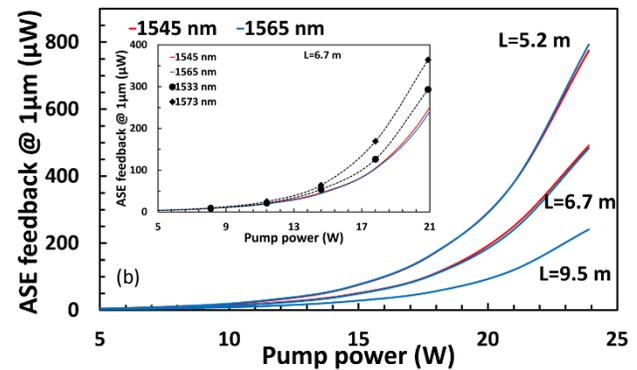
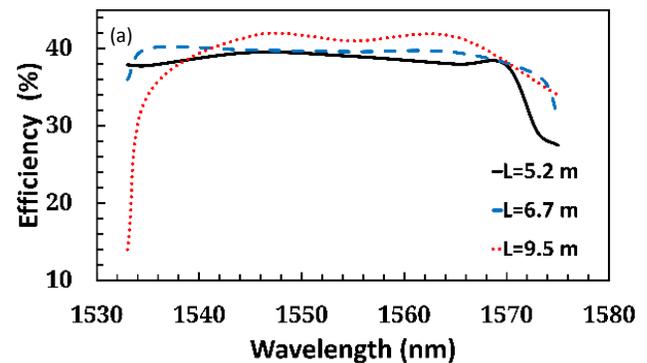


Fig. 4. (a) Efficiency evolution versus wavelength for 5.2 m (black curve), 6.7 m (blue curve), and 9.5 m (red curve) fiber lengths. (b) Variation of feedback at 1 μm with respect to pump power for the same fiber lengths at 1545 nm (red curve) and 1565 nm (blue curve) wavelengths. inset: variation of feedback at 1 μm for 6.7 m fiber length at 1533 nm (circles dotted curve), 1545 nm (red solid curve), 1565 nm (blue solid curve) and 1573 nm (diamonds dotted curve). These results are obtained without isolator.

Fig. 4(b) represents the backward emission at 1 μm for different fiber lengths at 1545 nm (red curve) and 1565 nm (blue curve). When 5.2 m fiber long is used, the feedback at 1 μm is about 800 μW for 24 W pump power and it decreases down to 500 μW and 250 μW using 6.7 m and 9.5 m fiber lengths, respectively. Therefore, the longer the active fiber, the more the photons emitted at 1 μm are reabsorbed. Moreover, for each fiber length, the curve of the emission at 1 μm at 1545 nm perfectly matches

the curve at 1565 nm. However, as we can see in the inset in Fig. 3(b), for side wavelengths, 1533nm and 1573nm, the curves start to diverge at 14.4 W pump power and the emitted power reaches 300 μ W and 400 μ W respectively, instead of 200 μ W at central wavelengths. The results of Fig.4 demonstrate that when the

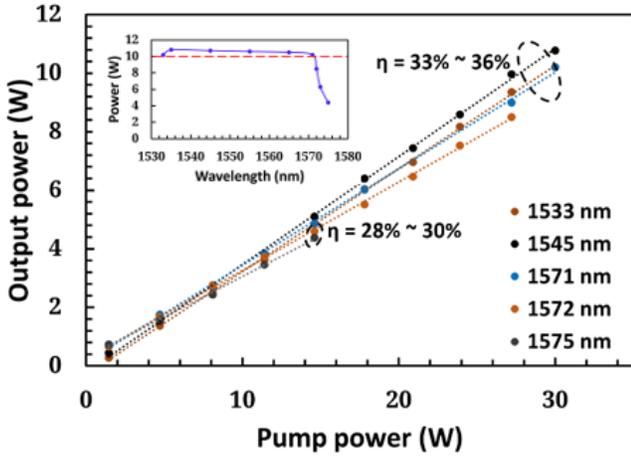


Fig. 5. Output power scaling versus pump power at different wavelengths. Inset: maximum output power achieved at each wavelength, the dashed red line represents the 10W threshold. These results are obtained after the isolator for a fiber length of 6.7 m.

MOPA becomes less efficient at 1.5 μ m wavelengths, it favors the emission at 1 μ m.

As the 6.7 m fiber long ensures the smoothest efficiency over the entire tuning range, the power scaling after the polarization-dependent isolator was realized using this fiber length, and the results are depicted in Fig. 5. An efficiency between 33 % and 36 % for wavelengths between 1533 nm and 1571 nm ($\Delta\lambda=38$ nm) is obtained with an output power higher than 10 W and a polarization extinction ratio (PER) higher than 20 dB. An output power of 11 W (at 1555 nm) and 10.2 W (at 1533 nm and 1571 nm) are obtained for a pump power of 30W. The MOPA becomes less efficient when the operating wavelength is beyond 1571 nm with efficiencies of 30 % at 1572 nm and 28 % at 1575 nm. Moreover, the output power at these wavelengths is limited to 8.5 W at 1572 nm, 6.3 W at 1573 nm and 4.4 W at 1575 nm which represent the threshold of laser emission in the 1.5 μ m-ASE band. Between 1545 and 1565nm, we were only limited by pump power. As we will see in the next paragraphs, this effect will significantly degrade the intensity noise. This effect appears also at 1533 nm when the pump power exceeds 30 W.

The spectrum at 10 W output power at different wavelengths is depicted in Fig. 6. In the worst scenario, an OSNR of 38 dB is obtained at 1533 nm (black curve) and the integrated power over 35 nm ASE band is less than 60 mW (0.6 % of total power). For other wavelengths such as 1545 nm (blue curve), 1565 nm (red curve) and 1571 nm (gray curve), the OSRN is higher than 55 dB, which is comparable to the state of the art but without 1 μ m mitigation strategy [17]. It is well known from the literature [22] that the MOPA architecture does not broaden the linewidth of the initial seed laser, the high power linewidth is thus of 18kHz.

5. Amplifier RIN study

An important point of this laser system is related to the

investigation of the RIN behavior. All measurements were conducted at full output power over the entire tuning range and the results are plotted in Fig. 7. As we can see in Fig. 7(a) for frequencies higher than 200 kHz, the RIN at 1533 nm (black), 1565 nm (red), and 1571 nm (blue) at 10 W output power falls to -160 dBc/Hz, and matches the RIN of the seed laser and of the pre-amplifier. Minor discrepancies are due to small difference in power impinging on the photodetector, as the measurement is ultimately limited by the shot-noise of the photocurrent. The slight increase of the 1533 nm curve is due to the higher level of ASE, but it still reaches a value close to -160dBc/Hz, as expected from a low noise behavior [19].

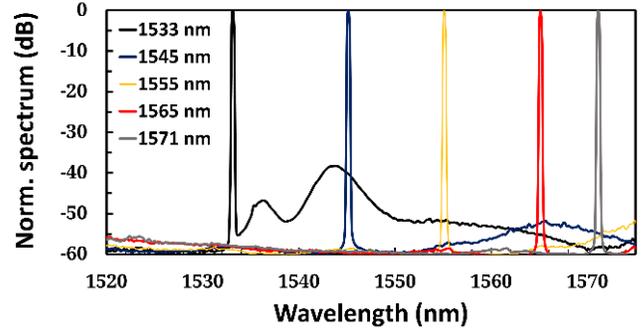


Fig. 6. Amplifier emitted spectrum at 10 W output power at 1533 nm (black), 1545 nm (Blue), 1565 nm (red) and 1571 nm (gray) wavelengths (optical resolution bandwidth 0.1 nm).

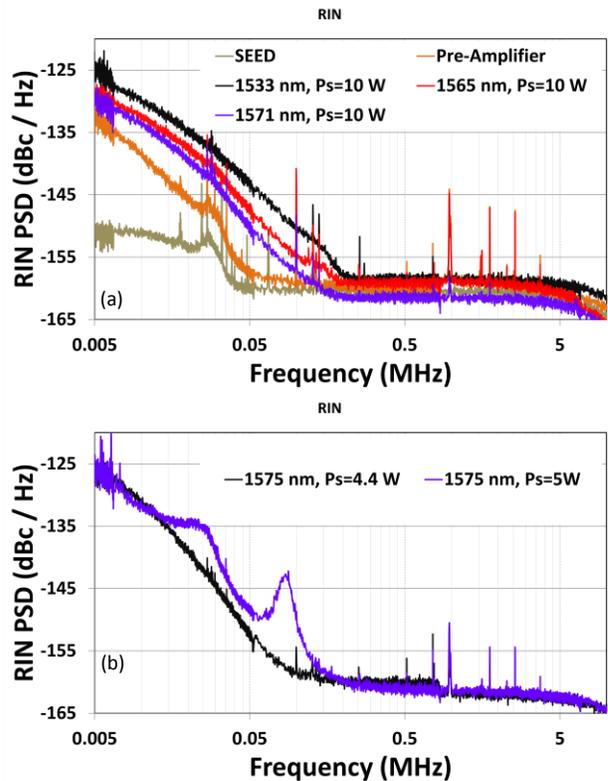


Fig. 7. RIN PSD of (a) the seed laser (brown), the pre-amplifier (orange), the amplifier at 1533 nm (black), 1565 nm (red) and 1571 nm (blue) at 10 W, (b) at 1575 nm at 4.4 W (black) and 5 W (blue). The

spikes between 500 kHz and 5 MHz are electronic pick-up noise. The fiber length is 6.7m.

This observation demonstrates the lack of SBS and any kind of parasitic laser oscillation in our MOPA [23]. To the authors knowledge, this is the first demonstration of a such ultra-low intensity noise in 10 W level tunable laser at 1550 nm. The fact that we reach -160dBc/Hz at 200kHz, paves the way to the implementation of fast noise reduction servo loops [24] as in this frequency range we are not limited by the electronics bandwidth.

For additional information, the RIN obtained at 1575 nm at 4.4 W and 5 W are represented in Fig. 7(b). Beyond 4.4 W, we can notice that the RIN increases around 80 kHz. This observation goes along with an appearance of laser emission in the 1.5 μ m-ASE visible on the OSA but not depicted here. Therefore, we believe that this observation on the RIN is a signature of a laser oscillation in the 1.5 μ m-ASE band.

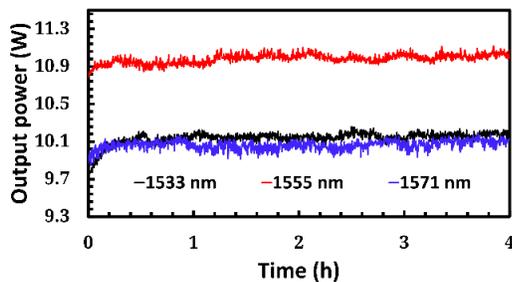


Fig. 8. Optical power stability measurement, after isolator, over four hours, at different wavelengths

Finally, the MOPA output power stability (Fig. 8 over four hours at 30 W pump power for three different wavelengths, 1533 nm (black curve), 1555 nm (red curve) and 1571 nm (blue curve) has been measured and it shows peak-to-peak fluctuation less than 3 % and rms below 0.5%.

In conclusion, the developed MOPA architecture provides an emission of more than 10 W of linearly polarized single frequency laser over 38 nm (1533 nm to 1571 nm) with an ultra-low intensity noise floor of -160 dBc/Hz beyond 200kHz and an OSNR greater than 38 dB. To our knowledge, this is the first demonstration of 10 W level tunable lasers at 1550 nm ensuring such an ultra-low-intensity noise level.

Funding. Agence Nationale de la Recherche Programme IdEx Bordeaux - LAPHIA (ANR-10-IDEX-03-02) ; Région Nouvelle Aquitaine (project n°2019-1R50301).

Acknowledgments. The authors acknowledge J. H. Codarbox, P. Teulat and A. Tizon for their technical support. The authors acknowledge financial supports from the French National Research Agency (ANR) in the frame of “the investments for the future” Program IdEx Bordeaux - LAPHIA (ANR-10-IDEX-03-02)

Disclosures. The authors declare no conflicts of interest.

Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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