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Abstract: We report on a linearly-polarized, continuous-wave Ytterbium-doped fiber laser continuously tunable on the fly over an unprecedented emission bandwidth ranging from 976 nm to 1120 nm and delivering a minimum of 10 W and a maximum of 41 W. Additionally, the bandwidth of the system can be tuned from 100 pm to more than 1 nm at all wavelengths

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1. Introduction

Widely tunable lasers around a wavelength of 1 μm presents a wide interest in applications such as photochemistry and spectroscopy which require narrow optical bandwidth, laser cooling where the laser wavelength has to be specifically adjusted, metrology or medical treatments. There is also an increasing attention of such sources for parametric applications as for instance frequency conversion, including Raman or optical parametric amplifiers [1–3]. To this purpose, rare earth doped double clad fibers and in particular Ytterbium (Yb) doped fibers are very well adapted as they can be directly pumped by laser diodes. Their exceptional gain and thermo-optical properties have allowed to reach several kilowatts of output power. Finally, Yb-doped fibers have theoretical emission bandwidth ranging from 976 nm to 1200 nm [4]. However, most of the tunable Yb-doped fiber lasers exploits the quasi-four-level system between 1030 and 1100 nm [5,6]. Recently, high-power emission around 976 nm has been reported resolving the problem of efficient laser operation of the Yb three-level system [7]. In fact, wavelengths emission around 976 nm presents two major drawbacks. First of all, transparency on the zero-phonon line should be achieved in order to prevent signal reabsorption. In Yb-doped glass material, transparency at 976 nm requires a very large population inversion all along the fiber and therefore a very high pump intensity. Then, since emission cross section is also high at 1030 nm, a competition between emission at 976 nm (three level transition) and 1030 nm (quasi-three level transition) will occur. Indeed, at 1030 nm, transparency is achieved with an inversion of 5 times lower compared to 976 nm. Consequently, the fiber will lase spontaneously at 1030 nm preventing any emission at 976 nm. As demonstrated in previous works, efficient operation on the 3-level system is in fact possible with an adapted opto-geometrical active double-clad fiber able to minimize the clad to core area ratio A_{clad}/A_{core} of the fiber [8]. The tunability over the entire Ytterbium emission band has been investigated with a set of four different volume-Bragg gratings (VBG) inserted in the laser cavity [9]. The fiber used in this work didn't allow emission below 980 nm. Finally, the output beam quality factor of this fiber specifically designed is evaluated at $M^2 = 3.5$ corresponding to a multi-mode operation.

Studies over the 980-1020 nm emission spectral range are even fewer. Indeed, the high level of population inversion required to overcome re-absorption at these wavelengths combined to the weak emission cross-section definitely limits the gain. At contrast, for higher wavelengths, i.e. > 1070 nm, the reabsorption is weak. The ytterbium transition is, in this case, a nearly pure four level where the gain is proportional to the overall upper-state population [10]. The remaining problem is then the competing strong gain originating from shorter wavelengths. Several approaches to selectively amplifiy these long emission wavelengths have been investigated and require specialty fibers to favour gain at long wavelengths and restrain amplified spontaneous emission (ASE) gain [11]. In the present context, where amplification from a single fiber is needed over the largest possible bandwidth, we choose a compromise leading to the emission at short wavelengths up to wavelengths around 1100 nm because methods to achieve gain at wavelengths above 1120 nm are very constraining and selective.

In this contribution, we demonstrate a high power continuous wave laser emission continuously tunable on the fly over an unprecedented emission bandwidth ranging from 976 nm to 1120 nm using a large-mode-area photonic crystal rod-type fiber. This fiber presents opto-geometrical parameters adapted to allow the existence of preferential gain at short wavelengths with high average power.

2. Ytterbium-doped fiber for operation between 976 nm and 1120 nm

2.1. Three level operation

As discussed in the introduction, the main difficulty preventing an efficient laser operation at 976 nm comes from the 3-level character of the system where emission and absorption cross-

sections are of the same order as depicted by *Paschotta et al* [10]. As mentioned earlier, laser operation at 976 nm is possible provided transparency is achieved. As we intent to scan the entire emission bandwidth, it is interesting to determine the necessary pump intensity required to reach the transparency threshold for all wavelengths as well as the corresponding population inversion.

Pump transparency intensity is given by:

$$I_{trans} = \frac{h\nu_p}{(\frac{\sigma_{ap}\sigma_{es}}{\sigma_{as}} - \sigma_{ep})\tau_{fluo}} \tag{1}$$

and corresponding population inversion by:

$$n_{trans} = \frac{\sigma_{al}}{\sigma_{al} + \sigma_{el}} \tag{2}$$

where h, ν_p and τ_{fluo} denote respectively the Planck's constant, the pump laser frequency and the fluorescence lifetime. σ_{es} σ_{as} are the emission and absorption cross-sections at the signal wavelength and σ_{ep} σ_{ap} are the emission and absorption of the pump radiation.

From (1) and (2), we deduce the transparency requires a population inversion less than 10% (I_p = 5 KW/cm^2) above 1020 nm (quasi-four level transition) and as much as 50% (I_p = 35 KW/cm^2) at 976 nm (three level transition).

Operation at 976 nm obviously requires a strong pump power. However, the necessary high pump power level enhances competition between the three and quasi-four level laser operation limiting the gain on the three level scheme. Indeed, gain at wavelengths around 1030 nm will appear before the transparency is achieved at 976 nm leading to undesirable laser oscillations at longer wavelengths. This gain competition between the three level transition and, for instance, the second peak emission at 1030 nm can be modelled as proposed by Nilsson et al [9]:

$$G_{1030} = 0.25.G_{976} + 0.72\beta\alpha \tag{3}$$

where G_{1030}, G_{977} are the gain at 1030 nm, and 976 nm respectively, α the pump absorption (dB) and β the clad to core area ratio.

Equation (3), reveals the interdependency of gains between different wavelengths (976 nm and 1030 nm in this case) depending on potentially adjustable intrinsic fiber parameters (second term in the right hand side of Eq. (3). The success of efficiently operating the laser on the three level scheme will involve optimization of these fiber parameters. On the one hand, one can minimize the second term and consequently the gain at 1030 nm by limiting the pump absorption by either reducing the fiber length or decreasing the dopant density at the cost of a large amount of unabsorbed pump power. On the other hand, one can minimize the clad-to-core area ratio. The later strategy is illustrated in the present experiment where a specialty fiber (rod-type fiber) has been used. The active fiber has a 80 µm core diameter and a 200 µm clad diameter leading to a β value around 8. With such a fiber, in a laser architecture, it is therefore possible to allow a sufficient gain at 976 nm while limiting the parasitic gain at 1030 nm to 50 or 60 dB, a level where matching losses can still be induced by optical filters or dichroic mirrors [7].

2.2. Four level operation

We will not develop here the quasi-three level (1030-1080 nm) emission range because it doesn't represent a technical challenge requiring particular designs of the fiber or the different elements of the laser.

It can be noted on Fig. 1 that Yb-doped fibers have a significant emission cross-section above 1100 nm and can provide sufficient gain over a range extending from 1100 nm to 1200 nm. Indeed, different approaches have been explored to obtain laser emission at longer wavelengths. For example, emissions beyond 1100 nm are very interesting as they will generate, by frequency doubling, yellow-orange light. The main difficulty to achieve large gains at these wavelengths is the competing ASE in the 1030-1080 nm band leading to parasitic lasing. Even if the inversion population to reach transparency at, for instance, 1140 nm is less than 0,1%, the ratio between the emission cross sections at 1140 and 1030 nm (respectively 50×10^{-27} m^2 and $634,6 \times 10^{-27}$ m^2) is only 1/13. Thus, ASE suppression in the 'natural' region can't be avoided unless inserting massive losses at these wavelengths. An alternative is to use long ytterbium-doped fibers however pumped at long wavelengths, e.g. 1060 nm, as the absorption cross-sections is sufficiently low [12]. In such a case, tunability could be achieve but only for wavelengths from the pump wavelength restraining in the same time the interesting range from 976 nm to 1080 nm. Another solution is to use photonic band gap fibers pumped at 976 nm specifically designed to induce large losses in the natural spectral region [11]. Unfortunately, the very selective filtering band associated to the photonic band gap structure doesn't allow tunability over a very wide spectral range.

3. Experimental setup

The experimental setup is sketched in Fig. 1. The tunable fiber laser is based on a 116 cm-long Yb-doped rod-type fiber with 80μm core diameter and 0.02 N.A [7]. Both fiber end facets are polished with an angle of 8 ° to avoid any parasitic lasing effects due to Fresnel back-reflections. The system is end pumped by a fiber-coupled diode laser at 915 nm (200μm, N.A 0.22) injected in the fiber cladding (200μm diameter, N.A, 0.55 and α_p = 11.6 (dB) through a dichroic mirror (M1; HT 976-1120 nm, HR 915 nm). The residual pump is recycled (M3) as absorption at 915nm is limited. The two telescope systems (L4 + L5 and L6 + L7) are used to adjust the laser beam size to the different polarizing elements. The resonator of the fiber laser is a unidirectional ring-cavity that incorporates an optical isolator (OI) (>30dB) to ensure unidirectional operation of the laser, half-wave plates and a polarizing beam-splitter. The tunability of our system is obtained by selecting the first order diffraction of an Acousto-Optic Tunable Filter (AOTF) (50 dB) with a filtering resolution of 600 pm at 1064 nm. Both half-wave plates before the isolator and the AOTF are adjusted to maximize the transmission of these polarizing elements. Additionally, the half-wave plate associated to the polarizing cube controls the output coupling and allows an easy optimization of the output power for each wavelength. It also permits to lower the laser threshold and therefore ease emission at unusual wavelengths.
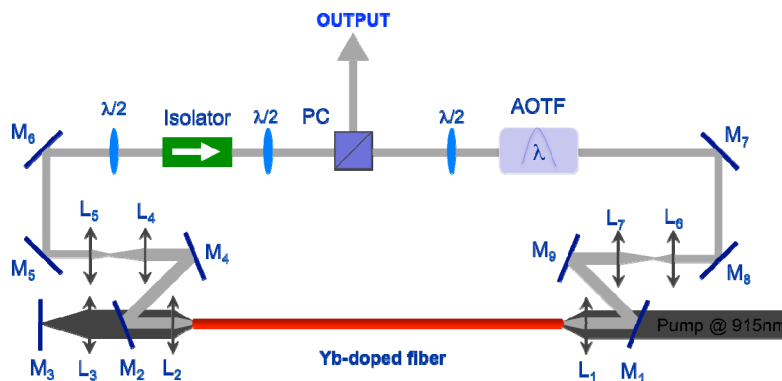

Fig. 1. Experimental setup of the tunable fiber laser. The ring cavity is composed of a Rod-type fiber pumped by a 915 nm diode laser through a dichroic mirror (M1), half-wave plates (λ/2), one Fardaray isolator and a polarizing cube (PC).

4. Experimental results

The output spectra of our tunable system are displayed on Fig. 2(a) for selected wavelengths. The laser is continuously tunable over a total bandwidth of 144 nm ranging from 976 nm to 1120 nm. The contrast between lasing signal and amplified spontaneous emission (ASE) is better than 50 dB across the tuning range except for wavelengths around 976 nm where it decreases to 40 dB and around the unusual wavelengths of 990 nm where it reaches 30 dB. The laser linewidth has been measured with an optical spectrum analyser with a resolution of 0.05 nm (ANDO AQ-6315E). The full width at half maximum is around 100 pm but depends on the central wavelength. Streifer *et al*, with a good agreement with experiment, have modelled this spectral narrowing [13]. Besides, our tunable system presents a bandwidth tunability as well. Indeed, by adjusting the modulation of the AOTF radio frequency driver, and in particular by overlaying several acoustic waves, one can continuously increase the laser bandwidth to several nanometers. Examples of larger bandwidths are shown in Fig. 2(b).
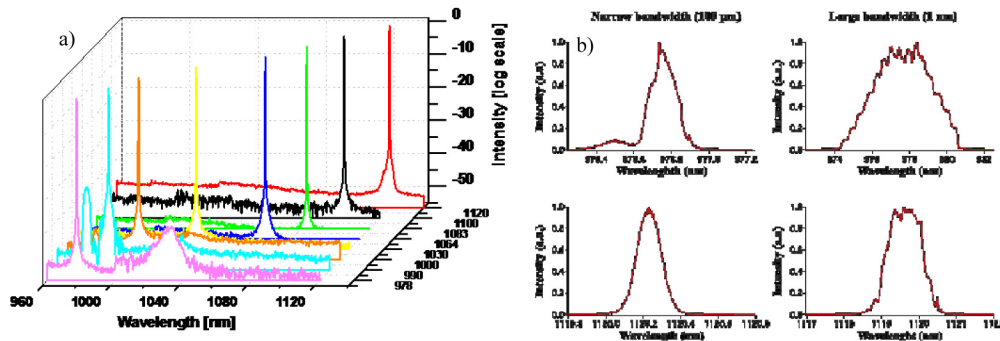

Fig. 2. (a) Narrow bandwidth output spectra for selected laser wavelengths from 976 nm to 1120 nm. (b) High-resolution spectra for large (> 1 nm) and narrow (100 pm) spectral bandwidth at 976 nm (top) and 1120 nm (down).

Figure 3 shows the fiber laser output power as a function of the wavelength. The maximum output power is defined by the parasitic lasing threshold mainly occurring at 1030 nm for emission above 1020 nm and at 976 nm for emission below 1020 nm. As expected from the absorption and emission cross-sections, there is strong power dependence on the wavelength characterised by a maximum output power at 1030 nm with 41 W and minima at 990 and 1120 nm with 10 W for a maximum pumping power of 92 W. Additionally, we have plotted the actual output power for the limited pump power of 92 W corresponding to the maximum pump power in the worst case. The beam quality factor (M^2) has been measured for several wavelengths across the full bandwidth and a far field intensity profile is plotted on Fig. 3. In all cases, a near diffraction limited beam quality $M^2 = 1.3 \pm 0,1$ has been measured. Variations observed of the M^2 at different wavelengths are within the error bars, however far field profiles displayed on Fig. 3 shows a slight improvement of the beam quality for higher wavelengths in agreement with the decrease of the normalized frequency of the fiber [14,15].

At the maximum launched pump power, the output power is not constant but we can adjust the pump power to maintain a constant output power of 10 W over the whole tuning range as depicted on Fig. 4. As expected, the pump power required to maintaining a constant output power almost follows the emission cross-section variations. However, the lasing threshold presents a different behaviour. In fact, to optimize the power for each output wavelength against ASE or parasitic lasing, the output coupler is adjusted by orienting the half-wave plate to lower the laser threshold at the specified wavelength [4].
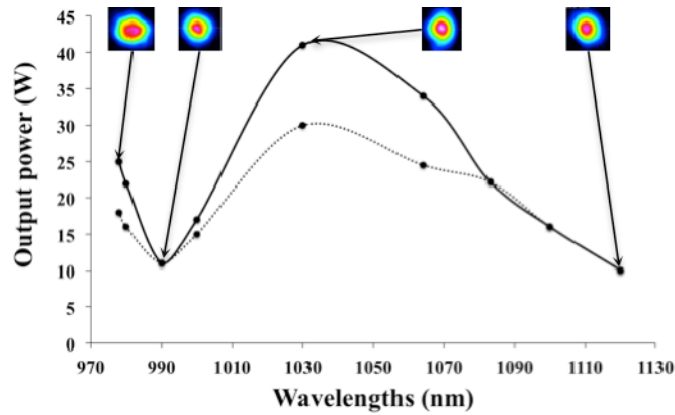
Fig. 3. Dashed: output power for 92 W launched pump power. Solid: maximum output power. Insets: far field beam profiles at different wavelengths

The overall slope efficiency is given on Fig. 4(b) with a minimum efficiency of $\eta = 10\%$ at 1120 nm and maximum at 1030 nm of $\eta = 37\%$. In a previous work in similar conditions [7], high-power CW operation was reported at 976 nm with a slope efficiency of 48% to be compared to the 27% measured here. The smaller value obtained here is attributed to the many optical elements introduced in our cavity, the unidirectional cavity, and the severe spectral filtering (combined with a diffraction efficiency of 80%) introduced by the AOTF to maintain a narrow bandwidth of 100 pm while the experiment in [7] was a free-running laser. As expected the slope efficiency is not constant. In fact, it is a function of several parameters some of which depending on the emission wavelength. For instance, the quantum defect varies linearly from 6 to 22%. Additionally, maximum output power is obtained by optimizing the output coupler for each wavelength leading to a complex wavelength dependence of the efficiency.
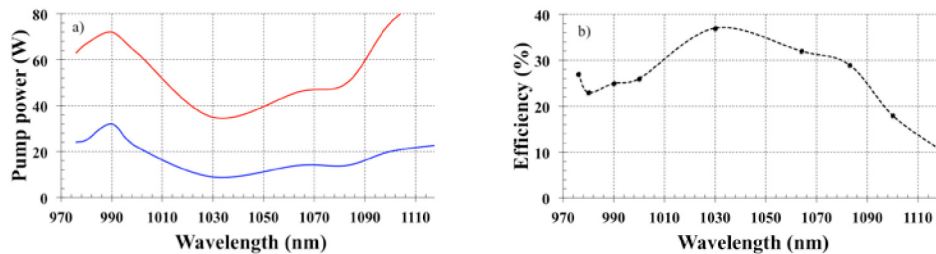

Fig. 4. (a) Pump power needed to obtain a narrow bandwidth constant output power of 10 W (red) and lasing threshold (blue) versus wavelength. (b) Corresponding slope efficiency.

5. Conclusion and outlook

We have demonstrated a narrow-bandwidth, high power continuous-wave Ytterbium-doped fiber laser emitting over a tuning range of 144 nm extending from 976 nm to 1120 nm with a commercial fiber. Our system delivers a minimum output power of 10 watts over the entire spectral range with a maximum output power of 41 W at 1030 nm. Integration of the present laser architecture into an all-fiber system is already under development and will involve new specialty flexible fiber. The possibility of extending the emission bandwidth below 976 nm is also considered around 960 nm as demonstrated in [16]. Recently, novel developments have been reported on frequency doubling of continuous-wave laser radiation [17]. These findings together with our tunable laser system will definitely give access to a new range of visible light efficiently available and continuously tunable from blue to yellow.