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Based on the control of the linear losses of the cavity, we demonstrate the possibility to achieve filterless laser emission above 1.6 μm, from a C-band double-clad Er:Yb doped fiber amplifier. The concept is validated in both continuous wave and mode-locked regimes, using a figure-of-eight geometry. A unidirectional ring cavity is also tested in the continuous regime. Spectral properties of laser emissions are characterized as a function of the intracavity linear losses.

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Erbium-doped fiber lasers find nowadays numerous applications, especially in optical telecommunications, where its spectral range emission coincides with the minimal attenuation of silicate fibers. Traditionally the amplifiers cover the so-called C-band, which spans from 1530 to 1565 nm. In order to increase the amplification bandwidth toward longer wavelengths, a new class of amplifiers has been developed in the spectral range 1565–1625 nm (an L-band amplifier). However, the available gain at 1610 nm remains considerably below the gain at 1550 nm [1]. This low gain value explains why there are few published works dedicated to erbium laser emission above 1.6 μm, either in the continuous wave (CW) regime or the mode-locked (ML) regime. In [2] a high-energy (1.5 μJ) femtosecond erbium-doped fiber laser is reported, based on a chirped pulse amplification (CPA) system. The oscillation at 1.6 μm is achieved through a limitation of the population inversion to about 40%, thus ensuring a higher gain at 1.6 μm than that at 1.55 μm (c.f., pp. 58–60 of [3]). An intracavity spectral filter is used to select a band around 1600 nm. In addition, it is demonstrated that a moderate population inversion (30%–40%) allows obtaining a positive gain at 1600 nm, while it is negative at 1550 nm (i.e., there is an absorption at 1550 nm). A simple way to limit the population inversion in laser operation is to control the linear losses of the cavity. Indeed, above the threshold the round-trip gain compensates the losses, meaning that the gain saturates to its threshold value. As a consequence, low losses ensure a low gain threshold, which in turn guarantees a moderate population inversion. A low loss cavity should allow obtaining the oscillation at 1.6 μm, without requiring any spectral filtering. Based on this principle, we have conducted several experiments for the realization of CW or ML erbium-doped double-clad fiber lasers operating above 1.6 μm, starting from a C-band amplifier. More precisely, we have experimentally investigated the spectral properties of the laser, as a function of the losses of the cavity. The latter can be varied either by a change of the output coupling ratio, or by a change of intracavity losses. This concept was first evidenced theoretically and experimentally in [4], in which it was demonstrated that the change of additive losses, resulting from a variable attenuator, allows switching from 1560 to 1530 nm. In [5], a tunable L-band CW fiber laser is demonstrated, using a fiber taper with a variable bend radius acting as a variable attenuator. In [4,5], no spectral filtering is inserted in the cavity. A large tunable spectral range covering the $(\mathrm{C}+\mathrm{L})$-band has been demonstrated in [6], with a C-band amplifier using an intracavity spectral filter and a control of the cavity losses, which have to be low. A variable output coupler has been used in [7], leading to a large wavelength tunable range without spectral filtering. Previous works [5–7] concerned CW operation, and the output power above 1.6 μm remained below 20 mW.

In this Letter, we present experimental results on the realization of a fiber source oscillating above 1600 nm, and delivering up to 125 mW in the CW regime. Two experimental configurations have been tested, with various output coupling ratios. The first setup is the figure-of-eight laser (F8L) cavity represented in Fig. 1. The cavity is composed of a unidirectional ring cavity (UR), coupled to a nonlinear optical loop mirror (NOLM) [8]. The UR cavity contains a double-clad Er:Yb doped 29 dBm fiber amplifier manufactured by Keopsys (model KPS-OEM-C-30-BO-BARE), and intended to amplify signals in the spectral range 1535–1555 nm. Depending on the orientation of the polarization controller (PC), the laser can operate in the CW or ML regime [9]. A variable attenuator is inserted in the NOLM, allowing us to continuously modify

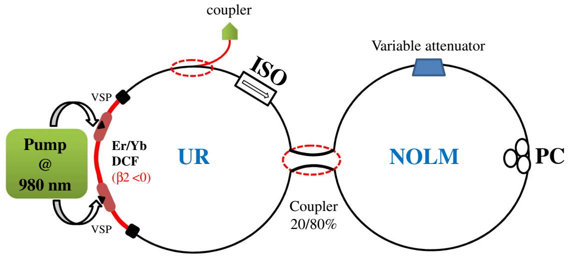

Fig. 1. F8L schematic.

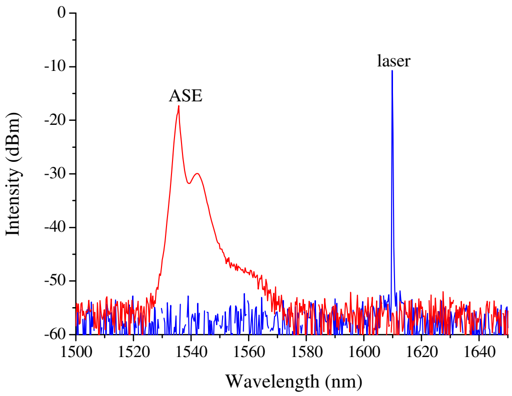

Fig. 2. Optical spectra of the laser and ASE.

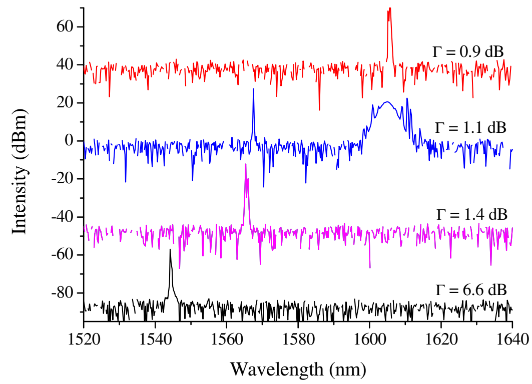

Fig. 4. Evolution of the optical spectrum as a function of the additional losses Γ for the F8L.

the linear losses of the cavity. The second setup is a classical unidirectional ring cavity with a variable attenuator. CW operation has been demonstrated in both configurations. In both experiments, the passive components such as couplers, polarization controllers, isolators, and variable attenuators have wide bandwidth transmission, allowing us to observe long wavelengths. These components are all polarization insensitive, and do not polarize the signal. The ML regime has been realized in the F8L.

Let us first consider the results obtained with the F8L. Let Γ be the additional losses (expressed in dB) induced by the variable attenuator. When $\Gamma = 0$ and the polarization controller is adjusted to obtain CW oscillation, the laser spontaneously operates at 1610 nm, as illustrated in Fig. 2. For comparison we have also plotted the amplified spontaneous emission (ASE) spectrum, which is strongly shifted toward shorter wavelengths, since the amplifier operates in the C-band. Hence as was expected, the 1.6 μm emission occurs for a low-loss cavity. The 1610 nm emission is observed for all the available pumping powers, up to 3 W, and for output coupling from 1 to 10%. Of course, while the output coupling ratio varies, the operating wavelength slightly varies, but in a very small range of about 1 nm. No other spectral emission takes place. The spectral linewidth is on the order of 1 nm. Spectral analysis were done with an optical spectrum analyzer (Anritsu 9710 C, with a resolution of 50 pm).

Figure 3 represents the evolution of the output power at 1610 nm versus the pumping power, for different output coupling ratios T. The characteristics are linear, and

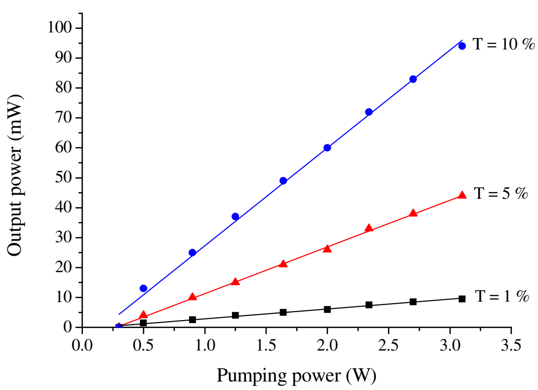

Fig. 3. Output power at 1610 nm versus the pumping power, for different output coupling ratios T, for the F8L.

the laser efficiency increases when the output coupling increases, as usually observed in fiber lasers [10]. We can note that the maximum available power at 1610 nm is about 100 mW, which largely exceeds what was previously reported [5–7]. The temptation is high to increase the output coupling, in order to extract more output power at 1610 nm. However, if the output coupling is further increased, other spectral components appear in the spectrum of the laser. This is demonstrated more rigorously by considering the evolution of the optical spectrum, as a function of the additional losses Γ, for a fixed pumping power. Results are given in Fig. 4, for a pumping power of about 0.5 W and $T = 1\%$. With $\Gamma = 0.9$ dB, the laser operates in the CW regime at about 1610 nm. If the losses are slightly increased to $\Gamma = 1.1$ dB, there is a progressive switch to a ML regime at 1605 nm, together with the emergence of a continuous component at about 1.57 μm. The ML is evidenced through the corresponding large optical spectrum, together with the spectral sideband characteristics of the soliton regime [11]. The fundamental repetition rate in the ML regime is 9.6 MHz, corresponding to a total cavity length $L = 20.75$ m. The total second-order group velocity dispersion is $\beta_2 L = 0.48\ \mathrm{ps}^2$. Although it is not our main concern, let us note that in the ML regime the emission is not a single pulse per cavity round-trip, but rather multipulse. The pulse duration is in the picosecond regime, and depends on the exact operating conditions. If the internal losses are still increased, the emission at 1605 nm vanishes, and it remains only the spectral component at 1.57 μm. This means that there is not enough gain at 1610 nm to compensate for the losses. This is in good agreement with the fact that 1610 nm can oscillate only for moderate population inversion, which is not compatible with high losses requiring greater inversions, which in turns favor shorter wavelength oscillation [1–3].

Results can be conveniently represented in a more synthetic form by plotting the central oscillating wavelengths as a function of Γ, as shown in Fig. 5. It can be seen that the CW emission at 1610 nm occurs only for minimal additional losses. There is also some switching between the ML and CW regimes. It is observed that the general tendency is a shift toward shorter wavelengths when the additional losses increase. In addition, the operating wavelengths undergo few discrete jumps.

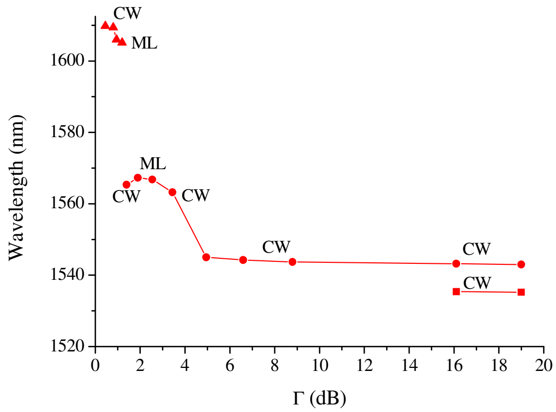

Fig. 5. Evolution of the oscillating wavelengths as a function of additional losses Γ for the F8L.

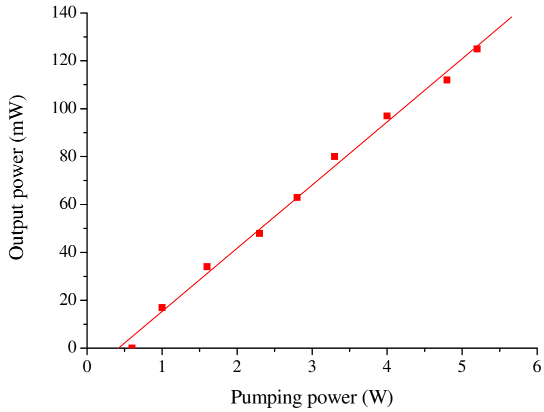

Fig. 7. Evolution of the output power at 1611 nm versus the pumping power for the ring cavity.

In such a representation, the solid lines are only a guide for the eyes, in order to easily follow the evolution of the different peaks' wavelengths.

As previously mentioned, depending on the orientation of the polarization controller, the laser can operate in the CW or ML regime. In the latter case, the value of additional losses determines the central wavelength of the laser. Indeed, for low losses ($\Gamma = 0$) the laser spontaneously operates in the ML regime at 1607 nm. As in the CW case, when Γ increases the short-pulse generation at 1607 nm no longer exists. The laser progressively evolves toward a CW regime at 1570 nm, then to a ML regime at 1567 nm, and finally to a CW regime at 1545 nm. The global evolution is given in Fig. 6. Let us note a range of additional losses for which a noise-like (NL) emission occurs [12]. In the latter case the central frequency is not useful, because the spectrum is nearly flat and large. In Fig. 6, NL emission takes place between the two dashed vertical lines.

Let us now consider the results obtained in a unidirectional ring cavity. In the research reported in this Letter, we used a double-clad Er:Yb doped 30 dBm fiber amplifier, manufactured by Keopsys (model KPS-BT2-C-30-BO-FA), with a maximum available pumping power of about 5 W, slightly greater than that used in the F8L. The output coupling is $T = 10\%$. Without additional losses, the laser spontaneously emits a CW signal at the wavelength 1611 nm, strongly shifted with respect to the ASE spectrum. The output versus pumping power characteristic is given in Fig. 7. The laser oscillates at 1611 nm for all the available pumping powers. The maximum output power is 125 mW, and the laser efficiency is about 2.5%. Because there is neither an intracavity polarizer nor a polarization controller, thus avoiding any ML mechanism, this configuration only operates in the CW regime. As a consequence, when the additional losses Γ are varied, the laser undergoes only a variation of the oscillating wavelengths. Results obtained with a pumping power of 1.6 W are displayed in Fig. 8. As in the F8L cavity, the general tendency is a shift toward shorter wavelengths. When Γ is increased, first the laser emits at 1610 nm, and progressively there is the emergence of a second operating wavelength at 1570 nm. Finally, above $\Gamma = 2.5$ dB, the laser only operates at about 1570 nm. This evolution is well-explained in terms of population inversion. Indeed, at low losses, the threshold population inversion is relatively low, thus favoring the oscillation above 1.6 μm. For intermediate losses, it is expected that the population inversion at the laser threshold is such that the gain cross sections (at 1600 and 1570 nm) are positive, and of the same order of magnitude. In this case, the laser emits on both wavelengths. For higher losses, the population inversion required to obtain CW oscillation is higher. In such a case, the gain at 1.57 μm is much higher than the gain above 1.6 μm, and the laser emits only at about 1.57 μm.

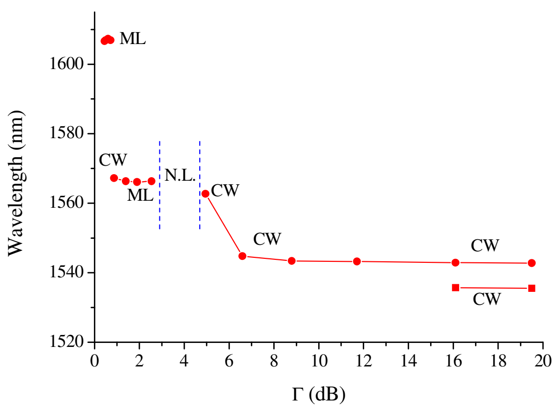

Fig. 6. Evolution of the oscillating wavelengths as a function of additional losses Γ for the F8L, but with a different orientation of the polarization controller. N.L. stands for noise-like emission.

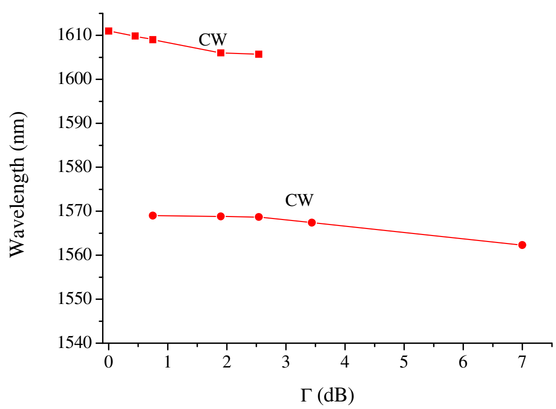

Fig. 8. Evolution of the oscillating wavelengths as a function of additional losses Γ for the ring cavity.

In summary, we have pointed out laser emission above 1600 nm, from a C-band erbium-ytterbium fiber amplifier. This emission is possible thanks to a control of the internal losses of the cavity. In the CW regime, we have obtained a maximum output power of about 125 mW, in a ring cavity configuration. The passive ML regime has been demonstrated from a F8L. In both configurations, we have investigated the evolution of the laser spectrum as a function of additional losses.

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