We report the experimental emission above 1.6 µm of harmonic mode locking of single-, two-, and three-soliton bunches in a C-band Er:Yb codoped silica fiber laser. The laser cavity consists of two connected fiber loops in the figure-of-eight configuration. In such a system the mode-locking regime arises spontaneously due to the nonlinear optical loop mirror, which acts as a saturable absorber. The 1.6 µm oscillation is enhanced by minimizing the linear intra-cavity losses. Depending on the pump power and the polarization controllers, the laser generates harmonic mode locking above 1.6 µm containing patterns with one, two or three pulses. These two last regimes have not been achieved so far at a long-wavelength range.

**Key words:** Long-wavelength range, harmonic mode locking, soliton bunches.

1. INTRODUCTION

The erbium-doped fiber (EDF) is primarily devoted to regenerate the signal undergoing attenuation. The concerning signal must coincide with the gain band of the amplifier. For this reason, the fiber amplifiers operating in C-band corresponding to the spectrum from 1525 nm to 1565 nm are widely used in fiber communication systems. They allow increasing the repeater spacing and also increasing the bit rate of wavelength division multiplexing (WDM) [1]. In order to respond to the growing demands for system capacity, a new generation of WDM called dense wavelength division multiplexing (DWDM) is developed. Such technology is able to transmit multiple wavelengths simultaneously beyond the conventional wavelength window on the same fiber. Consequently, the simple C-band fiber amplifier is not sufficient for assuring the amplification of all channels, in particular, the channels with long wavelengths operating in the range 1565–1625 nm (L-band). In fact, a fiber amplifier optimized in L-band becomes a necessity. It gives a possibility to transport multi-terabit traffic [2].

The laser emission in the L-band is easily obtained from amplifiers operating in the same window with positive feedback. It finds many applications such as spectroscopy [3], biomedical diagnostics [4], surgery of the cornea [5], and so on. The L-band fiber amplifier can be built by using a long length of erbium-doped fiber [6] or higher erbium concentration [7]. Feng and co-workers [8, 9] have observed experimentally, in the spectral range 1562–1605 nm, the simultaneous oscillations of more than 50 wavelengths in figure-of-eight laser employing a nonlinear optical loop mirror (NOLM) and including a Fabry-Perot filter. On the other hand, it is not easy to make laser emitting in L-band from C-band fiber amplifiers especially in the wavelengths above 1600 nm [5]. Indeed, the gain in the C-band is much higher than that occurring in L-band. However, a very interesting study given by Franco et al. [10] demonstrates for the first time experimentally and theoretically the possibility to vary the wavelength emission from 1560 nm to 1530 nm by changing the additive losses. Based on this technique and using a C-band amplifier the authors of reference [11] demonstrate a wide tunable erbium-doped fiber ring laser covering (C+L)-band.

The harmonic mode-locking (HML) is a common regime in all doped fiber lasers and it is independent of the optical configuration. The HML is a kind of multi-pulse regime characterized by a uniform distribution of patterns containing a single or several pulses along the cavity. The mode locking pattern can operate at various harmonics of the fundamental repetition frequency. The physical mechanism achieving it is well known in the case of HML of a single pulse but not completely understood in the case of HML of multiple solitons. Indeed, in the first situation both repulsive interaction between clustered solitons and continuous wave component stabilize the HML of a single pulse [12, 13]. The repulsive interaction can occur from gain modulation induced by depletion and recovery. In the second situation, the pulse dynamics is more complex because the basic pattern in HML is formed by several pulses. Both of these cases are favored in negative total dispersion causing the energy quantization [14]. Since the first experimental demonstration of HML [15], a lot of works have been done in various fiber laser configurations in C-band spectrum with different mode-locking patterns. For HML of a single pulse, we can mention as an example, 322nd HML and 634th HML which are obtained by nonlinear polarization rotation (NPR) [16, 17], 21st HML by graphene [18], and 369th HML by molybdenum disulfide (MoS2) [19]. For HML of an aggregate of solitons and still in C-band window, we can cite the work of Zhao et al. [20] where 15th HML of twin-pulse solitons is observed. In the reference [21] Zhao et al. demonstrate the 47th harmonic of bunches of a single pulse solitons and the 9th harmonic of bunches of twin-pulse solitons. The 50th harmonic of soliton crystals and the 24480th harmonic of noise-like incoherent pulses were reported [22, 23].

Recently, Meng et al. [24–26] have experimentally obtained HML of a single pulse and soliton liquid above 1.6 µm from C-band EDF amplifier associated with low linear cavity losses. As far as we know, no work has been reported in the literature on the generation of L-band passive harmonic mode-locking of two or
three pulses directly from a C-band amplifier. In addition, the observed pulses are very narrow and nearly transform-limited.

2. EXPERIMENTAL SETUP

Figure 1 gives the experimental setup able to produce emission above 1.6 µm of HML of single-, two-, and three-soliton bunches in a C-band Er:Yb codoped silica fiber laser. It consists of an all-fiber figure-of-eight laser constructed on the basis of a main cavity [unidirectional ring (UR)] connected to an auxiliary cavity (NOLM) by an 80/20 fused fiber coupler. The main cavity is composed of a C-band double-clad Er:Yb-doped 29 dBm fiber amplifier built by Keopsys company. It is pumped with the v-groove technique by laser diodes emitting about 3 W at 980 nm. The double clad fiber (DCF) has a length of 2.45 m and the inner cladding has an octagonal shape. The amplifier was built to amplify signals in C-band. The polarization insensitive isolator (ISO) is inserted between output coupler and polarization controller (PC) in order to avoid damages that can be caused by intense pulses due to the Brillouin effect [27]. The main cavity is then a unidirectional ring resonator where the wave propagates only in one direction. The auxiliary cavity is a NOLM to achieve mode locking, which contains a PC. The output signal is extracted with a 5% output coupler. The temporal properties of the output intensity are detected by a fast photodetector (TIA–1200) and analyzed by a fast oscilloscope (Tektronix TDS 6124C, 12 GHz, 40 GSa) and the pulse duration is measured with an optical autocorrelator with a resolution of 10 fs and scanning range of ±100 ps (Femtochrome FR-103 XL). The spectral properties are characterized with an optical spectrum analyzer (Anritsu MS 9710C).

![Fig. 1 – Schematic of the figure-of-eight laser.](image-url)
In order to obtain a long-wave oscillation we use the technique of Franco et al. [10], which consists in minimizing cavity losses. According to this technique, a 5% output coupler is used in our experiment. In such case, the gain in L-band becomes higher than in C-band. The total cavity length is 20.8 m, corresponding to a round trip time of 108 ns and a free spectral range frequency of 9.2 MHz. The net dispersion is negative and equal to $-0.48 \text{ ps}^2$. Consequently, multiple pulsing regimes are favored due to the energy quantization effect. In order to obtain the HML of a single pulse, we set the pump power equal to 900 mW and we choose an appropriate adjustment of the polarization controllers. We first find several grouped pulses and then evolve very slowly towards a regime in which the pulses are regularly spaced along the cavity. This dynamic is not new since it has been previously observed in HML of a single pulse emitted in a C-band [16]. Indeed, this behavior is caused by the repulsive interactions between solitons. Figure 2a gives the temporal evolution of the output intensity. The inset in Fig. 2a shows a zoom of the region framed in red, which exhibits a single pulse with pulse-to-pulse separation $T = 1.26$ ns. Thus, the temporal intensity involves about 86 individual pulses. The solitons are regularly distributed along the cavity with intensity fluctuations smaller than 18%. The spectrum in Fig. 2b indicates that the oscillation of HML of a single pulse is centered at $\lambda_c = 1609.5$ nm, while the spectral width is $\Delta\lambda = 4.48$ nm. The spectrum indicates also the presence of Kelly’s sidebands, which is one of the characteristics of the soliton regime. The autocorrelation trace of the signal is recorded in Fig. 3a. We assume that the intensity of the pulse has a sech-square shape for which the deconvolution factor is about 0.65, and the pulse duration is $\Delta \tau = 743$ fs. The pulse is nearly unchirped, as demonstrated by the time-bandwidth product equal to 0.385, which is close to 0.315 where hyperbolic-secant soliton is transform-limited. The experimental observation of HML of a single pulse at 1609.5 nm is confirmed via the radio frequency spectrum (Fig. 3b). The observed peak at 790 MHz proves that pulses at this repetition rate are produced. Since the free spectral range frequency is 9.2 MHz, the number of pulses in the cavity is about eighty-six. This value is in good agreement with the one obtained from the fast oscilloscope. The signal-to-noise ratio is about 24 dB. In addition, we can notice that the HML of a single pulse depends on the polarization controllers and pump power. Indeed, the laser state can be modified if the orientation angles of the polarization controllers are changed. This observation is obvious because the laser parameters depend on the polarization controllers, especially the nonlinear transmission of NOLM. Furthermore, it is possible to switch from 60\textsuperscript{th} HML of a single pulse to 141\textsuperscript{st} HML of a single pulse only by increasing delicately the pump power from 700 mW to 1250 mW. The evolution does not affect the pulse duration and the optical spectrum while the pulse energy is slightly varied. In the first state, the energy per pulse is about 14 pJ and it is about 12 pJ in the second state.
Now let us present the HML of two-soliton bunches in L-band from a C-band amplifier made by using a figure-of-eight fiber laser. Figure 1 shows the schematic of the first experiment, under certain conditions, yielding evidence of such regime. By fixing the pump level to 1 W and adjusting the polarization controllers, HML is achieved around $\lambda_c = 1610.7$ nm with two-soliton bunches as a basic pattern. The time evolution and spectrum are illustrated in Fig. 4a and 4b, respectively. The inset in Fig. 4a shows that two-soliton bunches are emitted every $T = 1.66$ ns, and it is homogenously distributed in the cavity. The pulse to pulse separation $\tau$ is 260 ps and the pulse duration $\Delta\tau$ is 877 fs (Fig. 5a), thus giving a small ratio between $\Delta\tau$ and $\tau$, $\Delta\tau/\tau = 0.003$. This value suggests that weak attractive interactions exist inside each pattern. In contrast to the previous HML regime, here the HML formation results from the equilibrium between the repulsive pattern interaction and the attractive pulse to pulse interaction.

The spectrum shows no modulation proving that the two-soliton bunches is not a twin-pulse soliton (i.e., the pulses are not bound). The full width at half maximum $\Delta\lambda$ is 3.65 nm and the time-bandwidth product is 0.370 corresponding to...
the nearly transform-limited pulse. The repetition rate of such regime was measured by radio frequency spectrum given in Fig. 5b, where it shows a frequency of 600 MHz. This frequency corresponds to the 65th harmonic of the fundamental repetition rate. The supermode noise suppression was around 21 dB indicating that the HML of two-soliton bunches is less stable than HML of a single pulse. It should be emphasized that the HML of two-soliton bunches is sensitive to the polarization controllers and pump power as previous HML regime.

In the following, we investigate the HML of three-soliton bunches generated under the same experimental parameters giving the HML of two-soliton bunches except the controller polarizations positions. In fact, for accurate controller polarizations positions, it is possible to observe another type of HML consisting of three regrouped pulses in one packet oscillating periodically at multiple of the round-trip frequency in long-wavelength. Our experimental set-up provides for the first time such regime directly from a C-band amplifier by managing the linear losses. Figure 6a illustrates the temporal behavior of HML of three soliton bunches. The inset in Fig. 6a shows that the time period is T = 4.15 ns, while the pulse to pulse time distance τ inside each pattern is around 570 ps. Obviously the last value
is not constant but varies slightly from the pattern to the other due to the fluctuations caused by a timing jitter. The same situation was observed in HML of two-soliton bunches. The HML of three-soliton bunches operates in long-wavelength range (1608.8 nm) as revealed by the optical spectrum in Fig. 6b. The absence of a modulation in the spectrum shows that the three-soliton bunch is not a triplet soliton molecule (the pulses are not bound). The 3 dB bandwidth is 4.82 nm and the pulse width is 701 fs (Fig. 7a). The time-bandwidth product is equal to 0.390, once again indicating a small chirp for sech² profile pulses. The duration of the pulses is small compared with the time distance between the adjacent pulses within the same packet. As a result, like the previous regime, weak attractive interactions exist inside pattern. This interaction coexists with a repulsive one taking place between patterns, which stabilizes the HML of three-soliton bunches. More analysis using radio frequency spectrum (Fig. 7b) is performed in order to emphasize the repetition rate of three-soliton bunches train and the supermode noise suppression. The two quantities are respectively 240 MHz and 16 dB. Thus, the observed regime exhibits the 26th harmonic. The stability is less than HML of two-soliton bunches and even lesser in HML of a single pulse.

Fig. 6 – HML of three-soliton bunches: a) temporal trace, b) optical spectrum.

Fig. 7 – HML of three-soliton bunches: a) autocorrelation trace, b) radio frequency spectrum.
4. CONCLUSION

In conclusion, we have experimentally obtained passive HML of single-, two-, and three-soliton bunches operating in L-band directly from C-band amplifier. We have characterized each regime, so the 141st harmonic of a single pulse, the 65th harmonic of two-soliton bunches and the 26th harmonic of three-soliton bunches have been observed, respectively. The pulses are nearly unchirped with sub-picosecond durations. The HML of a single pulse is more stable than the HML of two-soliton bunches, which is more stable than the HML of three-soliton bunches.

REFERENCES