# Bistability in an Erbium-Doped-Fiber Laser controlled by a Coupled External Signal

Juan C. Martín

***Abstract*—A sine-wave modulated erbium-doped-fiber laser with an external signal coupled into its cavity has been studied. Specifically, analysis on how the time-dependent laser emission changes as a function of the external signal power has been conducted. Under appropriate working conditions, different bistable behaviors have been found. In some cases, the system behaves as a "pilot lamp" which, once activated by the occurrence of a certain event, remains on until reset. For other working conditions, the system behaves as a binary memory whose states can be easily switched.**

***Index Terms*—All-optical devices, erbium-doped fiber, fiber laser, optical bistability.**

## I. Introduction

BISTABILITY phenomena in lasers constitute an attractive research topic for potential all-optical applications such as switches and memories [1-8]. As already known, in any bistable system there are what will be referred to in this document as input and output magnitudes: for a certain value of the input magnitude there are two possible output values which often can be selected by establishing the value of the input magnitude after departing either from a lower value and then increasing it or from a greater value and then decreasing it. In lasers, there is a considerable variety of bistable phenomena in which different input and output magnitudes can be employed: laser wavelength as output magnitude and pump power as input magnitude [1, 2], external injected signal power as input magnitude and laser power emission as output magnitude [3, 4], lasers with two possible counter-propagating modes, in which the mode excited can be shifted by means of a pulse injected whose propagation is opposite to the one of the current mode [5], etc. These phenomena have been mainly studied on semiconductor lasers, suitable for fast switching operations due to their fast dynamics, while works on bistability of erbium-doped fiber lasers (EDFLs) are relatively scarce. However, different bistable behaviors have also been reported for EDFLs: apart from the above mentioned wavelength selection [2], laser power controlled by pump power as input magnitude [6, 7], and, in the case of sine-wave modulated pump, temporal profile of the dynamic response controlled by the modulation frequency as input [8].

The system studied here is a slight variation of the latter: it deals with an EDFL with sine-wave modulated pump power and with injection of an external signal into the laser cavity. The output signal is the temporal profile of the laser emission and the power of the injected signal constitutes the input magnitude. The presence of both the laser emission and the injected signal within the same cavity gives rise to cross-gain saturation [7], which is the physical mechanism that causes the bistability phenomena studied in this instance. The most interesting ones are shown here. On the one hand, the system may act as a "pilot lamp", that is to say, it keeps track of the occurrence of an external signal whose power exceeded a certain threshold. On the other hand, and of particular interest, it behaves as a memory with two possible states which can be commutated by means of the appropriate external signal power.

## II. Experiment

Fig. 1 shows the experimental setup. It consists of a laser ring composed of six elements: an erbium-doped fiber, a wavelength-division multiplexer with which pump power is coupled into the ring, a 90/10 coupler whose corresponding 10% port constitutes the laser ring output, an optical isolator that only allows clockwise laser signal propagation, a tunable filter (1.7 nm of width) which allows selection of the lasing wavelength and a 95/5 coupler employed to couple an external laser signal into the ring. This signal is furnished by a CW tunable laser connected to the 5% port of the coupler. The intensity of the diode employed as pump power source (at the 1480 nm band) is modulated with a sine-wave profile by means of a function generator. The output of the pump diode passes through another 95/5 coupler. Output of the 95% port is coupled into the ring by means of the WDM, while the 5% port is employed to monitor the pump output profile. Both this pump monitor signal and the ring laser output signal are detected by PIN photodiodes connected to an oscilloscope.

The pump power modulation function is $P(t) = P_{av}[1 + m \cos(2\pi ft)]$, where $P_{av}$ is the average pump power coupled into the ring, m is the modulation depth and f is the modulation frequency. The EDFL ring output power will be referred to as $P_l$, while the external laser power coupled to the ring will be referred to as $P_{ext}$. Finally, wavelengths of the laser ring and of the external CW laser source will be denoted by $\lambda_l$ and $\lambda_{ext}$, respectively.

Manuscript received …. . This work was supported by the Spanish Ministry of Economy and Competitiveness (TEC2013-46643-C2-2-R project) and by the Diputación General de Aragón.

J. C. Martín is with the Department of Applied Physics and I3A, University of Zaragoza, Pedro Cerbuna 12, 50009 Zaragoza, Spain (e-mail: jcmartin@unizar.es).

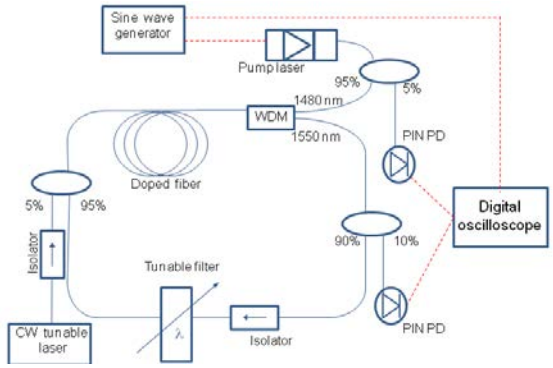

Fig. 1. Experimental setup.

The experiment consisted of two stages. In the first one, with the external laser signal turned off ($P_{ext} = 0$) and different combinations of $P_{av}$, m and $\lambda_l$, the laser ring response was analyzed as a function of f, both for ascending and descending f sweeps. This way, intervals of f where the system presents multistable behavior for specific $P_{av}$, m and $\lambda_l$ were identified [8]. In the second stage, for several combinations of $P_{av}$, m, $\lambda_l$ and f providing bistability, the EDFL output response $P_l(t)$ was analyzed as a function of $P_{ext}$, both for ascending and descending $P_{ext}$ sweeps.

The results presented here correspond to two cases representative of the phenomenology observed.

### *A. Case 1*

In the first stage of the experiment, $P_{av}$ = 27.7 mW, m=0.40 and $\lambda_l$ = 1538 nm. Fig. 2 shows the peak-to-peak amplitude of $P_l(t)$ as a function of the modulation frequency, both for ascending and descending frequency sweeps. As typical in EDF lasers, chaotic behavior was observed for some frequencies. In these cases, peak-to-peak amplitude was calculated as an average of a hundred consecutive periods. Within the bistability region that can be appreciated in Fig. 2, a frequency was chosen. For the sake of simplicity, it was preferred a frequency such that the responses corresponding to the ascending and descending sweep branches were both periodic. The chosen frequency was f = 14 kHz, which meets this condition as shown in Fig. 3. The two possible states of the system will be referred to as α and β states, obtained when f was fixed after an ascending and descending sweep, respectively.

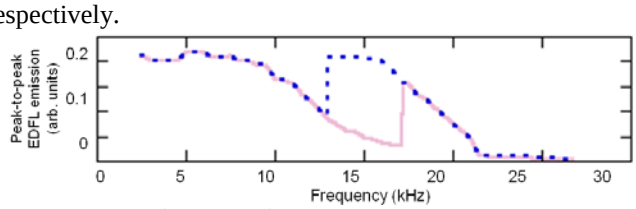

Fig. 2. Case 1, first stage of the experiment (no coupled external signal power): evolution of peak-to-peak EDFL ring laser emission, as the pump power modulation frequency is modified, either in ascending sweep (magenta, light solid line) or in descending sweep (blue, dark dotted line).

Fig. 4 shows the result obtained in the second stage of the experiment, carried out with $\lambda_{ext}$=1535 nm. At the beginning, the ring laser is in the α state and $P_{ext}$ = 0. As $P_{ext}$ is increased there is a gentle decrease in the peak-to-peak amplitude of $P_l(t)$, until a critical value $P_{ext}$ = 13.5 μW, where a sudden increase takes place. Obviously this steep increase does not mean that the average output power increases proportionally, but simply that there is a change in the profile of the response (Fig. 5). If $P_{ext}$ is still increased, peak to peak amplitude of $P_l(t)$ decreases (as well as the average output power, logically: the greater the $P_{ext}$, the less the ring laser average population inversion). Next, $P_{ext}$ is decreased. While its value is greater than the critical value, the ring laser response is the same than for the $P_{ext}$ ascending sweep. Nevertheless, if $P_{ext}$ is reduced further under the critical value, the ring laser response does not coincide with the one obtained for the $P_{ext}$ ascending sweep: instead, it gives rise to the blue dotted line in the plot which, eventually, leads to the β state for $P_{ext}$ = 0.

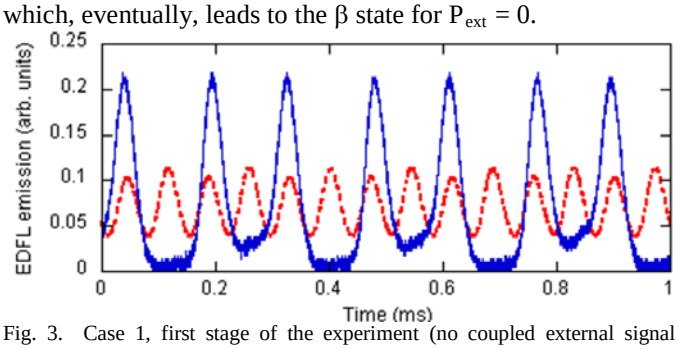

Fig. 3. Case 1, first stage of the experiment (no coupled external signal power): EDFL emission for pump modulation frequency of 14 kHz tuned by means of an ascending sweep (red, dashed line) or a descending sweep (blue, solid line). So, these are the system responses corresponding to its α and β states, respectively.

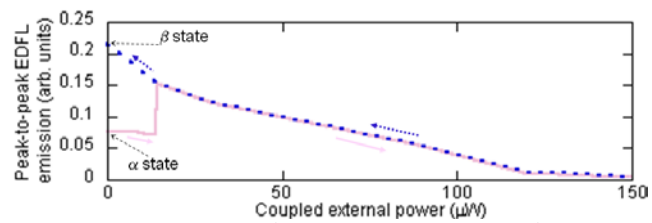

Fig. 4. Case 1, second stage of the experiment: evolution of peak-to-peak EDFL ring laser emission as the coupled external power is continuously modified, either in ascending sweep (magenta, light solid line) or in descending sweep (blue, dark dotted line).

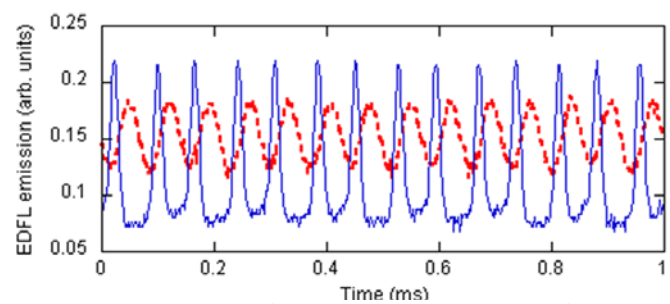

Fig. 5. Case 1, second stage of the experiment: EDFL emission for $P_{ext}$=13.1 μW (red, dashed line) and 14 μW (blue, solid line).

In this case, it has been observed that, provided that the modulation frequency remains fixed at 14 kHz, once the system falls into the basin of the β state (blue dotted line), it is not possible to modify $P_{ext}$ to drive the system to the basin corresponding to the α state (solid magenta line, $P_{ext}$ less than the critical value), neither by continuous $P_{ext}$ changes nor by sudden variations such as switching off the $P_{ext}$ source. Of course, it is possible to "reset" the system, that is to say, taking

it out of the β basin by means of two steps to be carried out once the external signal has been switched off: first, reduction of the modulation frequency to take the system out of the bistable range, and secondly, increase of the modulation frequency to place the system back into the bistable range. It can be said that the system acts as a "pilot lamp" which remains on (β state) since the moment that power of the external coupled signal exceeds a certain threshold until the system is reset.

### *B. Case 2*

For brevity, some of the similar details in cases 1 and 2 are skipped in this description. In the first stage of the experiment, $P_{av}$ = 24.0 mW, m=0.40 and $\lambda_1$ = 1538 nm. This change in $P_{av}$ with regard to case 1 gives rise to similar behavior to that shown in Fig. 2, but with bistable response between f=6.5 kHz and f=10.2 kHz. The modulation frequency chosen was f=9.3 kHz. Figure 6 shows the laser responses corresponding to the α and β states for this case.

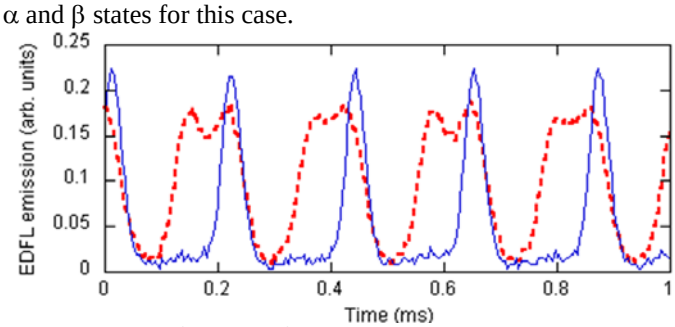


Fig. 6. Case 2, first stage of the experiment (no coupled external signal power): EDFL emission for pump modulation frequency of 9.3 kHz tuned by means of an ascending sweep (red, dashed line) or a descending sweep (blue, solid line). So, these are the system responses corresponding to its α and β states, respectively.

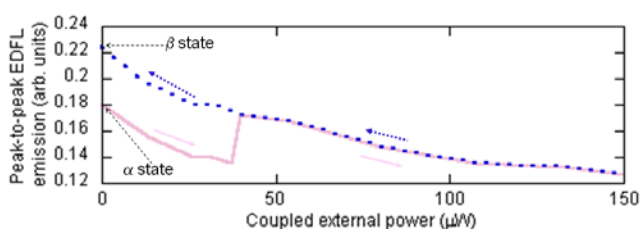


Fig. 7. Case 2, second stage of the experiment: evolution of peak-to-peak EDFL ring laser emission as the coupled external power is continuously modified, either in ascending sweep (magenta, light solid line) or in descending sweep (blue, dark dotted line).

In the second stage, $\lambda_{ext}$=1585 nm. Take into account that there are significant differences between the erbium absorption and emission values at the $\lambda_{ext}$ employed for cases 1 and 2 (1535 nm and 1585 nm, respectively), with this feature contributing to the observed differences in behavior with regard to case 1. However, concerning continuous $P_{ext}$ changes, no qualitative changes are observed, as Figure 7 shows: departing from the α basin, if $P_{ext}$ is increased up to a critical value ($P_{ext}$ = 38 μW), a transition to the β basin takes place, while departing from any state within the β basin, no gentle $P_{ext}$ change drives the system towards the α basin. Nevertheless, the system does show a different behavior with regard to case 1 when sudden $P_{ext}$ changes occur. Table I specifies the different system responses after a sudden $P_{ext}$ switch-off. In the lowest range, corresponding to $P_{ext}$ less than the above mentioned critical value (38 μW), the system response after switch-off corresponds to the basin of departure. The other two ranges are more interesting: owing to them, selection of the system's final state is possible by simply coupling an external power to the ring laser, with the appropriate value, and then turning off this power. Owing to this property, once the system is configured in the conditions corresponding to case 2, it constitutes a memory with two possible states and with an easy mechanism to switch from one state to the other.

TABLE I
SYSTEM RESPONSE AFTER SUDDEN $P_{EXT}$ SWITCH-OFF (CASE 2)

| Initial $P_{EXT}$ range | Final state |
|---|---|
| 0 – 38 μW | α or β (basin is kept) |
| 38 μW – 135 μW | β |
| Greater than 135 μW | α |

## III. CONCLUSION

An EDFL with sine-wave modulated pump power constitutes a system that can be configured to exhibit bistability controlled by the power of an optical signal coupled into the laser cavity. Different working conditions can be found in which the system furnishes bistable behaviors, all of them alike but not exactly the same. In view of the observed behavior, these systems may suggest designs of all-optical devices which act as "pilot lamps", optical power limiters, switches or memories.


## ACKNOWLEDGMENT

The author thanks Kirstin Carmouche for her helpful suggestions.


## REFERENCES


[1] C.H. Chen, S. Matsuo, K. Nozaki *et al*, "All-optical memory based on injection-locking bistability in photonic crystal lasers", *Opt. Express*, vol. 19, pp. 3387-3395, 2011.

[2] Q. Mao, S. Feng, W. Liu and J.W.Y. Lit, "Bistability-mapping for L-band dual-wavelength erbium-doped fiber laser by using fiber loop mirror with polarization controller", *IEEE Phot. Tech. Lett.*, vol. 18, pp. 1973-1975, 2006.

[3] S. Osborne, K. Buckley, A. Amann and S. O'Brien, "All-optical memory based on the injection locking bistability of a two-color laser diode" *Opt. Express*, vol. 17, pp. 6293-6300, 2008.

[4] K. Huybrechts, G. Morthier and R. Baets, "Fast all-optical flip-flop based on a single distributed feedback laser diode", *Opt. Express*, vol. 16, pp. 11406-11410, 2008.

[5] T. Pérez, A. Scirè, G. Van der Sande, P. Colet and C.R. Mirasso, "Bistability and all-optical switching in semiconductor ring lasers", *Opt. Express*, vol. 15, pp. 12941-12948, 2007.

[6] J.M. Oh and D. Lee, "Strong optical bistability in a simple L-band tunable erbium-doped fiber ring laser", *IEEE J. Quant. Electr.*, vol. 40, pp. 374-377, 2004.

[7] Q. Mao, and J.W.Y. Lit, "Optical bistability in an L-band dual-wavelength erbium.doped fiber laser with overlapping cavities", *IEEE Phot. Tech. Lett.*, vol. 14, pp. 1252-1254, 2002.

[8] I.J. Sola, J.C. Martín and J.M. Álvarez, "Nonlinear response of a unidirectional erbium-doped fiber ring laser to a sinusoidally modulated pump power", *Opt. Comm.* Vol. 212, pp. 359-369, 2002.