



Data Descriptor

Numerical and Experimental Data of the Implementation of Logic Gates in an Erbium-Doped Fiber Laser (EDFL)

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Abstract: In this article, the methods for obtaining time series from an erbium-doped fiber laser (EDFL) and its numerical simulation are described. In addition, the nature of the obtained files, the meaning of the changing file names, and the ways of accessing these files are described in detail. The response of the laser emission is controlled by the intensity of a digital signal added to the modulation, which allows for various logical operations. The numerical results are in good agreement with experimental observations. The authors provide all of the time series from an experimental implementation where various logic gates are obtained.

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1. Introduction

Among the many reasons why the Erbium-Doped Fiber Lasers has become a hot research topic are their long pump interaction with active ions, high gain margin, tiny size equivalent to the width of a hair, high damage threshold, excellent heat dissipation, and the fact that they have no bandwidth limitation, leading to better efficiency in laser pumping applications [1,2].

Chaos computing is an emerging research area that focuses on solving logical operations with analog systems that are themselves based on chaotic behavior, such as the Chua circuit and the logistic map, to name a few [3–6].

Considering the possible application of a chaotic system that can act as a logic gate based on a telecommunication system (such as EDFL), and the few works dealing with this subject from the point of view of [7,8], the present work reports the experimental and numerical data from the generation of AND and NOR logic gates using an Erbium-Doped Fiber Laser as a dynamical system, focusing on the storage of the data to provide the corresponding time series for further investigation and reproducibility of the experimental setup as well as the numerical model. By perturbing the system with a bias signal, it is possible to change the operating state of the laser and obtain a completely different logical state that is stable in time.

In addition, experimental time series are provided so that anyone can access the data without having an experimental setup based on an EDFL. The authors provide all time series from an electronic implementation where different logic gates are obtained, better described and published in [9], in a data set format available on [10].

2. Materials and Methods

2.1. Numerical Model

The normalized dynamics of an EDFL pump diode are described by Equation (1) and better described in [7–9,11,12].

$$\begin{aligned}\dot{x} &= axy - bx + c(y + r_w), \\ \dot{y} &= dxy - (y + r_w) + e\left(1 - \exp\left[-\beta\alpha_0 L\left(1 - \frac{y + r_w}{\xi_2 r_w}\right)\right]\right).\end{aligned}\quad (1)$$

To understand the dynamics of the EDFL, the bifurcation diagram of the local maxima of the laser intensity as a function of the pump modulation frequency f_m is calculated. To perform numerical simulation, the equations are described in Equation (1). The normalization procedure and further details can be found in the appendix of reference [9,13–15], and the system coefficients are described in Table 1. At a modulation amplitude $m = 1$, the laser system exhibits dynamic richness by varying the modulation frequency, showing a bifurcation diagram as in Figure 1a.

Table 1. Parameters of the normalized system of equations for the EDFL, Equation (1).

Parameter	Value
a	6.620×10^7
b	7.415×10^6
c	0.016
d	4.076×10^3
e	506
r_w	0.307
$\xi_2 r_w$	0.615
$-\beta\alpha_0 L$	-18

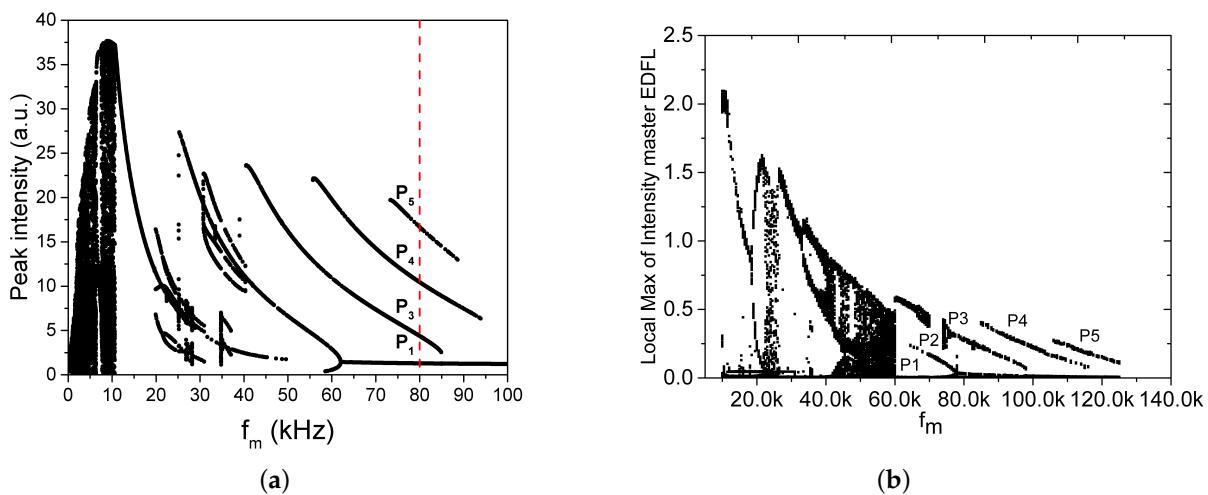


Figure 1. EDFL Bifurcation diagram. (a) Numerically calculated, (b) experimentally determined.

2.2. Experimental Setup

The experimental setup used in this work, shown in Figure 2, consists of a 1560 nm EDFL pumped by a 977 nm laser diode (LD). The laser cavity consists of an erbium-doped fiber of approximately 88 cm long with a core diameter of 2.7 μm and two fiber Bragg gratings (FBG1 and FBG2) with reflectivities of 100% and 95.88%, respectively. All components are interconnected with a monomode fiber. The laser diode is controlled by the pump controller (LDC). For all experiments performed, the pump current is set to 145.5 mA

(20 nW). The choice of the pump current is to ensure a relaxation frequency of the laser close to $F_r = 30$ kHz. To control the dynamics of the laser and to achieve the different logic gates, both the harmonic modulation and the bias signal are injected into the pump diode via a function generator (WFG) and a digital interface, respectively.

Figure 1b shows the bifurcation diagram of the experimental system, which agrees with the numerical estimate.

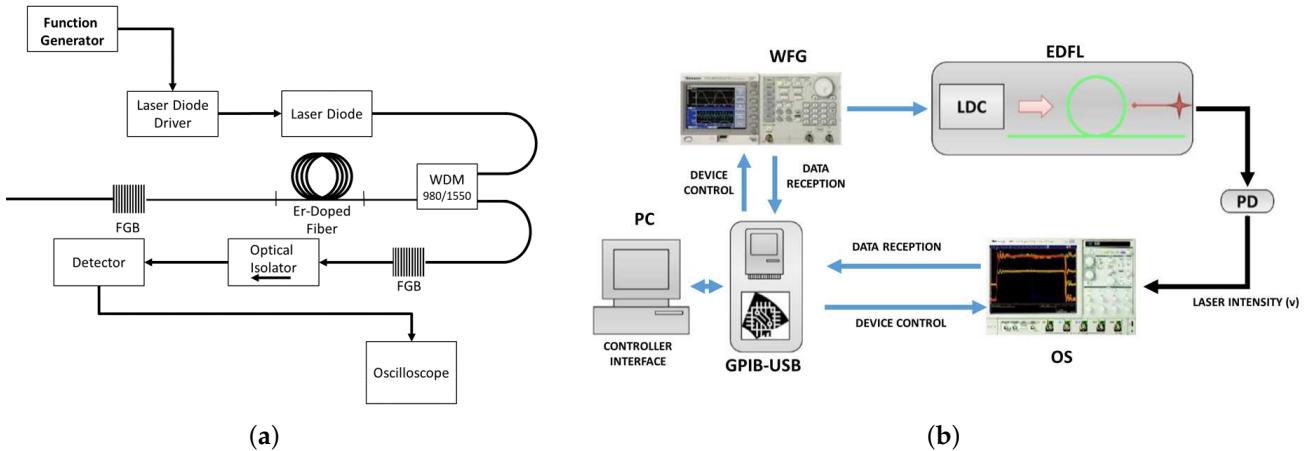


Figure 2. Experimental setup. (a) Optical elements required to put the erbium-doped fiber laser into operation. (b) Elements required to implement the logic gate based on the operation of the EDL. (WFG—Wave Form Generator; LDC—Laser Diode Controller; PD—Photo-Detector; WDM—Wavelength Division Multiplexing; OS—Oscilloscope; FGB—Fiber Bragg Grating).

2.3. Methods

To automate the experiment, we developed an interface in LabView 12.0 that allows us to control the following:

- The frequency and waveform fed into the laser modulation;
- The amplitude and frequencies of the digital signals I_1 and I_2 ;
- The acquisition of the signals coming from the EDL.

The automated equipment includes the following:

- DC power supply “Bk Precision 1760A”;
- Digital Oscilloscope “Agilent DSO-X 3102A”;
- Digital Arbitrary WaveForm Generator “Tektronix AFG 3102”;
- Diode Laser Controller “ThorLabs ITC510”.

The virtual interface that automates the experiment completes the following processes:

- Equipment initialization
 - Set the acquisition time and number of oscilloscope samples.
 - (Oscilloscope): $T = 1$ s, samples per sec = 500 k. The configuration of the vertical axis is given considering the acquired signal, a sample is taken from Photodetector (PDB450C-AC with a detection range from 800 nm to 1700 nm), the maximum of the laser intensity is determined, and the window is set.
 - (Laser) The relaxation frequency should be 30 kHz. This is achieved by setting the fixed pump current to 119.8 mA. The active medium corresponds to a piece of heavily doped erbium fiber (SCL110-01 from Leibniz-IPHT).
 - (WFG) The modulation frequency limits $40 \leq f_m \leq 60$ kHz are fixed $\Delta f_m = 1$ kHz. The amplitude of the digital signal is swept from 0.2 V to 2 V.
- Signal Generation

The pump power injected to the laser has the following numerical form:

$$P_{pump} = P_p \frac{1 - \exp[-\alpha_0 \beta L(1 - N)]}{N_0 \pi r_0^2 L}, \quad (2)$$

$$P_p = p[1 - m \sin(2\pi f_m t)].$$

where P_p is the pump power at the fiber input, β is a dimensionless coefficient, and N is the average of the upper level of the laser potential (propagation direction of the laser emission). For further information, see [9,13–15] and the references therein.

- The pump signal remains fixed, and 1Vp-p modulation amplitude and variable modulation frequency are fixed.
- Two signals are generated for the digital signal, corresponding to I_1 and I_2 . The relationship between them is established by the generation frequency; in our case, it is 1/3 (ratio). This guarantees that the signal I_d has no repetition pattern in the sampling window (1 second). Consider an input signal I_d defined as the sum of two digital decorrelated signals $I_d = I_1 + I_2$.
- The amplitude of the digital signal is variable from $0.2 \leq A_d \leq 2$ V and is controlled via the control interface (manual or automatic).
- Pumping the laser current with the sum of the signals
 - The sum of the variables is formed with the summing amplifier in cascade with an inverting amplifier, both with a gain of one.
 - The output of the sum of the signals is fed into the pump current of the laser controller.
- Visualization and data acquisition
 - The interface allows us to visualize the laser intensity, the local maxima, and the frequency spectrum of the laser intensity (output of the EDL). Once the result is displayed, it is possible to save the results in the form of time series (TS). You can choose to save only the laser response or the frequency spectrum and local maxima of the TS.

3. Data Description

The data sets described here, both numerical and experimental, are created by fixing the modulation frequency and by varying the amplitude of the digital signal, and available on [10]. Once the value of $A_d = 2$ is reached, the interface increases the value of the modulation frequency by Δf_m , and the amplitude sweeps $A_d \in [0.2 - 2]$ V are performed again.

3.1. Numeric Time Series

Sweep of the parameter space A_d, f_m . Each file contains a matrix of 1×2^{17} data corresponding to the variable x of the numerical system representing the laser intensity. The files are named “IL_fxx_Azz.dat”. The xx values correspond to the changes in frequency, while the zz values are associated with the amplitude of the digital signal. For example, the file “IL_f50_A100.dat” means that the system is modulated with a frequency $f_m = 50$ kHz with a digital amplitude $A_d = 1$ V, and the behavior is displayed in Figure 3. The first file is called “IL_f40_A10.dat” ($f_m = 40$ kHz, $A_d = 0.1$ V), while the last file is called “IL_f60_A100.dat” ($f_m = 60$ kHz, $A_d = 1$ V).

In the same folder, there is a file with the title “Ia.dat” and a file “Ib.dat”. In each of the files, there is only one time series corresponding to the digital signal I_1 and I_2 . Both files are column time series with a total of 2^{17} samples.

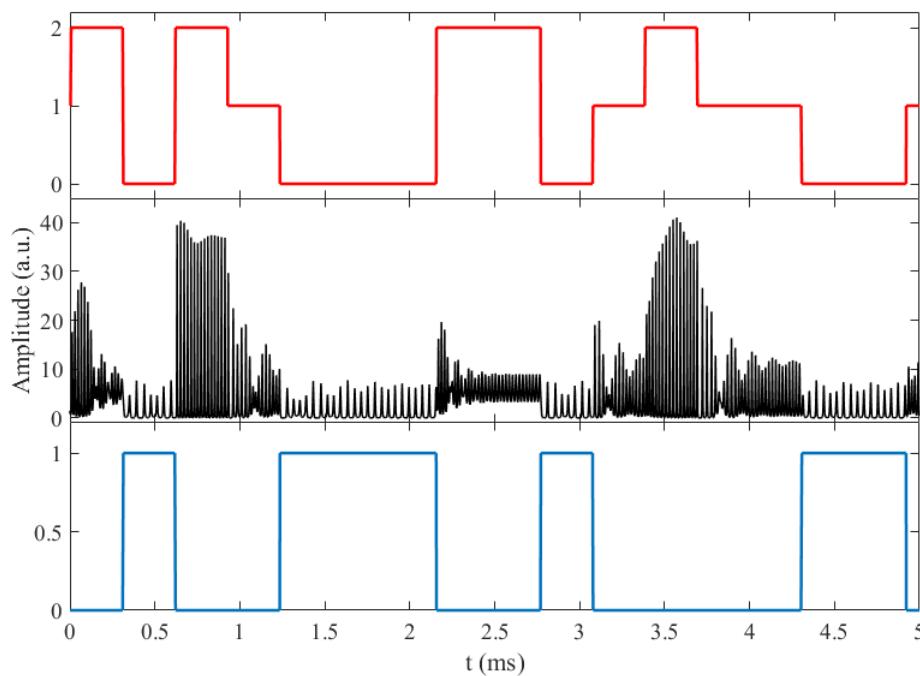


Figure 3. EDFL behavior corresponding to a digital amplitude $A_d = 1$ V, for $f_m = 40$ kHz (black line). Digital input signal I_d (red line) and output of the logic gate determined when P_2 is taken as logic 1 and the response in P_1 is taken as logic 0 (blue line). Note that the obtained logic operation corresponds to an NOR operation where only the set $(0, 0)$ leads to a logic output 1.

3.2. Experimental Time Series

Time series obtained by the experimental preparation described above. The data correspond to a sweep in both the modulation frequency and the amplitude of the bias signal I_d . There are two types of files in this folder:

1. Time series corresponding to the generated digital signal (I_d). The file contains an array with $3 \times 500,000$ samples. Column 2 is the continuation of the series stored in column 1, while column 3 is the continuation of the series stored in column 2. In total, the time series of the digital signal consists of 1,500,000 data points. This type of file is called “*DIGINP_XX_ZZ.dat*”. The XX values correspond to the modulation frequency used, which is within the previously defined range ($f_m \in [40-60]$ kHz), with $\Delta_{f_m} = 1$ kHz. The ZZ values represent the amplitude of the digital signal I_d fed into the system, which is in the range $A_d = [0.2-2]$ V.
2. Time series of laser response stored via digital oscilloscope. There is a matrix of $3 \times 500,000$ data stored in the file, where column 2 is a continuation of column 1 and column 3 is a continuation of column 2. In total, there is a time series of laser intensity of 1,500,000 data. This type of file is called “*INTLAS_XX_ZZ.dat*”. The XX values correspond to the modulation frequency used, which is within the previously defined range ($f_m \in [40-60]$ kHz), with $\Delta_{f_m} = 1$ kHz. The ZZ values represent the amplitude of the digital signal I_d fed into the system, which is in the range $A_d = [0.2-2]$ V.

For example, the file shown in Figure 4 (black line), named “*INTLAS_40_8.dat*”, corresponds to the response of the laser at a modulation of 40 kHz and a digital signal amplitude of 0.8 V, where the input signal that excites the system is contained in the file “*DIGINP_40_8.dat*” shown in Figure 4 (red line).

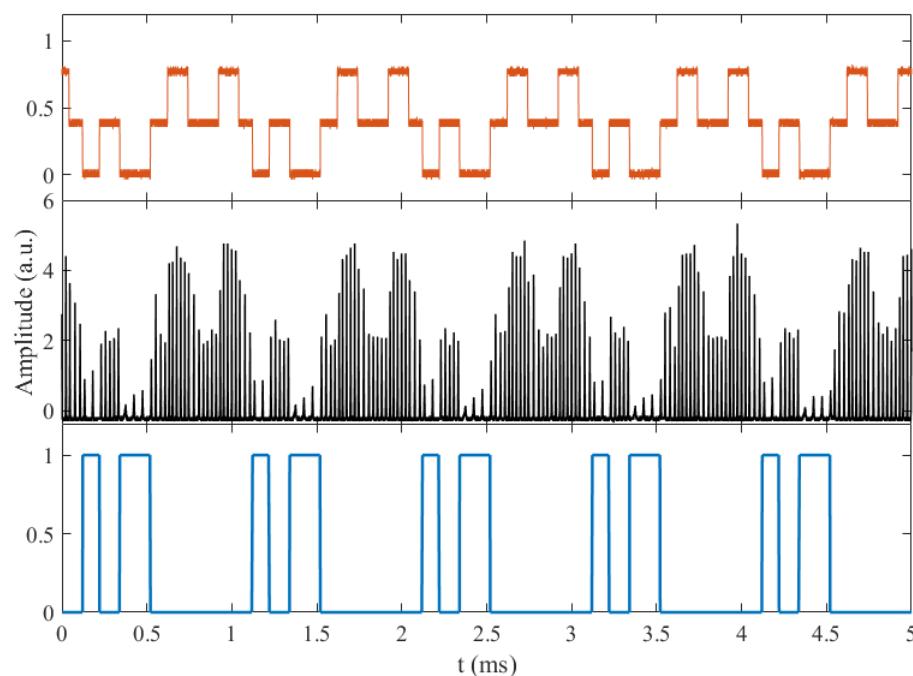


Figure 4. Experimental behavior of laser intensity corresponding to a digital amplitude $A_d = 0.8$ V, for $f_m = 40$ kHz (black line). Digital input signal I_d (red line) and the output of the logic gate determined when P_2 is taken as logic 1 and the response in P_1 is taken as logic 0 (blue line). Note that the obtained logic gate corresponds to a NOR, where only the set $(0, 0)$ leads to a logic output 1.

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References

1. Pisarchik, A.N.; Barmenkov, Y.O.; Kir'yanov, A.V. Experimental characterization of the bifurcation structure in an erbium-doped fiber laser with pump modulation. *IEEE J. Quantum Electron.* **2003**, *39*, 1567–1571. [[CrossRef](#)]
2. Meucci, R.; Marc Ginoux, J.; Mehrabbeik, M.; Jafari, S.; Clinton Sprott, J. Generalized multistability and its control in a laser. *Chaos Interdiscip. J. Nonlinear Sci.* **2022**, *32*, 083111. [[CrossRef](#)]
3. Sinha, S.; Ditto, W.L. Dynamics based computation. *Phys. Rev. Lett.* **1998**, *81*, 2156. [[CrossRef](#)]
4. Cafagna, D.; Grassi, G. Chaos-based SR flip-flop via chua's circuit. *Int. J. Bifurc. Chaos* **2006**, *16*, 1521–1526. [[CrossRef](#)]

5. Munakata, T.; Sinha, S.; Ditto, W.L. Chaos computing: Implementation of fundamental logical gates by chaotic elements. *IEEE Trans. Circuits Syst. I Fundam. Theory Appl.* **2002**, *49*, 1629–1633. [[CrossRef](#)]
6. Murali, K.; Sinha, S.; Ditto, W.L.; Bulsara, A.R. Reliable logic circuit elements that exploit nonlinearity in the presence of a noise floor. *Phys. Rev. Lett.* **2009**, *102*, 104101. [[CrossRef](#)] [[PubMed](#)]
7. Jaimes-Reátegui, R.; Afanador-Delgado, S.; Sevilla-Escoboza, R.; Huerta-Cuellar, G.; García-López, J.H.; López-Mancilla, D.; Castañeda-Hernández, C.E.; Pisarchik, A. Optoelectronic flexible logic gate based on a fiber laser. *Eur. Phys. J. Spec. Top.* **2014**, *223*, 2837–2846. [[CrossRef](#)]
8. García-López, J.H.; Jaimes-Reátegui, R.; Afanador-Delgado, S.M.; Sevilla-Escoboza, R.; Huerta-Cuellar, G.; López-Mancilla, D.; Chiu-Zarate, R.; Castañeda-Hernández, C.E.; Pisarchik, A.N. Experimental and Numerical Study of an Optoelectronics Flexible Logic Gate Using a Chaotic Doped Fiber Laser. In *Recent Development in Optoelectronic Devices*; Intechopen: London, UK, 2018; pp. 97–114.
9. Afanador Delgado, S.M.; Echenausía Monroy, J.L.; Huerta Cuellar, G.; García López, J.H.; Reátegui, R.J. Implementation of Logic Gates in an Erbium-Doped Fiber Laser (EDFL): Numerical and Experimental Analysis. *Photonics* **2022**, *9*, 977. [[CrossRef](#)]
10. Echenausía-Monroy, J.L.; Afanador-Delgado, S.; Huerta-Cuellar, G.; García-López, J.H.; Jaimes-Reátegui, R. Numerical and Experimental Data of the Implementation of Logic Gates in an Erbium-Doped Fiber Laser (EDFL). *Mendeley Data* **2020**, V1. [[CrossRef](#)]
11. Pisarchik, A.N.; Kir'yanov, A.V.; Barmenkov, Y.O.; Jaimes-Reátegui, R. Dynamics of an erbium-doped fiber laser with pump modulation: Theory and experiment. *JOSA B* **2005**, *22*, 2107–2114. [[CrossRef](#)]
12. Pisarchik, A.N.; Jaimes-Reátegui, R.; Sevilla-Escoboza, R.; Huerta-Cuellar, G.; Taki, M. Rogue waves in a multistable system. *Phys. Rev. Lett.* **2011**, *107*, 274101. [[CrossRef](#)] [[PubMed](#)]
13. Reátegui, R.J. Dynamic of Complex Systems with Parametric Modulation: Duffing Oscillators and a Fiber Laser. Ph.D. Thesis, Centro de Investigaciones en Optica, Leon, Mexico, 2004.
14. Magallón, D.A.; Jaimes-Reátegui, R.; García-López, J.H.; Huerta-Cuellar, G.; López-Mancilla, D.; Pisarchik, A.N. Control of Multistability in an Erbium-Doped Fiber Laser by an Artificial Neural Network: A Numerical Approach. *Mathematics* **2022**, *10*, 3140. [[CrossRef](#)]
15. Esqueda-de-la Torre, J.O.; Jaimes-Reátegui, R.; García-López, J.H.; Pisarchik, A.N.; Huerta-Cuellar, G. Effects of Optical Laser Injection in Multistable Erbium Fiber Lasers. *Chaos Theory Appl.* **2022**, *4*. [[CrossRef](#)]

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