Laser amplification: experiment and electronic simulation

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The experimental results of a molecular nitrogen laser system based on a master oscillator and an amplifier with Blumline configurations are reported, as well as an electronic system based on a microcontroller and operational amplifiers which qualitatively reproduce the results obtained with the laser system. The usefulness of the developed electronic system and its application during university level lectures and popularization talks about lasers, photonics and quantum electronics is discussed.

Keywords: Laser amplifiers; electronic amplifiers; opto-electronics.

Se reportan los resultados experimentales de un sistema láser molecular de nitrógeno formado por un oscilador maestro y un amplificador basados en configuraciones Blumline, así como el desarrollo de un sistema electrónico basado en un microcontrolador y amplificadores operacionales que cualitativamente reproducen los resultados obtenidos con el sistema láser. Se discute la efectividad de la simulación electrónica desarrollada y su aplicación en la impartición de cursos y conferencias sobre láseres, fotónica y electrónica cuántica a nivel licenciatura y de divulgación.

Descriptores: Amplificadores láser; amplificadores electrónicos; opto-electrónica.

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1. Introduction

When teaching courses on lasers, photonics and quantum electronics, or lecturing on science at a popular level, it is ideal to have lasers that can be operated in front of the public at hand. However, due to economic or technical factors, this may prove difficult, with the exception of low power lasers such as semiconductor laser diodes and helium-neon gas lasers. It is generally not always possible to demonstrate a modern solid state or gas laser with several amplifying stages such as those found in a specialized institute or research center. On the other hand, it is interesting that these lasers are the most important ones when discussing many scientific and industrial laser applications. A clear example is the most powerful laser built at the Livermore National Laboratory in the USA, which will be used among other things to carry out inertial confinement nuclear fusion studies. This laser is based on an oscillator-multi-amplifier solid state architecture (see: http://www.llnl.gov/nif/project/index.html). Having in mind didactic uses, a molecular Blumline nitrogen laser based on a master oscillator and an amplifier was developed as well as an electronic system based on a microcontroller and operational amplifier that qualitatively reproduces the results of pulse shape form and gain observed on the laser system in the oscilloscope, but clearly not the real energetic and temporal characteristics. In this way, depending on the financial and technical resources, as well as on the level of the expected public, the lecturer can choose between several demonstration options, using either a real laser, an electronic simulation, or both.

The second section describes the basic concepts about laser amplification. The third section shows the construction of an amplifying laser system based on a nitrogen oscillator and amplifier. In the fourth section, the construction of an electronic system based on a microcontroller and operational amplifiers circuits is described that qualitatively models a nitrogen oscillator and amplifier system. The fifth section discusses the results obtained and finally in the sixth section the conclusions are presented.

2. Optical Amplification

In an optical amplifier, the intensity increase per unit length, *dI/dz*, is described by the equation [1]:

$$\frac{dI}{dz} = \alpha I, \tag{1}$$

where α is the gain per unit length coefficient. Without saturation, or for a small signal, the gain α is given by:

$$\alpha = [N_2 - (g_2/g_1)N_1]\sigma, \tag{2}$$

where N_2, N_1, g_2 y g_1 are the population inversion densities and the upper and lower energetic levels degeneracies. σ is the cross section of the stimulated emission given by:

$$\sigma = \frac{c^2}{8\pi n^2 f^2 \tau_R} g(f), \tag{3}$$

where $c, n, f, g(f)$ and τ_R are the speed of light, the refraction index, the light frequency, the line shape function, and the radiative lifetime of the laser transition. The last term is given by:

$$\tau_R = \left(\frac{\varepsilon_o}{2\pi}\right) \frac{m_e c^3}{f_{21} e^2 f_o^2} \quad . \tag{4}$$

Where ε_o, e, m_e, f_o y f_{21} are the permittivity of vacuum, electron charge, electron mass, frequency at the line center, and the oscillator strength of the laser transition. The line shape function can be Lorenzian or Gaussian, and typically one is dominant over the other. The lineshape function for nitrogen lasers is Gaussian because fundamentally, it is determined by Doppler broadening, which is an inhomogeneous process.

In the small signal regime, for initial intensity I(0) at z = 0, the intensity in the amplifier medium along its propagation in z is described by Eq. (1) with solution:

$$I(z) = I(0)e^{\alpha z}. \tag{5}$$

For a laser amplifier of length z = l, when the total gain per pass, αl, is sufficiently small, the term $e^{\alpha l}$ may be expanded and the following approximation for the gain is valid:

$$I(l)/I(0) = [1 + \alpha l]. \tag{6}$$

This expression describes a linear relation between the input and the output signal in the laser amplifier which is valid only for small signals. The saturation gain coefficient for lasers with homogeneous lineshape broadening is given by [1]:

$$\alpha_s = \frac{\alpha}{1 + (I/I_s)}, \tag{7}$$

For lasers with inhomogeneous lineshape broadening, such as nitrogen lasers, [1] becomes:

$$\alpha_s = \frac{\alpha}{[1 + (I/I_s)]^{1/2}}, \tag{8}$$

In Eqs. (7) and (8), $I_s$is the saturation intensity, *i.e.* the intensity value where the gain coefficient α decreases to a value α/2 for homogenously broadened lasers, or $\alpha/\sqrt{2}$ for inhomogenously broadened lasers. At high intensities, in the saturation regime, the relation between the input and output is not lineal anymore. This is clearly shown in the experimental results discussed in the following section. If there is saturation, Eq. (1) can be written as *dI/dz* = $\alpha_s I$, where the saturation gain coefficient may be substituted from Eqs. (7) for the homogeneous case, or (8) for the inhomogeneous case. The differential equation obtained may be easily solved approximately using the Newton binomial expression for the term [1 + $(I/I_s)]^n$ (where n = -1 for the homogeneous case and n = -1/2 for the inhomogeneous one) keeping only up to first order terms for I. In this way, a logistic equation is obtained both for the homogeneous and the inhomogeneous case. This equation has the form:

$$\frac{dI}{dz} = I\left(a - bI\right), \tag{9}$$

where a and b are constants. Its solution may be found in any basic differential equation book; taking $I(0) = I_o$, we obtain:

$$I\left(z\right) = \frac{aI_o}{bI_o + \left(a - bI_o\right)e^{-az}}, \tag{10}$$

This expression describes very precisely the saturation phenomenon. This will be described experimentally, from the optical as well as the electronic point of view, in the following sections of this work.

3. Oscillator-amplifier laser system

Reports on nitrogen lasers for didactical purposes based in the Blumline design are plentiful. These lasers are easy to build, and their physics and operational characteristics are well documented [2-5]. Some of the most important aspects of these lasers are the following. Nitrogen molecules are excited by a pulsed electric discharge producing emission mainly in a band centered around 337.1nm. The discharge electrons excite the upper laser transition by direct electronic impact, thus producing population inversion. Since the upper state has a lifetime of 47ns and the lower state 10 μs, the excitation pulse must be very short. The transient nature of the population inversion in the N_2 molecule severely limits the power of these lasers [3-5], and only by using systems based on oscillators followed by amplifiers can the final power be increased [6-9]. In this work, a Blumline circuit [3-5] is used for the oscillator and the amplifier. They were built using a printed board plate 1.5 mm thick, with copper on both sides and using electrodes of 30 cm length. The measured capacitance of the plates was 3 nF. To operate the laser, a spark gap made of spherical electrodes with a 20 mm curvature radius and adjustable separation at atmospheric pressure were used. As shown in Fig. 1, at the end of the oscillator a spherical mirror was used in order to reduce the divergence of the beam produced. In order to obtain maximum power in an N_2 laser a high excitation density is needed over a short period of time compared to the excited time of the laser (< 40 ns) [3-5]. In order to have an efficient oscillator-amplifier system, the optical pulse produced by the oscillator must reach the amplifier at the exact time when it has the highest population inversion. This means that there must be good synchronization between the fire ring of the oscillator and the amplifier. To do this, optical and electrical delay lines may be used. Figure 1 shows the system used with an optical delay line. For our laser, two independent N_2 supplies and vacuum system were used for the oscillator and the amplifier, and the operating frequency was 1 MHz. Figure 2 shows the most important experimental results; this is the energy plot of the pulses produced by the amplifier, and the same pulses once amplified by the laser amplifier. The points show the experimental results and the continuous line the best possible fit to the solution of a logistic equation. The effect of saturation is clear. For laser pulses with small input energies, the input and output signals may be described by a linear relation; however, once the input signal increases, the linear input-output relation is lost and the amplifier is in the non-linear saturation regime

4. Electronic System

The electronic system was built using a microcontroller and the program *Proteus isis Profesional v6.7*. This allows the generation of a Gaussian shape pulse (which represents the laser pulse obtained by the laser oscillator) which is amplified using operational amplifiers, providing a gain of one thousand, similar to the one obtained using the laser amplifier described in the previous section.

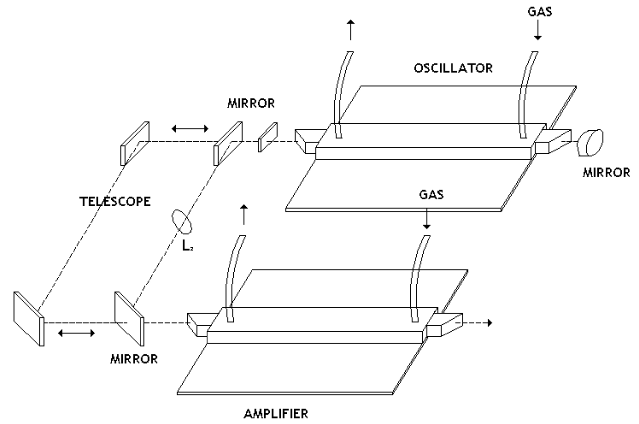

FIGURE 1. Schematic diagram of the oscillator-amplifier laser system built showing the optical delay line required to optimize the output power.

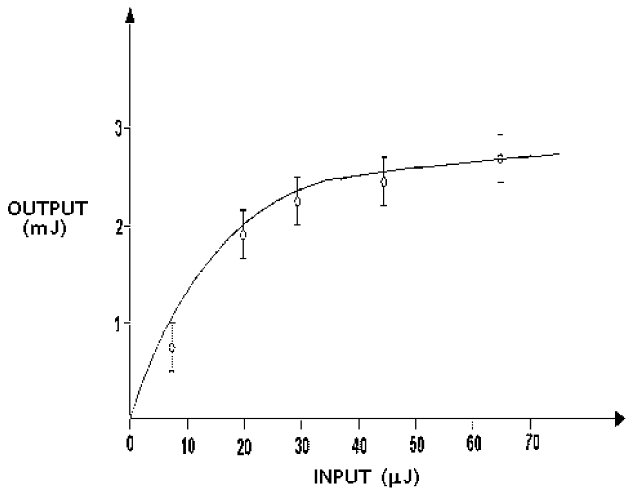

FIGURE 2. Input-output energy behavior of the laser amplifier. Points show the experimental data of the energy pulses produced by the oscillator (input) which are introduced into the amplifier, as well as the energy of the same pulses at the end of the amplifier (output). The continuous line shows the best fitting to the solution of a logistic equation.

The microcontroller PIC16F84, is shown in Fig. 3. This is a programmable integrated circuit [10] that can be used to control the operation of any specific task. The input and output pins may be used to monitor or control motors, relays, actuators and any other electronic or electric device using the right interface. Once the microcontroller is programmed, it carries out the specified instructions, while running.

The microcontroller PIC16F84 has a total of 37 instructions. It is an integrated circuit of 18 pins built using CMOS technology and is produced in several presentations such as DIP (conventional) and SOIC (superficial). The operating frequency of the clock (oscillator) varies between 4 and 20 MHz.

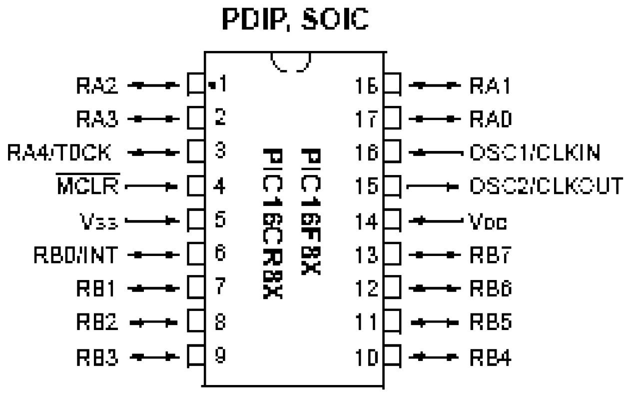

FIGURE 3. Schematic diagram of the microcontroller PIC16F84.

Port "A" has 5 lines (RA0 to RA4). In our program, one is used as a start signal. Port "B" has 8 lines (RB0 a RB7). They are used as output signals to produce the binary values that represent a digitalized Gaussian shape signal. Both ports with a total of 13 lines may be independently programmed as input or output. In our case they are used to generate a digital signal that represents the output signal of the laser oscillator. Pin No. 3 belongs to port RA4 and is called "TOCKI". This line may be programmed as input, output or time counter. To operate the microcontroller needs a 5 V DC supply through input pins No. 14 (+) and No. 5 (-) as shown in Fig. 3.

A 4MHz crystal clock signal is introduced through pins No. 15 and No. 16.

The microcontroller PIC16F84 uses four full periods per instruction. Therefore, with a 4 MHz crystal, the microcontroller actually runs at 1 MHz.

Once the RESET key is pressed, all registers are set to their original logical states. In order to generate a signal that will represent the optical pulse produced by the laser oscillator, the following function was used: $f(x) = [3/(10x^2+1)]$. The digital values obtained from this function at the output of the microcontroller were introduced into a digital-to-analog converter (DAC0808) in order to obtain the analog electronic signal that represents the optical output of the laser oscillator. Since the analog signal from the DAC has a peak value of 10 V, and since it will be required to amplify this signal by the thousand, an operational amplifier circuit (LM741) was used to reduce the amplitude to a few mV [11]. Initially, an inverting amplifier is used to reduce the amplitude of the signal obtained from the DAC with a gain less than one given by:

$$V_o/V_i = (-R_f/R_1) \tag{11}$$

Next, a second operational amplifier circuit is used in order to obtain the non-inverted original signal with a larger magnification. To do so, a non-inverting amplifier was used with gain $V_o/V_i = (1 + R_f / R_1)$, which can not be less than a unit. Figure 4 shows both inverting amplifiers used after the DAC. Finall,y a non-inverting operational amplifier was used to represent the gain (of the order of 10^3) provided by the

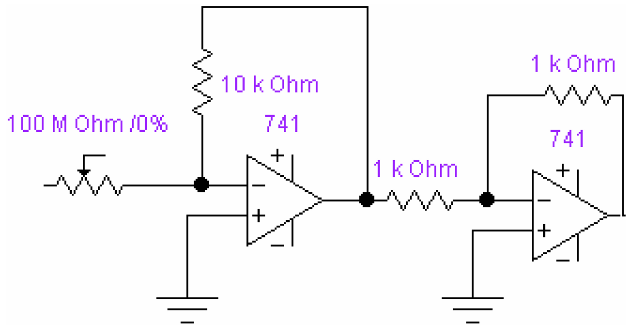

FIGURE 4. Inverting operational amplifiers used after the D-A converter in order to produce the electronic signal which represents the optical pulse produced by the laser oscillator.

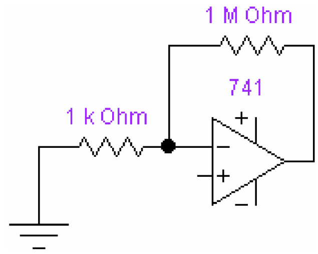

FIGURE 5. Electronic representation of the laser amplifier.

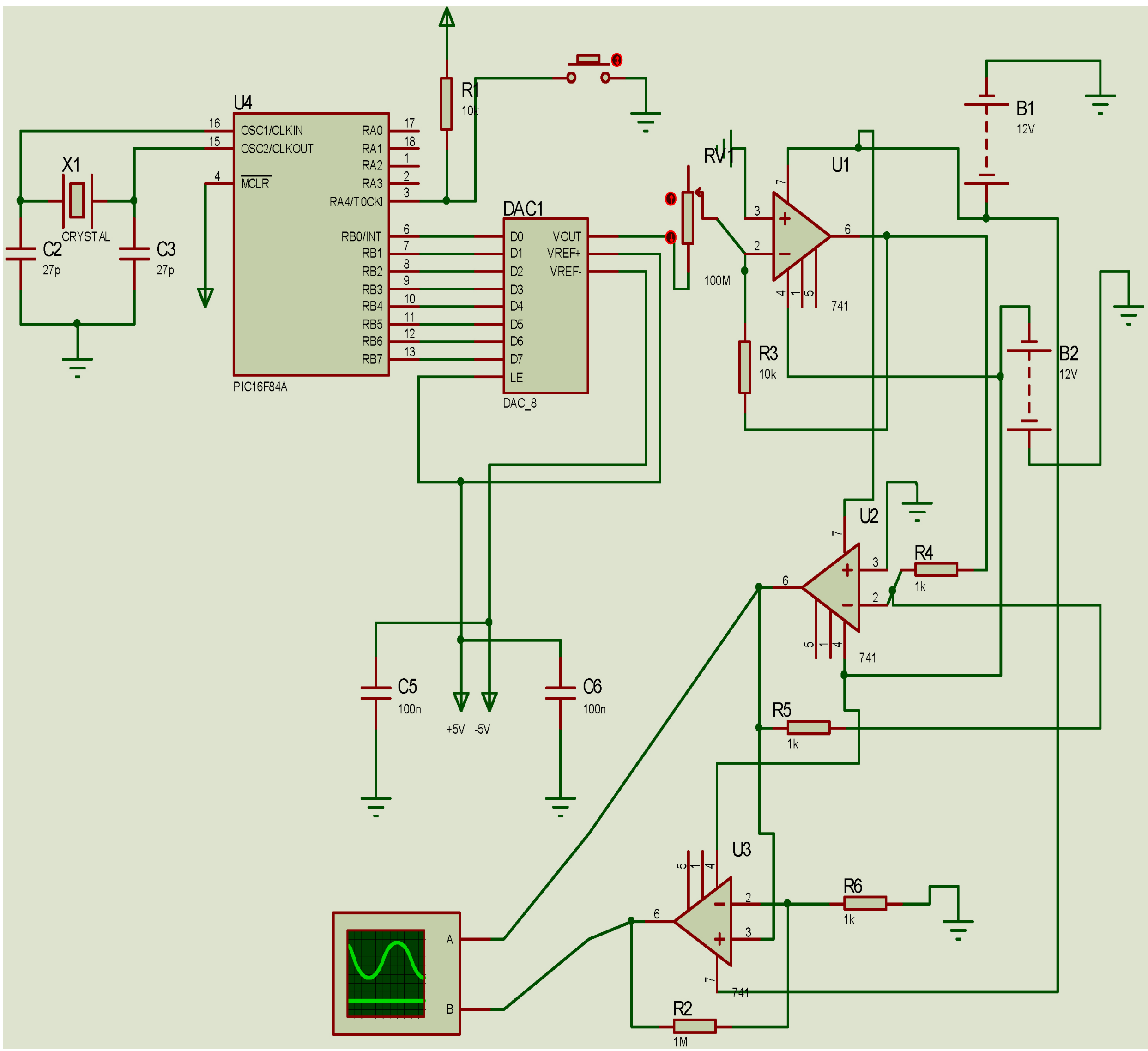

FIGURE 6. Full schematic diagram of the electronic system to simulate the oscillator-amplifier laser system. The output digital signal from the microcontroller is transformed into an analog signal through a DAC, and this signal is amplified with a less than one gain using two inverting operational amplifiers. This signal represents the optical signal produced by the laser oscillator and is sent to channel 1 of the oscilloscope. Finally this signal is amplified using a non-inverting operational amplifier, which represents the laser amplifier, and is sent to channel 2 of the oscilloscope.

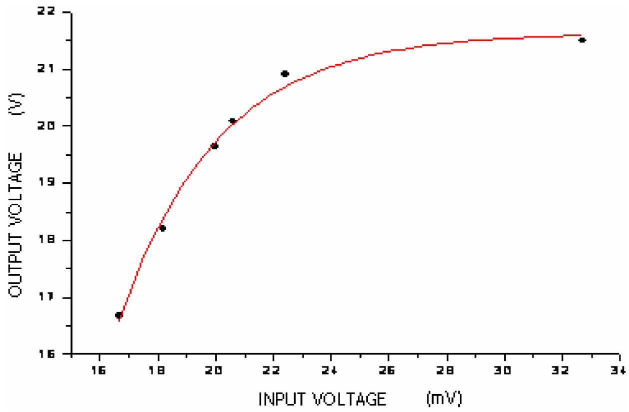

FIGURE 7. Input-Output plot obtained with the electronic system. This is qualitatively similar in gain to that obtained experimentally using the laser system. The continuous line shows the best fitting to the solution of a logistic equation.

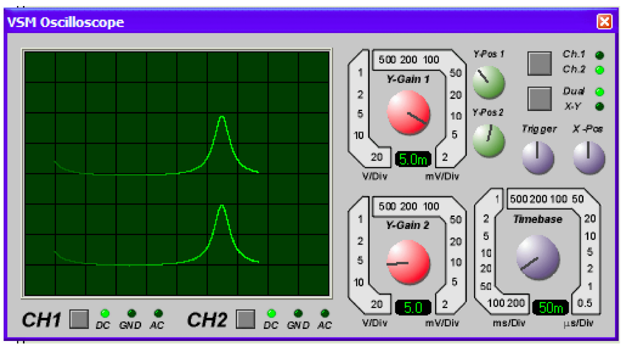

FIGURE 8. Oscilloscope results showing, in the upper part, the electronic signal which represents the optical signal produced by the laser oscillator and, in the lower part, the electronic signal which represents the amplified optical signal. Vertical voltage scales show a gain of 1000.

laser amplifier. The gain of this amplifier is given by:

$$V_o/V_i = (1 + R_f/R_1) \tag{12}$$

Figure 5 shows the non-inverting operational amplifier circuit. It should be noted that Eqs. (6) and (12), which describe the optical and electronic amplification in a laser and an operational circuit respectively, are isomorphic. Both represent the linear amplification of small signals. As will be shown in the following section, both the optical and the electronic amplifier will work in this project in the upper limit of the linear amplification where the non-linear saturation region begins.

5. Results

Figure 6 shows the full schematic electronic diagram of the electronic simulation of the oscillator-amplifier laser system. The 4 MHz crystal generates the clock signal for the microcontroller. The output digital signal of the microcontroller is transformed into an analog signal using a DAC. This signal is amplified with a less than one gain, using two inverting operational amplifiers. The electronic signal obtained represents the optical pulse produced by the laser oscillator, and is sent to channel 1 of the oscilloscope. Next, this signal is amplified using a non-inverting operational amplifier circuit and sent to channel 2 of the oscilloscope. As (was) already mentioned, it should be noted that we are working in the non-linear saturation region of the amplifier, and therefore the output is no longer linear. Figure 7 shows the input-output plot obtained with the electronic system which is qualitatively very similar to the one obtained using the laser amplifier shown in Fig. 2. Figure 7 does not show experimental error bars because they are too small. The continuous line represents the best fitting to the experimental data. Finally, Fig. 8 shows the oscilloscope obtained results of the electronic signals that represent the optical signal of the laser oscillator and amplifier clearly showing a gain of the order of 10^3, very similar to that observed in the optical laser system.

6. Conclusions

In this paper, experimental results are presented on the electronic modeling of a molecular N_2 laser oscillator-amplifier system, based on Blumline configurations. The electronic system is based on a microcontroller and operational amplifier circuits which qualitatively reproduce the results obtained by the laser fundamentally in relation to gain and pulse shape and clearly not in relation to the temporal and energetic characteristics. The results presented here are a pedagogical tool that make it possible to understand clearly the relation between the equations describing the amplification of a laser pulse in an active laser medium [Eq. (1) and its solution Eq. (5)] with what physically takes place in a laser in the linear [Eq. (6)] and non-linear or saturation regime [Eq. (10)]. The electronic device presented here was successfully (according to the public) used during the lecturing of undergraduate courses and popular science talks about lasers, photonics and quantum electronics.

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