

# A Pure Optical Arrangement Using an Optical Transistor to Form a Temporally Controlled Sequence of Nanosecond Pulses

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**Abstract** – We describe and analyse in detail our new approach to developing a simple, purely optical, device for converting continuous laser radiation into a series of nano (or sub-nano) pulses with controllable duration and temporal (and spatial) spacing. The basis is the application of the optical transistor, which we have introduced as an optical device, to control light by light in a purely optical way. In particular, we show the possibility of using a saturable Cr<sup>4+</sup>:YAG absorber with its typical manufacturing parameters. The same methodology is possible using saturable dyes as the control medium.

**Keywords** – optical transistor, control light by light; Cr<sup>4+</sup>:YAG absorber; sequence of nanosecond pulses; brightening medium.

## I. INTRODUCTION

The development of methods and techniques to produce laser light in nano- and sub-nanosecond pulses, especially rectangular in shape and variable in duration (~1 ns to several tens of ns), is a matter that is continually receiving attention in the literature and practice. Such pulses are of great interest for use in optical communications test systems, high-speed optoelectronics, remote vibration control of objects and scientific research.

This paper presents a novel method for converting continuous laser radiation into a series of nano- and sub-nanosecond pulses with controlled duration and temporal spacing. The primary objective is to define and theoretically model the proposed approach, rather than to generate practical results.

### A. General presentation

In this work, we develop an original and simple-to-implement purely optical approach that we have proposed for the desired transformation of laser radiation. The approach allows the formation from incident continuous laser radiation of a series of short pulses of the order of nano- and sub-nanoseconds, or the shortening of a nanosecond pulse by applying an interference wedge structure (IWS) [1,3,4]. In the solution, light is very efficiently controlled by light. In particular, we show the possibility of an attractive use of a saturable Cr<sup>4+</sup>:YAG absorber with its typical fabrication parameters. Such an absorber operates at the wavelength (1.06 μm) of one of the most common lasers, Nd:YAG, which increases the practical importance of such a study [2].

In order to address the challenge of transforming continuous laser radiation into a controlled series of nano- or sub-nanosecond laser pulses, we have developed a purely optical approach utilising our novel optical element, which we refer to as an "optical transistor" [3]. The optical transistor plays a pivotal role in our solution, facilitating the modulation of continuous-wave laser beams into pulse sequences without the necessity for electronic components. A general overview is provided in Fig. 1. In the configuration, the optical transistor is based on a Cr<sup>4+</sup>:YAG crystal plate and operates as a Fabry-Pérot interferometer (FPI). This configuration is fundamental to achieving precise control over the light.

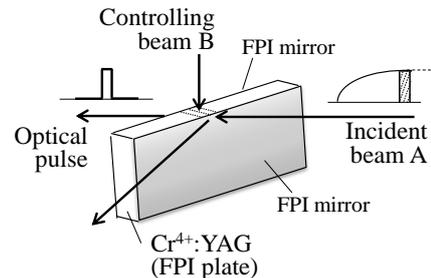


Fig. 1. The optical transistor structure [3,5] functions as a Fabry-Pérot interferometer (FPI), employing its intrinsic interference properties to achieve precise control over optical transmission and reflection.

The FPI has two input channels. The first input is a horizontally directed beam (denoted as Incident beam A) that enters the interferometer through the mirrors. The second input is a vertically directed beam (Controlling beam B) that enters directly into the gap between the mirrors. In a standard FPI, resonance transmission depends on factors such as mirror reflectivity, the thickness of the interferometer, the refractive index at the beam's entry point, and the angle of incidence. In our implementation, an additional level of control is introduced through the direct illumination of the gap between the mirrors with the vertical beam. The beam interacts with the saturable absorber medium situated within the confines of the gap.

The introduction of Incident beam A through the highly reflective mirrors results in a low transmission coefficient through the FPI, due to the high reflectivity of the mirrors. Nevertheless, the introduction of a low-power vertical beam directly into the gap enables effective control of the FPI's transmissivity. This method allows for the precise initiation

and termination of the pulse sequence, as the vertical beam can modulate the absorption properties of the medium within the FPI.

This innovative approach not only facilitates the efficient conversion of continuous-wave laser radiation into short pulses but also offers a robust mechanism for controlling light using light itself. A significant benefit of this approach is its simplicity, as well as its resistance to external magnetic and electric field disturbances, which enhances stability and precision. In addition, the versatility of the optical transistor enables smooth wavelength tuning of the incident laser beam, further extending its applicability in various practical applications.

The basic element and the principle of our solution here are illustrated in Fig 2.

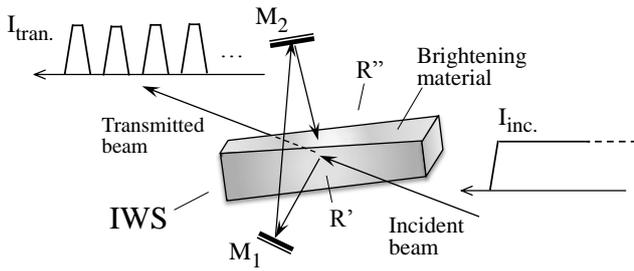


Fig. 2. Principle of controlling light by light using an optical transistor. Here: IWS - Interference Wedged Structure;  $I_{inc}$  - intensity of the incident beam;  $I_{tran}$  - intensity of the transmitted beam;  $R'$ ,  $R''$  - side reflection coefficients of the interferometric structure;  $M_1$ ,  $M_2$  - two mirrors forming an optical delay line.

The element depicted in Fig. 2 (the fundamental configuration) is realised as an interference wedged structure IWS, illustrated in the schematic of the basic design as a single angle and was defined by us as an optical transistor [3]. The configuration is achieved by the use of two dielectric mirrors, which are either parallel, in the case of a Fabry-Perot interferometer, or form a small angle, in the case of a Fizeau interference wedge. The IWS structure with brightening materials is formed as a crystal by  $Cr^{4+}$ :YAG or cuvette with an optically saturable solution. The incident beam  $I_{inc}$  is the entering light beam in the IWS with temporal intensity, as indicated in the graphs. The transmitted beam  $I_{tran}$  is formed by the passed and treated beam of constant intensity ( $I_{inc}$ ) through the IWS. The graph of its temporal transformation is shown as a sequence of pulses. The two mirrors  $M_1$  and  $M_2$  with full reflection form an optical delay line. In the IWS, the mirrors with coefficients of reflection  $R'$  and  $R''$  represent the side of the crystal (or cuvette). The element depicted in the subsequent figure enables the intensity of a light beam to be regulated by a considerably less intense optical beam.

### B. Theoretical analysis and fundamental principles.

The functionality of the optical transistor was adapted to enable the generation of a series of short pulses (nanosecond duration) from a continuous-wave incident light beam, with precise self-control of their length and inter-pulse distance. In the optical transistor solution, which is an interference structure, the implementing pair of

parallel mirrors has a high reflection coefficient, exceeding 80%–95%. This pair of mirrors determines the highly expressed interference effects, similarly to a Fabry-Perot interferometer, and allows for high transmission in the interference region for the incident light beam. The parameters have been chosen to satisfy the condition of the relationship between the element thickness (distance between mirrors) at the incident segment and the wavelength of the incident beam:

$$\frac{k \cdot \lambda}{2} = e \cdot n \cdot \cos \theta \quad (1)$$

where  $e$  is the element thickness,  $n$  is the refractive index,  $\lambda$  is the wavelength and  $\theta$  is the angle of incidence at which there is a maximum of the interferometer transmission - spectral resonance for transmission.

The solution that employs a wedged structure enables the tuning of the transmission frequency with the translation of the wedge and variation in thickness, thereby facilitating the operation of the device at a specified interval for different wavelengths. The operation of the element in our solution is based on two key principles: firstly, the high sensitivity of the structure to internal losses; and secondly, the utilisation of an alternative approach that we have also incorporated into the solution. This approach involves the use of a suitable light beam to access and illuminate the inner medium between the mirrors. This is achieved not through highly reflective mirrors, but directly through the open end (gap) of the structure. The incident (working) beam is directed at the end of the interferometry mirrors, as illustrated in the provided figure. The gap of the interference structure is filled with a medium, which, when illuminated, reduces the absorption of radiation and increases the transmission for the incident beam through the mirrors. This is typically accomplished in Fabry-Perot (FPI) or Fizeau Wedge (FW) interferometers working beam. Therefore, we introduce a control beam that directly and efficiently illuminates the medium through the opening between the interference structure's mirrors. Furthermore, the losses in the gap are significantly diminished when illuminated with the control beam. The medium may be a  $Cr^{4+}$ :YAG crystal or a suitable dye solution. When illuminated directly with 1.06  $\mu m$  radiation, the  $Cr^{4+}$ :YAG crystal becomes transparent and its absorption of this wavelength decreases significantly. Consequently, the transmission in this region of the FPI or FW increases significantly. This phenomenon could also be observed if a suitable dye solution is employed, but in a more complex configuration, involving the introduction of a cell, either filled or with the flow of the dye solution.

The high reflection coefficient of the mirrors, which is in the order of 90-95 %, results in a significant dependence of the interferometer transmission on losses, even those of a minor amount, in the medium located between the interferometer mirrors. The interferometer effectively blocks the propagation of radiation incident on it as it is reflected by the front mirror, specifically the mirror on which the working beam falls.

In our proposed solution, the interferometer's transmission is controlled by direct illumination of the introduced medium between the mirrors forming the

interferometer, a medium that can be readily brightened, through the gap between the mirrors. The illumination is direct, originating from a second external source. Of particular interest is the use of incident radiation itself, as presented in the following sections of this work. Consequently, a pair of mirrors or a system of mirrors directs the reflected controlling radiation, which is separate from the incident beam in the device, to the gap situated immediately adjacent to the incident beam's transmission section (see diagram). This allows the radiation to penetrate the illuminating medium between the mirrors without undergoing any reflection loss in the mirrors themselves. The direct illumination of the medium, rather than through the highly reflective mirrors of the interferometer, results in a notable reduction in absorption within the specially selected introduced medium. This leads to the interferometer device becoming highly transmissive to the incident radiation, which would otherwise be transmitted through the interferometer mirror.

The intensity  $I$  of the transmitted beam through a FPI is governed by the fundamental principles of interference and is described by the following expression [2]:

$$I = \frac{I_o(1-R)^2 a}{(1-a \cdot R)^2 + 4a \cdot R \sin^2(\delta/2)} \quad (2)$$

In this relation, the following definitions apply:  $I_o$  is the intensity of the incident beam,  $R$  is the reflectivity of the interferometer's mirrors,  $a$  is the absorption coefficient of the light intensity for a single pass through the interferometer gap and  $\delta$  is the phase difference [2]. In the case of the saturable absorber  $\text{Cr}^{4+}:\text{YAG}$  we have used the typical initial absorption characteristics as a function of illuminating power. For the case of simplicity, the experimental data for the absorption of  $\text{Cr}^{4+}:\text{YAG}$  as a function of incident energy density (in  $\text{J}/\text{cm}^2$ ), with a pulse duration of approximately 20 ns at a wavelength of  $1.06 \mu\text{m}$  have been directly applied [5-7]. The sample length is accepted to be 0.265 cm. The non-saturated transmissivity for an energy density of  $0.01\text{--}0.1 \text{ J}/\text{cm}^2$  is approximately 0.55, while the saturated transmissivity at higher energy densities (greater than  $0.5 \text{ J}/\text{cm}^2$ ) is approximately 0.85.

A well-established calculation, based on the provided data, yields a non-saturable absorption coefficient  $\alpha=2.23 \text{ cm}^{-1}$ . As the input energy of the illumination increases, the absorption decreases. For energy levels between 0.4 and 0.6 J within the same pulse duration, the absorption coefficient is  $0.61 \text{ cm}^{-1}$ . It can thus be concluded that the transmissivity of the saturated sample is approximately 1.5 times greater than that of the non-saturated sample. This effect is typical when the sample is used in a conventional manner to control light with light, resulting in a maximum controlled light intensity variation of approximately 1.5 times across all controlling intensities. However, the utilisation of our devices has the potential to significantly enhance this effect, achieving an increase in light variation intensity by an order of magnitude, approximately 15–17 times, in both saturated and non-saturated cases.

It is of interest to consider the dependence of the transmitted radiation, defined by the transmission coefficient  $T$ , with respect to the maximum (taken to be 1) of the losses in the interference gap, as this dependence affects the construction of the system. Fig. 3 illustrates a cycle of calculations utilising the methodology detailed in the authors' previous work, as referenced in [1, 3], which explores the dependence of interferometer transmission on the reflectivity  $R$  of its mirrors, which can be controlled by regulating the internal losses within the interferometer. Fig.3(a) depicts a single pass of the beam through the interferometer active medium; whereas Fig. 3(b) illustrates a scenario involving two passages with a reversible mirror.

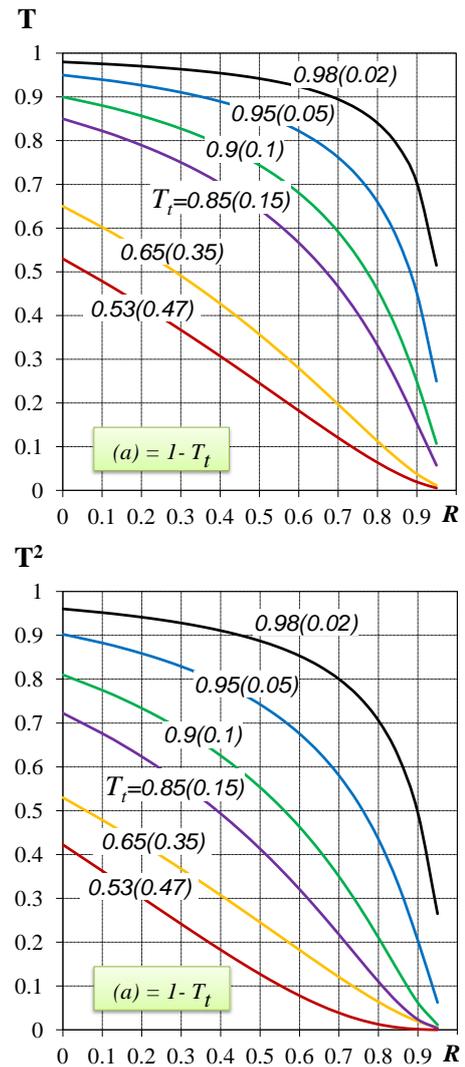


Fig.3. Series of calculation (the methodology, in detail in authors' work [1, 3] for the considered interference structure) - the dependence of the transmission of the interferometer structure  $T$  on the reflection coefficient  $R$  of the forming mirrors and the internal losses ( $a$ ) of the medium ( $T_i$  - transmission of the medium placed between the mirrors of the interferometer). (a) single pass and (b) double pass with a reversible mirror of the beam through the interferometer active medium

The graphs illustrate the curves of this dependence, calculated for the specified parameter. The relative transmission, expressed as a percentage, with respect to the

maximum transmission, which is assumed to be 1, of the medium is also shown. Additionally, the graphs present the relative absorption and scattering losses as the operating radiation passes through the medium. It is evident that the transmission of the introduced medium between the mirrors of the interferometer is dependent on the losses in this medium. Furthermore, it is possible to effectively vary the transmission of the interferometer by illuminating the introduced brightening medium.

A modification of the losses in the medium between the mirrors, from 0.15 to 0.02, in combination with a reflection coefficient of the interferometer mirrors of 0.8, resulted in a notable change in the interferometer transmission, from 0.32 to 0.85. This alteration in transmission is a significant outcome, as it demonstrates the potential for radiation control of the interferometry structure through the control of losses in the introduced brightening medium.

### C. Formation of a series of short pulses using the incident radiation itself for control

The proposed approach involves the formation of illuminating radiation using an appropriate deflection of the working beam and the introduction of the deflected radiation directly, bypassing the highly reflective mirrors. This method allows for direct illumination of the medium, which is achieved by increasing the transmission of the incident beam and reducing the reflected radiation in the inner medium. This results in a reduction of the luminance of the medium and an increase the losses within it, leading to a stopping of the transmitted radiation. The reflected radiation then increases, which again illuminates the medium and causes it to become transparent again. This process is repeated at a frequency set by the time of the medium brightening. Further details of the self-transformation of the incident continuous beam, which is denoted as 1, and the incident laser beam, can be found in Fig. 4, which also illustrates the output of pulse trains 8 and 9 from the system.

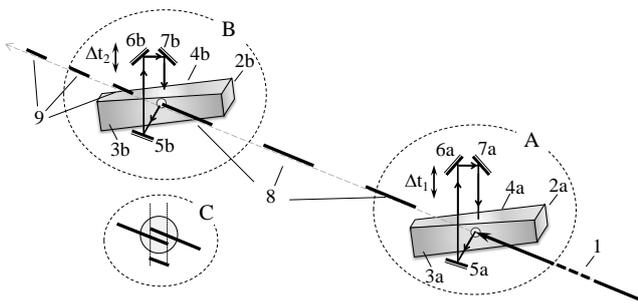


Fig. 4. The principle of self-conversion of the incident continuous beam using an optical transistor. With the designations “a” and “b”, in addition to the numbers, the corresponding elements of the two optical transistors are indicated. The incident beam is 1, the output pulse trains are marked as 8 and 9 respectively. Sub-blocks A and B correspond to the two transformation stages of the input beam 1. Sub-block C demonstrates the principle of pulse formation.

In the figure, two identical optically coupled sub-block A and sub-block B are given in series to self-transform the

incident continuous laser beam into a train of equidistant laser pulses of nano-durations. In the figure, the numerical notations (2 to 7) are the same for both sub-blocks, with an additional notation “a” for the first and “b” for the second.

Let us consider the transformation of continuous radiation - the incident beam into a series of nano- or sub-nanosecond pulses. The interferometer with the brightening medium is denoted 2a, and its sides 3a and 4a. The optical line from the mirrors 5a, 6a and 7a deflects the incident radiation reflected from the wall of the interferometer 3a and directs it to the medium through the The transformation of a continuous radiation cw Nd:YAG emitting beam with a power of 5 W that enters the crystal Cr<sup>4+</sup>:YAG (the incident beam) into a series of nano- or sub-nanosecond pulses will be considered here. The device is presented with the notation of its elements in Fig. 4. The brightening medium is specially treated crystals of Cr<sup>4+</sup>:YAG, which are denoted 2a, and its sides are denoted 3a and 4a. The optical line formed by the mirrors 5a, 6a and 7a deflects the incident radiation, which is reflected from the wall of the interferometer 3a, and directs it to the medium through the gap between the mirrors. Initially, the absorber located between the interferometer mirrors 3a and 4a is not illuminated. The radiation entering directly into the interferometer medium, formed by the incident beam 1, is reflected by the wall-mirror 3a of the interferometer and then reflected by the mirrors 5a, 6a and 7a. This illumination of the interferometer medium causes it to become transmissive to the radiation, enabling the interferometer 2a to operate in transmission for the incident beam. The radiation illuminating the interferometer passes through the optical line 5a, 6a and 7a. During this time interval, the interferometer transmits the incident main radiation. This is because, during the nanoseconds that the radiation passes through the crystal (or cell), it interrupts the radiation incident through the marked line onto the intermediate medium. Once the illuminating radiation has traversed the line, the illuminated medium becomes transmissive. During this interval, the interferometer is open, allowing the radiation from beam 1 of the incident beam to pass directly through, thereby forming the passed nanosecond pulse, which has duration equal to the time required for light to pass through the optical line 5a, 6a and 7a. The interferometer is then “closed”, and the incident radiation is directed again through the line 5a, 6a and 7a to the open end of the brightening medium. During this period, the interferometer does not transmit. The described process is repeated at regular intervals, with each repetition defined by the time taken for the light to travel through the line 5a, 6a and 7a. This results in the periodic transmission of light pulses of nanosecond duration and identical intervals between pulses through the interferometer from the incident beam. In this manner, the continuous incident radiation on the structure passes in successive time intervals, transforming itself into a series of short optical pulses with the same time interval between them. The duration of the pulses can be varied in the nanosecond range by varying the length of the optical line 5a, 6a and 7a.

The second stage, sub-block B, functions in a comparable manner, employing an appropriate delay as indicated by the optical line lengths 5b, 6b, and 7b (the elements and notations are analogous to those in sub-block

A). This entails the further cutting off of a portion of the incident pulse from the first stage, thereby reducing the pulse duration and the interval between pulses in the train. A detailed analysis, similar to the previous one, demonstrates that the additional pulse shortening in the second stage is greater than twice that in the first stage. The complex sub-block C represents schematically the formation of the shortened pulses.

In a practical solution, the brightening medium can be a dye solution that absorbs incident radiation at a rate on the order of nanoseconds. Alternatively, to shorten the pulse for slower modulation, a combination of radiation at a wavelength of 1,06  $\mu\text{m}$  with the aforementioned dye solution is suitable. The utilisation of the solid-state brightening absorber  $\text{Cr}^{4+}:\text{YAG}$  as a dye laser medium, in addition to its greater accessibility, offers the benefit of a faster response time, occurring in units of nanoseconds. However, this technical solution is relatively more complex, entailing the introduction of a cell of liquid, a faster decay rate, and alterations to the properties of the liquid.

The developed optical system, which is purely optical in nature, has the capability of transforming continuous laser radiation into a series of nanosecond pulses that can be controlled in both duration and time distance. This system has the potential for effective application in the detection of moving or vibrating objects. The detection process is initiated by registering the change in distance between the pulses in the train. The initial test experiments have demonstrated a reasonable degree of alignment with the detailed theoretical development described.

To illustrate, the system under discussion lends itself well to the combination of continuous-wave laser radiation from a continuous-wave working Nd:YAG laser (at 1.06  $\mu\text{m}$ ) and is also adaptable for long pulses of approximately milliseconds, with an absence or relatively low level of pulsation. In the final case, we consider an emitted Nd:YAG laser with a power of 20 W and a spot diameter of 1 cm, which is assumed to be Gaussian. If the beam is collimated to a diameter of approximately 0.5 cm at the input of the system, the average continuous-wave power of the beam can be approximately 80 W/cm<sup>2</sup>. If the laser used is an Nd:YAG laser with pulse energy, this beam can be used in the aforementioned laser-optical system, and the emitted beam can be transformed into a sequence of short nanosecond pulses, which can be useful for a variety of applications.

## II. CONCLUSION

This work proposes a novel, purely optical technique for transforming continuous laser radiation, especially from long-pulse laser emission, into a sequence of nanosecond pulses that are temporally controlled in both duration and

time spacing. The resulting sequence displays consistent characteristics in terms of both duration and spacing. It is noteworthy that our solution does not necessitate the use of a pre-formed input pulse train via Q-modulation of the base laser. Instead, only an emitting laser with stable temporal characteristics is required, particularly one that emits continuous radiation.

Furthermore, the proposed system can be adapted for time-domain laser beam control, specifically using a deflected portion of the working beam. The formation of such a pulse sequence is of significant interest, particularly for essential applications in remote laser positioning systems - monitoring vibrations and movements of objects - as well as in traditional scientific research. A key advantage of purely optical formation and control of the sequence, in comparison to electro-optical methods, is the complete absence of influence from electric, magnetic, and electromagnetic fields.

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