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M. Andreana, F. Baronio, Matteo Conforti, A. Tonello, C. de Angelis, et al.. Mode-locking operation of a flash-lamp-pumped Nd:YAG laser at  $1.064\mu\text{m}$  with Zakharov-Manakov solitons. *Laser Physics Letters*, 2011, 8 (11), pp.795-798. 10.1002/lapl.201110071 . hal-02395130

**HAL Id: hal-02395130**

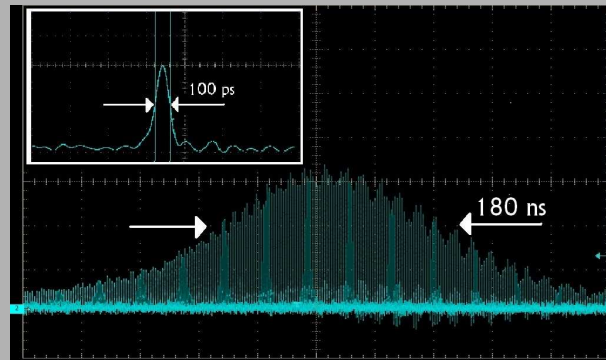
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Submitted on 5 Dec 2019

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**Abstract** We report experimental results on the mode-locked operation of a flash-lamp-pumped Nd:YAG laser at  $1.064 \mu\text{m}$ . The KTP crystal, which induces passive mode-locking, exploits the existence and properties of spatial Zakharov-Manakov soliton dynamics. A train of pulses with duration close to  $100 \text{ ps}$ , repetition rate of  $136 \text{ MHz}$  and modulation depth almost 100% has been produced. The mode-locked pulses are modulated with a longer  $180 \text{ ns}$  pulse envelope with repetition rate of  $10 \text{ Hz}$ .



Oscilloscope trace of a train of mode-locked  $100 \text{ ps}$  pulses of the flash-pumped Nd:YAG at  $1.064 \mu\text{m}$ . Inset: selected mode-locked pulse within the train.

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# Mode-locking operation of a flash-lamp-pumped Nd:YAG laser at $1.064 \mu\text{m}$ with Zakharov-Manakov solitons

M. Andreana<sup>1,\*</sup>, F. Baronio<sup>2</sup>, M. Conforti<sup>2</sup>, A. Tonello<sup>1</sup>, C. De Angelis<sup>2</sup>, V. Couderc<sup>1</sup>

<sup>1</sup> XLIM, CNRS and University of Limoges, 123 av. Albert Thomas, Limoges 87060, France

<sup>2</sup> Dipartimento di Ingegneria dell'Informazione, University of Brescia, Via Branze 38, Brescia 25123, Italy.

Received: ...

Published online: ...

**Key words:** mode-locking; nonlinear optics; solitons

**PACS:** 42.60.Fc, 42.65.-k, 42.65.Tg

## 1. Introduction

Pulsed lasers in the infrared and near infrared have been widely used in the fields of spectroscopy, nonlinear optics, remote sensing, micro-surgeon, micromachining and optical communication [1,2,3,4,5]. This kind of laser resources can be efficiently obtained by actively or passively Q-switching and mode-locking in solid-state lasers [6,7,8,9,10]. For high peak power applications, passively Q-switched and mode-locked lasers are more desirable than actively ones because of their compactness and simplicity.

A great variety of passive mode-locking techniques permit to produce short and ultra-short laser pulses: fast saturable absorber mode-locking, which makes use of the saturation properties of a dye molecule or a semiconductor

[11,12,13]; slow saturable absorber mode-locking, which exploits the dynamic saturation of the gain medium [14]; Kerr lens mode-locking, which exploits the self-focusing property of a transparent nonlinear optical material [15]; nonlinear quadratic mode-locking, which exploits quadratic nonlinear phenomena exhibiting intensity-dependent transmission or reflection [16,17,18].

In this Letter, we report experimental results on passive nonlinear quadratic mode-locking operation of a Nd:YAG laser. The laser is optically pumped with flash lamps [7]. The quadratic KTP crystal, which acts as saturable absorber, exploits the existence and properties of non diffractive spatial three wave solitons [19,20,21], in particular Zakharov-Manakov (ZM) soliton waves [22,23,24]. It is the first time, to the best of our knowledge, that such non-

\* Corresponding author: e-mail: marco.andreana@xlim.fr

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linear waves have been applied to build a pulsed laser. A train of pulses with duration close to  $100\text{ ps}$ , modulation depth near  $100\%$  and repetition rate of  $136\text{ MHz}$  has been produced. The flash-lamp pumped laser operates in a regime where the mode-locked pulses are modulated with a longer  $180\text{ ns}$  pulse envelope with repetition rate of  $10\text{ Hz}$ .

## 2. Nonlinear absorption mechanism

We consider the optical spatial non-collinear scheme with type II second harmonic generation (SHG) in a birefringent crystal. Two orthogonally polarized beams at the fundamental frequency (FF) are injected into the nonlinear birefringent medium to cross and overlap at the input face of the crystal. Each field is linearly polarized and aligned with a polarization eigenstate of the crystal. The corresponding wave-vectors are tilted with respect to the direction of perfect collinear phase matching, so that the sum-frequency harmonic propagation direction lies in between the directions of the two input waves. Depending on the input intensities, three different propagation regimes exist [24]. Linear regime: the beams injected at the (FF) do not interact. Frequency conversion: parts of the beams at FF interact and generate a field at the second harmonic (SH); the beams at FF which do not interact behave linearly. Solitonic regime: the beams at FF interact and generate a field at the SH; the generated field sustains a Zakharov-Manakov soliton at SH that, after a certain propagation length, decays into solitons at FF. The high intensity generated solitons at FF are spatially shifted with respect to the linear components at FF. Figure 1 shows typical numerical dynamics of the FF and SH beams, in the ordinary propagation plane  $x - z$ , in the linear, frequency conversion and solitonic regimes.

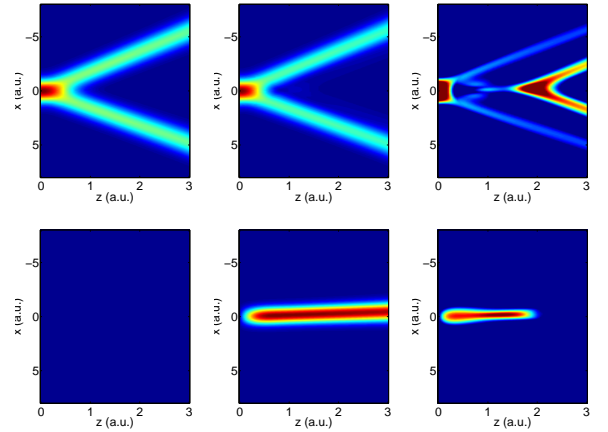
A device with nonlinear transmission (reflection) can be implemented by simply spatially transmitting (reflecting) the soliton beams at FF and only partially reflecting (transmitting) the linear beams at FF [25]. A typical intensity-dependent transmission, calculated in the case of a birefringent crystal, which may sustain ZM solitons, combined with a filter which provides  $100\%$  transmission of the soliton components and  $15\%$  transmission of the linear components, is shown in figure 2. Data correspond to a single-pass transmission through the set-up.

We use this mechanism for mode-locking of a flash-lamp-pumped Nd:YAG oscillator.

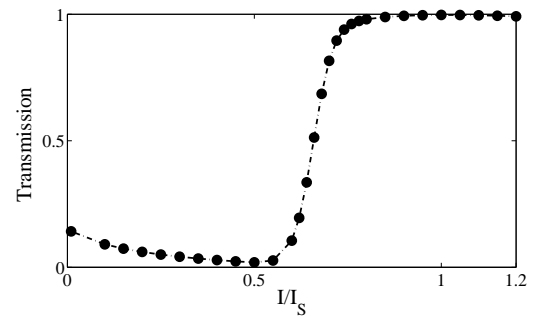
## 3. Experimental set-up and results

The oscillator configuration used in our experiments is shown schematically in figure 3.

The set-up consists of two flat mirrors M1 and M2. M1 has  $80\%$  reflectivity at  $1.064\ \mu\text{m}$ , and  $6\%$  at  $0.532\ \mu\text{m}$ ; M2 has  $90\%$  reflectivity at  $1.064\ \mu\text{m}$ , and  $6\%$  at  $0.532\ \mu\text{m}$ .

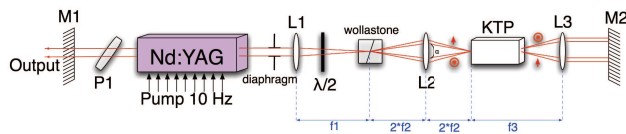


**Figure 1** Numerical dynamics of beams at FF (top row) and beams at SH (bottom) in the ordinary  $x - z$  plane. Left column, linear regime; central column, frequency conversion regime; right column, solitonic regime.



**Figure 2** Numerical data on the intensity-dependent transmission of a quadratic saturable absorber made by the combination of a type II SHG crystal, which may sustain ZM solitons, and a spatial filter which provides  $100\%$  transmission of the FF soliton components and  $15\%$  transmission of the FF linear beams.  $I$  is the intensity of FF input beams,  $I_s$  define the ZM soliton threshold.

The laser output is delivered through mirror M1. The active medium is a  $1.1\%$  atomic doped Nd:YAG rod of  $10\text{ cm}$ , transversely pumped by two flash lamps with a typical energy of  $25\text{ J}$ . The repetition rate is  $10\text{ Hz}$ . Single-transverse mode operation is ensured by a circular aperture (diaphragm) of  $1\text{ mm}$  in diameter. We use a Brewster polarizer, P1, to ensure the linear polarization of the beam; a lens, L1, a half-wave plate and a Wollstone cube polarizer to produce two independent beams with perpendicular linear polarization states. The two beams have almost the same amount of energy. Through lens L2, the beams are focused and spatially superimposed in the plane of their beam waist with a circular shape around  $200\ \mu\text{m}$  full width at half maximum in intensity (FWHMI). A  $3\text{ cm}$  long KTP crystal cut for



**Figure 3** Schematic set-up of the flash-lamp-pumped Nd:YAG laser operating in the mode-locked regime. L1, L2, L3 lenses; P1 polarizer; M1, M2 mirrors.

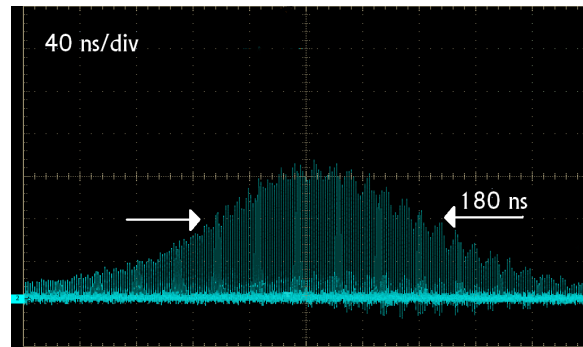
type II second harmonic generation is positioned such that its input face coincides with the plane of superposition of the two beams. The crystal is oriented for perfect phase matching. The directions of the linear polarization state of the two beams were adjusted to coincide with the ordinary and the extraordinary axes, respectively, of the KTP crystal. The wave-vectors of the input fields were tilted at angles  $0.7^\circ$  and  $-0.7^\circ$  (in the crystal) with respect to the direction of perfect collinear phase matching for the extraordinary and the ordinary components, respectively. Lens L3 ensures the beam recombination after reflection on mirror M2.

The choice and alignment of lens L3 can provide transmission of soliton beams at  $1.064 \mu\text{m}$ , and partial transmission of linear beams at  $1.064 \mu\text{m}$ , which are spatially shifted with respect to nonlinear waves. Thus, the combination of KTP crystal, which may sustain ZM solitons, and the lens L3 may behave as a saturable absorber. In fact, in a way similar to what is observed with a saturable absorber, the mode-locked regime is reached by increasing the pump level above an intensity threshold. The threshold intensity for mode-locked operation is estimated to be about  $800 \text{ MW}/\text{cm}^2$ .

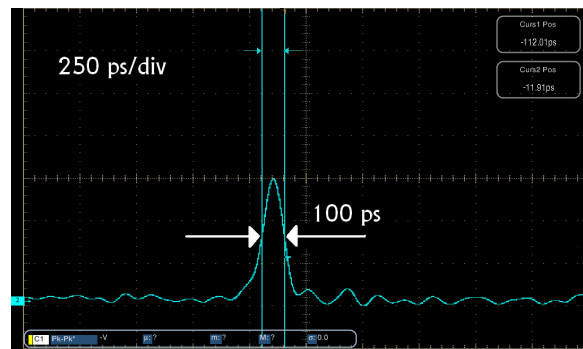
Figure 4 shows the mode-locked train of energetic pulses, with an envelope duration of  $180 \text{ ns}$  FWHMI. The mode-locking regime is simultaneously accompanied by a repetitive  $10 \text{ Hz}$  Q-switching like regime, due to the flash pumping repetition rate. Figure 5 shows a mode-locked pulse within the envelope train, with a duration of about  $100 \text{ ps}$  FWHMI. The mode locked pulse repetition rate is  $136 \text{ MHz}$ , which match with the cavity round trip time, and the modulation depth is almost 100%. The profile and the duration of the envelope train and the pulses are measured with fast photodiode and oscilloscope (minimum bandwidth  $12 \text{ GHz}$ ). The stability of peak power from shot to shot is close to 80%.

## 4. Conclusion

We have demonstrated, for the first time to our knowledge, the passive mode-locked operation of a flash-lamp pumped Nd:YAG laser using a type II phase-matched KTP crystal, exploiting Zakharov–Manakov solitonic dynamics, as saturable absorber. The mode-locked regime has produced train of pulses with duration close to  $100 \text{ ps}$ , repetition



**Figure 4** Characterization of the pulse train delivered by the mode-locked flash-lump-pumped Nd:YAG laser. The envelope train duration is about  $180 \text{ ns}$  FWHMI.



**Figure 5** Characterization of the profile and duration of a pulse selected in the central part of the pulse train delivered by the mode-locked flash-lump-pumped Nd:YAG laser. The envelope duration is about  $100 \text{ ps}$  FWHMI.

rate of  $136 \text{ MHz}$  and modulation depth almost 100%. The mode-locked pulses are modulated with a longer  $180 \text{ ns}$  pulse envelope with repetition rate of  $10 \text{ Hz}$ . The intensity threshold for mode locking is imposed by the corresponding threshold of soliton formation.

*Acknowledgements* The present research in Limoges is supported by the VINCI program 2010, in Brescia it is supported by Fondazione CARIPLO grant  $n^\circ 2010 - 0595$ .

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