Optics Communications 284 (2011) 398–404

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Optimal performances of a mode-locking technique: Theoretical and experimental investigations of the frequency-doubling nonlinear mirror

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ARTICLE INFO

Article history:
Received 21 January 2010
Received in revised form 29 April 2010
Accepted 29 August 2010

Keywords:
Frequency-doubling nonlinear mirror
Mode-locking
Picosecond
Nd:YAG laser

ABSTRACT

We present a detailed analysis of the mode-locker consisting of a nonlinear crystal and a dichroic mirror, introduced by Stankov and known as the frequency-doubling nonlinear mirror (FDNLM). Our aim is to determine optimal values for two physical parameters: the *conversion efficiency* η_0 of the nonlinear crystal, and the *reflection coefficient* R_ω of the output mirror. The optimization is based on a set of three figures of merit: the *reflected intensity*, the *pulse shortening ratio* and the *Gaussian shape factor*, which are combined to yield a final *decision factor*. Experimental investigations of η_0 and R_ω carried out using a FDNLM mode-locked Nd:YAG laser show good agreement with the theoretical predictions. In addition, a comparative study with other available experimental results is presented. This work demonstrates the capacity of this method to evaluate the best performance of this mode-locking not only for the steady-state pulse domain but also in the transient one.

1. Introduction

Over the last decades the mode-locking principle has widely opened the road for generating ultra short laser pulses in both the picosecond and femtosecond time scales. Indeed all-solid-state mode-locking techniques such as additive-pulse mode-locking (APM), semiconductor saturable asbsorber mirror (SESAM), soliton mode-locking, saturable Bragg reflector (SBR), and Kerr lens mode-locking (KLM) have attracted more consideration than other techniques based on organic dyes, because of their shot-to-shot and day-to-day stabilities, very fast responses, and self-starting ability [1,2].

The frequency-doubling nonlinear mirror (FDNLM) mode-locker, originally proposed by Stankov consists of a nonlinear crystal coupled to a dichroic mirror. Its additional advantages over the aforementioned techniques are the following: it can provide passive *negative* as well as *positive* mode-locking and it can be applied over a wide spectral range from infrared to visible where many nonlinear crystals are available [3–7].

The performances of the FDNLM to generate mode-locked laser pulses have been demonstrated in many works, not only for continuous pulse-train lasers (CPT), (usually abbreviated by cw, not to be confused with continuous-wave lasers) but also for pulsed pulse-train lasers (PPT) [3,4,8–10]. The latter case generally corresponds to flashlamp-pumped lasers that usually generate more energetic pulses than CPT ones. Recently optical pulses as short as 12 ps with a good shot-to-shot stability have been generated from a flashlamp-pumped Nd:YAG laser. This laser setup combines on the one side, active mode-locking by using an acousto-optic mode-locker (AOML) and on the other side both passive-positive and -negative mode-locking by using a FDNLM and a two-photon absorber (TPA) respectively [11,12]. That configuration has been successfully integrated into a sum-frequency generation spectrometer in order to probe molecular monolayers deposited on metallic surfaces [11,13].

Alongside the running experiments, the pulse shortening mechanism of the FDNLM has been described by Stankov by means of a simple theoretical model where the device reflection is represented by an intensity-dependent nonlinear reflection coefficient [14]. Later an analytical solution has been derived by Barr for the steady-state condition in the case of pulse propagation inside a laser cavity containing both an AOML and a FDNLM [15]. Note that the previous condition can be reached after a large number of pulse round trips inside the laser cavity which is appropriate to describe the function of FDNLM for continuous pulse-train lasers mode-locking. More complicated numerical models based on coupled wave equations for each oscillating mode have been developed in many works to describe the transient behavior of the optical pulse inside a laser oscillator actively and passively mode-locked by an AOML and by a FDNLM respectively, which turns to be convenient to simulate the mode-locking process in flashlamp-pumped lasers [16–23].

However, as one may notice, simulating oscillators that are actively as well as passively mode-locked with both passive-positive and -negative mode-locking using a FDNLM and TPA components respectively, becomes a cumbersome task especially for the determination of the physical parameters involved. In our opinion, this

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doi:10.1016/j.optcom.2010.08.071

difficulty accounts for the fact that rather than focusing on post-model analysis, all the aforementioned works investigate complicated analytical or numerical models, often limited to the pulse shortening ratio (PSR) and to the reflected intensity (I_r) (called the reflected pulse power in Ref. [20]) as the figures of merit of the FDLNM performances. In Ref. [21], the variations of nonlinear reflectivity, reflected energy and pulse lengthening ratio, are used with a new parameter called "steadiness" to describe the effect of the single-pass group delay in the crystal. Furthermore, in Ref. [22], the FDNLM nonlinear reflectivity is used with an additional parameter named "phase mismatch". Note that steadiness and phase mismatch could become important parameters and introduce additional complexity when the nonlinear crystal is relatively long as it is the case in Refs. [21] and [22] where LBO and $LiIO_3$ crystals of 15 and 30 mm were used. In our experiments relatively thin crystals in the range of 2 to 4 mm were used in order to avoid complexities and to select only two basic parameters, i.e. the dichroic mirror reflectivity R_ω and the second harmonic peak-power conversion efficiency η_0 as will be shown in the forthcoming sections.

In this work we present an extension of the Stankov model by defining a set of three functions of the two principal parameters of the FDNLM: the peak-power conversion efficiency η_0 of the nonlinear crystal, and the reflection coefficient R_ω of the mirror. These three running factors or figures of merit are: the reflected intensity (I_r), the pulse shortening ratio (PSR) and the Gaussian shape factor (GSF). The final decision factor that results from a weighted product of the three figures of merit yields best values for η_0 and R_ω and thus provides optimal performances of the FDNLM, as well as better understanding of the device functioning. In order to verify our predictions, experimental measurements have been carried out with a flashlamp-pumped Nd:YAG laser actively and passively mode-locked by using an AOML and a FDNLM combined with a TPA.

2. Theoretical investigation

2.1. The frequency-doubling nonlinear mirror (FDNLM)

The general configuration of a FDNLM is depicted in Fig. 1, in which a second harmonic generation (SHG) crystal is coupled to a dichroic mirror with a proper separation between them. In the first stage the fundamental wavelength (FW) pulse I_i passes through the SHG crystal (optimized for type I interaction) generating a pulse at the second harmonic (SH) with intensity proportional to the conversion efficiency of the crystal, η. At this stage special attention should be paid to the polarizations of interacting waves and to the crystal cut in order to maximize the second harmonic as shown on Fig. 1. The two pulses are then re-injected inside the crystal after being selectively reflected by the dichroic mirror that has reflection coefficient R_ω for the fundamental wavelength and $R_{2\omega}$ (≈ 1) for the second harmonic.

In the second stage, a down-conversion process takes place when the phase difference between the fundamental and the second harmonic, accumulated during propagation in air, reaches an odd multiple of π. The two passes through the crystal make this device similar to a mirror with an intensity-dependent reflection coefficient R_{NL}. In passive-positive action, the FDNLM reflects the high intensity part of the incident pulse more than the lower one, which leads to shortening the reflected pulse. The instantaneous reflection coefficient R_{NL} has been formulated by Stankov with respect to a normalized incident pulse intensity I_i as follows: [14]

$$R_{NL}(t) = B(t)\left\{1 - \tanh^2\left[\sqrt{B(t)}\operatorname{atanh}\sqrt{\eta(t)} - \operatorname{atanh}\sqrt{\eta(t)/B(t)}\right]\right\} \quad (1)$$

with

$$B(t) = \eta(t) + [1-\eta(t)]R_\omega \quad \text{and} \quad \eta(t) = \tanh^2\left[\sqrt{I_i(t)}\operatorname{atanh}\sqrt{\eta_0}\right],$$

$$\text{for} \begin{array}{l} \eta_0 \in [0, 1[\\ R_\omega \in [0, 1], \end{array}$$

where the two functions $\eta(t)$ and $B(t)$ represent the instantaneous second harmonic power conversion efficiency in the nonlinear crystal and the fraction of the total intensity (FW + SH) reflected by the dichroic mirror, respectively. From Eq. (1) one finds that R_{NL} is a function of time t and of the two principal parameters of the FDNLM, R_ω and η_0. η_0 is the power conversion efficiency $\eta(t)$ at the maximum of the incident pulse i.e. $\eta_0 = \eta(t=0)$. Nevertheless the expression of η_0 depends on the crystal characteristics and also on the incident intensity I_0:

$$\eta_0 = \tanh^2\left[\sqrt{\frac{8\pi^2 L^2 \left|\chi_{eff}^{(2)}\right|^2 I_0}{(n_\omega^0)^3 \lambda^2}}\right]. \quad (2)$$

$\chi_{eff}^{(2)}$ is the effective second-order susceptibility and n_ω^0 is the ordinary refractive index at the fundamental wavelength (λ) for the nonlinear crystal of length L. I_0 is the maximum intensity (peak intensity) of the injected pulse. The behavior of η_0 is represented in Fig. 2 as a function of I_0 for different crystal lengths in the case of β-barium borate (β-BBO cut at θ = 22.8 ° for type I interaction). The two dashed vertical lines shown on Fig. 2 indicate the estimated range of the intensity inside the cavity (determined by both the gain medium and the GaAs platelet inserted in the cavity as a TPA) in our experimental setup [10,11,13]. By rescaling Fig. 2 one can find η_0 for any different crystal types and irradiation intensities, and then find the corresponding crystal length that should be used in the laser oscillator. Noteworthy Eq. (2) is an approximation for an incident *plane* wave, which is not generally the case in experiments. However integrating the instantaneous conversion efficiency $\eta(t)$ over temporal profile and spatial distribution variations, as shown in Eq. (3), results in an *overall conversion efficiency* η_{oc} more adequate for comparison to experimental data. Table 1 shows the correspondence between the peak-power conversion efficiency η_o and the overall efficiency η_{oc} calculated for a

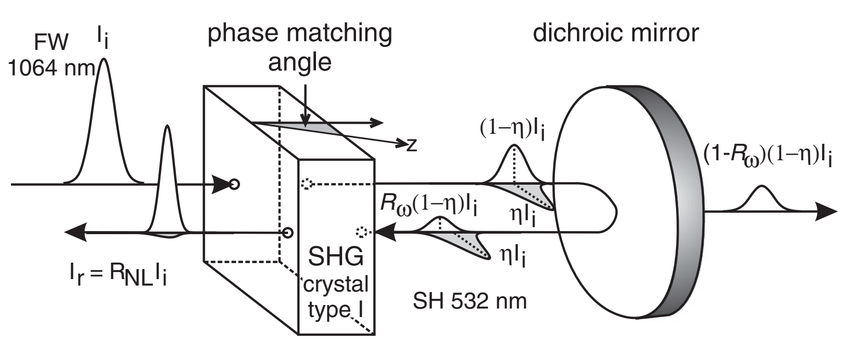

Fig. 1. Schematic view of the two passes into the frequency-doubling nonlinear crystal (see the text for more details).