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Widely tunable optical parametric oscillator driven by a pulsed diode-pumped nonlinear-mirror mode-locked Nd:YAG laser

Jin Yu *, Daniela Grando, Luca Tartara, Vittorio Degiorgio

I.N.F.M. and Dipartimento di Elettronica, Università di Pavia, via Ferrata 1, 27100 Pavia, Italy

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Abstract

We report on the development of a pulsed diode end-pumped Nd:YAG laser mode-locked by a nonlinear mirror and stabilized by an acousto-optical modulator. With the introduction of appropriate intracavity loss, the laser is able to generate 22.8 ps pulses with the energy of 4.5 μJ. After amplification and frequency doubling stages, the second harmonic radiation is used to non-collinearly synchronously pump a β-barium borate optical parametric oscillator in a walk-off compensated scheme. The system demonstrates a wide-tuning range from 635 nm to 2.55 μm for the signal output, with maximum average conversion efficiency as high as 42%.

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Keywords: Nonlinear-mirror; Mode-locking; Diode-pumped laser; Optical parametric oscillator

1. Introduction

Optical parametric generation (OPG) is widely recognized as a major approach to produce coherent radiation continuously tunable over different spectral regions, which is highly desired in nonlinear optics, spectroscopic analysis, material study and medical sciences. Synchronous pumping of an optical parametric oscillator (SPOPO) with a train of picosecond or femtosecond pulses provides an effective way to obtain not only an enhanced parametric gain in the OPG process, but also a decreased risk of crystal breakdown since pump sources with low or moderate input power are involved.

In the case of the picosecond SPOPO's, the role of pump sources was traditionally fulfilled by either fundamental wave output or higher-order harmonics of pulsed Nd:YAG lasers passively mode-locked by organic saturable dyes. Such a method of passive mode-locking is inevitably connected with problems of photo-chemical instability, performance degrading and necessity of periodical replenishment and maintenance. In the late 1980s an all-solid-state technique, named as nonlinear-mirror (NLM) mode-locking, was proposed by Stankov [1] as a promising candidate to generate picosecond pulses by using a rugged structure having a short response time and maintenance-free features. The scheme of NLM mode-locking was first introduced into flash-lamp pumped pulsed neodymium-doped lasers, resulting in short pulses with duration ranging from several tens to one hundred picoseconds [2,3]. It should be noted that the strong pump level of these flash-lamps enables the utilization of a large output coupling, comparable to dye mode-locked lasers, and accordingly exploits larger saturable modulation.

On the other hand, the rapid progress of semiconductor technology within the past decades allows the design and building of compact, reliable, efficient and low-noise diode-pumped lasers. In fact, the scheme of diode-pumping is extremely suitable for neodymium-doped materials, whose absorption band around 810 nm overlaps with the emission spectrum of GaAlAs diode lasers quite well.

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* Corresponding author. Tel.: +39 0382 985811; fax: +39 0382 422583. *E-mail address:* jinyu@unipv.it (J. Yu).

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With laser diodes as pumping sources, cw mode-locked Nd:YAG lasers were able to deliver transform-limited highly repetitive picosecond pulses at nanojoule level [4,5]. The more powerful pulsed diode-pumped Nd^{3+} lasers were operated both in side-pumping and end-pumping geometries, with different nonlinear crystals, such as type-I phase-matched BBO, LBO or type-II phase-matched KTP [6–8], utilized as intracavity pulse compressors. In these experiments, better performance and shorter laser pulses were obtained by adjusting the 'effective' saturable absorption, that is, by testing the combination of output couplers with different transmission and nonlinear crystals of various length.

In fact, in these pulsed ultrashort lasers, the whole process of pulse evolution acts as the result of a very complex interplay among different mechanisms present within the laser cavity, involving the simultaneously existing Q-switching and mode-locking. The ultimate achievable pulsewidth depends on different interconnected factors, such as laser enhancement and spectral confinement in the gain medium, pulse shortening in the saturable absorber and energy loss owing to the distributed intracavity loss, etc. Apart from saturable absorption characteristics, the development of the laser pulses can also be influenced through appropriate modulation of the dissipative loss within the resonator, to modify the pulsing dynamics and thus reach a better balance between the laser gain, saturable and non-saturable losses.

In this article, we describe an all-solid-state master oscillator-power amplifier (MOPA) OPO system based on a diode-pumped, active/passive NLM mode-locked Nd:YAG laser. The system is specially designed to give picosecond pulses with energy of the order of tens of microjoules and tunable over a very extended range of wavelengths. We show first that the output 1.064 μm pulses can be greatly shortened by introducing an additional intracavity loss into the NLM mode-locked laser cavity. After subsequent stages for energy amplification and frequency doubling, the obtained picosecond green 532 nm pulses are directed into a β-barium borate (BBO) crystal and an OPO is operated in a synchronous pump scheme. With the proper design and combination of an all-solid-state mode-locked laser oscillator and an OPO non-collinearly driven by the 532 nm radiation, the signal wavelength extends from visible (635 nm) to near infrared (2.55 μm), and the corresponding idler varies from 3.2 μm to 672 nm.

2. Nonlinear mirror mode-locked quasi-cw master oscillator

The master oscillator within the MOPA-OPO chain plays an important role in determining the ultimately achievable spectral and temporal qualities of the whole system. The diode-pumped NLM mode-locked lasers provide a stable and practical seed in driving the OPO's.

The laser resonator is chosen to be a Z-folded telescopic one, as sketched in Fig. 1. The active medium is a ∅4 mm × 15 mm Nd:YAG rod with neodymium concentration of 1.0at.%. End-pumping scheme is selected with a fiber-coupled GaAlAs diode array (BrightSolution srl, Italy, Model FDL-60Q) functioning as the pump source, delivering quasi-continuous pulses with energy as much as 12 mJ in the form of nearly-rectangular shots with duration of ~236 μs at a repetition rate of 10 Hz. Due to the limitation of the diode itself, the emission wavelength of this pump source could only be tuned to ~805 nm, to overlap the second highest peak within the absorption spectrum of trivalent neodymium ions around 800 nm. An active mirror geometry is employed with one end-surface of the active rod deposited with a coating highly reflecting at lasing wavelength (1.06 μm) and highly transmitting at the pump fluency (~0.8 μm), and the other end, which is 2° wedged along with the rod axis, is coated for high transmission at ~1.0 μm. Because of the low duty cycle of the pump source, no active cooling is required. The rod is simply housed in an air-cooled heatsink presenting a good heat dissipation.

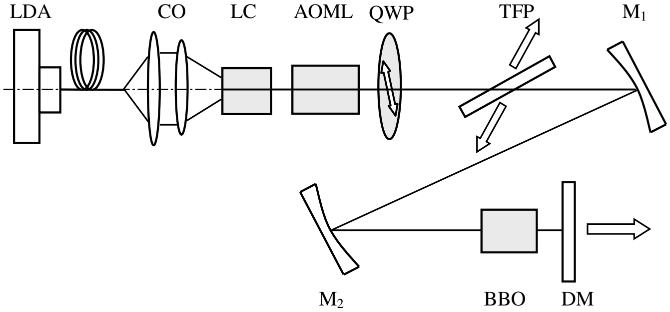

Fig. 1. NLM oscillator setup. LDA, laser diode array; CO, coupling optics; AOML, acousto-optical modulator; LC, laser crystal, Nd:YAG; QWP, quarter-wave plate; TFP, thin film polarizer; M_1 and M_2, highly reflecting mirrors for 1.06 μm with radius curvature 750 and 200 mm, respectively; DM, dichroic mirror with reflectivity of 100% at 532 nm and 69% at 1.06 μm.

The whole laser cavity is defined by the pumping surface of the Nd:YAG rod and by the output dichroic mirror (DM), completely reflecting the second harmonic (SH) at 532 nm but transmitting about 31% of the fundamental wave (FW, 1.06 μm). Two concave mirrors, M_1 with a radius of curvature of 750 mm and M_2 with a radius of curvature of 200 mm, form an intracavity Newtonian telescope. The defocusing of this telescope is designed so that the transverse cavity mode magnification fulfills two criteria: an appropriate oscillating TEM_{00} mode size (~0.76 mm, always defined as $1/e^2$ intensity radius) within the active rod (slightly larger than the size of the focused pump beam ~0.7 mm), and, at the same time, a focused waist on the DM (~0.14 mm) to ensure an efficient frequency doubling conversion within the nonlinear crystal (NLC) and thus to form a strong intensity-dependent reflection modulation in the double-passage NLM configuration. The tilting angle of these two folding mirrors is kept at a small value (~3°) to minimize the influence of cavity astigmatism and to obtain nearly transform-limited oscillation.