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# Diode-pumped self-starting Kerr-lens mode locking Nd:YAG laser

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## Abstract

Self-starting Kerr-lens mode locking of a longitudinally, diode pumped Nd:YAG laser is obtained using a piece of glass as the only additional intracavity element. To our knowledge, this is the first Nd:YAG laser operating in these conditions. It is obtained following a design procedure that minimizes the sensitivity on the values of the either fluctuating or poorly known parameters of thermal origin in the laser rod. This procedure is of general interest for KLM lasers. The prototype produces transform-limited pulses of 4.5 ps at a 101.5 MHz repetition rate, with an average output power of 800 mW (at 1064 nm) for a pump power of 3 W (at 808 nm).

*Keywords:* Kerr-lens mode locking; Diode pumped; Self-starting

## 1. Introduction

Since the first observation of Kerr-lens-induced mode locking (KLM) in a Ti:Sapphire laser [1,2], this mode of operation has been attempted in almost every type of solid state lasers [3]. Reaching KLM in diode pumped Nd:YAG laser has been a goal for years. Nd:YAG is the most commonly used solid state laser medium [4]. It is of lower cost, and less fragile, than alternatives as Nd:YLF. High power continuous wave (CW) diodes at 808 nm (the usual Nd:YAG pumping band) have become standard, and the same happens regarding the optics coated at 1064 nm. If the mode locking output is to be amplified, the practical advantages of using Nd:YAG are even more evident.

Up to now, there was an obstacle to reach KLM in Nd:YAG, this was the thermal induced birefringence (in Nd:YLF, for example, it is overwhelmed by the permanent birefringence of the host crystal). In spite of this obstacle, KLM was obtained in a diode pumped Nd:YAG, but an intracavity electro-optical modulator was needed to start the mode-locking [5]. As the modulator could not be removed from the cavity, the practical advantage over active mode locked operation was negligible. Recently [6], 6.7 ps near transform limited pulses were obtained by adding a piece of nonlinear glass as in a previous setup using Nd:YLF [7], but the diode pumping was replaced by a CW Ti:Sapphire laser pumping. The mode quality of the pumping laser allowed reaching an optimum matching be-

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tween the oscillating mode and the active region. From this last result, it was clear that the problem to beat in order to reach self starting KLM in diode pumped Nd:YAG is the poor quality of the geometry of the active volume. It makes the thermally induced lens and aberrations difficult to evaluate and, in consequence, to appropriately design the cavity to maximize the KLM strength.

In this paper we report, for the first time to our knowledge, a self-starting diode-pumped KLM Nd:YAG laser. We have eluded the obstacle of the uncertainty in the values of the thermal effects by adjusting the point of operation of the cavity in such a way that the influence of these effects is minimized. This procedure of cavity design is crucial to obtain KLM in Nd:YAG, but it is of the broadest interest, because low sensitivity to thermal effects (which are usually difficult to control) is desirable for any active medium. We believe the obtained pulses (4.5 ps) are the shortest among KLM Nd-doped crystals without using group velocity dispersion (GVD) compensation devices. The overall performance of the design allows to build a very simple setup and low cost source of ps pulses.

In the next section we describe the cavity design procedure. In the Section 2 we report the observed performance. In the Section 3, we sketch an argument explaining why transform limited pulses in the 5 ps range are attainable in lasers of this kind.

## 2. Design of the cavity

A scheme of the basic setup is shown in Fig. 1. The outputs of two high power CW diode lasers SDL-2372-P1 of 2 W (at 808 nm) nominal output power are combined and focused together onto the Nd:YAG rod with an $f = 80$ mm cylindrical lens in the horizontal plane and two $f = 19$ mm cylindrical lenses in the vertical plane. This arrangement produces a pump beam waist on the laser rod of approximately 60 μm ($1/e$ radius of the intensity). The size of the waist is practically the same in both planes, but the divergence angles of the pump beam on each plane are different, due to the characteristics of the diode laser emission. The Nd:YAG rod is 3-mm diameter, 5-mm long, 1.1%-doped and its second surface is 2° wedged to suppress etalon effects. The laser cavity is the simplest design in these type of lasers, being a single Z-folded one without slits or apertures (other than the soft aperture due to the active medium and thermal effects). Two high-reflecting 100-mm ROC spherical mirrors produce a focus inside a rod of SF57 glass (length: 8 mm) set at Brewster angle of incidence. A wedged, plane, 6% transmission mirror is the output coupler.

The conditions of cavity design of KLM lasers are fairly well established but, in the Nd:YAG case, there are some elements inside the cavity whose optimum values are not known with precision. This fact forbids a straightforward design of the cavity. The ‘unknown’ elements are caused by thermal effects. The pump radiation is strongly absorbed within the first two to three millimeters of the Nd:YAG crystal. Assuming a Gaussian pump beam profile, the thermally induced variation of the index of refraction is nearly parabolic in the central region of the pumped spot, which therefore acts as a positive, thick lens [4]. This effect is usually approximated assuming a curved mirror placed at the rod’s surface

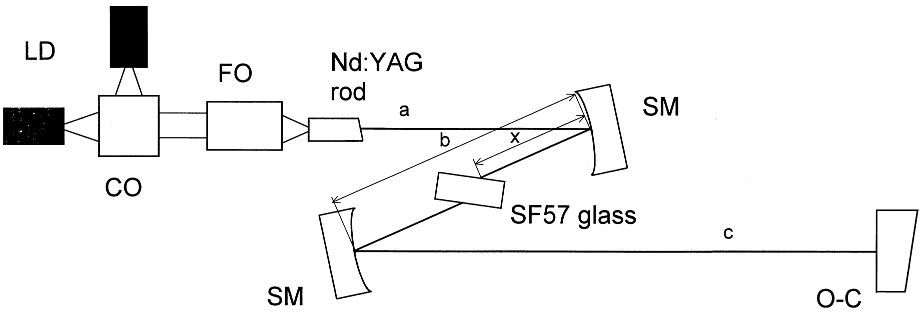

Fig. 1. Scheme of the cavity. LD: laser diodes. CO: collimating and combining optics. FO: focusing optics. SM: 100 mm ROC spherical mirrors. O-C: wedged output coupler. The dimensions are $a = 343$ mm, $b \approx 104$ mm and $c = 1006$ mm (see the text).

at the end of the cavity [6–8]. Outside the central pumped region, the index variation profile is logarithmic. This produces a strong phase distortion, that is approximated assuming the presence of a Gaussian aperture at the rod's end position. The values of the equivalent curved mirror and aperture cannot be safely computed from measuring the pump spot size and intensity, because the pump beam is far from being Gaussian.

In order to get an estimation of the values of the equivalent curved mirror and aperture, the Nd:YAG rod is aligned for laser emission with a plane output coupler mirror. The pump beam properties on the active medium are the same that for the Z-folded cavity. The output beam parameters (size and curvature) are then measured at different distances. The beam is numerically back-propagated, and values for the aperture and curved mirror are obtained. As the output beam is not Gaussian the beam parameters at different distances are not fully consistent, and the fit is not perfect. Anyway, this simple method allows us to estimate the value of the focal length of the equivalent curved mirror (the parameter with the largest error) between 50 and 200 mm (for 3 W pump power).

The equivalent curved mirror on the pumping end produces a beam waist that can be (due to the indeterminacy of its exact value) either inside the laser rod or outside as well. This uncertainty discourages using the rod as the nonlinear medium. This naturally leads to a design where a piece of material of high nonlinear index is placed at the focus between the folding mirrors. We have designed the cavity in such a way that a tight focus of radius about 20 μm is located near the midpoint of the folded arm, quite independent of the exact value of the equivalent curved mirror. In order to find the point of operation, we have performed a stability analysis of the cavity through the *ABCD* matrix formulation. The main free parameters are the distances between the two folding mirrors ($b$ in Fig. 1), the relative position of the nonlinear element ($x$) and the inverse of the equivalent mirror focal length ($\Psi$). An incidence half-angle of 10° on the spherical mirrors is found to compensate the astigmatism introduced by the SF57 rod.

Two of the stability limits are found to be independent of the thermal effects (they are the vertical straight lines in Fig. 2). The value of $b$ is therefore chosen near one of these limits ($b = 103.8$ mm). The

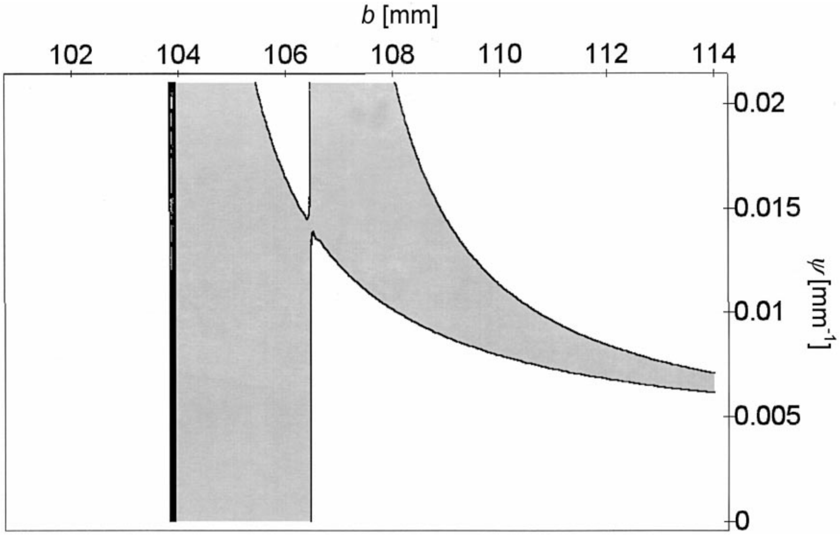

Fig. 2. Regions of geometrical stability (in gray) for the cavity as a function of the distance between concave mirrors $b$ and the inverse of the equivalent curved mirror focal length, $\psi$. The curved lines are thermal effects-dependent stability limits. The vertical straight lines are thermal effects-independent stability limits. Values of $a$ and $c$ as in Fig. 1.

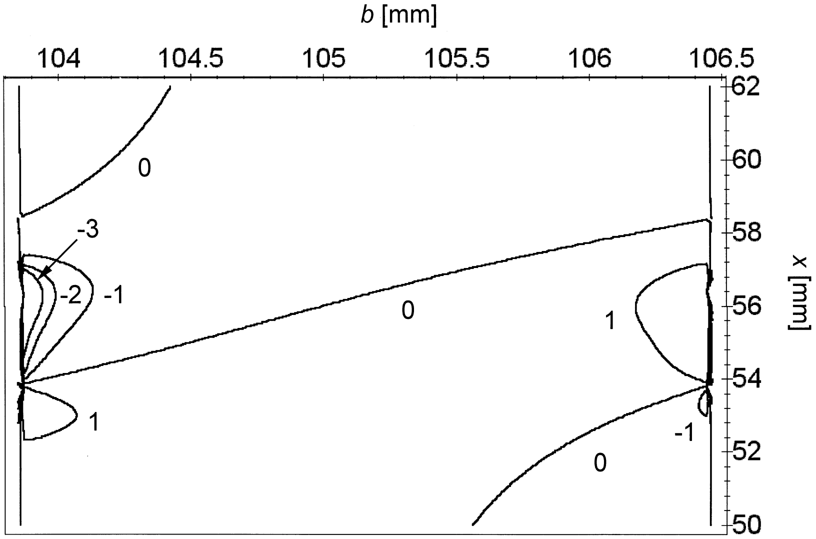

Fig. 3. Small signal relative spot-size variation $\delta$ as a function of the distance between the concave mirrors, $b$, and the position of the nonlinear element inside the resonator, $x$. The point of operation is $b \approx 104$ mm (minimum sensitivity to thermal effects, Fig. 2) and $x \approx 56$ mm (minimum $\delta$ on the $b = 104$ mm line). Values of $a$ and $c$ as in Fig. 1. The resonator is stable for 103.8 mm $< b <$ 106.5 mm.

lengths of the Nd:YAG rod's arm $(a)$ and of the output coupler arm $(c)$ are chosen following these two conditions. One: the mode size on the end of the YAG rod matches the pump beam size (60 μm). Two: the intersection point between the thermally independent limit and the thermally dependent limit (this point is about $\psi = 0.012$ mm$^{-1}$ in Fig. 2) should be at a value of the focus of the equivalent curved mirror shorter than the previously estimated values. This leads to $a = 343$ mm and $c = 1006$ mm. In this way, the working point ends up in a position where the mode beam parameters (size and curvature) are weakly dependent of the thermal effects. The total stability range of this cavity is $\Delta b \approx 2$ mm (nearly half the value in similar designs) and the position of the tight focus is always between 52% and 54% (measured from the midpoint towards the output) of the total folded arm length for a wide region of the parameters.

The KLM strength remains to be maximized. The position $x$ of the SF57 rod is still a free parameter. The KLM pulse-shaping strength is calculated following Refs. [9,10]. The relevant factor is the small signal relative spot size variation $\delta$, which must be negative and as large (in modulus) as possible. A map of the $\delta$ factor for different cavity parameters $b$ and $x$ shows that at $b = 103.8$ mm (determined before) and $x \approx 56$ mm the laser is in a region of strong KLM effect (Fig. 3). We check that the behavior of the $\delta$ factor is weakly dependent of the thermal effects if the equivalent mirror has a focal length larger than 120 mm. Regions near the determined point of operation show the same pulse shaping features for even stronger thermal lensing effects.

## 3. Experimental results

According to our experience, before attempting to achieve mode-locking, it is necessary to reach a high pump power density on the active medium and a matching as good as possible between the pumped region and the laser mode. The pump efficiency is optimized in an auxiliary plane-parallel cavity (length: 4 cm). By adjusting the pump focusing optics, we obtain about 1.35 W for 3 W pump power (with the same 6% output coupling). In other words, a conversion efficiency of 45% (quantum efficiency: 60%). The Z-folded cavity is then aligned for maximum output power. We reach an output power about 1 W. In these conditions, the threshold pump power is about 100 mW. After a slight adjustment of both spherical mirrors and the position of the SF57 rod in order to maximize mode beating, the mode locking emission starts spontaneously. The average output power in these conditions is smaller (about 800 mW) than in the optimal alignment condition.

The mode-locking repetition rate is measured to be 101.5 MHz. For a pump power of 3 W (at 808 nm) the average intracavity power is 12.6 W. Mode locking is not achieved with an intracavity power lower than 9.3 W even after realignment. A time-averaged spectral bandwidth of 71 GHz FWHM for the KLM output is measured with a 133-GHz FSR, 4-GHz resolution scanning Fabry–Perot interferometer. Fig. 4 shows a background-free intensity autocorrelation trace for the pulses. It is measured less than 4.5-ps FWHM assuming a $\mathrm{sech}^2$ shape. This practically is the transform-limited value for the measured bandwidth (4.4 ps). The obtained pulse length is less than half the value we had obtained in a similar cavity, with active phase modulation mode-locking [11]. To our knowledge, it is also the shortest pulse length reported with a KLM Nd-doped laser without using GVD compensation.

The output beam is uniform and circular, in spite of the unequal divergence angles of the pump beam and of a small remaining cavity astigmatism. If the values of the laser parameters are slightly modified the mode locking disappears and the output is CW. There is no appreciable difference between the spot size and shape, nor in the average output power and the spectral width, between the CW, mode-beating, and mode locking operations. The mode locking operation is sensitive to perturbations (air currents, vibrations). In a non controlled environment, it is interrupted about twice per minute, but it re-starts spontaneously. If the cavity is placed inside a box on a vibration isolated table, the mode locking is stable for hours. In this sense, its performance is equivalent to the KLM Ti:Sapphire laser.

In order to study the transient period of self starting, we modulate the current injected into one of the pumping diodes. When the current drops from 2.5 A to 2 A, the laser passes to CW operation. The mode locking operation starts spontaneously about 250 ms after the current recovers the 2.5 A value (see Fig. 5). The transient time increases with the modulation depth. For example, if the current drops to 1.5 A, the mode locking starts after 600 ms. We believe that these long transients (of the order of $10^7$ to $10^8$ roundtrips) are related with a thermal relaxation in the laser rod. A detailed study of this effect is currently being performed.

The obtained pulses are practically transform limited (chirp-free). This feature is not obvious, because

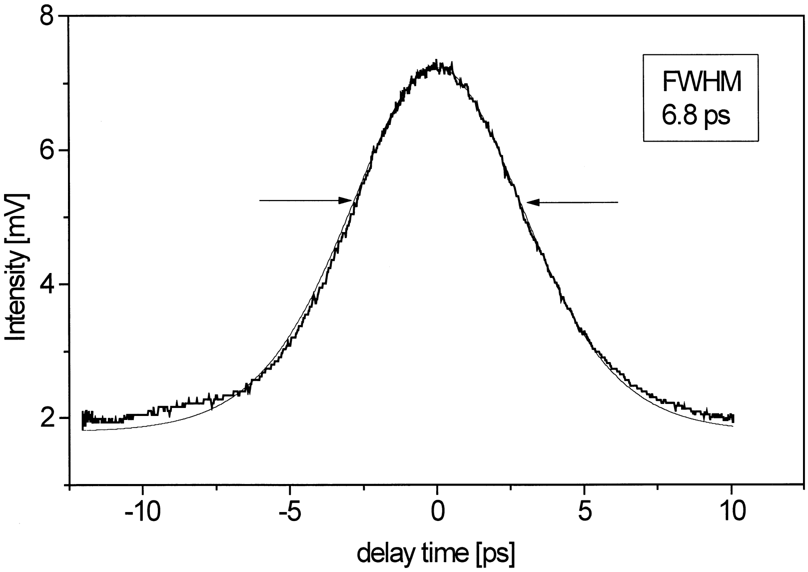

Fig. 4. Background free autocorrelation trace of the KLM pulses. The fit corresponds to a 4.5-ps $\mathrm{sech}^2$ pulse.

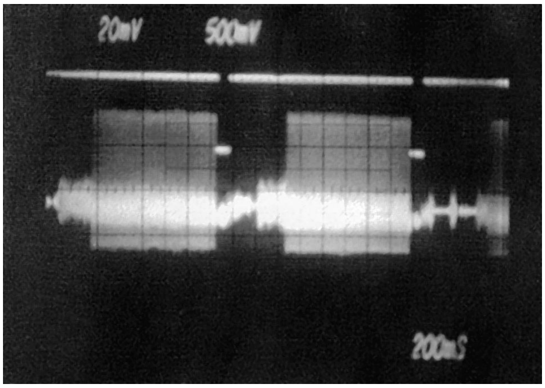

Fig. 5. Oscilloscope trace showing the self starting mode locking. Upper trace: modulated current in one of the pumping diodes. The current drops from 2.5 A to 2 A during about 80 ms. Lower trace: fast photodiode signal of the laser output. The mode locking starts spontaneously about 250 ms after the injected current recovers the mode locking value.

there is no GVD compensating device inside the cavity. The pulses suffer a net positive dispersion each round trip, due both to the linear material dispersion, and the nonlinear Self-Phase Modulation (SPM). However, these effects are small for our pulse's duration. The effect of the SPM and the GVD can be estimated using the standard matrix propagation through a dispersive nonlinear medium; the pulse duration exiting a piece of SF57 glass, assuming an initial duration of $\tau_0 = 4.5$ ps and no initial chirp is

$$\tau_{\mathrm{SG}}^2 = \tau_0^2 \left[ \left( 1 + \frac{\sqrt{2}\, Ub\beta'' z^2}{\tau_0^3} \right)^2 + \left( \frac{2\beta'' z}{\tau_0^2} \right)^2 \right],$$

where $U$ is the (intracavity) pulse energy, $b$ is the nonlinear SPM coefficient defined as in Ref. [12], $\beta''$ is the glass GVD coefficient and $z$ the length of the material. These parameters are, for our laser, $U = 110$ nJ, $\beta'' = 1.46 \times 10^{-4}$ ps$^2$/mm and $b \approx 3.9 \times 10^{-3}$ ps/nJ. Expression (1) gives a pulse broadening factor of $10^{-4}$, which is by all means negligible. In consequence, our laser operates in the regime of pure self amplitude modulation (SAM). This means that the mode locking action is mainly due to the mode size reduction at some aperture (implying a reduction of the losses) for increasing power. This favors short pulse operation in a way analogous to a fast saturable absorber. According to the fast-saturable absorber mode-locking theory [13,14], cavities with SAM and negligible SPM and GVD produce chirp-free, stable pulses (see Fig. 2 in Ref. [13]) in agreement with our observations.

## 4. Summary

A diode-pumped, self-starting Nd:YAG KLM laser using a piece of SF57 glass as the only intracavity element (besides the active medium) is described. The cavity is a single Z-folded one, and there are no slits or apertures added. It is one of the simplest cavity design reported for this kind of lasers. The successful solution is reached by looking for a region of the parameters where the influence of the (mostly uncontrollable) thermal effects is minimized. The design procedure is also useful for laser media other than Nd:YAG and, in general, whenever low sensitivity to overcome poorly known or fluctuating parameters in the laser rod is necessary.

The output pulses are practically transform-limited 4.5 ps FWHM, with an average output power of 800 mW for a pump power of 3 W. They are among the shortest for Nd-doped KLM lasers. They are produced by (self) amplitude modulation at the aperture formed by the active region. No solitonic pulse-shaping effects (which are known to be crucial in Ti:Sapphire) seem to be present here. The described prototype is a compact, simple and low cost all-solid state source for ps pulses at 1064 nm wavelength.

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