Nonlinearly coupled, gain-switched Nd:YAG second harmonic laser with variable pulse width

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An all-solid-state, gain-switched, green laser is developed using a side diode-array pumped Nd:YAG laser and a $KTiOPO_4$ (KTP) crystal as an intracavity frequency doubler. The effect of nonlinear coupling on the pulse width of the fundamental is studied and is found to be in good agreement with the experimental measurement. In this preliminary experiment, a peak power of 40 W at 532 nm corresponding to a pulse width of 409 ns is obtained for an average pump power of 2 W. Compared to a Q-switched laser, it is simple and does not require a high voltage RF driver or saturable absorbers in its operation. The laser may be useful where relatively longer nanosecond pulses are required such as eye surgery, micromachining, and underwater communication. © 2009 Optical Society of America

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1. Introduction

Stable nanosecond pulses of relatively longer width can be obtained by employing the technique of gain switching in solid state lasers. It is exploited from the phenomenon of relaxation oscillation observed due to their long upper state lifetimes. The first spike in a sequence of relaxation oscillation is selected by narrowing the excitation pulse and thereby switching the laser gain from above-threshold at the onset of the first spike to below-threshold just after its completion. Nd lasers are very appropriate for this purpose because of their relatively high emission cross section and moderately high upper-state lifetime.

An all-solid-state nanosecond green laser has immense applications in underwater communication, chemical processing, micromechanics and surgery, especially for the treatment of eye as 532 nm is easily absorbed by the various parts of the eye, particularly the retinal vessels. The green lasers as obtained by frequency doubling of the lasers operating around 1 μm are also a potential pump source for other laser materials, such as dyes and Ti:Sapphire.

Short nanosecond pulses with high peak power are usually generated by Q switching the lasers using an active device such as an acousto-optic modulator, an electro-optic modulator, or by using passive devices such as saturable absorbers. Although the peak power and pulse energy of the gain-switched lasers are low compared to the Q-switched lasers, they have their own distinct advantage and are a competitive technique, especially in the fiber lasers and microchip lasers. The technique of gain switching has an advantage over active Q switching because of its simplicity in operation, as it requires no high voltage or

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rf drivers. This technique also has some advantage over passive Q switching as it does not require any extra cavity component, such as a saturable absorber, which induces losses inside the cavity.

A gain-switched, single-mode frequency Nd:YAG laser was reported earlier by Owyoung *et al.* [1]. An efficient gain switching with a 100 ns pulse at a 1 MHz repetition rate was also reported in a Nd-doped fiber laser [2]. In diode-pumped $Nd:YVO_4$ and Nd:YAG lasers, the technique of gain switching was earlier demonstrated by Larat *et al.* [3]. Later, Sheng *et al.* reported a high-repetition-rate, gain-switched $Nd:YVO_4$ microchip laser [4]. The overcoupling increases the width of a Q-switched pulse. The theory of pulse lengthening in a Q-switched intracavity frequency-doubled laser was given earlier by Murray and Harris [5], and Young *et al.* demonstrated pulse lengthening in a Q-switched Nd:YAG laser operating at 946 nm using a lithium iodate crystal [6]. Later, Kracht *et al.* also demonstrated this technique in a Q-switched Nd:YLF laser operating at 1053 nm using a lithium triborate (LBO) and a $KTiOPO_4$ (KTP) crystal [7]. To the best of our knowledge, there is no report on the study of overcoupling in gain-switched lasers. Here we report for the first time on an all-solid-state, gain-switched green laser using a side diode-array pumped Nd:YAG laser and a KTP crystal for intracavity frequency doubling. We obtain a peak power of 40 W corresponding to a pulse width of 409 ns and pulse repetition rate of 150 Hz for an average absorbed pump power of 2 W. Here we employ a high-finesse cavity at the fundamental wavelength and low-finesse cavity at the frequency doubled wavelength for efficient intracavity second harmonic generation (SHG). The gain-switched pulses of different widths and repetition rates are achieved by changing the diode current, pump pulse repetition rate, and the pump pulse width. We also study the effect of overcoupling in the Nd:YAG laser due to the presence of the intracavity second harmonic (SH) generating crystal. We also calculate the pulse width of the fundamental radiation from the theory of relaxation oscillation both with and without taking nonlinear coupling into consideration. We obtain an experimental SH pulse width of 409 ns compared to a calculated pulse width of 107.6 ns at the fundamental wavelength without the nonlinear coupling. The increase in the pulse width because of nonlinear coupling due to intracavity SHG is also theoretically predicted from the coupled rate equation for the pulsed SHG laser. These values are then compared with the measured data.

2. Experiment

The schematic for the gain-switched green laser is shown in Fig. 1. A Nd:YAG rod of length 63 mm and diameter 2 mm with a Nd^{3+}-doping concentration of 0.6% is used as the gain medium. The central 32 mm of the rod is effectively pumped radially by 18 temperature-tuned pulsed-laser diode bars emitting at the wavelength of 808 nm. The pump pulse duration and the repetition rate can be varied over the range of 40–550 μs and 50–1 KHz, respectively. Because of the limitations on the peak current applicable in the laser diodes, the maximum average pump power of 2 W is used for a pump pulse width of 40 μs and a repetition rate of 150 Hz. Mirror M1 is a flat mirror having a high reflectivity at 1064 nm. Mirror M2 is concave with a radius of curvature of 200 mm with high reflectivity at 1064 nm and has a high transmittance at 532 nm and is placed at a distance of 385 mm from M1. The lasing wavelength of 1064 nm is confined in the cavity using mirror M3, which has a high reflectivity at the lasing wavelength. The distance between M2 and M3 is optimized at 10.5 cm. The KTP crystal (Castech, USA) with $\theta = 90°$, $\phi = 23.6°$, and antireflection coated at 1064 and 532 nm is placed near M3 within the cavity to generate the SH radiation. The cavity is optimized to achieve a small beam diameter of 200 μm at the center of the KTP crystal and a comparatively larger beam spot size of 1 mm at the Nd:YAG crystal that ensures a single transverse mode of operation. An additional mirror M4 with a high reflectivity at 532 nm is used behind mirror M3, so that the output is obtained from only one end of the resonator. This mirror is position very carefully to avoid any back conversion. The gain-switched pulse width is measured by a 500 MHz digital storage oscilloscope (Techtronix-3054A) after detection with a Si photodiode (HS-40, UDT sensor). The green output power is measured with a highly sensitive powermeter (NOVA II, 30A-SH, Ophir) in the mW range.

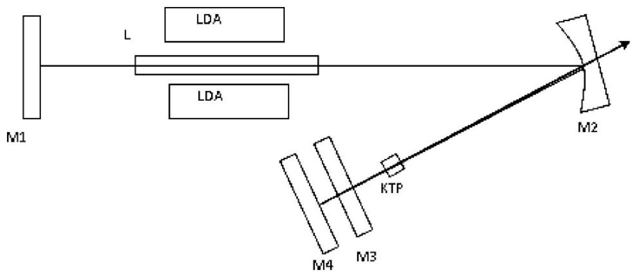
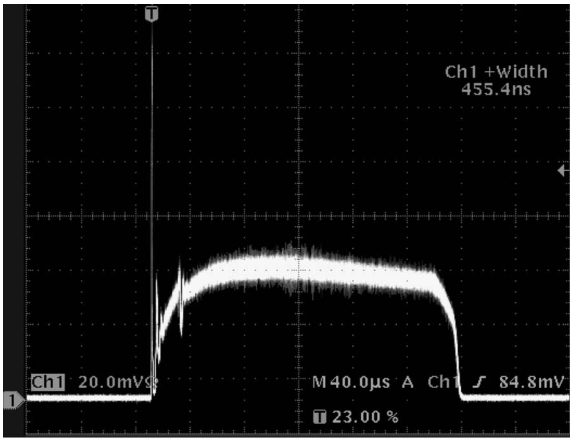


Fig. 1. Schematic of the experimental setup: L, Nd:YAG rod; LDA, laser diode array; M1, rear mirror (HR@1064 nm); M2, concave mirror (HR@1064 nm, ROC = 200 mm); M3, plane mirror (HR@532 nm); M4, plane mirror (HR@1064 nm).

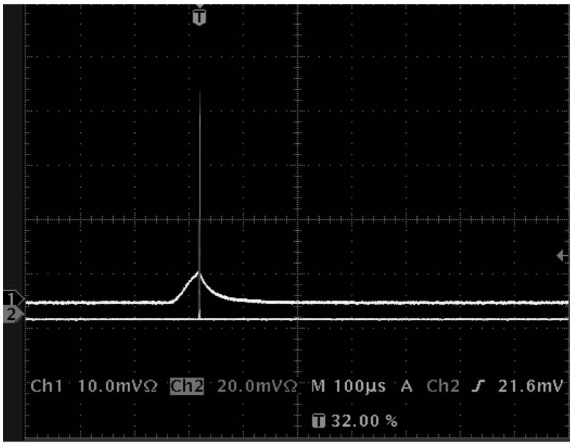
3. Results and Discussions

A. Experimental Results

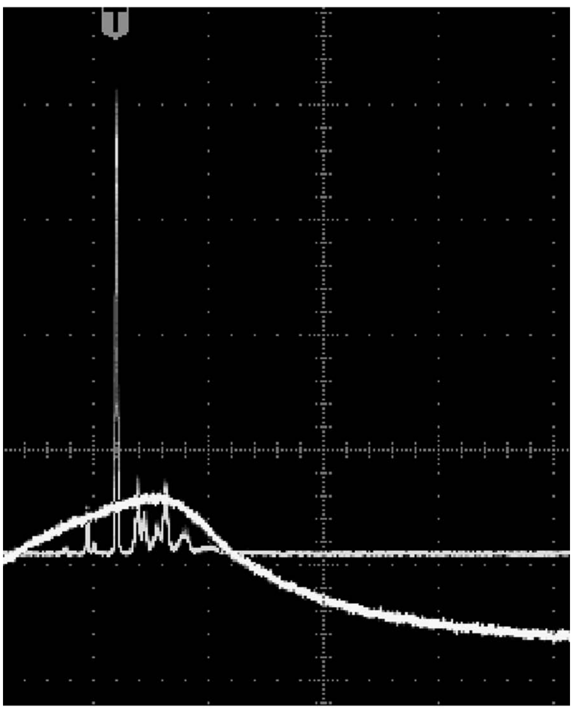
The oscilloscope traces of the quasi-CW output of the green laser are shown in Figs. 2(a)–2(c) for a pump pulse width of 200, 40, and 100 μs, respectively. The initial spike in the output is due to the relaxation oscillation. After a few initial spikes the laser stabilizes [Fig. 2(a)] for the rest of the pump pulse duration. We reduce the pump pulse width to some tens of microseconds for obtaining the gain switching [Fig. 2(b)]. The green laser has a maximum peak power of 40 W with a pulse width of 409 ns at an average pump power of 2 W. The pulse repetition rate of



(a)



(b)



(c)

Fig. 2. Oscilloscope trace of the green output for different pump pulse widths: (a) 200 μs, (b) 40 μs, (c) 100 μs, multisubpulse output.

the green laser can be varied from 50 to 1 KHz. The increase of pump power by varying the diode current accelerates the photon density, population inversion, and also the depletion. So the ascending and descending of the optical output pulses get steeper, thus reducing the pulse width. As the fall time of the gain-switched pulses scales up with the finesse of the cavity, the requirement for efficient SHG leads to a much longer fall time than the rise time of the pulses, particularly at the higher pump power, which not only make the pulses asymmetric in shape but also lead to longer pulse duration (FWHM).

On increasing the diode current or the pump pulse width, multiple laser pulses are observed as shown in Fig. 2(c). This phenomenon is called multi-subpulse output. When the diode current is increased, the delay time between the gain-switched pulse and the pump pulse decreases, which is due to the faster buildup of the population inversion. So we get multiple pulses for a fixed-pump pulse width. The number of subpulses can be controlled by varying the pump pulse width. The multi-subpulse output can be useful in micromachining.

B. Width of Fundamental Pulse Without SH Coupling

In solid state lasers, the period of relaxation is approximately given by [8]

$$T_R \approx 2\pi[\tau_C T_M\{(P/P_{th}) - 1\}^{-1}]^{1/2}. \tag{1}$$

Here τ_c is the cavity photon lifetime, T_M is the fluorescence lifetime, P is the effective pump power, and P_{th} is the threshold pump power. For pumping well above the threshold the above equation can be generalized to

$$T_R \approx 2\pi[(\eta L/c)(A/\sigma)(h\nu_P/P)]^{1/2}. \tag{2}$$

Here A is the effective mode area at the gain medium, L is the cavity length, η is the refractive index, σ is the stimulated emission gain cross section, and ν_P is the frequency of the pump photon. For the laser cavity without the SH crystal, the gain-switched pulse width of the fundamental frequency can be estimated by assuming a triangular pulse with equal rise and fall time t_0. For the laser operating much above the threshold, the pulse width can be approximated to be [2] $T_0 \approx T_R/\pi^2$.

The estimated variation of the pulse width of the fundamental radiation with the input current is shown in Fig. 3. We obtain a peak pulse width of 107.6 ns for an input power of 2 W. The estimated pulse width of the fundamental radiation is much less than the observed and calculated pulse width of the SH radiation. This is due to nonlinear coupling of the laser.

C. Width of SH Pulse

For Q-switching or gain-switching operation of the laser with an intracavity SH generating crystal, the normalized rate equations are written as [5]

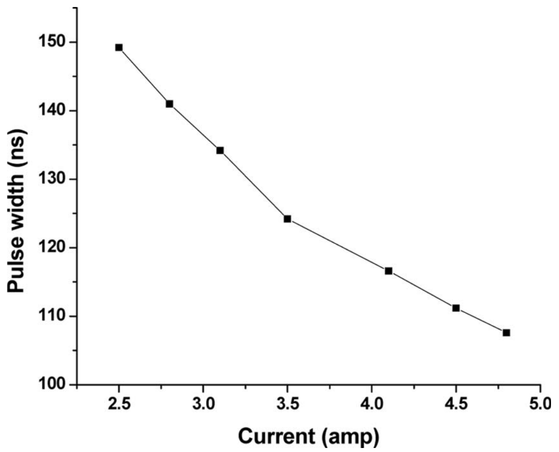


Fig. 3. Predicted pulse width of the fundamental radiation with diode current.

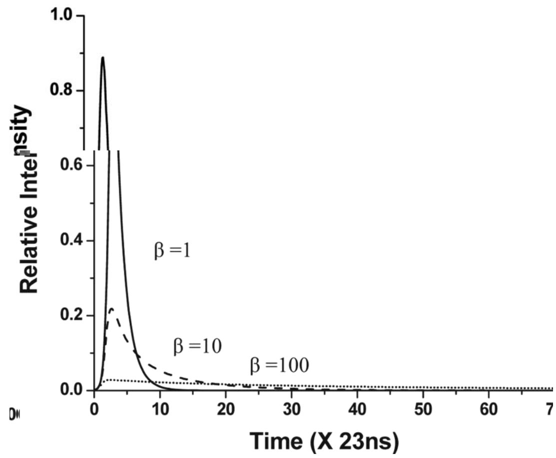


Fig. 4. Calculated variation of the width of SH pulse for different nonlinear coupling (β).

$$dn/dT = -\phi.n, \quad (3)$$

$$d\phi/dT = \phi(n-1) - \beta\phi^2. \quad (4)$$

Here

$$n = N/N_{\mathrm{th}} = (\sigma c/LA)\tau_C N, \qquad \phi = (\sigma c/LA)\tau_C u,$$
$$T = t/\tau_C \quad \text{and } \beta = (LA/\sigma c)K, \quad (5)$$

where

$$K = h\nu(c/L)^2(P_{SH}/P_F^2)$$
$$= (8\pi h/\omega^2)(\eta\nu)^3(dl)^2(c/L)^2[\sin^2(\Delta kl/2)/(\Delta kl/2)^2]. \quad (6)$$

In the above equations N is the population inversion, N_{th} is the threshold population inversion, u is the total number of photons per pertinent cavity mode, τ_c is the photon lifetime, L is the optical length of the resonator, l is the length of the nonlinear crystal, Δk is the phase-mismatch for the SHG, and d is the effective nonlinear coefficient. The value of n before lasing depends upon the pumping power. The higher the pumping power, the greater the value of n.

The population of the upper state after a time t as a function of the pump rate is given by

$$n(t) = n_\infty - (n_\infty - n_f)\exp(-t/\tau_c). \quad (7)$$

Here n_f is the population of the upper state after lasing and is negligible. $n_\infty = \tau_f(P_{\mathrm{abs}}/Alh\nu_p)$ is the population density after infinite time and P_{abs} is the absorbed pump power [9].

The numerically simulated pulses of the SH wavelength for different values of nonlinear coupling β is shown in Fig. 4. The increase in the pulse width of the SH radiation is attributed to the overcoupling effects. The intracavity photon density of the fundamental decreases due to the generation of its SH radiation. The additional term $\beta\phi^2$ in the rate equation arises due to the SHG. This increases the time to depopulate the upper level, increasing the pulse width as a result. The value of β can be altered by changing the nonlinear interaction parameter K. The value of K depends on nonlinearity, nonlinear crystal length, and the phase-match parameter. The experimental and theoretical variation of the pulse width with the input pump power is shown in Fig. 5. At an input power of 2 W we obtain an experimental value of the peak pulse width of 409 ns comparable to the calculated value of 415 ns. To identify the effect of the phase mismatch on the pulse width, in Fig. 6 we plot the pulse width of the SH with detuning of the crystal about the phase-match point for different values of initial inversion. The pulse width is the maximum at the exact phase-match point and it decreases with detuning in both sides. Pulse width decreases with an increase of initial inversion. This result conforms with the results

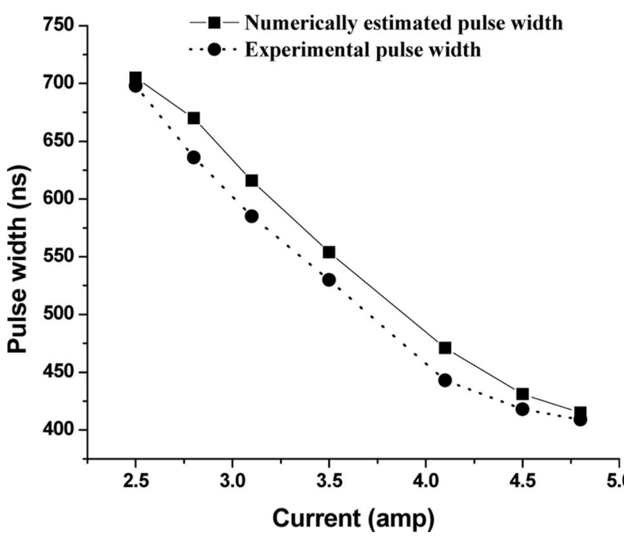


Fig. 5. Calculated and experimental pulse width of the SH output with different pump current.

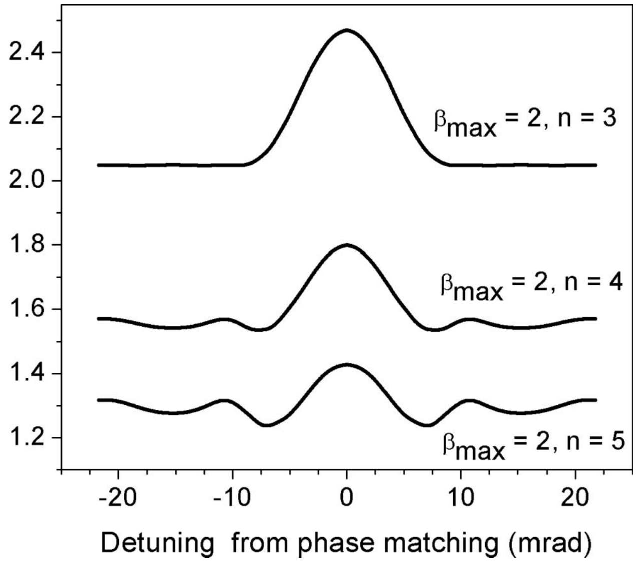


Fig. 6. Pulse width (in units of cavity decay time) of the SH pulses as a function of the detuning of KTP crystal from the exact phase matching for initial inversion $n = 3$, 4, and 5 and with fixed value of 2 for the maximum coupling parameter (β).

shown in Fig. 4, as the value of β is maximum at the phase-matched point.

In the present setup for a given crystal, it is not possible to detune the crystal from phase-matching by a large amount, as it may damage the cavity mirrors. Here both the cavity mirrors have 100% reflectivity at 1064 nm and almost full transmission at 532 nm. As such, 532 nm radiation is the only radiation coupling out of the cavity. A small detuning can decrease the generation drastically, causing an enormous increase in intensity of the radiation at 1064 nm in the cavity. The coating of the cavity mirrors cannot withstand such a catastrophic increase of radiation intensity. However the decrease of pulse width is observed for a small detuning (0.2°) around the phase-matching point. The effect of coupling could also be verified by using crystal samples of various thicknesses; however, here it is realized by varying the duration and energy of the pump pulse as shown in Fig. 5—but this way of controlling the pulse width is not energy efficient.

4. Conclusion

A gain-switched, intracavity SH Nd:YAG laser transversely pumped with a pulsed-laser diode array is developed. Gain switching is achieved by reducing the pump pulse width to the extent of the first relaxation undulation. A KTP crystal is used as an intracavity frequency doubler. The effect of nonlinear coupling on the pulse width of the fundamental is studied and is found to be in good agreement with the experimental measurement. A peak power of 40 W at 532 nm corresponding to a pulse width of 409 ns is obtained for an average pump power of 2 W at 150 Hz. Compared to a *Q*-switched laser, it is simple and does not require a high voltage RF driver or saturable absorbers in its operation. The laser may be useful where relatively longer nanosecond pulses are required such as eye surgery, micromachining, and underwater communication.

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