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Passive synchronized Q-switching between a quasi-three-level and a four-level laser

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ABSTRACT

Synchronized Q-switching between quasi-three-level and four-level lasers is interesting for sum-frequency generation into the blue and ultraviolet. We report, for the first time, stable synchronized Q-switching between a quasi-three-level laser at 946 nm and a four-level laser at 1064 nm in an all passive approach. While timing jitter of the individual free-running lasers were on the order of 10 μs, the relative timing jitter, defined as one standard-deviation of the experimental data, was only 9 ns between the two synchronized pulses. The minimum delay between the two pulses was 64 ns during stable operation, which gave a 79% temporal overlap when normalized against the zero-delay scenario. Preliminary results show promise for non-linear frequency conversion, which could lead to high power pulsed blue and ultraviolet lasers.

Keywords: Lasers, Q-switched, diode-pumped, solid-state, Nd:YAG

1. INTRODUCTION

Synchronized pulsing of different wavelength lasers is by no means a new concept. In fact, simultaneous dual-wavelength operation of a ruby laser was reported by Schawlow and Devlin[1] just seven months after Maiman's demonstration of the world's first laser. In 1965, Caviello et al. demonstrated synchronized Q-switching between the 694.3 nm and 692.9 nm line in a ruby laser[2].

The main motivation for synchronized Q-switching in early works were in long distance interferometery[3] and in power scaling[4]; in recent years, however, considerable interests have been placed on non-linear frequency mixing, which implies that the lasers should be able to operate at fairly different wavelengths in order to cover a wide spectral range. Fig. 1 shows the possible wavelengths that is covered by sum frequency mixing the various transitions of Nd:YAG, including the quasi-three-level transitions at 939 nm and 946 nm.

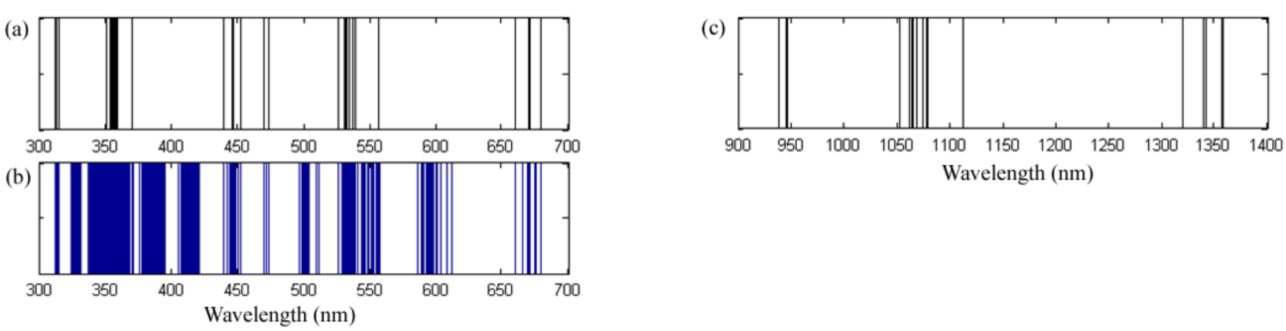

Figure 1. Spectral range of non-linear frequency mixing covered by Nd:YAG up to the third harmonic. (a) only the degenerate wavelengths of 2ω and 3ω, (b) possibilities using sum-frequency mixing, (c) fundamental wavelengths including the quasi-three-level transitions at 939 nm and 946 nm.

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The main difficulty in synchronization of Q-switched lasers with significantly different wavelengths lies in compensating for their respective different gain cross-sections. In Nd:YAG, for example, the gain cross-section of the 946 nm transition is ten times less than that at 1064 nm[5,6]. In addition, if one of the lasers is a quasi-three-level system, the effect of gain difference is further worsened due to reabsorption.

Using an active approach, Herault et al. synchronized a quasi-three-level laser at 912 nm and a four-level laser at 1063 nm by adjusting the opening times of the two active Q-switches[7]. By making the 912 nm pulse relatively long, a good temporal overlap was achieved. The authors reported a timing jitter of 40 ns and subsequently generated 9 kW of peak power at 491 nm through non-linear cavity dumping.

To the authors' knowledge, there has only been one publication on passively synchronized Q-switching between a quasi-three-level laser and a four-level laser. Zhang et al. obtained simultaneous dual-wavelength operation at 1064 nm and 946 nm by introducing a relatively large loss on the 1064 nm laser. Unfortunately, the authors did not report on the temporal characteristics of the synchronized pulses and reported fluctuations in the output power[8].

In this paper, two separately pumped Nd:YAG laser crystals were used to equalize the repetition rates at 946 nm and 1064 nm respectively, and stable synchronization is reported for the first time. A single Cr:YAG saturable absorber (SA), placed in a common section of the two cavities, was used to synchronize the two pulse trains. Synchronization is obtained by careful mode matching of the two lasers in the SA, and controlling the pump power of each laser individually. The relative timing jitter between the two pulses was 9 ns, which is defined as the root-mean-square deviation from the mean delay, or one standard deviation of the experimental data. A minimum delay of 64 ns was observed between the two pulse trains, and by making one pulse relatively long when compared to the other, a 79% temporal overlap was achieved compared to the zero-delay scenario.

2. EXPERIMENT

2.1 Experimental Setup

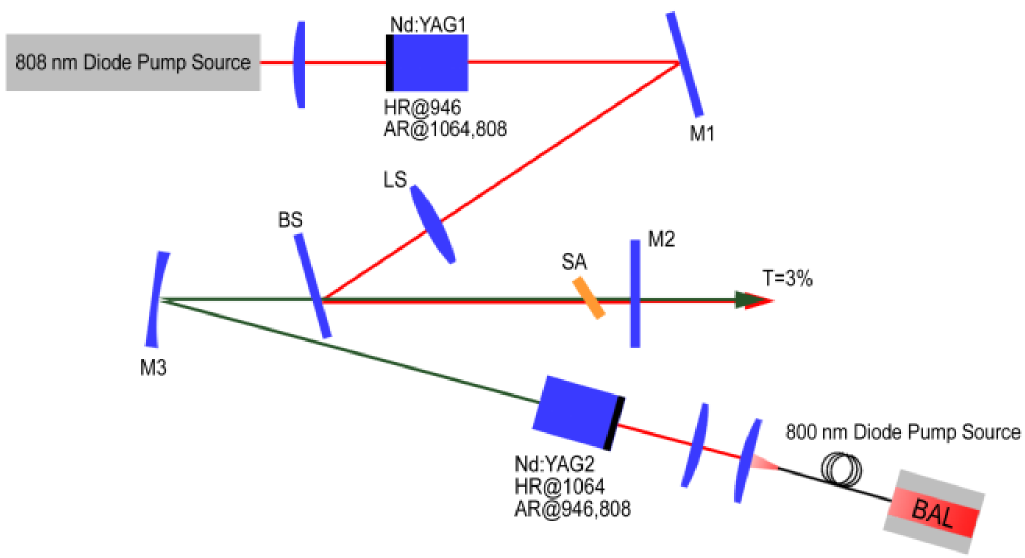

Figure 2. Experimental setup for a Y-shaped cavity with a shared Q-switch between the 946 nm and 1064 nm lasers. Nd:YAG1 and Nd:YAG2 are the alser crystals for 946 nm and 1064 nm, respectively. SA is the saturable absorber.

Fig. 2 illustrates the experimental setup. The HR facet of Nd:YAG1, mirrors M1, BS and M2 form the 946 nm cavity, while the HR facet of Nd:YAG2, mirrors M3 and M2 form the 1064 nm cavity. The SA is a 0.97 mm Brewster-cut Cr:YAG specified for 85% unsaturated transmission at 1064 nm at normal incidence. Taking into account the SA is oriented at Brewster's angle and using the absorption cross-sections published by Zhang et al.[9], the unsaturated transmission at 1064 nm and 946 nm are calculated to be 82% and 83%, respectively. BS is a dichroic mirror used to couple the 1064 nm beam into the 946 nm laser cavity, while mirror M2 acts as the output coupler for both lasers. M2 is coated for 3% transmission at both 1064 nm and 946 nm.

The mode sizes of the two lasers are shown in table 1 below:

Table 1. Experimental mode sizes for the 946 nm and 1064 nm lasers.

	946 nm	**1064 nm**
Pump diode mode size inside laser crystal	59 μm (h) x 80 μm (v)	70 μm (in both directions)
Cavity mode size inside laser crystal	77 μm (in both directions)	88 μm (h) x 108 μm (v)
Cavity mode size inside SA	24 μm (in both directions)	72 μm (h) x 97 μm (v)

For efficient Q-switching in a quasi-three-level laser, two operating conditions should be met: 1) good overlap between the pump and cavity modes inside the laser crystal. 2) a small cavity mode inside the passive Q-switch to achieve efficient bleaching. These imply that the 946 nm laser cavity is most efficient near the stability limit, where stability of the cavity itself is very sensitive to perturbation. Thus, an intracavity lens was used instead of a curved folding mirror to avoid astigmatism, which would have further reduced the stability region. The intracavity lens, LS, has a focal length of 75 mm and an insertion loss of 1.9%.

Following the method used by Herault et al.[7], the 946 nm laser cavity in Fig. 2 was made relatively long to ensure a good temporal overlap between the two pulses. The 946 nm cavity length was 37 cm, while the 1064 nm cavity length was 19 cm. These resulted in 200 ns and 45 ns FWHM pulse widths for the 946 nm and 1064 nm lasers, respectively.

Throughout the experiments presented here, the incident pump power of the 946 nm laser was held fixed at 1.6 W, while the pump power of the 1064 nm laser was varied. Detailed pump source specifications can be found in a separate publication[10].

2.2 Results and Discussion

Stable locking of the two pulses was observed over a wide range of pump powers. Fig. 3 illustrates the repetition rates of the two lasers. As a base-line comparison, repetition rates of the two individual free-running lasers were first measured with the other laser switched off. These are plotted in dashed lines.

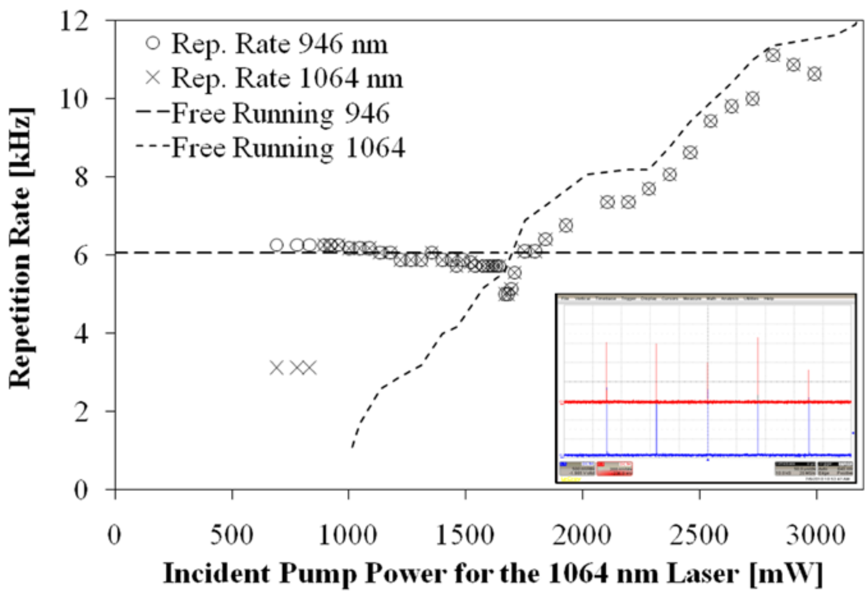

Figure 3. Repetition rates of the synchronized system and of the respective free-running lasers at 946 nm and 1064 nm. Incident pump power of the 946 nm laser was held fixed at 1.6 W while the pump power of the 1064 nm laser was varied. Inset shows oscilloscope traces of the two lasers at 11 kHz.

The repetition rates of the synchronized lasers are plotted in circles and crosses for the 946 nm laser and 1064 nm laser, respectively. It can be clearly seen that the repetition rates of the two lasers are stably locked up to 11 kHz, almost twice the free-running repetition rate of the 946 nm laser. The corresponding oscilloscope trace at 11 kHz is shown in the inset on the lower right-hand corner. The first three data points in Fig. 3 indicate 2:1 synchronization, where a 1064 nm laser pulse is generated with every other 946 nm pulse. This is due to the relatively low gain at low pump powers and is in agreement with previous publications[11,12].

It should be noted that when the free-running repetition rates of the two lasers are equal, the synchronization becomes unstable. The unstable regime is narrow, within tens of mW of incident pump power, and will be described later in the manuscript.

It can be seen in Fig. 3 that the synchronized lasers operate at the higher repetition rate of the two lasers: when the 1064 nm free-running repetition rate is below that of the 946 nm laser, the synchronized lasers operate at the free-running repetition rate of the 946 nm laser; when the 1064 nm free-running repetition rate is above that of the 946 nm laser, the synchronized lasers operate at the free-running repetition rate of the 1064 nm laser. This can be explained as follows: the higher-repetition rate laser (master) reaches threshold sooner than the lower-repetition rate laser (slave), and once the master laser bleaches the SA, the slave laser reaches threshold as well and is able to emit a pulse synchronously. Thus, the slave laser is able to emit its pulses at an earlier time than it would have otherwise, reaching the same repetition rate as the master laser.

Since the slave laser only starts to build up after the SA is bleached by the master laser, a small delay between the two pulses is observed when the free-running repetition rates of the two lasers are not equal. This is plotted in Fig. 4 below. A positive delay indicates the 1064 nm laser is leading the 946 nm laser, while a negative delay indicates it is lagging the 946 nm laser. The switching point at 1.6 W, when the 1064 nm laser becomes the master laser, corresponds to the point when the free-running repetition rates of the two lasers are equal.

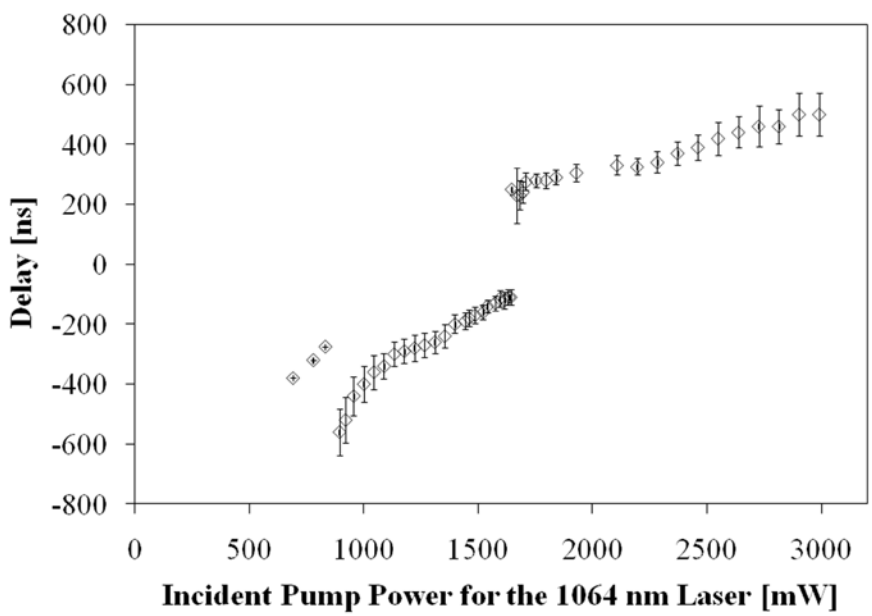

Figure 4. Relative delay between the two pulses as a function of the 1064 nm laser pump power. Error bars show the 6-standard deviation jitter measurement over 1000 pulses. No jitter measurements were made for the first three data points, where a 1064 nm pulse arrives only with every other 946 nm pulse.

As mentioned above, the synchronization is unstable at the switching point. To better understand the dynamics of the synchronization, particularly in this unstable regime, the coupled rate equations[12] was adapted to include a three-level system, and was used to qualitatively model the temporal dynamics of the synchronized lasers. The one-dimensional model assumes that the photons are evenly distributed throughout the laser cavity, and focuses on the temporal characteristic of the synchronized system. The pulse build-up (output power) and cavity losses are shown qualitatively as functions of time in Fig. 5 (a) and (b). The 1064 nm laser absorbed pump power is increased by 100 mW in Fig. 5 (b), while all other parameters were fixed. Dashed lines indicate the lasers are below threshold.

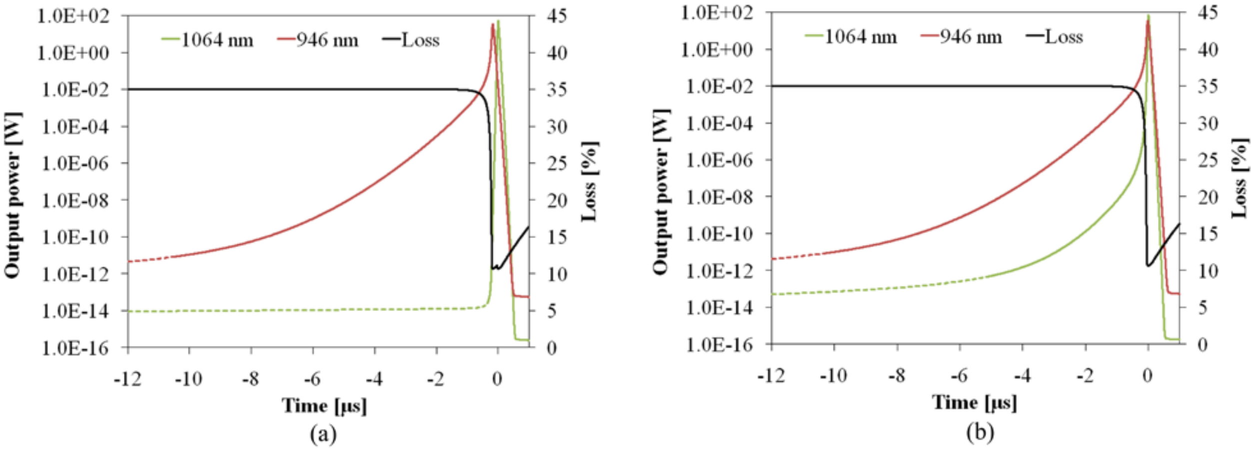

Figure 5. Qualitative plots of the pulse build-up (output power) and cavity losses for (a) when the 946 nm laser is the master laser and (b) when the free-running repetition rates of the two lasers are equal.

It can be seen that when the 946 nm laser is the master laser (Fig. 5 (a)), the point at which the 1064 nm laser reaches threshold is well defined; particularly, when the SA is bleached. The instantaneous excess gain in the 1064 nm laser is then directly related to the pumping rate. This explains the dependence of the delay on the 1064 nm laser pump power – as the pump power and excess gain is increased, the 1064 nm laser build-up time, and hence, also the delay, is decreased. A similar argument could be made for when the 1064 nm laser is the master laser.

If the repetition rates of the two lasers are matched (Fig. 5 (b)), both lasers reach threshold before the SA is bleached. As a result, both lasers are building up rapidly due to stimulated emission. In this case, small gain fluctuations that advance or delay the threshold of either laser, on the order of microseconds, can have a critical impact on the timing of the two pulses. Thus, the 946 nm pulse would build-up first at times, while the 1064 nm pulse would build-up first at others. This leads to a significantly large timing jitter at the switching point. The error bars in Fig. 4 show the relative timing jitter between the two pulses observed experimentally. Following the convention by laser manufacturers and previous publications[13,14], the jitter is defined as the root-mean-square deviation from the mean delay at a particular pump level. In Fig. 4, however, the error bars are drawn to indicate ± 3 standard deviations so that they can be visible. The minimum jitter observed was 9 ns, and the minimum delay for stable operation depends effectively on the timing jitter of the individual free-running lasers[15]. As mentioned above, the unstable operating regime was observed to be very narrow.

To investigate the minimum delay that can be obtained with the current setup, the 1064 nm cavity mode size inside the SA is reduced to match that of the 946 nm laser in the horizontal direction (to 24 µm (h) x 80 µm (v)). The minimum delay between the two pulses was reduced to 64 ns when the 946 nm laser was the master laser. Fig. 6 shows the corresponding oscilloscope traces, which contains 200 traces superimposed with the same trigger reference point. The jitter in this case was 12 ns. The temporal overlap, defined as the product of the two signals integrated over the pulse duration, was found to be 79% when normalized against the zero-delay scenario. The focusing lens of the 1064 nm laser pump beam was changed from 40 mm to 20 mm to suppress higher order modes. Further reduction of the 1064 nm SA mode size was not possible due to physical limits with the current setup.

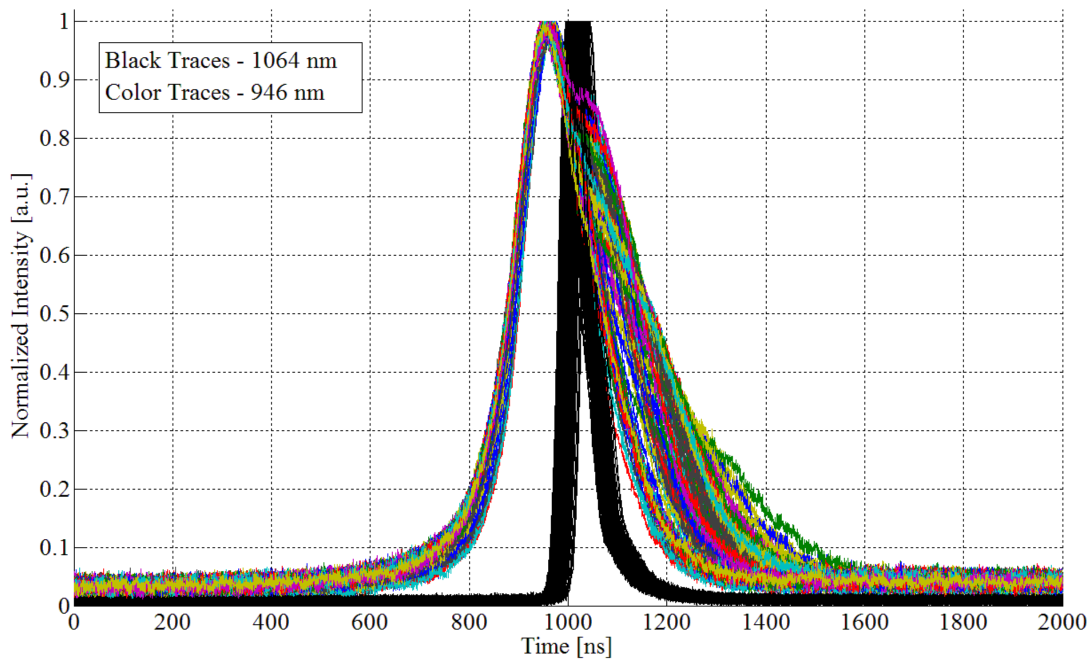

Figure 6. Superposition of 200 oscilloscope traces of the two laser pulses. Color traces show the 946 nm pulses while the black traces show the 1064 nm pulses.

3. CONCLUSION

We demonstrated for the first time, stable synchronized Q-switching between a quasi-three-level laser and a four-level laser using a passive Q-switch. A numerical model shows the temporal dynamics of the synchronized system, the origin of the delay between the two pulses, and the instability when the repetition rates of the two lasers are equal. Timing jitter at the best operating point was observed to be 9 ns, which is comparable to a previously published active system[7]. By better matching the mode sizes inside the SA and making one pulse relatively long when compared to the other, a temporal overlap of 79% was obtained when normalized against the zero-delay scenario. The stability and temporal overlap reported here show potential for applications in sum-frequency generation.

4. ACKNOWLEDGEMENT

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