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Injection mode-locked guide star laser concept and design verification experiments

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Abstract: Injection mode-locking combined with stretched Q-switching of a ring resonator are proposed and demonstrated as a promising approach for advanced, guide star lasers. The concept uses two Nd:YAG lasers, producing a macro-micro pulse-burst output, optimized for efficient sum-frequency generation. We demonstrate wavelength, bandwidth and timing control required to maximize the atmospheric Na fluorescence.

OCIS codes: (140.3580) Lasers, solid-state; (010.1080) Adaptive optics.

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1. Introduction

The use of lasers to create artificial guide stars for adaptive optics is currently revolutionizing ground based astronomy by permitting correction of the optical aberrations due to the atmosphere and allowing near diffraction limited performance of large aperture, ground based telescopes when no natural guide star is available near the science object [1, 2]. Light emitted at 589 nm is used to excite sodium fluorescence in the upper atmosphere, thereby creating an artificial point-like source of light, or guide star, which can be used as a source for adaptive optics in a telescope to correct for aberrations in the intervening atmosphere. For extremely large ground based telescopes (ELTs) in the 30 m to 100 m diameter class [3], a single Na guide star does not provide sufficient sampling of the atmosphere [4] and a more complex approach is required using multiple laser guide stars distributed across the aperture of the telescope to allow tomography of the intervening atmospheric aberrations [2]. This approach has resulted in the need to develop improved laser sources. There is thus a demand for increased power and improved pulse burst formats to maximize utility and efficiency [3]. The particular requirements for our work are summarized in Table 1 [5] and include a total optical power ≥ 50 W and a waveform consisting of pulses of duration less than 3 μs, operating at pulse repetition frequencies (PRF) up to 800 Hz. Furthermore, the emission must be exactly tunable to the D_2 line of Na, and have a bandwidth that can be optimized between 1 GHz and 3 GHz to enable use of all the Doppler broadened Na available and maximize photon return [1]. Finally, engineering requirements of reliability, robustness and efficiency are important for applications of lasers to telescopes situated on remote mountain tops.

Table 1. Laser Performance Requirements

Output power	≥ 10 W per beam, 5 beams
Temporal format	Pulsed, PRF variable 600 Hz -800 Hz Pulse length 1-3 μs
Wavelength	Na D_2 with ability to tune on/off
Bandwidth	1-3 GHz
Beam quality	< 1.2 x diffraction limited

Approaches to the laser include the first generation dye lasers [6], the more reliable sum-frequency generation (SFG) using solid state lasers [7,8] and recently fiber lasers [9,10], combined with various laser waveform techniques ranging from cw to mode-locking [11]. However, to the best of our knowledge no single approach has fully satisfied all the requirements simultaneously. We have proposed a novel approach [12, 13] using injection mode- locking [14,15] that has the potential to satisfy the above requirements. The concept is summarized below and we also describe critical design verification experiments to demonstrate the viability of the concept.

2. Injection mode-locked guide star laser concept.

Our approach uses sum-frequency generation of two mode-locked Nd:YAG lasers to achieve the desired Na wavelength, similar to previous designs [7,8,11]. Our major contribution is the application of injection mode-locking [14, 15] as a robust method for simultaneous control of the absolute wavelength, bandwidth and timing for SFG. An additional feature is the use of a novel, efficient resonator involving stretched Q-switching [16]. Together, these two techniques are used to produce a burst of high peak power micro-pulses optimized for efficient SFG and contained in longer macro-pulses, separately optimized to minimize bleaching of the sodium in the upper atmosphere. While injection mode-locking using a single injected pulse has previously been used to create single short pulses in CO_2 [14] and Nd:YAG [15] lasers, to the best of our knowledge it has not previously been used to produce a long macro-pulse consisting of many micro-pulses with simultaneous control of the bandwidth.

The overall concept is shown in Fig. 1. It uses two cw non planar ring oscillator (NPRO) lasers [17], each stabilized accurately to the wavelengths near 1064 nm and 1319 nm required to produce the Na wavelength by SFG [7]. For robust operation and control we propose using an active servo to accomplish this as shown, but in practice this may not be necessary due to the inherent stability of the NPROs [18]. From the output of each of these cw lasers, we slice a pulse of about 1 ns duration to inject into the slave power resonator for injection mode-locking. Accurate control of the width of the injected pulse is used to control the bandwidth of the micro-pulses of the injection mode-locked output. Precise timing of the two injected pulses is required for efficient single-pass SFG. This is ensured by operating both pulse slicers in series from the same high voltage pulser, thus minimizing timing jitter between the 1064 nm and the 1319 nm micro-pulses.

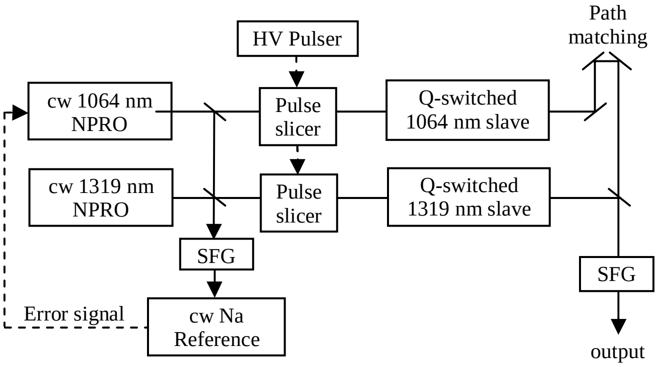

Fig. 1. Overall design concept. Two cw NPRO lasers provide the absolute wavelength control and tuning, and synchronized pulse slicers provide timing and bandwidth control of injection mode-locked slave lasers for subsequent SFG at the Na wavelength.

3. Design verification experiments using a subscale, 1064nm laser.

3.1 Seed pulse production

To investigate bandwidth control by injection mode-locking, we have assembled a versatile pulsed seed source consisting of an NPRO master laser followed by two 50 ohm Pockels cells between linear polarizers. Two independent high voltage avalanche transistor pulsers are used to provide fast rise time (100 ps) electrical pulses to the Pockels cells. This setup allows complete control of the optical pulse width, by using one Pockels cell to turn on the pulse and the other to turn it off, with an adjustable time delay between the two events.

Using this pulse slicer, we have produced optical seed pulses of peak power up to 0.5 W, and pulse duration continuously adjustable between 1 ns and 200 ps, with examples shown in Fig. 2. The near-cw light rejected by the pulse slicer would be used to lock the master lasers to the sodium wavelength by cw SFG, if required. The jitter between the trigger of the high voltage pulse generators and the output of the mode-locked laser (see below) was measured, using a fast sampling oscilloscope, to be < 10 ps rms. This low jitter proves that timing of the output micro-pulses is determined by the input pulse, as required for efficient SFG of two mode-locked lasers, and allows for very precise control of the pulse width in our design verification experiments.

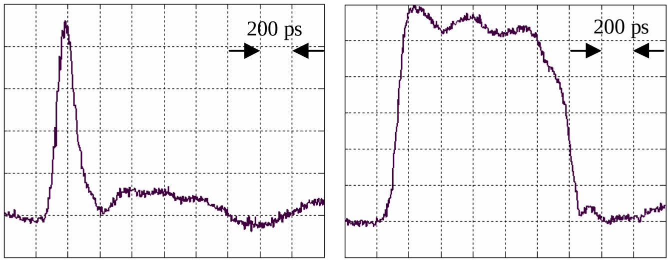

Fig. 2. Optical pulses of variable duration produced by our double Pockels cell switch.

3.2 Slave laser

The slave laser (Fig. 3) was assembled for use in the design verification experiments only. It uses a conduction cooled Nd:YAG zigzag slab, 4.00 mm x 4.32 mm x 36.14 mm, which is side pumped in the zigzag plane by pulsed semiconductor lasers. The laser makes use of a 3.5 m long ring oscillator incorporating a Q-switch, a thin film polarizer (TFP) for injection and extraction and a half wave plate (HWP). Together, these elements allow the efficient production of stretched Q-switched pulses [16]. Telescopes were included to provide resonator stability while creating a large size TEM_{00} mode (ω = 1.2 mm) inside the zigzag slab [19]. This configuration permits efficient extraction of the stored energy, avoids damage to optics from the high peak power micro-pulses and reduces the optical gain per round trip, which lengthens the output macro-pulse width [20].

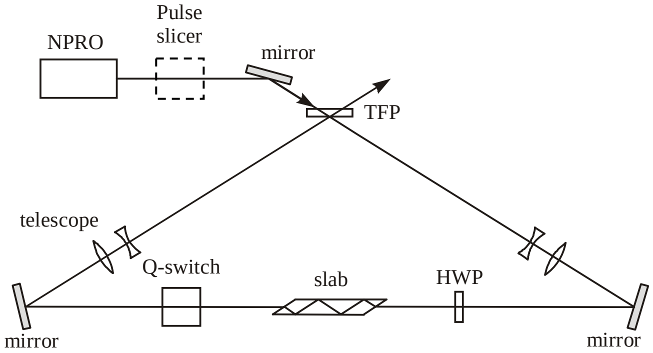

Fig. 3. Slave laser configuration, showing pulse injection into a traveling ring oscillator via a polarizing beam splitter (TFP), and the arrangement of polarizing elements (HWP) and Q-switch required to stretch the macro-pulse formed.

For injection mode-locking, a π-polarized seed pulse is injected into the resonator through the TFP. For the first pass, the seed pulse polarization is converted to σ by the HWP, and with no voltage applied to the Q-switch the seed pulse passes through without a change in polarization. It is thus completely reflected by the TFP and then converted to π polarization by the HWP. Voltage has meanwhile been applied to the Q-switch rotating the polarization back to σ thus trapping the pulse within the ring and enabling development of the giant pulse. Once the pulse has built up sufficiently, the voltage applied to the Q-switch is reduced slightly, allowing a controlled out-coupling fraction of the TFP. By varying this voltage the stretching of the output pulse can be controlled. Thus the Q-switch in our resonator produces no polarization rotation losses during build-up of the pulse and, instead of being opened completely to cavity dump the pulse as in conventional regenerative amplifiers [15], it is used to stretch the output pulse. Due to the broad bandwidth of the injected seed pulse, no servo was required to keep the slave locked to the master oscillator.

3.3 Design verification results.

Initial experiments were done to investigate injection mode-locking with no pulse stretching. The slave laser produced a near diffraction limited ($M^2 = 1.06$) 1064 nm beam. A typical output of the injection mode-locked slave resonator is shown in Fig. 4. The optimized output was 20 mJ per macro-pulse at 50 Hz PRF, limited by the pump lasers used. This is the energy per macropulse of a laser with average power of 16 W operating at 800 Hz PRF, and our initial result is thus already of significance to conventional laser guide star requirements. Each macro-pulse consists of more than 30 micro-pulses separated by 12 ns, the round trip time of the slave resonator. This could be adjusted in terms of the 16 ns Na fluorescence life time [1,7] to minimize bleaching and thus optimize the photon return from the guide star. The waveform shown was obtained on every pulse without the need for any feedback to the slave oscillator and it was observed that the shape of each micro-pulse from the slave laser closely resembled that of the input seed pulse.

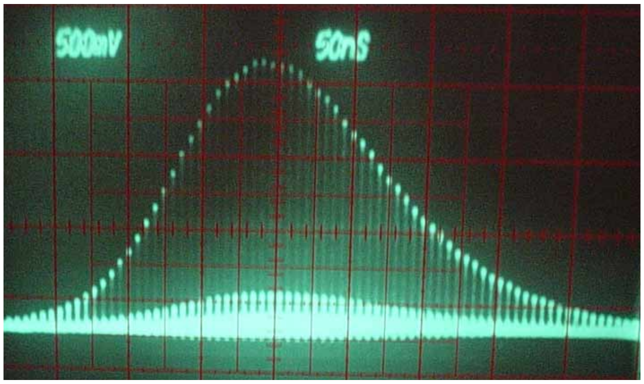

Fig. 4. A single macro-micro pulse output, consisting of a train of injection mode-locked micro-pulses. The time scale is 50 ns per half cm, or 0.9μs across the whole picture.

The input pulse width was measured using a sampling oscilloscope and a fast detector with an overall detection bandwidth of 12 GHz, with typical seed pulse shapes obtained as shown in Fig. 2. The bandwidth of the output of the slave laser was measured by integrating the output of a scanning Fabry-Perot interferometer over many macro-pulses. An example of one of these bandwidth measurements is shown in Fig. 5(a). While the resolution of the Fabry-Perot is 40 MHz, longitudinal laser modes can not be resolved in this figure due to the drift of modes within the envelope of the lasers spectrum, caused by changes in the slave cavity length from thermal expansion. The irregular shape of the spectrum is believed due to the irregular shape of the injected seed pulse (Fig. 2). A plot of the FWHM of a Gaussian fit to each spectrum is shown as a function of the injected seed pulse width in Fig. 5(b). We thus succeeded in controlling the bandwidth of the output from 0.8 GHz to 2.3 GHz. The bandwidth of the final SFG is expected to be approximately twice that of the fundamental wavelengths [7] and the results obtained thus essentially satisfy the system requirements. It is not expected to be difficult to modify the temporal shape of the seed pulse or to increase its duration slightly if a lower bandwidth is desired.

The BBO Q-switch was driven by a specially designed pulser, capable of pulse stretching as discussed. Excellent throttled Q-switching and resulting macro-pulse stretching with no loss in pulse energy was achieved as shown in Fig. 6. The tendency towards a flat top envelope will facilitate subsequent SFG optimization.

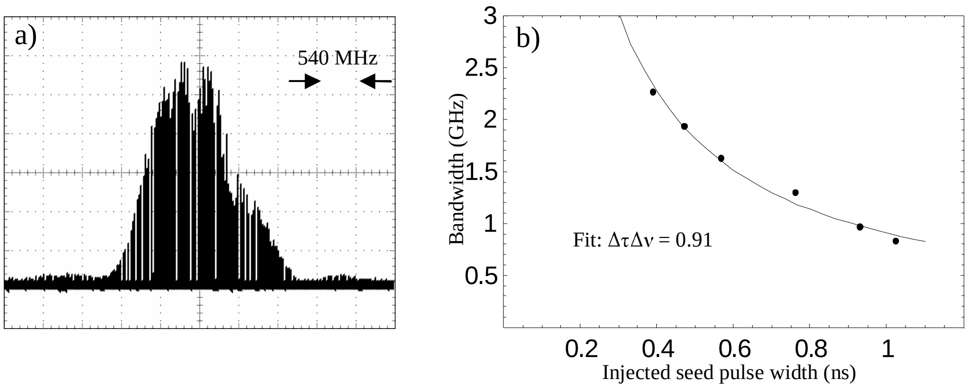

Fig. 5. (a). Spectrum of the slave output corresponding to a seed pulse width of 760 ps. The FWHM bandwidth is 1.3 GHz. (b) Plot of measurements of slave laser bandwidth versus the width of the seed pulse. The curve is a fit to the data with a time-bandwidth product of 0.91 as shown.

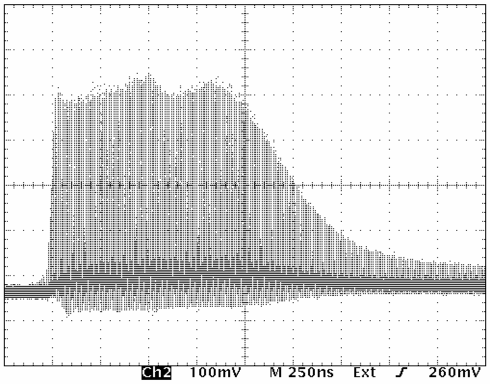

Fig. 6. Example of a stretched macro-pulse, 10 mJ per pulse, 50 Hz. The un-stretched macro-pulse in this case is similar to Fig. 4, but with FWHM width of 300ns.

4. Discussion and conclusion

We have proposed a new concept for sodium guide star lasers that appears to satisfy most critical requirements for planned telescope designs. Our design verification experiments have demonstrated the viability of our approach, including demonstrating a preferred pulse burst waveform, detailed bandwidth control, wavelength control and low timing jitter. Additional work is in progress to demonstrate the concept at 1319 nm and to optimize the concept at the power and wavelengths for the Na guide star. This optimization will include a simplified pulse slicer, optimized laser sources, the possible use of additional laser power amplifiers and optimized SFG. Detailed designs and proof of concept experiments for our approach remain to be done, but some critical design issues have already been demonstrated by others such as the operation of simple extra cavity SFG using mode-locked pump lasers [11] and the realization of 50W class SFG Na guide star lasers [21].

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