# Generation of Fourier-transform limited 35-ns pulses using a ramp-hold-fire seeding technique in a Ti:Sapphire laser

Thomas Walther,* Matthew P. Larsen,† and Edward S. Fry
*Department of Physics, Texas A&M University, College Station, TX 77843-4242, U.S.A.*

(Dated: May 2, 2001)

We report on an injection seeded Ti:Sapphire laser pumped by the second harmonic of a Nd:YAG laser. The resonance between the low power seed laser and the slave cavity is achieved using a ramp-hold and fire technique. Due to the triangular cavity design, the spatial beam profile is excellent, and combined with the narrow linewidth pulses, the conversion efficiencies for non-linear frequency generation are excellent.

## I. INTRODUCTION

Injection seeding is the most frequently used technique to produce single-longitudinal mode output from pulsed lasers in the ns-regime. It is accomplished by pre-populating a single longitudinal mode of a slave cavity with photons from a narrow linewidth laser source. Provided that the seed radiation is sufficiently strong, mode competition will establish single longitudinal mode oscillation in the cavity. The wavelength of the laser pulses is easily tunable via tuning of the seed laser. However, the slave cavity must be in resonance with the frequency of the source when the slave cavity Q-switch is fired, or (if a pulsed laser is used as a pump) when the pump pulse arrives.

Currently the most common method to ensure resonance of the slave laser cavity with the seed laser frequency is the pulse build-up technique [1]. When on resonance, an injection seeded laser has a shorter pulse build-up time than an unseeded one, since the laser pulse builds up from a pre-populated mode rather than from spontaneous emission. Hence, adjusting the cavity length such that the average pulse build-up time is minimized leads to seeded laser output. However, a feedback signal is only obtained once after each laser shot. This leads to difficulties at low repetition rates and in mechanically noisy environments.

A different technique, which has since been dubbed the ramp-and-fire technique was introduced by our group several years ago [2]. In this approach the light leakage of the seed laser through one of the cavity mirrors is monitored with a photo diode, while a piezo stack mounted on one of the cavity mirrors rapidly ramps the cavity length. Typical ramp times are on the order of 30 $\mu$s. The photo diode signal is produced by interference between the part of the incident seed light that does not pass through the complete cavity and the part that has made one or more complete round trips through the cavity. As the cavity length is ramped, the interference signal reaches a maximum, when these two parts of the seed beam are in phase. At this point the seed laser is in resonance with the cavity and the Q-switch can be fired. In an alternative version, the rapid change of the cavity length is produced by the change in optical path length due to heating of the laser rods by the flashlamps [3]. Optimum seeding is achieved for every laser shot even in the case of extremely noisy environments [4]. However, the drawback of the ramp-fire technique is that the laser pulse occurs at a random time during the ramp pulse. Thus, synchronization of different laser systems is difficult.

Finally, the conventional dither lock technique is available, in which the slave cavity is constantly kept in resonance with the seed laser by modulating its length and applying a feedback signal [5]. The latter has a disadvantage when flashlamp pumping is employed, since the high thermal load on the laser rod changes the index of refraction, which as a consequence radically alters the optical path length, making it difficult to keep the slave laser in resonance with the seed beam.

We demonstrate in this paper an injection seeded Ti:Sapphire laser, pumped by the second harmonic of a Nd:YAG laser with Fourier-transform limited pulses in the ns-regime by extending our earlier method to a ramp-hold-fire technique [6, 7]. The excellent spatial profile of our laser beam paired with the narrow linewidth leads to excellent non-linear conversion efficiencies. We demonstrate second (SHG) and third harmonic generation (THG).

## II. EXPERIMENTAL SETUP

The slave cavity has a ring design consisting of a spherical high reflector (radius of curvature $r = 2$m) mounted on a piezo stack, a Brewster angle dispersion prism (for limited frequency selection) and a flat 80% output coupler (cf. Fig. 1). The Brewster angle Ti:Sapphire crystal (20 mm long, 0.125” diameter, c-axis parallel to the laser polarization, 3.5 cm$^{-1}$ absorption at 532 nm) is pumped by the second harmonic of a Q-switched, flashlamp pumped Nd:YAG laser (modified Molectron YD-32). The pump radiation is slightly focused ($f$=50 cm) 4 cm in front of the Ti:Sapphire crystal. The pump beam has a diameter of approximately 1 mm at the input face of the Ti:Sapphire crystal, which is slightly larger than the eigenmode of the cavity (waist diameter = 0.5 mm).

---

*Electronic address: `thw@tamu.edu`

†present address: CVI Laser Corp., 111 Highland Drive, Putnam, CT 06260

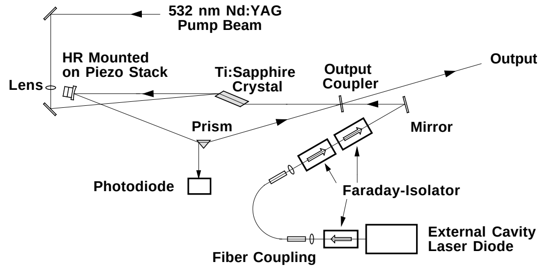

FIG. 1: Experimental setup of the cavity. Lasing occurs only in the counter-clockwise direction, since the seed laser is only propagating in this direction.

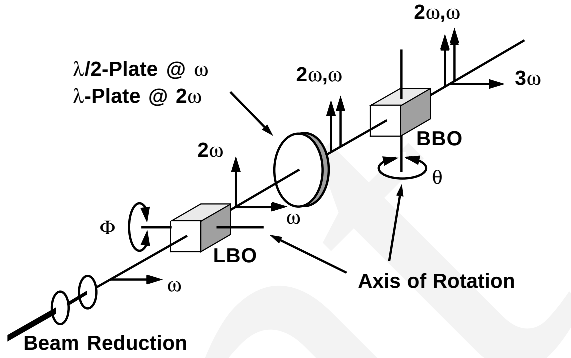

FIG. 2: Setup of the third harmonic generation. Details see text.

The seed radiation is supplied to the cavity through its output coupler by a polarization preserving single mode fiber. The external cavity diode seed laser (Environmental Optical Sensors, Inc., Model 2010) is protected with a total of three Faraday-isolators (-35 dB reverse attenuation each) against unwanted laser light from a clockwise lasing direction. Of course, in the case of successful seeding the clockwise lasing direction is completely suppressed. Typical seed powers incident on the output coupler were $\approx$ 2 mW.

The signals observed by the photo diode are produced by interference of the part of the beam reflected by the prism during the first pass with beams that have made different numbers of roundtrips in the cavity before being reflected out by the prism (cf. Fig. 1). A digitized voltage ramp is amplified and drives the piezo. The interference signal observed by the photo diode is amplified, and electronically squared twice in order to sharpen the maximum. The signal peak is detected by differentiation. When the resonance is detected, the electronics produces a latch signal, which stops the high voltage ramp applied to the piezo. The time from the detection of the peak to the latch signal that stops the counter is approximately 100 ns. This is very short on the relevant time scales. Specifically, the ramp slope is 2.3V/$\mu$s, and 630 V is required to drive the piezos through one free spectral range of the cavity ($\approx 250$ MHz); thus, in 100 ns the cavity resonance frequency is only shifted by $<$ 100 kHz. Consequently, one can be certain that the ramp voltage is actually held almost precisely on the interference maximum.

Once the ramp has been stopped, the electronics also produces an active feedback signal to stabilize the cavity and control fluctuations due to ringing in the piezo after the sudden stop of the ramp. This was achieved using a sample and hold circuit combined with a PID controller.

The second and third harmonic radiation are generated in a Lithium Triborate (LBO, $LiB_3O_5$) - Beta Barium Borate (BBO, $\beta$-$BaB_2O_4$) combination. The setup including the polarization direction of the different pulses as well as the rotation axes to achieve phase matching of the crystals is depicted in Fig. 2. First, the beam diameter of the fundamental (diameter $\approx$ 1.0 mm) is reduced by approximately a factor of two using a telescope. Second, the fundamental is doubled using a type-I process in an LBO (5×5×10 mm$^3$, $\theta = 90.0°, \Phi = 35.7°$) crystal. After the LBO crystal the second harmonic and the fundamental beam have polarizations perpendicular to each other. Due to the more than a factor of 3 higher non-linear coefficient for the type-I versus type-II summing process of fundamental and second harmonic in BBO, we opted for the former. We use a waveplate that is $\lambda/2$ at $\omega$ and $\lambda$ at $2\omega$, in order to rotate the polarization direction of the fundamental, but leave the polarization of the second harmonic unchanged. A BBO (5×5×7 mm$^3$, $\theta = 47.5°$) crystal is used for frequency summing of fundamental and second harmonic. The third-harmonic is polarized perpendicular to the fundamental and second harmonic and can be separated easily using a beam splitting polarizer.

LBO was chosen for the SHG step (instead of BBO), since LBO shows smaller beam walk-off, which leads to a better beam overlap in the second crystal. Nevertheless the distance between the two crystals was reduced as much as possible. We tested a BBO/BBO combination in unseeded operation. Although the SHG was more efficient in the BBO crystal, the overall THG efficiency was slightly smaller, due to the larger beam walk-off in BBO.

## III. RESULTS

Fig. 3 (top) shows the ramp voltage and photo diode signal as a function of time when the electronic hold signal is disabled. The interference maximum when the slave cavity is in resonance with the seed laser is clearly visible. Due to the inertia of the mirror/piezo assembly, mechanical ringing can be observed at the end of the ramp. The bottom part of Fig. 3 shows the ramp voltage and photo diode signal when the hold signal is enabled. Specifically, when a resonance is detected, the voltage ramp on the piezo is stopped and is held at a fixed value, which in turn holds the cavity in resonance until the pump pulse arrives. The ramp duration was chosen to be about 300$\mu$s in order to suppress effects of the mechanical ringing of the piezo stack, when the hold signal is triggered. The electronics holds the cavity length stable for several hundred microseconds.

Fig. 4 shows the output energy of the Ti:Sapphire laser as a function of the pump energy. The Ti:Sapphire laser was operating at 761.1 nm, which is about 20 nm from the gain

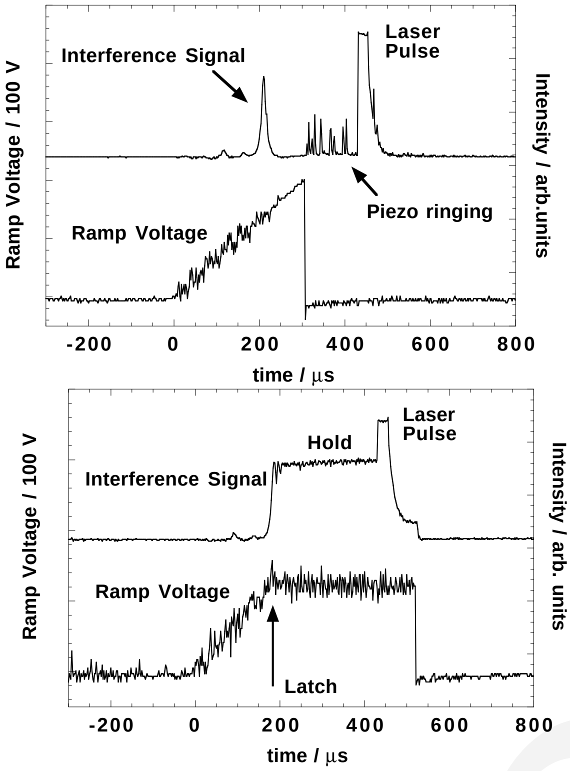

FIG. 3: Piezo Voltage and interference signal of the seed diode laser as monitored by the photo diode. The top (bottom) figure shows the signals when the latch signal on the piezo ramp is disabled (enabled) .

peak of the Ti:Sapphire laser [8]. The slope efficiencies are 49.0%±2.1% for seeded and 24.7%±2.7% for unseeded operation, respectively. The lasing thresholds were 6.2 mJ and 7.8 mJ for seeded and unseeded operation, respectively. As to be expected, the threshold is slightly lower in the seeded case, and the output energy is roughly twice that of the unseeded case. The latter is due to the suppression of the clockwise lasing direction.

The pulse duration of the Ti:Sapphire as well as the pulse build-up time were measured using fast photo-diodes. Fig. 5 shows build-up time and pulse duration for the seeded Ti:Sapphire laser. We measured pulse-buildup times of 65 ns and 88 ns for the seeded and unseeded case, respectively. The reduced build-up time in the seeded case is due to the prepopulation of a single longitudinal mode. The pulse duration is 35 ns (FWHM) when the laser is seeded.

In order to check the performance of our seeding system, the linewidth of the seeded pulsed laser was determined using a scanning 50 cm confocal Fabry-Perot etalon (Free spectral range 150 MHz). The Fabry-Perot was slowly scanned (100 sec) and the output signal as a function of the etalon length was measured with a photo diode. The latter was either directly recorded via an A/D card or integrated with a gated integrator (SRS 250) and then recorded. Hence, it is the time averaged linewidth of the lasers that is being determined; the result is 12.5 MHz (FWHM) (c.f. Fig. 6). The relation between the Fourier transform limited linewidth $\Delta\nu$ of a Gaussian laser pulse and its duration $\Delta\tau$ is given by [9]:

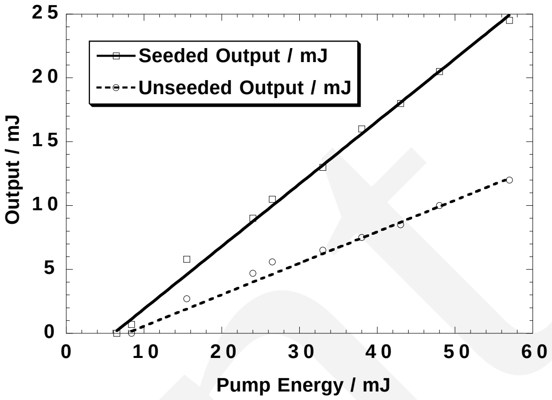

FIG. 4: Output energy of the Ti:Sapphire laser as a function of pump energy incident on the crystal.

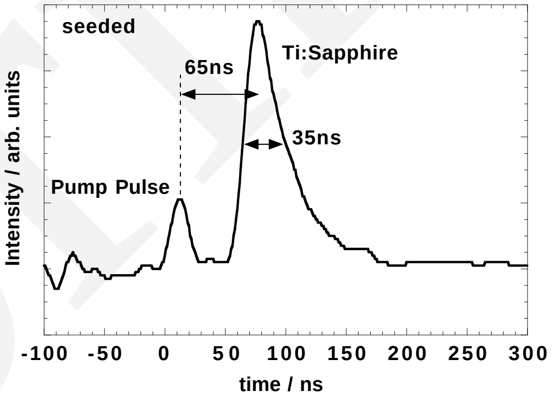

FIG. 5: Pulse buildup time and temporal shape of the seeded Ti:Sapphire laser.

$$\Delta\nu = \frac{2\ln 2}{\pi\Delta\tau}.$$

For a Gaussian pulse with duration of $\Delta\tau$=35 ns, the corresponding linewidth $\Delta\nu$ yields $\Delta\nu$=12.5 MHz. Although the temporal pulse form of the Ti:Sapphire laser is not strictly Gaussian, we conclude that our laser produces Fourier transform limited laser pulses.

Since the resonance is found before each laser shot, every single shot provides Fourier transform limited pulses. The technique is insensitive to temperature fluctuations or other slow variations. Vibrations can cause a problem when their bandwidth exceeds the time response of the PID controller.

The diode laser could be tuned by $\pm5$ nm without loss in performance of injection seeding. Larger scans require slight realignment of the slave cavity due to the dispersion in the prism used in our resonator design.

Finally, Fig. 7 shows the output energy of the second (380.55 nm) and third harmonic (253.7 nm) versus the energy at the fundamental wavelength (761.1 nm) of the Ti:Sapphire laser for seeded operation. Using the relationships $\eta_{\rm SHG} = I(2\omega)/I(\omega)$ and $\eta_{\rm THG} = I(3\omega)/I(\omega)$, we find maximum efficiencies of 34% (SHG) and 11% (THG), respectively. These

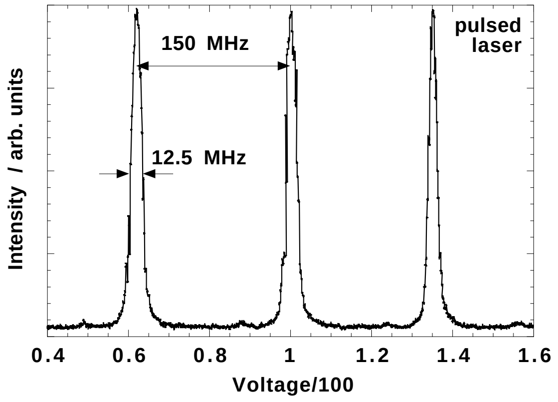

FIG. 6: Linewidth measurement of the seeded Ti:Sapphire laser with a slowly scanned Fabry-Pert etalon with a free spectral range of 150 MHz; there are ≈ 25 successive laser shots in each peak.

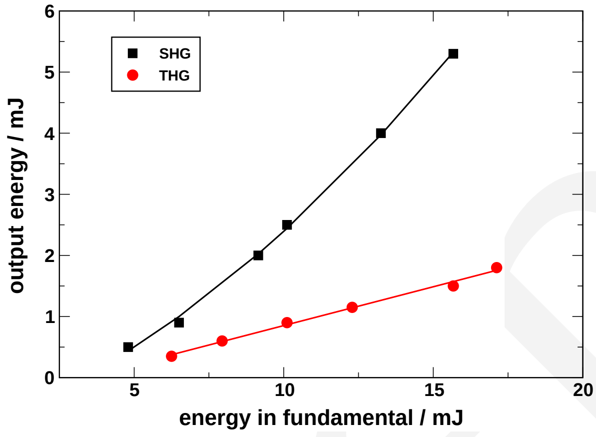

FIG. 7: Output energy of the non-linear processes as a function of the energy at the fundamental.

values are in good agreement with predictions by the program SNLO [10].

In summary, injection seeding of a Ti:Sapphire laser pumped by the second harmonic of a Nd:YAG laser using a new ramp-hold-fire technique was successfully implemented. The resonator features a particularly simple design. The Ti:Sapphire laser produces Fourier-transform limited laser pulses of 35 ns duration. Up to 25 mJ at 761.1 nm were produced. Efficient SHG (34%) and THG (11%) were demonstrated using two type-I phasematching processes in a LBO/BBO crystal combination.

The time response of the ramp system could be improved by employing electro-optic crystals that are oriented such that an applied voltage only alters the phase, but not the polarization of the light. We have already demonstrated this intracavity phase modulation technique to correct for frequency chirp on the nanosecond time scale [11]. This scheme could be adapted for the present task and would eliminate the possibility of mechanical ringing and thus enable faster ramp times which would lead to the applicability of the technique in noisy environments.

The authors would like to thank E. Thomas for help with the electronics. This project was supported by the National Science Foundation grant PHY-9732459, the Robert A. Welch Foundation grant A-1218, and the Texas Advanced Research Program grant 10366-0367-1999.

## REFERENCES

[1] R.L. Schmitt and R.A. Rahn, “Diode-laser-pumped Nd:YAG laser injection seeding system,” Appl. Opt. **25**, 629–633, (1986).

[2] S. W. Hendersen, E. H. Yuen, and E. S. Fry, “Fast resonance-detection technique for single-frequency operation of injection-seeded Nd-YAG lasers,” Opt. Lett. **30**, 715–717, (1986).

[3] V. Wulfmeyer and J. Bösenberg, “Single-mode operation of an injection-seeded alexandrite ring laser for application in water-vapor and temperature differential absorption lidar,” Opt. Lett. **21**, 1150–1152, (1996).

[4] E. S. Fry, Q. Hu, and X. Li, “Single frequency operation of an injection-seeded Nd-YAG laser in high noise and vibration environments,” Appl. Opt. **30**, 1015–1017, (1991).

[5] A. Kasapi, G.Y. Yin, and M. Jain, “Pulsed Ti:Sapphire laser seeded off the gain peak,” Appl. Opt. **35**, 1999–2004, (1996).

[6] M. P. Larsen, E. Thomas, Th. Walther, and E. S. Fry, “Injection seeding of a Ti:Sapphire laser using a ramp-hold-fire technique,” in Conference on Lasers and Electro-Optics, Vol. 11 in 1997 OSA Technical Digest Series, (Optical Society of America, Washington, D. C., 1997), pp. 362–363.

[7] M. P. Larsen, “Injection seeding of a Ti:Sapphire laser using a ramp-hold-fire technique,” M.S. thesis, Texas A&M University, College Station, TX, (1997).

[8] C. Tian, Th. Walther, R. Nicolaescu, X.J. Pan, Y. Liao, and E.S. Fry, “Synchronous, dual-wavelength, injection-seeded amplification of 5 ns pulses in a flashlamp-pumped Ti:Sapphire laser,” Opt. Lett. **24**, 1496–1498, (1999).

[9] D.J. Bradley. “Methods of generation,” . in S.L. Shapiro, editor, Ultrashort Light Pulses, volume 18 of *Topics of Applied Physics*, chapter 2, pp. 17–81. Springer Verlag, Heidelberg, (1977).

[10] SNLO nonlinear optics code available from A. V. Smith, Sandia National Laboratories, Albuquerque, NM 87185-1423 through `http://www.sandia.gov/imrl/XWEB1128/xxtal.htm`.

[11] R. Nicolaescu, Th. Walther, and E.S. Fry, “Linewidth narrowing of a pulsed Alexandrite laser by intracavity phase modulation,” in Conf. on Lasers and Electro-Optics 1998, Vol. 6 in 1998 OSA Technical Digest Series, (Optical Society of America, Washington, D.C., 1998), pp. 179–180.