# Generation of 3.5 nJ femtosecond pulses from a continuous-wave laser without mode locking

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Using time-lens compression in a loop configuration, we generate 516 fs pulses at 3.5 nJ pulse energy from a continuous-wave 1.55 $\mu$m source without mode locking. Just as a spatial lens can expand or focus a beam in space, so can a time-lens broaden or compress a pulse in time. By placing a time-lens in a loop, we maximize the efficiency of bandwidth generation by using one time-lens driven at low power to emulate a stack of many lenses. Our system is compact, is all fiber, and allows large tuning of the repetition rate and continuous tuning of the pulse width and center wavelength. © 2007 Optical Society of America

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We describe an approach for pulse generation based on time-lens compression in a loop configuration that enables us to obtain what we believe to be unprecedented energetic femtosecond pulses from a single-mode continuous-wave (CW) laser without mode locking. A time-lens refers to a device that imposes a quadratic phase in time onto an incoming pulse or temporal profile just as a spatial lens imposes a quadratic phase in space onto a spatial profile [1,2]. In our work, a sinusoidally driven, fiber-integrated, $\mathrm{LiNbO_3}$ electro-optic phase modulator serves as the time-lens, where the cusp of the sinusoid is used to approximate the proper quadratic phase. Just as a spatial lens can expand or focus a beam in space, so can a time-lens broaden or compress a pulse in time. Time-lens compression using integrated electro-optic modulators was shown in the past to generate picosecond pulses by applying ~1 W of sinusoidal RF modulation [2–4]. Hero experiments in which kilowatts of RF power were applied to a bulk modulator achieved 550 fs pulses at 514 nm but with limited pulse energy (~picojoule) and fidelity [5]. More practical time-lens pulse generators have been limited to compressed pulse widths of more than 2 ps. More recently, time-lenses have been combined with nonlinear compression techniques to surpass this limit [6,7], though with the disadvantage of performance's being dependent on optical power. Our method for pulse generation circumvents these issues by using one time-lens driven at low RF power (~1 W) in a loop to emulate many stacked lenses. By effectively stacking time-lenses, we achieve 516 fs pulses at 3.5 nJ energy starting from a CW 1.55 $\mu$m input. Our system is compact, is all fiber, and allows large tuning of the repetition rate and continuous tuning of the pulse width and center wavelength.

The experimental setup is shown in Fig. 1. The femtosecond pulse generator consists of a seed source shown before point A, a time-lens loop that generates chirped optical bandwidth shown between points A and B, followed by an amplification and compression stage after point B. The general operating principle is to allow pulses to circulate the loop $N$ times, where they will acquire bandwidth for every pass of the time-lens. After generating the desired bandwidth, pulses are ejected from the loop, amplified, and then dechirped. To generate the seed source, the output (20 mW) of a single-mode distributed feedback (DFB) laser at 1.55 $\mu$m is pulse carved into a 33% duty cycle pulse train by a Mach–Zehnder modulator. Pulses are amplified and then picked by an intensity modulator to a lower duty cycle corresponding to a repetition rate that is an integer multiple of the fundamental loop frequency. A pulse pattern generator clocked at approximately 10 GHz is used as a frequency divider to provide the electrical drives to the pulse picker as well as to the input and output switches in the loop. Note that one pulse picker is drawn for clarity, though there are actually two pulse pickers in the setup to provide a higher extinction seed source. The

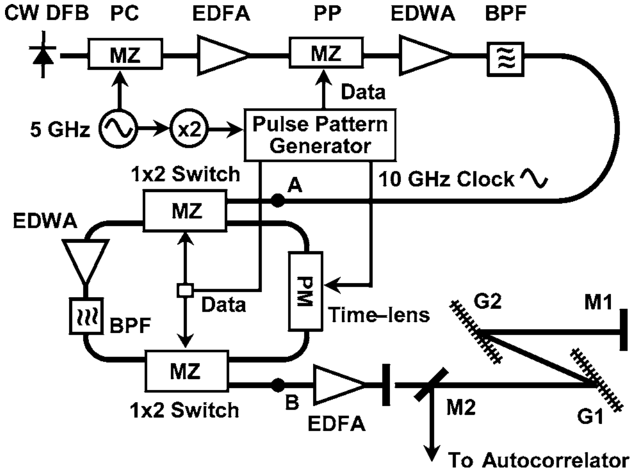

Fig. 1. Experimental setup consisting of a seed source before point A, a time-lens loop shown between points A and B, and an amplification and compression stage beyond point B. DFB, distributed feedback laser; MZ, Mach–Zehnder modulator; PC, pulse carver; EDFA, erbium-doped fiber amplifier; PP, pulse picker; EDWA, erbium-doped waveguide amplifier; BPF, bandpass filter; PM, phase modulator; M, mirror; G, grating.

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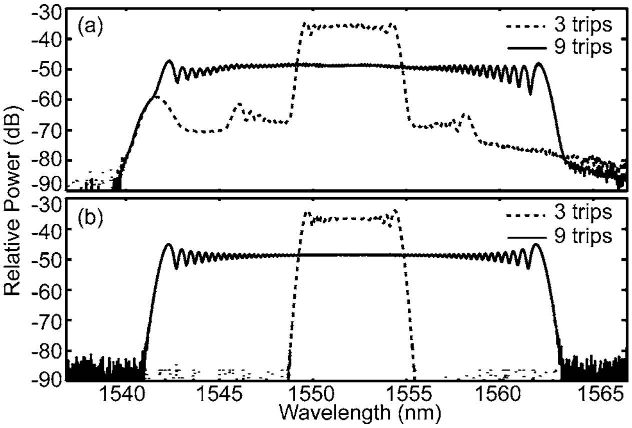

Fig. 2. Optical spectra of pulses ejected from the time-lens loop for three trips around the loop (dashed line) and nine trips (solid line). (a) Experimental traces; (b) calculated traces. All spectra are taken at a 0.2 nm resolution bandwidth.

combination of two pickers gives approximately 40 dB (20 dB each) extinction to ensure that most of the energy resides in the "ON" pulses. The timing of the electrical gates that open and close the input and output loop switches are adjusted such that one pulse enters the loop as the previous exits. An erbium-doped waveguide amplifier (EDWA) inside the loop compensates for the loss of the switches and phase modulators (~17 dB total) and is followed by a filter to remove the gain peak of the EDWA at 1530 nm. One phase modulator is drawn for clarity, though there are actually two modulators inside the loop. Each modulator is driven at approximately 1.0 W of RF power by the 10 GHz sinusoidal clock. The total phase modulation is approximately $10\pi$ rad per pass. Note that for the placement of the phase modulator in the loop, the number of passes through the time-lens corresponds to $N-1$. For maximum bandwidth generation, we allow pulses to circulate the loop nine times (eight passes through the time-lens), achieving an $80\pi$ rad phase shift. The fundamental loop frequency is approximately 28.64 MHz (~7 m of fiber), a 3.18 MHz repetition rate for nine loops. The input and output switches in the loop serve to further clean up unwanted energy between pulses. After ejection from the loop, the pulses are amplified and then compressed by a grating pair. The entire fiber loop is made of polarization-maintaining components to provide superb stability and reproducibility.

Figure 2(a) shows the experimental spectra generated for three trips (dashed curve) and nine trips (solid curve) through the loop. Each pass through the time-lens adds approximately 2.5 nm of bandwidth per pass, i.e., 20 nm for nine trips. The excellent match between the experimental results and the calculated traces shown in Fig. 2(b) demonstrates the predictability of our system. The small discrepancies between the experimental spectrum and the calculated trace for three trips are explained by two phenomena that the theoretical trace does not take into consideration. The first is the spectral hump at 1543 nm, which coincides with a gain peak of the EDWA. The second is the side modulation 30 dB down from the signal peak, which is due to incomplete pulse ejection. We do not see these features in the spectrum for nine trips because of the amplified spontaneous emission filter inside the loop which rejects power below 1541 nm and above 1577 nm. The square top feature of the spectra is indicative of aberration from the ideal quadratic in the phase drive [2,8].

For the case of nine loop trips, we amplify ejected pulses from 0.025 to 11 mW and compress them using approximately 2.0 $\mathrm{ps}^2$ of anomalous dispersion provided by a grating compressor. Figure 3(a) shows the experimental second-order interferometric autocorrelation after amplification and compression with the experimental intensity trace shown in the inset. The intensity autocorrelation gives an autocorrelation width of 697 fs. By applying the deconvolution factor calculated for this pulse shape, we obtain a pulse width of 516 fs. Once again we note the remarkable match between the experimental and the calculated traces shown in Fig. 3(b). Currently, our pulse energy is limited by the nonlinearity generated in the optical amplifier after the loop. The pulse exiting the amplifier is approximately 3.5 nJ with an 18 ps pulse width (inset, Fig. 4). Note that the pulses exiting the loop are slightly compressed from the initial 33 ps input owing to nonnegligible anomalous dispersion during bandwidth accumulation. The clean output pulses obtained in our experiments show promise that our system could be easily incorporated into a chirped amplification system to achieve even larger pulse energy. We note that the pulse quality can be further improved by using a correction time-lens to correct aberration in the nonideal phase drive [2,8].

We demonstrate coarse repetition rate tuning by viewing pulses ejected from the loop with a real-time oscilloscope, Fig. 4. For demonstration we choose to detect three trips (dashed curve) and nine trips (solid curve). The nine-trip trace displays a repetition rate of approximately 3.18 MHz, and the three-trip trace shows a repetition rate of 9.54 MHz as expected. Increasing the number of trips beyond nine, and corre-

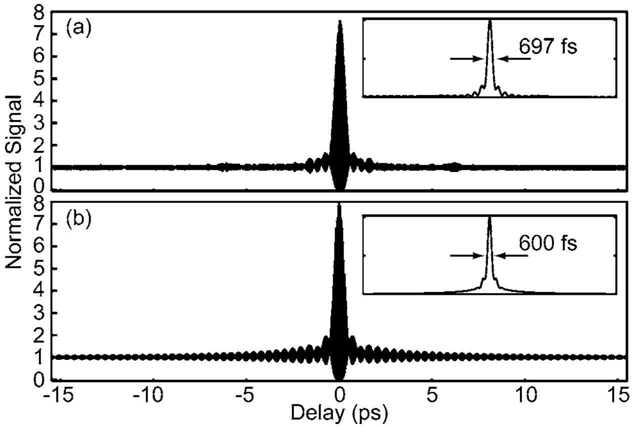

Fig. 3. Interferometric autocorrelation traces for nine trips. Insets, intensity autocorrelations. (a) Experimental trace giving a 697 fs autocorrelation width (516 fs deconvolved). (b) Calculated trace giving a 600 fs autocorrelation width (444 fs deconvolved).

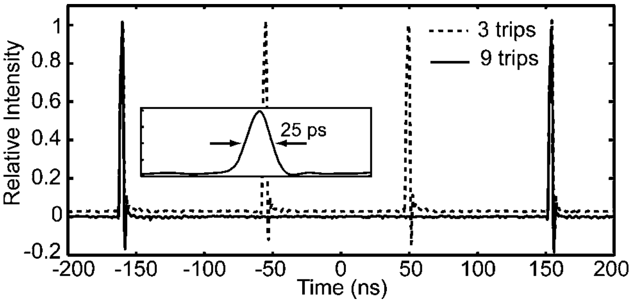

Fig. 4. Real-time oscilloscope trace of pulse trains ejected from the loop for three trips (dashed line) and nine trips (solid line). Inset, enlargement of one of the pulses for nine round trips obtained by using a large-bandwidth sampling oscilloscope. The impulse response of the optical channels for the real-time and sampling oscilloscopes are 1.0 ns and 17 ps, respectively.

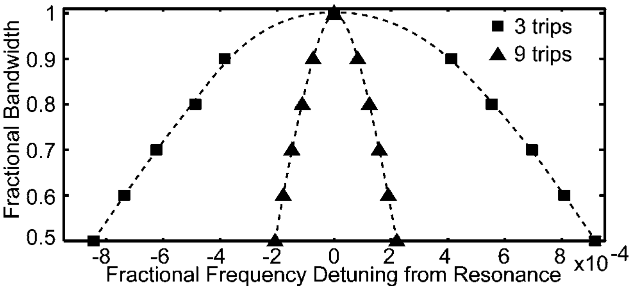

Fig. 5. Fraction of remaining bandwidth for fine frequency adjustment away from resonance. Squares, tolerance for three trips; triangles, tolerance for nine trips. Dashed curves are drawn to aide the eye.

spondingly reducing the RF drive voltage to the phase modulator, will reduce the repetition rate without significantly changing the pulse spectrum. Though not continuously variable, the ability to change the number of loop trips gives good flexibility for tuning the repetition rate. By integrating some of the discrete loop components together, the loop length could be shortened significantly to provide an even larger tuning range.

We characterize the tolerance of our system to fine frequency adjustment by examining the degradation in generated bandwidth for detuning from the resonance frequency (i.e., the repetition rate for a given number of trips that provides the broadest bandwidth). To obtain maximum efficiency for bandwidth generation, pulses must be centered under the cusp of the sinusoidal phase drive for every trip around the loop. Figure 5 shows a plot of the measured fractional bandwidth remaining for a given fractional detuning from the resonance. For each point on the curve, the RF delays to the phase modulators are adjusted to ensure symmetric bandwidth generation. In this way we force pulses to walk off the center of the cusp of the phase drive symmetrically (they arrive too early in the beginning and too late in the end). As expected, the three-trip case is approximately four times more robust to detuning than the nine trip. For practical fine-tuning of frequency, Fig. 5 shows that for nine trips the frequency can be detuned by approximately 0.008% of the resonance, 255 Hz out of 3.182219 MHz, for retaining 90% of the maximum bandwidth. Such a large tolerance to detuning demonstrates the stability of the system against environmental perturbations. For example, fused silica has a thermal–optical coefficient of $10^{-5}/°\mathrm{C}$. A 5 °C fluctuation in temperature in the fiber would therefore detune the resonance frequency by approximately 160 Hz, causing only a 5% change in overall bandwidth. Because only a small number of round trips are necessary to generate femtosecond pulses (in contrast to a mode-locked laser), the precise repetition rate of our system is entirely set by the RF driving frequency, allowing continuous fine tuning of the repetition rate within a small range without changing any optical components.

In summary, we demonstrate an all-fiber system for generating femtosecond pulses of a few nanojoules from CW light without mode locking. The flexibility of this new system allows continuous tuning of bandwidth by electronically changing the number of round trips through the loop, adjusting the phase modulator drive, or by offsetting the phases of loop modulators. Coarse repetition rate tuning can be achieved electronically at integer numbers of the fundamental loop frequency by adjusting the number of loop trips, and fine frequency adjustment can be continuously varied over small ranges of the order of ~100 Hz. The center wavelength can be finely adjusted through temperature tuning of the DFB source and coarsely tuned by simply switching to a different DFB laser within the limits of the electro-optic components and amplifiers. Our technique can be further extended to 1.06 and 1.3 $\mu$m, where spectral bandwidth is even easier to generate because of the lower $V_\pi$ of the phase modulator. Finally, we note that such a time-lens loop platform may serve as a convenient means for optical arbitrary waveform generation [9]. Arbitrary phase and amplitude could be imparted to pulses inside or outside the loop via existing or additional fiber-integrated phase and amplitude modulators.

## References

1. B. H. Kolner and M. Nazarathy, Opt. Lett. **14**, 630 (1989).
2. J. van Howe and C. Xu, J. Lightwave Technol. **24**, 2649 (2006).
3. B. H. Kolner, Appl. Phys. Lett. **52**, 1122 (1988).
4. A. A. Godil and D. M. Bloom, Appl. Phys. Lett. **62**, 1047 (1993).
5. T. Khayim, M. Yamauchi, D. Kim, and T. Kobayashi, IEEE J. Quantum Electron. **35**, 1412 (1999).
6. M. Hanna, P. Lacourt, S. Poinsot, and J. M. Dudley, Opt. Express **13**, 1743 (2005).
7. C. B. Huang, Z. Jiang, D. E. Leaird, and A. M. Weiner, Electron. Lett. **42**, 1114 (2006).
8. J. van Howe, J. Hansryd, and C. Xu, Opt. Lett. **29**, 1470 (2004).
9. Z. Jiang, D. Leaird, and A. M. Weiner, J. Lightwave Technol. **24**, 2487 (2006).