Generation of high repetition rate femtosecond pulses from a CW laser by a time-lens loop

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Abstract: We demonstrate a novel method for femtosecond pulse generation based on a time-lens loop. Time division multiplexing in the loop is performed so that a high repetition rate can be achieved. Pulse width less than 500 fs is generated from a continuous wave (CW) laser without mode locking, and tunable repetition rate from 23 MHz to 400 MHz is demonstrated. Theoretical analysis shows that the repetition rate is ultimately limited by the in-loop interference. By using a 2×2 optical switch, such interference is further suppressed, and repetition rate as high as 1.1 GHz is demonstrated.

OCIS codes: (320.7090) Ultrafast lasers; (060.2380) Fiber optics sources; (320.5520) Pulse compression

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1. Introduction

Femtosecond pulses at high repetition rates are required for a variety of applications, such as ultrafast sampling [1] and frequency metrology [2]. Passive mode-locking is the main approach to achieve fs-pulses. The repetition rate of passive mode-locked laser is limited by the cavity length. Although a compact cavity [3, 4] or a combination of active modulation and passive mode-locking [5] can be used to achieve a high repetition rate, passive mode-locked lasers have limited tunability in their repetition rate without changing the optical components. In addition, the repetition rate is sensitive to environmental perturbations unless active feedback stabilization is incorporated for the cavity length. Femtosecond pulse generation based on time-lens pulse compression has been demonstrated to have much better repetition-rate tunability and stability [6, 7]. A time lens refers to a device that imposes a quadratic phase in the time domain onto a pulse, in analogy to a spatial lens imposing a quadratic phase in space onto a spatial profile [8, 9]. A time lens can broaden or compress a pulse in the time domain. In practice, a time lens can be approximated by an electro-optic modulator driven by

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a sinusoidal electrical waveform that is properly synchronized with the incoming pulse train. The repetition rate and the temporal width of the output pulses are entirely determined by the driving frequency and the modulation strength, respectively. Thus, pulse generation by the time lens has significant advantages in the flexibility and control of the pulse train, i.e., the pulse width and repetition rate can be tuned without changing any optical components.

Ultra-large modulation depth is required to achieve a pulse width under 500 fs. Earlier experiments in which kilowatts of RF power were applied to a bulk modulator achieved 16.25 GHz, 550 fs pulses at 514 nm, but the pulse quality is poor, and difficult to amplify [6]. More practical time-lens pulse generators have been limited to compressed pulse widths of around 2 ps. To get fs-pulses with low RF power (~ 1W), a loop containing only one time lens has been demonstrated to emulate many stacked lenses [7]. In such a time-lens loop two 2×2 switches were used to control the injection and ejection of the pulses. The input pulse propagates multiple round-trips in the loops in order to obtain the required modulation depth. By effectively stacking the time lenses, 516 fs pulses at 1.55 μm were generated from a continuous-wave (CW) laser. However, the all-fiber loop, which contains a number of necessary optical components, is a few meters long. Since the minimum interval between adjacent pulses is the total time the pulse resides in the loop (i.e., round-trip time of the loop multiplied by the number of loops), the output pulse train has a low repetition rate of 3.18 MHz. Thus, in the demonstrated time-lens systems, there is a trade-off between the pulse width and the repetition rate. The shortest pulse is obtained at the expense of a low repetition rate.

In this paper we demonstrate a novel technique where ultra-short pulse width and high repetition rate can be achieved simultaneously in an all-fiber time-lens loop. Rather than generating the femtosecond pulses one by one as in the previous setup [7], the proposed time-lens loop is time-division multiplexed, i.e., a large number of pulses is present in the loop, and being phase-modulated by the same time lens. By such multiplexing, 436-fs pulses with a repetition rate of 397.76 MHz are demonstrated experimentally, which is more than two orders of magnitude higher than that of the previous time-lens loop. We also demonstrate large tunability of the repetition rate, and obtained femtosecond pulse trains with repetition rates from 23.40 MHz to 397.76 MHz by the same time-lens loop without changing any optical components. Our theoretical analysis shows that the repetition rate is limited by the interference of pulses within the loop. In order to minimize such interference, a time-dependent loss, which is realized by a 2×2 optical switch in our experiment, is added in the loop. Femtosecond pulses with 1.1 GHz repetition rate are experimentally demonstrated.

2. System design

Figure 1(a) shows the proposed time-division multiplex time-lens loop. The femtosecond pulse generator consists of a seed source shown before point A, a time-lens loop shown between points A and C where chirped optical bandwidth is generated, followed by an amplification and compression stage beyond point C. The general operating principle is to allow pulses, which come from the seed source, to circulate the loop many times where they will acquire bandwidth for every pass through the time lens. After generating the desired bandwidth, pulses are ejected from the loop, amplified and then dechirped.

The seed source consists of a DFB laser at 1.55 μm. The 13 dBm CW output of the laser is pulse carved into 33-ps, ~ 10-GHz RZ-pulse train by a Mach-Zehnder modulator (MZM). The return-to-zero (RZ) pulses are amplified and pulse-picked one out of every M pulses by an intensity modulator. T is the period of the original RZ-pulse, T ~ 100 ps in our experiment. After filtering the ASE noise, pulses are injected into the time-lens loop. The power of the input pulse train is maintained at -0.8 dBm for different input repetition rate in our experiment. Inside the loop an erbium-doped waveguide amplifier (EDWA) is used to compensate for the loss. Note that 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 a ~ 10 GHz sinusoid. The total phase modulation is approximately 10π radians

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per pass. Obviously the round-trip-time of the loop has to be *NT* (*N* is an integer) in order to synchronize the time lens and the input pulse train.

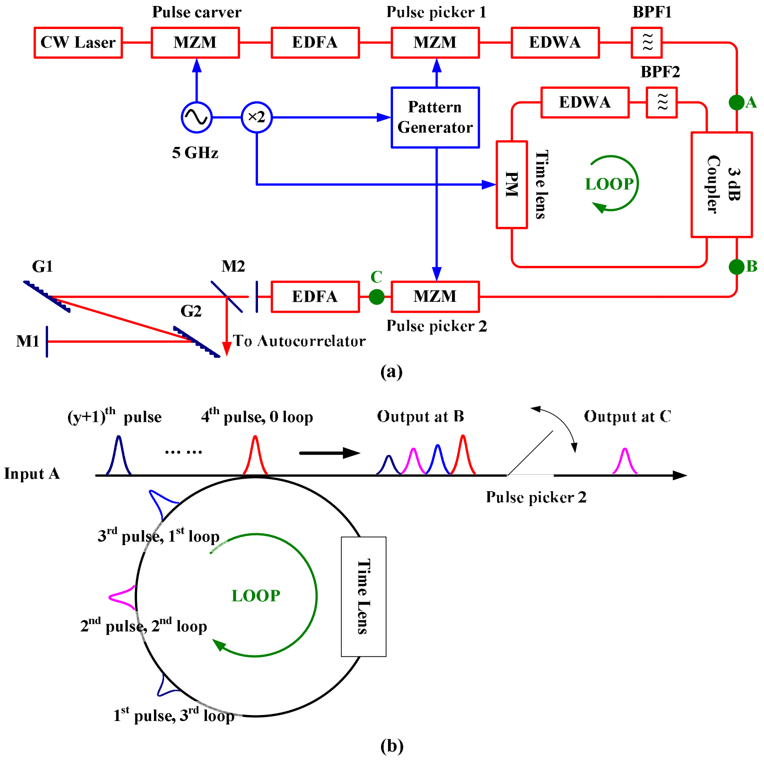

Fig. 1. (a) Experiment setup of the time-division multiplexed time-lens loop based on a 3-dB coupler. EDFA: erbium-doped fiber amplifier; BPF: bandpass filter; PM: phase modulator; M: mirror; G: grating. (b) The principle of the multiplexing of the loop.

The principle of the time-division multiplexing of the loop is shown in Fig. 1(b). Each input pulse will occupy one of the *N* slots of the loop after injection. Because the loop length (*NT*) and the pulse period after pulse picker 1 (*MT*) are both integer numbers of *T*, pulse overlap will occur. Pulse overlap between the in-loop pulse and the newly-injected pulse occurs after the first input pulse traveled in the loop for a total time (*NTx*, where *x* is the number of loops traveled) that equals to an integer number (*y*) of periods of the pulse-picked pulse train (*MTy*), i.e. the first pulse overlaps the $(y+1)^{th}$ pulse. The equation that governs this overlapping condition is then

$$N \times x = M \times y \tag{1}$$

Since the first pulse is not overlapped by the pulses between the second and the y^{th} pulse, *x* and *y* are co-prime (i.e., no common factor other than 1).

Though such pulse overlap leads to interferences and power fluctuations in the ultra-short pulse after dechirping, the effect can be ignored if the number of loops is large (i.e., *x* is large). Because the time-lens loop is a lossy loop (estimated at 0.5 dB per loop in our setup), the pulse energy after *x* loops will be small when *x* is large. After the pulse experiences enough loops so that its bandwidth is the same as that of the filter in the loop, additional loop loss will occur when the pulse is further bandwidth-broadened by the time lens and then filtered. In addition, the overlapped pulses have very different spectral bandwidth and temporal duration after dechirping. This low coherence between the overlapped pulses greatly reduces the interference beating of the electric fields. We study this interference by numerical modeling, which was highly accurate in predicting the system performance in previous experiments [7]. In our simulation model, T=100 ps and N=473 corresponding to a fiber length of approximately 10 meters. Standard single mode fiber with dispersion of 17 ps/nm/km is used. The modulation depth of the time lens is 10π, producing approximately 2.5 nm of spectral bandwidth per loop. Gain variations across the spectrum of the EDWA in the loop are also considered. A total of 9 loops are needed to generate the desired bandwidth for the femtosecond pulse. All the simulation parameters are chosen based on our experiment setup. In our simulation, x=25 is selected, i.e., the output pulse after the desired 9 loops overlaps with the pulse after 34 loops. We find that the power difference between the 9-loop and the 34-loop pulses is 15.5 dB. After dispersive dechirping to compress the pulse that has circulated 9 loops (9-loop pulse), the calculated frequency-resolved optical gating (FROG) traces of the two pulses are shown in Fig. 2(a). It can be seen that the 9-loop pulse is compressed into an ultra-short pulse while the 34-loop pulse still has a large pulse width. Furthermore, because of the uneven gain spectrum and the in-loop dispersion, there are temporal and spectral walk-offs between the two pulses, which makes their interference (i.e. the overlap of the two pulses in Fig. 2a) even lower. Clearly the low coherence between the overlapped pulses dramatically reduces the interference beating of the electric fields, as shown in Fig. 2(b). The peak power fluctuation induced by the random phase relationship between the two pulses is within ±2% at x=25. When x is larger than 50, such fluctuations can be completely negligible (±0.1%). A more efficient way to reduce the interference is to use a time dependent loss, e.g. an intensity modulator inside the loop which could provide an additional large loss to the pulses that experience the desired loop number before they overlap with the new incoming pulses.

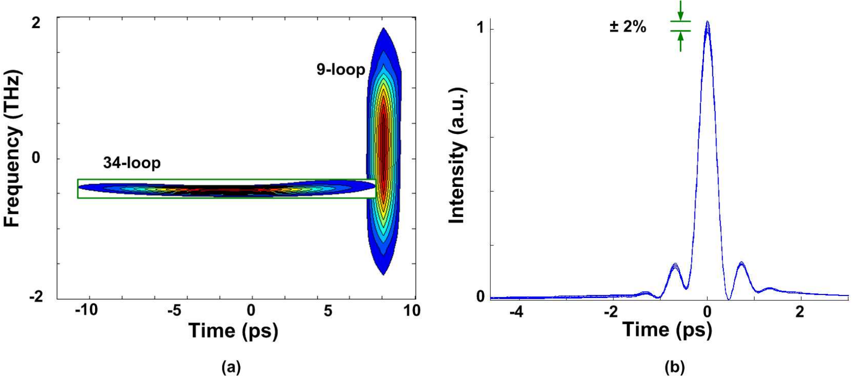

Fig. 2. (a) The calculated FROG trace of the 9-loop and 34-loop pulses. (b) The intensity profile of the output pulse.

Since each pulse injected into the loop will generate a group of pulses sequentially experiencing 0, 1, 2, 3, … loops, all the groups of pulses are then interleaved together (without interference based on the above analysis) at the output of the loop, point B in Fig. 1, forming a pulse train with repetition rate much higher than $1/MT$ due to the multiplexing. Note that the periodicity of such pulse group is still MT, so the pulse experiencing the desired loop number (9 in our design) in each group can then be easily picked by an intensity modulator, the pulse picker 2 in Fig. 1(a), which is driven by the pattern generator. At point C, the output pulse train with desired bandwidth and a repetition rate of $1/MT$ is then generated.

The high repetition rate and large tunability of the proposed time-lens loop is also indicated by Eq. (1). Without changing any optical component, N is a constant. M is then selected so that x can be large enough to ignore the pulse interference in the loop. In the simplest case where N is a prime number, we get y=N and x=M. We assume that x_{min} is the minimum value so that we can ignore the in-loop interference. For example, in our loop x_{min} is 25 if ±2% power fluctuation is the maximum interference allowed. Then the value of M can be, in theory, any integer lager than x_{min} except the multiples of N. Thus, the repetition rate, $1/MT$, can be almost any value less than $1/x_{min}T$. The highest repetition rate, $1/x_{min}T$, is no

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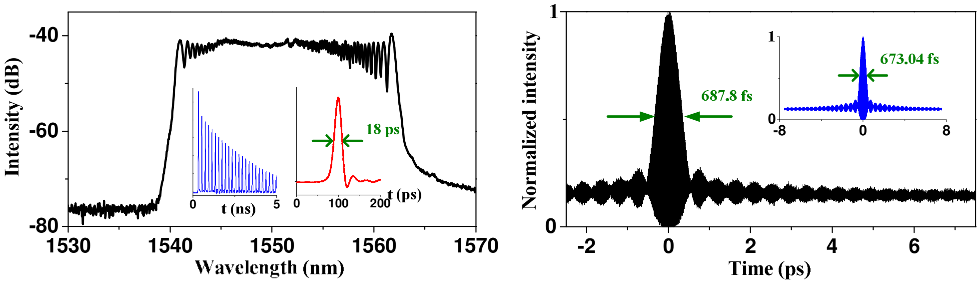
longer constrained by the loop length and the number of loops, a remarkable flexibility that is not achievable before. The stability of the frequency and phase of the generated ultrashort pulses could also be predicted since the pulses are generated from a CW laser without mode-locking. High-quality coherence could be achieved by using a stabilized, narrow line width CW source.

3. Experiment result

In our system the fiber loop length is approximately 10 meters, corresponding to *N* of 473. The entire loop was made of polarization maintaining components to provide superb stability. Pulse picker 2 was synchronized so that the 9-loop pulse in each pulse group was picked. In order to demonstrate the large tuning rang of the pulse repetition rate, we have chosen *M* as 425, 125, and 25, and obtained broad bandwidth pulses with repetition rates of approximately 23.40 MHz, 79.55 MHz, and 397.76 MHz, respectively. The output power of the pulse train is kept unchanged at -13.5 dBm when the repetition rate is tuned. Since the generated pulses are chirped, they could be amplified directly without further stretching to a few nJ [7], sufficient for supercontinuum generation. Figure 3(a) shows the spectrum after the loop circulation when *M*=25 (397.76 MHz pulse train). Each pass through the modulator builds about 2.5 nm of bandwidth for a total of about 22 nm. The square top feature of the spectrum is indicative of aberration in the phase drive from the ideal quadratic profile, which was also predicted by the numerical modeling and observed in previous experiments [7]. Note that the pulses exiting the loop were compressed from the initial 33 ps to around 18 ps, owing to the non-negligible anomalous dispersion of the loop.

After ejection from the loop the pulses were amplified to 11.6 dBm and compressed by a grating pair which gives approximately 1.36 ps^2 of anomalous dispersion. Figure 3(b) shows the measured second-order interferometric autocorrelation trace with the calculated trace in the inset. The autocorrelation trace gives a pulse width of 688 fs. Taking into account the deconvolution factor calculated for this pulse shape gives a pulse width of 436 fs. Pulse trains with different repetition rates were obtained by tuning the value of *M*. The same amplification and dechirping were applied to the pulse trains at 23.40 MHz and 79.55 MHz, and the measured pulse widths are 457 fs and 459 fs, respectively.



(a)

(b)

Fig. 3. (a) The measured spectrum at point C in Fig. 1(a). The spectrum was taken at 0.2 nm resolution bandwidth. Insert: (left) an example of the measured output at point B; (right) the measured time-domain pulse shape at point C corresponding to the spectrum. (b) The measured interferometric autocorrelation trace of the dechirped pulse giving a 688 fs autocorrelation width with 436 fs deconvolved. Insert: calculated trace giving 673 fs autocorrelation width with 427 fs deconvolved.

The theory in section II showed that the maximum repetition rate is limited by the in-loop interference. In order to mitigate such interference effect, the value of x_{min} must be large. In order to increase the repetition rate, a time-dependent loss can be used to remove the pulses after they have circulated the desired number of loops. Thus, the value of x_{min} could be as small as the desired loop number (9 in our experiment), and the repetition rate can be significantly increased. Figure 4 shows the experimental setup for the higher repetition rate

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femtosecond pulse generation. A high speed 2×2 switch is used to replace the 3-dB coupler in the previous setup. The switch introduces a large loss to the pulses that have circulated the desired number of loops by ejecting them out of the loop, while simultaneously injecting a new pulse into the loop. The performance is now only limited by the extinction ratio of the 2x2 switch (~ 18 dB in our experiment, but higher performance devices are commercially available). The loop length of this setup corresponds to N of 404. By setting $M = 9$, we obtained broad bandwidth pulse trains with a repetition rate of about 1.1 GHz. In our experiment the power of the input RZ pulse train is -3 dBm and the output power is -12 dBm. Figure 5(a) shows the spectrum after the loop circulation. After ejection from the loop the pulses were amplified and compressed by the same grating pair. Figure 5(b) shows the measured second-order interferometric autocorrelation trace. The calculated trace is in the inset. The measured autocorrelation FWHM is 742 fs, which corresponds to a pulse width (FWHM) of 471 fs after taking into account the deconvolution factor calculated for this pulse shape.

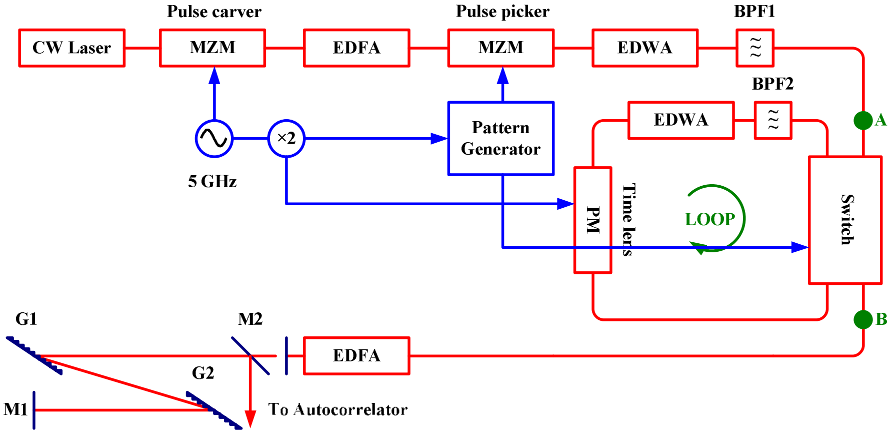

Fig. 4. Experiment setup of the time-division multiplexed time-lens loop based on a 2×2 switch.

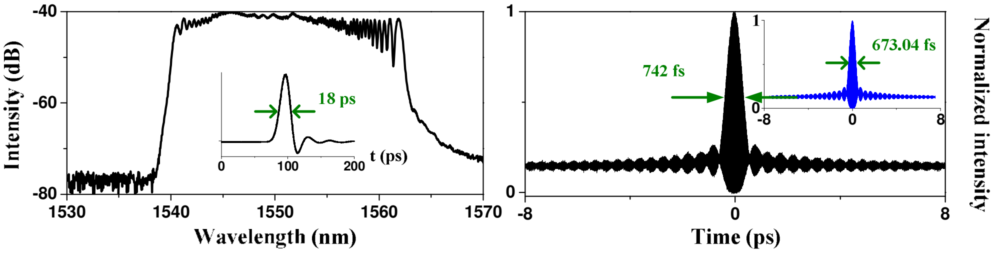

Fig. 5. (a) The measured spectrum and the time-domain pulse shape (insert) at point B in Fig. 4(a). The spectrum was taken at 0.2 nm resolution bandwidth. (b) The measured interferometric autocorrelation trace of the dechirped pulse giving a 742 fs autocorrelation width and 471 fs deconvolved. Insert: calculated trace giving 673 fs autocorrelation width with 427 fs deconvolved.

An alternative, perhaps more flexible, approach is to construct the time lens loop by inserting the time dependent loss (the 2×2 switch or a simple MZM) before the 3-dB coupler inside the loop in Fig. 1(a). The advantage of such a design is that the repetition rate can be tuned based on Eq. (1) without changing the output pulse width while the highest repetition rate of 1.1 GHz can still be achieved. In order to overcome the insertion loss of the 3 dB coupler and the switch, however, a higher gain amplifier inside the loop will be required.

4. Conclusion

In summary, we demonstrated a novel time-lens loop to generate femtosecond pulses with high repetition rate. A 3-dB-coupler-based time-lens loop was proposed to time-division multiplex the use of the time lens so that high repetition rate can be achieved. Femtosecond pulses with pulse width less than 500 fs and repetition rate from about 23 MHz to 400 MHz were obtained from a CW laser without mode-locking. A theoretical analysis was performed and showed that the maximum repetition rate was limited by the pulse interference within the loop. In order to decrease such interference, a 2×2 switch was used to replace the 3-dB coupler, and femtosecond pulse with 1.1 GHz repetition rate was demonstrated. Our system is compact, robust, and all fiber. Our technique can be extended to 1.06 μm and 1.3 μm where spectral bandwidth is even easier to generate due to the high efficiency of the phase modulator.