Progress In Electromagnetics Research M, Vol. 64, 35–41, 2018

Generation of Ultrahigh Speed, Ultrashort Flat-Top Picosecond Electrical Pulses by Laser Pulse Shaping and Ultrafast Electro-Optics Sampling

Michael G. Zhao[1], Chen Xu[2, *], and Michiko Minty[2]

Abstract—A novel method is proposed and demonstrated to generate ultrahigh speed, ultrashort flat-top picosecond electrical pulses by combining laser pulse shaping with ultrafast electro-optics sampling technique. Starting with high repetition rate laser pulses, a sequence of birefringent crystals is employed to produce optical pulses with flat-top temporal profile and tunable duration. Subsequent measurement of optical waveforms by an ultrafast photodetector yields high-speed, ultrashort flat-top picosecond electrical pulses. By using two sets of YVO4 crystals for laser pulse shaping, we report on the generation of 704 MHz, 48 picoseconds and 704 MHz, 88 picoseconds flat-top electrical pulses with 16–30 picoseconds rise or fall time. To the best of our knowledge, these results are better than or comparable with the best performance using step recovery diodes and the direct electro-optics sampling technique.

1. INTRODUCTION

High-speed, ultrashort flat-top picosecond (ps) electrical pulses have been used widely in real-time analog signal processing, high-speed communication, ultrafast signal sensing, laser diode driver, and semiconductor transistor switching time tests. To meet many challenging applications, it is necessary to develop a ps generator that could produce electrical pulses with ultra-high speed, ultrashort duration, flat-top profile, and ultrashort rise or fall time.

Conventionally, two approaches have been developed to generate ps electrical pulses. The most common one is to use the step recovery diode (SRD). In the SRD, the diode functions as a charge-controlled switch and its p-n junction is charged and discharged by application of a step voltage [1]. The dynamic characteristics of the SRD have been used as an electrical pulse shaper for producing short electrical pulses with very fast rise and fall time. However, due to the finite transient time as well as various parasitic effects, it is very hard to configure the SDR for generating electrical pulses with high-speed, ultrashort pulse duration, and ultrashort rise and fall times [1]. In a recent experiment [2], a pair of step recovery diodes was used to generate 100 MHz pulse repetition rate, 62 ps pulse duration, and 30–150 ps rise and fall times. However, it is very difficult to further improve the pulse repetition rate. Also, the ringing trails and pulse distortion from an ideal flat-top temporal profile are clearly observed [2].

The second approach for producing ps electrical pulses utilizes direct electro-optics sampling of laser pulses. In this method, optical pulses from a laser are sent to a high-speed detector, a special photodiode with ultrafast electronic circuits to convert fast optical pulses to electrical signals, and electrical pulses are generated through subsequent measurement. Because state-of-the-art lasers have been built to generate repetition rates of up to 100 GHz [3] and photodetectors of 45 GHz bandwidth are commercially available [4], the electrical pulses from an electro-optics sampling generator could be

---

Received 19 September 2017, Accepted 13 January 2018, Scheduled 19 January 2018

* Corresponding author: Chen Xu (chenxu@bnl.gov).

[1] Ithaca High School, Ithaca, NY 14850, USA. [2] Brookhaven National Lab, Upton, NY 11973, USA.

as high as 20 GHz in principle [5]. The electro-optics sampling technique for producing high-speed electrical pulses is significantly advantageous over the SRD.

Indeed, Alnair-labs [6] has reported on the generation of electrical pulses with repetition rates of up to 5 GHz, pulse duration as short as 30 ps and 17 ps fast rise-time. However, there are two major issues with ps electrical generators from the Alnair-labs. First, ps electrical pulses from a direct electro-optics sampling generator are still distorted from ideal flat-top temporal profiles. Second, it is unclear how to vary the duration of the output electrical pulses. Technical issues make it limited for many scientific and technical applications.

To overcome the major drawbacks with ps electrical generators from the Alnair-labs, a new method is proposed to generate ultrahigh-speed, truly flat-top ps electrical pulses with tunable duration. The idea is to incorporate laser pulse shaping with ultrafast electro-optics sampling technique, and a two-step approach is taken to achieve the target performance. First, longitudinal laser pulse shaping is developed to produce optical pulses with flat-top temporal profile and tunable duration, starting with high repetition rate laser pulses. Second, ultrafast electro-optics sampling of laser shaping pulses is conducted to generate electrical pulses. By this means, we are able to engineer ultrahigh-speed, ultrashort flat-top ps electrical pulses with tunable pulse duration.

2. METHOD

An experimental setup has been designed to achieve the two-step approach for producing ultrahigh-speed, ultrashort flat-top ps electrical pulses. As shown in Fig. 1, the integrated parts include: (I) laser; (II) longitudinal laser pulse shaping; and (III) ultrafast electro-optics sampling. Since the laser is already available in the lab, major effort has been made to develop the two latter parts. Details of the integrated system will be described below.

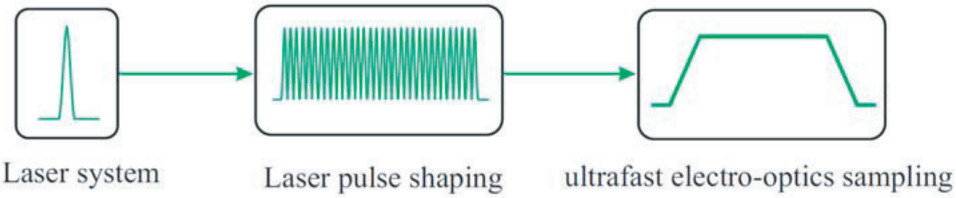


Figure 1. Schematic of the experimental setup.

2.1. Laser

The laser is an Ytterbium-doped fiber laser delivering 704 MHz, 2.3 ps (full width at half maximum, FWHM) pulses at 1036 nm. Infrared pulses are frequency-doubled to produce green pulses at 518 nm. The green laser pulses exhibit a 2.1 ps (FWHM) Gaussian temporal profile. While the laser can deliver more than 30 W average green power, only 2 mW average green power is picked up for laser pulse shaping and subsequent measurement.

2.2. Longitudinal Laser Pulse Shaping

The approach to longitudinal pulse shaping is to make use of a stack of birefringent crystals [7]. Since the ordinary wave (o-wave) and extraordinary wave (e-wave) exhibit distinct group velocities, one pulse will be divided into two pulses when it propagates through a birefringence crystal. With N crystals, one pulse will be separated into 2^N sub-pulses. Separated sub-pulses are alternatively polarized, and superposed to produce an approximate flat-top temporal profile [7].

To engineer a desired temporal profile, the polarization of incident laser pulses is set at 45° with respect to the axes of the birefringent crystals such that all sub-pulses are divided with equal intensity. Also, the crystals have been chosen with a decreasing half-thickness such that the time interval between its neighboring pulses is equal and determined by the thinnest crystal. Various pulse shapes and durations can be acquired by changing the duration of input optical pulses and the number of separated sub-pulses [7].

For the proof-of-principle demonstration, two sets of crystal stacks have been employed. A set of four YVO4 crystals (19.68 mm, 9.84 mm, 4.92 mm, 2.46 mm) was used to separate each input pulse into sixteen sub-pulses, and another set of five YVO4 crystals (39.76 mm, 19.68 mm, 9.84 mm, 4.92 mm, 2.46 mm) to divide each input pulse into thirty-two sub-pulses. The YVO4 crystal is chosen since it has a relatively large group delay between two polarizations [7]. A one-millimeter YVO4 crystal introduces 1.05 ps delay between o-wave and e-wave and the time interval between two neighboring sub-pulses is 2.5 ps. All the crystals have been installed onto kinematic rotation mounts for precise orientation. Through careful alignment, the laser beam is perpendicularly incident on all the crystals and its incident polarization is set at 45° with respect to the axes of all the crystals.

The temporal profile of laser pulse shaping is simulated with a MATLAB program. The laser intensity is the sum of all the sub-pulses through laser pulse shaping. Since the divided sub-pulses are alternatively polarized, the laser intensity profile can be separated into the sum of o-wave and e-wave intensities. Also, a random phase of each pulse has been assumed in the simulation since it is very sensitive to the slight variation in the crystal thickness. So, the laser intensity is

$$\begin{aligned} I &= \left|E(t)\right|^2 = \left|E_o(t) + E_e(t+\tau) + E_o(t+2\tau) + E_e(t+3\tau) + \ldots\right|^2 \\ &= \left|E_o(t) + E_o(t+2\tau) + \ldots\right|^2 + \left|E_e(t+\tau) + E_e(t+3\tau) + \ldots\right|^2, \end{aligned}$$

where E_o and E_e are the o-wave and e-wave electric fields, and $\tau = 2.5$ ps is the time interval between two neighboring sub-pulses.

Simulations of the temporal profiles are shown in Fig. 2. Pulse durations, determined by the total thickness of all the shaping crystals, are shown to be 40 ps by using four shaping crystals (Fig. 2(a)) and 80 ps by using five shaping crystals (Fig. 2(b)). The rise and fall time is 2.1 ps, preset by the duration of input pulses. Although sub-pulses are divided with equal intensity, modulation is clearly observed, due to the phase interference among sub-pulses. More shaping crystals [7] or longer input pulse duration [8] can be used to produce a truly flat-top profile. However, any slight phase variation from the change in crystal thickness will have a dramatic impact on the profile, causing instability. Therefore, a tradeoff must be made between the stability and the ripple. Simulations show that an approximate 40% peak-to-peak modulation in the laser shaping pulses would be the best choice to ensure that the temporal profile is nearly immune to any phase variation of all the sub-pulses. Fortunately, the subsequent measurement has almost smeared out the ripple, due to the finite response time in the detector, and ultrashort flat-top ps electrical pulses could still be generated.

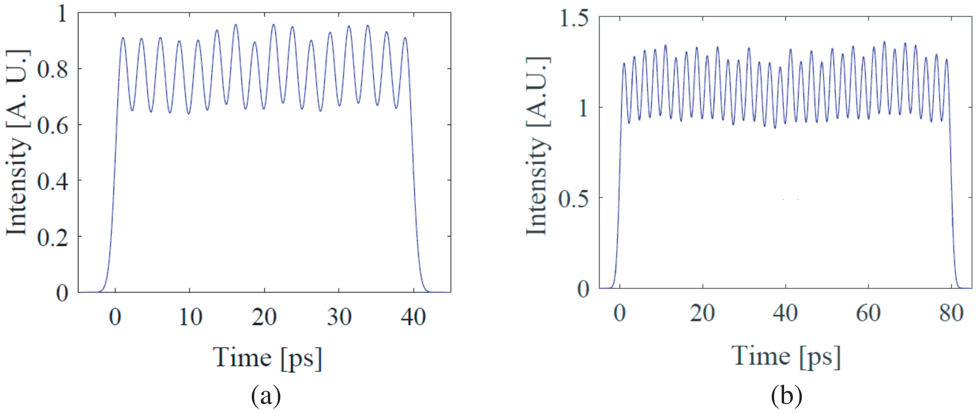


Figure 2. Temporal profiles of laser pulse shaping with four (Fig. 2(a)) and five crystals (Fig. 2(b)).

2.3. Ultrafast Electro-Optics Sampling

Figures 3(a) and 3(b) show the schematic and experimental setup for ultrafast electro-optics sampling, respectively. The laser pulses behind the shaping crystals are coupled into a single mode fiber through

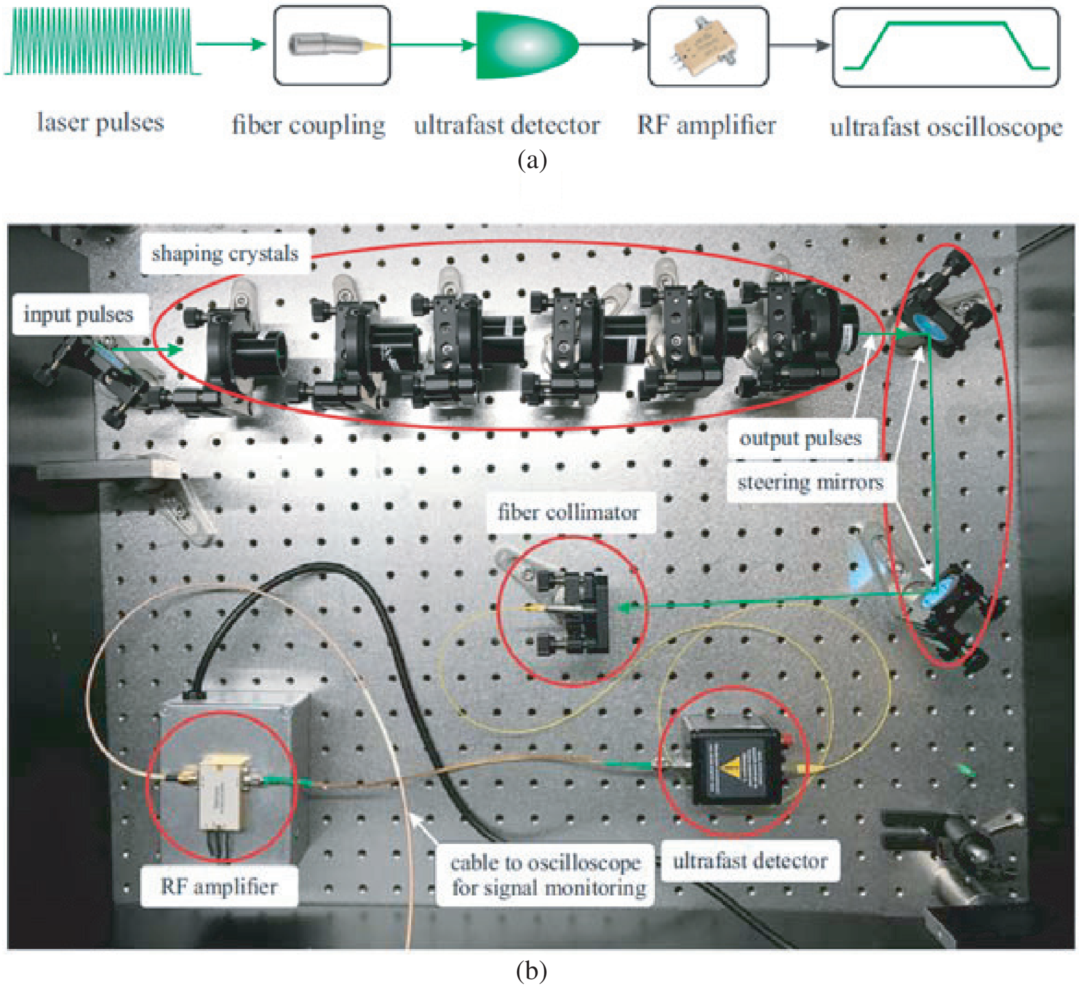


Figure 3. Schematic (Fig. 3(a)) and setup (Fig. 3(b)) for ultrafast electro-optics sampling.

a fiber collimator (CFS18-532-FC-pigtailed aspheric collimators, Thorlabs). Two mirrors in front of the collimator are used to steer the beam for maximizing the coupling efficiency. The laser beam from the single mode fiber is connected to a 25 GHz ultrafast detector (1414 High Speed Detector, Newport) through a fiber FC/FC connector. The signal from the detector is amplified through a 40 GHz radio frequency (RF) amplifier (PSPL 5882, Tektronix) and sent to a 70 GHz sampling oscilloscope (WaveExpert100H, LeCroy) for monitoring. After a series of combination, the system's bandwidth is limited to 25 GHz or 14 ps (10–90)% rise time.

3. EXPERIMENTAL RESULTS AND DISCUSSION

For the sake of comparison, our experiment has been conducted in three cases.

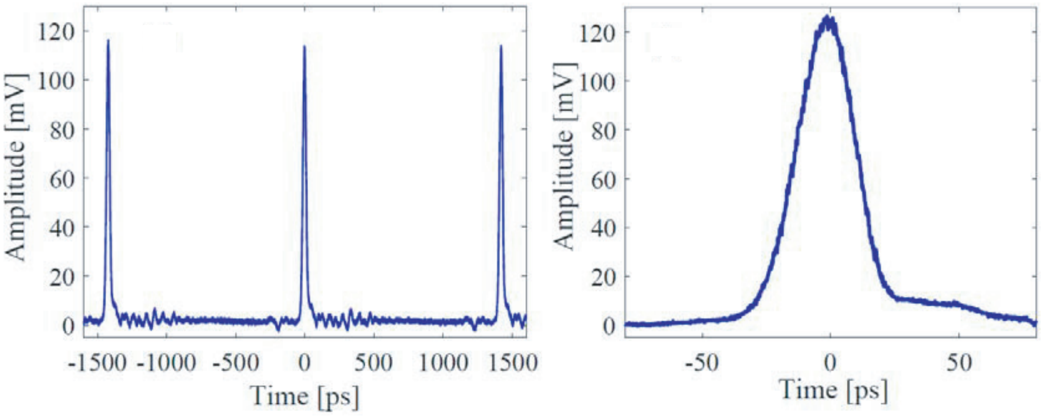
Case I: no crystal for laser pulse shaping will be used, and the temporal profile of optical pulses from the laser system will be measured directly.

Case II: a set of four YVO4 crystals (19.68 mm, 9.84 mm, 4.92 mm, 2.46 mm) has been used for pulse shaping. The 1st, 3rd, and 5th crystal is oriented at 45° relative to the horizontal direction.

Case III: a set of five YVO4 crystals (39.76 mm, 19.68 mm, 9.84 mm, 4.92 mm, 2.46 mm) has been used for pulse shaping. The 39.76 mm crystal is replaced by two 19.68 mm crystals. The 1st, 3rd, and 5th crystal is oriented at 45° relative to the horizontal direction.Due to the loss in the fiber coupling and the laser pulse shaping, about 1 mW average green power is coupled into the ultrafast detector.

3.1. Generation of 704 MHz, 27 ps Gaussian Electrical Pulses

Figure 4 shows electrical pulses that were generated without using laser pulse shaping. Electrical pulses with a time interval 1.42 ns or a repetition rate of 704 MHz was obtained (Fig. 4(a)). Zooming in the single electrical pulse (Fig. 4(b)), the duration is 27 ps (FWHM), and the rise and fall times are 21 ps and 20 ps, respectively. The electrical pulses exhibit an approximately Gaussian distribution. Because the time resolution is the root mean square sum of the rise time of the electrical pulses and the system's response time (14 ps), the real rise and fall times of the electrical pulses can be de-convoluted to be 16 ps, and 14 ps, respectively. This result is better than the best performance using the SRD [2] and the direct electro-optics sampling [6] in terms of pulse duration and rise and fall time.



(a) (b)

Figure 4. High-speed electrical pulses without laser pulse shaping. Fig. 4(a) shows a train of 704 MHz electrical pulses while Fig. 4(b) is the measurement of the duration, 27 ps (FWHM).

3.2. Generation of 704 MHz, 48 ps and 88 ps Flat-Top Electrical Pulses

To generate flat-top ps electrical pulses, laser pulses are first longitudinally shaped through two sets of YVO4 crystals and then detected through ultrafast electro-optics sampling. Figs. 5(a) and 5(b) are electrical pulses that are produced through four YVO4 crystals (19.68 mm, 9.84 mm, 4.92 mm, 2.46 mm) and five YVO4 crystals (39.63 mm, 19.68 mm, 9.84 mm, 4.92 mm, 2.46 mm), respectively. The repetition rate of these electrical pulses is 704 MHz (not shown), indicating that the pulse repetition rate has not been changed in the pulse shaping process. The duration of the single electrical pulse (Fig. 5(a)) is 48 ps, and the rise and fall times are 28 ps, and 33 ps, respectively. The duration of electrical pulses is longer than from optical pulse alone, owing to the response time of the detector, cables and connectors. De-convoluting the response time from the sampling system, the real rise and fall times of the electrical pulses are 24 ps and 30 ps, respectively. However, unlike the electrical signals obtained without laser pulse shaping, the flatness is gradually established in the middle of the electrical pulses, which is important for many applications.

As shown in Fig. 5(b), the single electrical pulse exhibits a duration of 88 ps, which is again a little bit longer than from optical pulses, owing to the response time of the detector, cables and connectors. The rise and fall times are 23 ps and 30 ps, respectively. Dis-entangling the response time from the sampling system, the real rise and fall times are 18 ps and 27 ps, respectively. Thanks to the longer input duration, the flatness of the electrical signals is well established and the ripple is less than 10%. While the flatness reported here is better than the result from Alnair-labs [5], it could be further improved through more precise alignment.

It should be noted that the proposed concept could be used to generate electrical pulses with higher speed and variable duration. Also, the amplitude, flatness, rise or fall time of electrical pulses could be further improved. Since the system's bandwidth is 25 GHz, limited by the combination of detector,

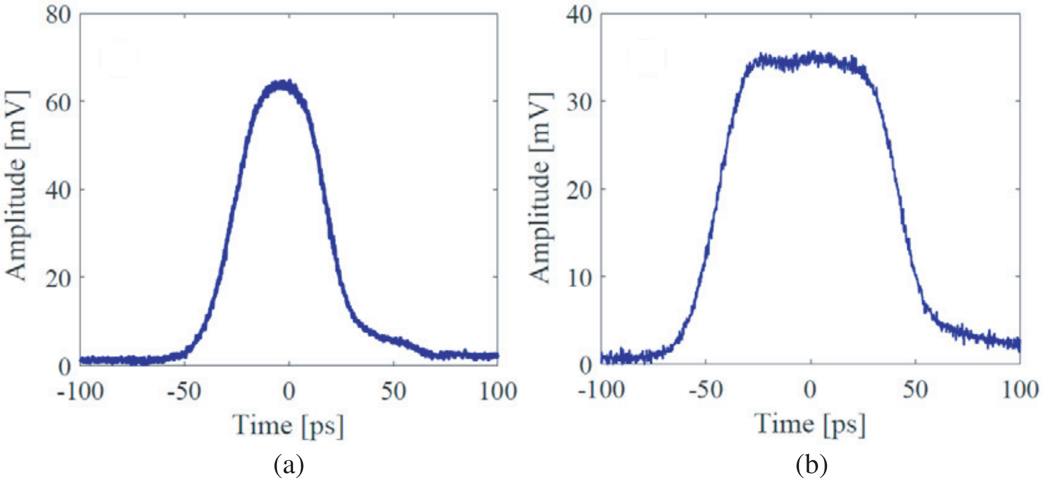


Figure 5. High-speed electrical pulses that are generated with four crystals (Fig. 5(a)) and five crystals (Fig. 5(b)) for laser pulse shaping. The duration is 48 ps and 88 ps, respectively.

cables and connectors, it is reasonably believed that the pulse repetition rate of 10 GHz and a rise or fall time of 15 ps could be achievable [5]. To achieve 20–30 ps flat-top electrical pulses, it is important to minimize the system's response time. On the other hand, to generate more than 100 ps flat-top electrical pulses, laser pulse shaping technique based on Michelson interferometer [8] would be a better choice as it is easily used to achieve longer delay between sub-pulses. The amplitude of the electrical pulses could be increased to 1–10 V by using more RF amplifiers. Moreover, nonlinear laser pulse shaping [10] would be better used to produce truly flat-top electrical pulses since propagation of ps pulses through optical fibers could directly lead to the truly flat-top optical pulses. It is thus suggested that longitudinal laser pulse shaping [7, 9], nonlinear laser pulse shaping [10], and ultrafast electro-optics sampling technique be combined to develop a system toolbox for generating ultrahigh speed,ultrashort truly flat-top ps electrical pulses in the future.

4. CONCLUSION

We have proposed and demonstrated a new method for producing ultrahigh-speed, ultrashort flat-top ps electrical pulses. By combining longitudinal laser pulse shaping with ultrafast electro-optics sampling technique, the generation of 704 MHz, 48 ps and 704 MHz, 88 ps flat-top electrical pulses have been successfully accomplished. The rise or fall time is 18–30 ps. The electrical pulses exhibit an excellent flatness and the ripple is nearly minimal. By using the direct ultrafast electro-optics sampling technique, we have also produced 704 MHz, 27 ps, Gaussian electrical pulses. The rise and fall times are 16 ps and 14 ps, respectively. To the best of our knowledge, these results are better than or comparable with the best performance using the SRD [2] and the direct electro-optics sampling technique [5]. This new approach could be extended to develop a system toolbox for generating higher speed, variable duration, ultrashort truly flat-top ps electrical pulses, and find various applications in real-time analog signal processing, high-speed communication, ultrafast signal sensing, laser diode driver, and so on.

ACKNOWLEDGMENT

This work is sponsored by US Department of Energy (DE-SC0012704).

REFERENCES

1. "Pulse and waveform generation with step recovery diodes," *Application Note*, AN 918, Hewlett-Packard, Palo Alto, October 1984, Available at Hewlett-Packard HPRFhelp.

2. Zou, L., S. Gupta, and C. Caloz, "A simple picosecond pulse generator based on a pair of step recovery diodes," *IEEE Microwave and Wireless Components Letters*, Vol. 27, 467, 2017.
3. Mangold, M., C. A. Zaugg, S. M. Link, M. Golling, B. W. Tilma, and U. Keller, "Pulse repetition rate scaling from 5 to 100 GHz with a high-power semiconductor disk laser," *Optics Express*, Vol. 22, 6099, 2014.
4. "Link to 45 GHz detector," https://www.newport.com/f/40-ghz-and-45-ghz-photodetectors.
5. "The pulse repetition rate should be less than half the bandwidth of the sampling circuit, due to the rise and fall times".
6. Data sheet from Alnair labs, http://www.alnair-labs.com/product-EPG-210.php.
7. Zhou, S., D. Ouzounov, H. Li, I. Bazarov, B. Dunham, C. Sinclair, and F. W. Wise, "Efficient temporal shaping of ultrashort pulses with birefringent crystals," *Applied Optics*, Vol. 46, 8488, 2007.
8. Sharma, A. K., T. Tsang, and T. Rao, "Theoretical and experimental study of passive spatiotemporal shaping of picosecond laser pulses," *Physical Review Special Topics — Accelerators & Beams*, Vol. 12, 033501, 2009.
9. Siders, C. W., J. L. W. Siders, A. J. Taylor, S.-G. Park, and A. M. Weiner, "Efficient high-energy pulse-train generation using a $2n$-pulse Michelson interferometer," *Applied Optics*, Vol. 37, 5302, 1998.
10. Grischkowsky, D. and A. C. Balant, "Optical pulse compression based on enhanced frequency chirping," *Applied Physics Letters*, Vol. 41, 1, 1982.