A Novel Electro-Optic Measurement System using Multiple Wavelengths

by

Limin Ji

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Supervised by Prof. Thomas Y. Hsiang and Prof. William R. Donaldson

Department of Electrical and Computer Engineering Arts, Sciences and Engineering Edmund A. Hajim School of Engineering and Applied Sciences

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Curriculum Vitae

The author was born in Baotou, China in 1981. She graduated from Beijing Institute of Technology with high honors in 2003, obtaining a Bachelor of Science degree in Electrical Engineering. She began her graduate studies in the Electrical and Computer Engineering Department at the University of Ottawa, Canada in January 2004 under the supervision of Professor Mustapha C.E. Yagoub. Her research focused on neural- and fuzzy neural-based computer-aided design techniques that can efficiently characterize and model RF/microwave transistors. She received a Master of Science degree in Electrical Engineering in June 2005. She then started her doctoral studies in September 2005 in the Department of Electrical and Computer Engineering at the University of Rochester. Under the supervision of Professor Thomas Y. Hsiang and Professor William R. Donaldson, she carried out her doctoral research in multi-wavelength electro-optic measurement.
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Abstract

In this thesis, I present a novel, replicated multi-wavelength electro-optic measurement system. In the proposed system, multiple laser sources at different wavelengths go through an electro-optic modulator at the same time to measure a single electrical pulse. The primary aim is to increase the number of temporal measurement points beyond what can be achieved by conventional methods. Since the SNR is substantially reduced by the EO modulator, a pulse replicator is added into the system to recover this ratio. The SNR is improved by averaging the train of replicated pulses. In addition to increasing the SNR of the signal, the optical replicator enhances the high-frequency response of the detected optical pulse beyond what can be achieved in a single measurement. This system is suitable for the extraction of single shot, high-bandwidth signal from environments with high levels of electro-magnetic interference (EMI) and ionizing radiation, which requires that the detection apparatus be far from the measurement point.


## Publications


Said Gaoua, **Limin Ji, Ze Cheng, Farah A. Mohammadi, Mustapha C.E. Yagoub**, “Fuzzy Neural- Based Approaches for efficient RF/Microwave Transistor Modeling”,


Presentations


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List of Symbols and Acronyms

AM: Amplitude Modulation
AOM: Acousto-Optic Modulator
BW: Bandwidth
CNT: Carbon Nanotubes
CW: Continuous Wave
DC: Direct Current
DPMO: Diode-Pumped Master Oscillator
DR: Dynamic Range
DWDM: Dense Wavelength Division Multiplexing
EMI: Electro-Magnetic Interference
ENOB: Effective Number of Bits
EO: Electro-optic
EOS: Electro-optic Sampling
FFT: Fast Fourier Transform
FM: Frequency Modulation
FP laser: Fabry Perot laser
ICF: Inertial Confinement Fusion
IR: Infrared
LD: Laser Diode
LLE: Laboratory for Laser Energetics
LLNL: Lawrence Livermore National Laboratory

MW-SPT: Multi-Wavelength Sampling Pulse Train

MZ: Mazh-Zehnder

NA: Numerical Aperture

NIF: National Ignition Facility

NOLM: Nonlinear Optical Loop Mirror

OMSA: Optically Modulated Saturable Absorption

P-APM: Polarization Additive-Pulse Mode

PC: Polarization Controller

RF: Radio Frequency

SBR: Saturable Bragg Reflectors

SBS: stimulated Brillouin scattering

SINAD: Signal-to-Noise And Distortion ratio

SNR: Signal-to-Noise Ratio

SRS: Stimulated Raman Scattering

UV: Ultraviolet

Vπ: half-wave voltage

WDM: Wavelength Division Multiplexing
Foreword

The author performed all experimental procedures in this thesis unless specified below:

Chapter 2, Figure 2.7: The laser was built by A. OKISHEV from LLE.

Chapter 4, Figure 4.1 ~ 4.6: The pulse replicator described in Figure 4.1 ~ 4.6 and used throughout the thesis was produced by Prof. W.R. Donaldson, Prof. Marcian and R. G. Roides.

Chapter 5, Figure 5.22: The box of the EO measurement system shown in Figure 5.22 was designed and made by LLE design group; the electronic circuits on the left part of the box was installed by LLE electronics group.
Chapter 1. Introduction

Electro-optic sampling is a technique to measure ultrafast electric field with subpicosecond temporal resolution and microvolt sensitivity. [1][2] The foundation of this technique is the electro-optic effect, which is a change in the optical properties of a material in response to an electric field that varies slowly compared with the frequency of the light. This effect could be divided into two categories. One is the change of the absorption, including electroabsorption, Franz-Keldysh effect, quantum-confined Stark effect and electro-chromatic effect [3-5]. The other category is the change of the refractive index, including Pockels effect (or linear electro-optic effect), Kerr effect (or quadratic electro-optic effect) and electro-gyration [6-8]. Among the electro-optic effects, the Pockels effect produces a change in birefringence in an optical medium induced by a constant or varying electric field. The Pockels effect is used to make Pockels cells, which are voltage-controlled wave plates. The EO sampling technique is based upon the interaction of ultra-short optical pulses and the unknown electrical transient in a traveling-wave Pockels cell employed as an ultrafast intensity modulator. There is only a short time interval in which the electric field at the probe can influence the light. This temporal resolution is
determined entirely by the width of optical pulses and by geometrical considerations and thus the measurement bandwidth can be extremely high. Another advantage is that it allows for contactless characterization, which is important particularly for microwave frequencies where contacting is a delicate issue.

Almost all the III-V and II-VI semiconductors are electro-optic crystals. A change in either an external or internal field would produce a net stress in the crystal and lead to a lattice distortion. The lattice distortion causes the changes in the crystal birefringence, which makes the light propagating through the crystal experience the electric field applied to the crystal by having its polarization rotated. By placing the crystal between two crossed polarizers, the transmitted light intensity is proportional to the electric field for small electric fields. Therefore, the electric field can modulate the light by proper arrangement of the crystal direction with respect to the electric field direction. If there is a transient electric field across the crystal, the index ellipsoid will change rapidly and optical pulses with comparable or higher resolution could be applied to identify this electric field transient and this transmission function is a sinusoidal function. That is, the ultra-short optical pulses could be used to detect the ultrafast electric field change via the electro-optic effect.

The first Ultrafast Electro-Optic Sampling (EOS) method was invented by Valdmanis and Mourou in the early 1980’s [1]. The electric field at the electro-optic probe changes the polarization of the light, in a very short time interval when ultra-short optical pulses are used. By slowly varying the arrival time of the probe pulse, they obtained a full waveform of a periodic signal. There are basically two types of
EOS systems. One is the pump-probe system that uses two copies of optical pulse trains with a variable time delay to allow sequential sampling of different portions of a waveform. The other kind uses a synchronized single pulse train to introduce a small frequency offset between some harmonic of the pulse repetition rate and the electronic oscillator [9]. Figure 1.1 from [1] shows a general layout of an electro-optic sampling system.

This system uses a lithium niobate traveling wave Pockels cell between two polarizers as the modulator. The laser source was a colliding pulse mode-locked laser. Its output was a 120 fs pulse train at 100 MHz. The output pulse train was split into two beams. One beam drove the electrical signal source and the other went through the Pockels cell to sample the electrical signal. The transmitted beam and the rejected beam at the analyzer were measured by two detectors at the same time. After the detectors, the signals went to a differential system consisting of one differential amplifier, one lock-in amplifier and one signal averager. This system provided higher signal sensitivity and more resistance to laser fluctuations.
Since then, different techniques have been applied in the EOS area to improve the efficiency and sensitivity of the system. For example, Q. Wu and X.C.Zhang’s work in “Free-space electro-optic sampling of terahertz beams”, the measured waveform is an exact cross-correlation of the incident terahertz and the optical pulses through proper velocity matching [10].

For the EO sampling system discussed above, continuous and repetitive pulse trains were needed to generate repeated signals that were sampled. However, there are cases where the accurate measurement of the single shot pulse shape is critical. An important case is the OMEGA and OMEGA EP laser systems. The OMEGA laser used for Inertial Confinement Fusion (ICF) is required to produce stable, high-
contrast pulse shapes in order to achieve the highest possible compression of the target [11].

The OMEGA laser facility at the University of Rochester Laboratory for Laser Energetics is a part of the national laser fusion effort [12]. The fusion energy is obtained by the implosion of a target composed of spherical capsule containing deuterium and tritium, with a laser beam that symmetrically illuminates the target. The OMEGA laser is based on a Nd:glass system (1053nm) in which its infrared (IR) radiation is converted to the ultraviolet (UV) third harmonic light (351nm). OMEGA can place 30kJ UV on target for pulse durations of up to 4ns. OMEGA EP operates in a pulse-width range of 1 to 100ps at 1053nm [12]. For widths of 10ps or greater, the on-target energy will be up to 2.6kJ and this high energy level makes it hard to use the ordinary detectors directly, especially inside the target chamber.

Another good example is the National Ignition Facility (NIF) which begins ignition experiments at Lawrence Livermore National Laboratory (LLNL) in 2010 [13]. In this system, the master oscillator generates a very small, low-energy laser pulse. The pulse may range from 100 trillionths to 25 billionths of a second long, and has a specific temporal shape as requested by NIF experimenters. The low-energy pulse is split and carried on optical fibers to 48 preamplifier modules for initial amplification and beam conditioning. In the preamplifiers the energy is increased by a factor of ten billion to a few joules. The 48 beams from the 48 preamplifiers are then split into four beams each for injection into the 192 main laser amplifier beamlines [14]. But these
systems have a repetition rate of one shot per hour, which makes it impossible to use averaging or any other similar techniques to get their pulse shape.

This is not the only case. For example, a single laser pulse could be connected with one damage spot on a surface in one-on-one damage testing [15]. Measurement of pulse shape through diffuse media yields information on its structure, absorption and scattering properties [16]. Scientific measurement of noise-initiated process require single-shot measurements, such as nonlinear pulse generation via stimulated Brillouin scattering (SBS), stimulated Raman scattering or sonoluminescence [17][18]. Single-shot capture is more and more important in various applications nowadays and is our primary reason to start this work.

For conventional EOS systems, the sampling signals are derived from optical pulses as short as 100fs. Therefore, the repetitive electrical signals are characterized with much shorter on time scales than available with conventional electronic instruments, like oscilloscopes and transient digitizers. However, those techniques are not applicable in single-shot mode. The pump-probe techniques use a single optical pulse to sample a small portion of each of the repetitive trains of electrical pulses. Some other schemes use integrated fiber-optic components to generate optical replicas to be sampled at different time delays [19]. Their basic goal is to increase the temporal resolution while increasing the number of temporal measurement points, beyond what the conventional electronic instruments can achieve. In single-shot mode applications, these techniques have severely degraded signal-to-noise ratio (SNR, the ratio of signal power to the noise power, where $P = k_B T \Delta f$, $k_B$ is
Boltzmann’s constant in joules per Kelvin, $T$ is the absolute temperature in kelvins and $\Delta f$ is the bandwidth in hertz over which the noise is measured), and dynamic range (DR, the ratio of the peak to the signal level where the SNR equals 1), due to the sinusoidal transfer function that relates the electrical input and the output. Additionally, these techniques are not very attractive due to the steady increase in the sampling rate achieved by conventional electronic instruments. An example is the NIF DANTE EO data acquisition. Its desired DR is 10000:1; the desired Bandwidth (BW) is 6GHz, compared to the BW of a Tektronix TDS 6604 digital storage oscilloscope of 30 GHz; its desired Effective Number of Bits (ENOB), a measure of the quality of a digitized signal [20] is 13.28771238, compared to the current ENOB of 5.00, where ENOB = $(\text{SINAD-1.76})/6.02$ SINAD stands for Signal-to-noise and distortion ratio and is the ratio of the wanted signal to the sum of all distortion and noise products after the DC term is removed [21].

The conventional way to reduce noise on periodic signals is to average temporally sequential events, which has the benefit of improving the SNR by a factor of $\sqrt{N}$, where $N$ is the number of traces [22]. But it does not work for nonrepetitive, single-shot events, as demonstrated in Figure 1.2 below. The reason is that the temporal jitter between the averages would wash out the high frequency components. However, there will be no difference in the bandwidth of the electronic and opto-electronic systems if there were no jitter in the electronic system. In the optical replicator, the spacing between pulses can be accurately measured. There is a sharp step in the red (single-shot averaged using full fiber replicator) curve around 2ns;
while the blue curve, the multi-shot averaged curve, shows a more rounded edge or in other words, information loss. The original electrical signal is shown as the green curve in Fig 1.2 as well. Another problem with the sequential averaging is that the acquisition speed is reduced by a factor of N.

![Figure 1.2 Single-shot, single-shot-averaged, and multi-shot-averaged pulse shapes. Arbitrary offsets have been added for clarity. Figure from paper by Marciante et.al [22]](image)

However, there are still many ways to solve the problems. The single-shot pulse could be replicated and averaged with itself to receive the benefits of averaging without degrading SNR and DR or reducing the acquisition speed as shown in Figure 1.2. The details of this technique will be introduced in Chapter 4. In next chapter, the idea of the multi-wavelength EO sampling method will be explained in details, including the preliminary work and a demonstration experiment.
Chapter 2. Multi-Wavelength Method

The idea of using multi-wavelength optical pulse train to carry out EO sampling of electrical transients and microwave signals was first proposed by Yariv and Koumans in 1998 [23]. The detail of their proposal is introduced in section 2.1. However, they did not demonstrate the idea experimentally. Section 2.2 provides some theoretical considerations of our proposed system and a demonstration experiment is presented in section 2.3. In the proposed system, multiple laser sources at different wavelengths are modulated simultaneously. The eventual aim is to increase the number of temporal sampling points comparable to what can be achieved by conventional methods like pump-probe EOS. This multi-wavelength method is the first step in this single-shot EO measurement system. The second step is using a full fiber pulse replicator to further improve the SNR and the DR of the whole system. The full fiber pulse replicator is introduced in Chapter 4 and the whole EO sampling system is explained in detail in Chapter 5.
2.1 First Proposal of the Multi-wavelength Electro-optic Sampling Method

In 1998, A. Yariv and R.G.M.P Koumans from California Institute of Technology proposed an ultra-high speed sampling scheme using a multi-wavelength sampling pulse train (MW-SPT) in [23]. The idea is to use wavelength multiplicity to increase the sampling rate of A/D converters. The developments of wavelength division multiplexing (WDM) ‘add/drop’ filters [24] and the semiconductor mode locked lasers are crucial for this proposed multi-wavelength technique [25-26]. The MW-SPT was made up of pulses having different wavelengths from the conjunctive pulses and in a repeating fashion as shown in Figure 2.1. For example, if the required sampling rate is 100Gsample/s, the spacing between two adjacent sampling pulses will be 1/100G = 10 ps; for 10 different wavelengths, the spacing between the pulses with same wavelength is 10×10 = 100 ps; the sampling rate for one wavelength is 100G/10 = 10Gsample/s.
Figure 2.1 The MW-SPT in [23].

The schematic view of their proposed system is shown in Figure 2.2. The MW-SPT is fed into an electro-optic modulator which is driven by the microwave signal to be sampled. The output from the modulator is sent to an optical high resolution wavelength demultiplexer to be separated into 10 individual parallel optical pulse trains. The result is 10 individual parallel optical pulse trains with a relatively low sampling rate which could be detected by photo detectors and converted into digital signals by low sampling rate A/D converters, as shown in Fig. 2.2(b). The sampling rates reduced from 100 Gsamples/s to 10 Gsamples/s for each channel. Nowadays, there are 45 GHz oscilloscopes with 11 ps time resolution available. If there is only a factor of 2 difference with a much less complicated system, it is not practical to choose this system over an oscilloscope.
Figure 2.2 The MW-SPT system in [23]. (a) MW-SPT sampling microwave signal at 100Gsamples/s.
(b) Stream of samples at 100 Gsamples/s wavelength demultiplexed (WDM) into 10 parallel 10
Gsamples/s streams detected by photo detectors (PD) and processed by electronic A/D converters.

The key part in the proposed method is the generation of MW-SPT. To avoid
distortion among the pulses, pulse to pulse fluctuations should be small. In addition,
the pulse width for all pulses should be small compared to the sampling time, to make
sure each individual pulse acts essentially as delta functions during the sampling
process. The proposed setup to generate the MW-SPT is shown in Figure 2.3.
However, the main drawback of this system is that the pulse train was not repeated and therefore SNR was sacrificed for BW. Also, their proposed system was designed for short electrical pulses only. In our new EO measurement system, two important improvements are accomplished. First, our proposed system is capable of processing both long electrical pulse (typically the replicators have ~10 nS spacing) and short ones (limited by the response of the EO modulator to 10 pS). Second, the pulse train is replicated by a full fiber pulse replicator to improve the SNR and the DR of the system. The framework of the proposed method will be introduced in the following section.

To record single-shot events, the optical pulses at different wavelengths, at least as long as the electrical transient being measured, are simultaneously present in a fiber-optic-coupled, >16-GHz LiNbO₃ EO modulator via a fiber combiner. For some applications like the OMEGA, the extraction of single-shot, high-bandwidth signal
from environments with high levels of electro-magnetic interference (EMI) and ionizing radiation requires that the detection apparatus be far from the measurement point. The isolation of the recording apparatus from the detector can be accomplished by converting the measured electrical signal into an optical pulse and transporting that pulse over a long optical fiber [17].

### 2.2 Effect of Wavelength-dependent Modulation Depths

The measurements made at different wavelengths are independent samples and averaging will increase the signal-to-noise ratio. The improvements in the signal-to-noise ratio increase as the square root of the number of pulses being measured. Each pulse has a different sensitivity to the electrical signal. The transmission of the EO modulator is

\[
T = A_0 \times \sin \left( \frac{\pi (V + V_0)}{V_{\pi}} \right) + C_0
\]

(1)

where \( T \) is the transmission coefficient of the >16GHz LiNbO\(_3\) Mazh-Zehnder modulator [27], \( V \) is the transient output voltage, \( V_{\pi} \) is the half-wave voltage, \( A_0 \) is the amplitude of the modulation, \( V_0 \) is the phase offset in voltage units and \( C_0 \) is the offset of the amplitude and typically should equal approximately \( A_0 \). If the signal voltage is
adjusted so that the peak voltage is less than but approximately equal to $V_\pi (\lambda_0)$ for $\lambda_0$ (the longest optical wavelength being modulated), all the lower wavelengths will undergo multiple waves of polarization rotation as $V_\pi$ scales inversely with the optical frequency [28]. Usually, this is undesirable since it leads to ambiguous voltage measurements as shown in Figure 2.4, where $\Delta T$ could correspond to either $\Delta V$ or $\Delta V'$. However, this ambiguity can be removed if multiple wavelengths are modulated simultaneously with different $V_\pi$’s, where $\Delta V$ is the derivative of power-voltage relation function corresponding to the uncertainty of power $\Delta P$ as illustrated in Figure 2.5.

$$P(t) = P_0 \sin^2\left[\frac{V(t) \times \pi}{2 \times V_\pi} + \phi\right]$$

Where $\Phi$ is the phase radian units, $V_\pi$ is the half-wave voltage and $P_0$ is the measured optical power.

Therefore, the measurement at wavelength where $V_\pi$ has the lowest $\Delta V$ can be used to remove the $\pi$-phase jumps at other wavelengths where the applied voltage exceeds their respective $V_\pi$ thresholds if the 1st wavelength is biased at either a minimum or maximum. After combing the voltage errors at two different wavelengths quadratically, see eqn. (5), the infinities are removed completely as shown in Figure 2.5 (b) where the former ‘gaps’ are replaced by a curve with finite values. The first step in converting the optical signal back to an electrical signal is to do the voltage reconstruction at the
lowest optical frequency, giving $V_0(t)$. Next, signals at the higher frequencies are reconstructed. If the external transients do not exceed $V_{\pi i}$

$$V_i(t) = 2\sin\left[\frac{1}{2}T_i(t)^{1/2}\right]V_{\pi i}.$$  \hspace{1cm} (3)

Otherwise,

$$V_i(t) = 2\left\{-a\sin\left[\frac{1}{2}T_i(t)^{1/2}\right] + \frac{\pi}{2}\right\}V_{\pi i} + V_{\pi i}.$$  \hspace{1cm} (4)

The total voltage error after averaging the errors from two different wavelengths is calculated as the average of $\Delta V$ for two different wavelengths:

$$\Delta V_{\text{total}} = \frac{1}{\sqrt{\left(\frac{1}{\Delta V_1}\right)^2 + \left(\frac{1}{\Delta V_2}\right)^2}}$$

Figure 2.4 The Resolution reaches zero at extrema.
An example is shown in Figure 2.5 where the curves are generated by a Matlab program where \( \Delta V_1 \) and \( \Delta V_2 \) are defined as \( \cdots \); in Figure 2.5(a), blue curve stands for the voltage error for a short wavelength laser and the red curve for a long wavelength laser versus the transient magnitude. Both curves show the characteristic that the voltage error reaches infinity around \( V_\pi \). However, the locations of those ‘gaps’ are different for different wavelengths. By carefully selecting the wavelengths, the resulting curves could overlap each other’s ‘gap’ and the ambiguities could be removed by suing the unambiguous curve to constrain the ambiguous curve as demonstrated in Figure 2.5(a). By applying function (5), the lower \( \Delta V \) sets in, as shown in Figure 2.5(b), restoring \( \Delta V \) to a finite value.
2.3 Experiment with Two Different Wavelengths

To demonstrate this technique, two lasers with wavelengths at 980nm and 1064nm were fed into the fiber-optic-coupled, >16-GHz LiNbO3 EO modulator at the same time and then separated as shown in Figure 2.6.
Figure 2.6 The two-wavelength EO measurement system uses off-the-shelf components.

The laser with wavelength 1064nm is a diode-pumped master oscillator (DPMO) [29]. It is an all-solid-state, highly stable, fiber coupled laser system producing 20–30 ns flat-top square single-frequency pulses at the up to 300 Hz repetition rate. The DPMO consists of single-frequency, Q-switched Nd:YLF laser, pulse slicer, and diagnostics (Q-switched pulse envelope, sliced square pulse, frequency control). The main features of DPMO are high amplitude and frequency stability, high reliability and low maintenance. The laser is shown in Figure 2.7.
1.2 W SDL single-stripe diode is used as a pump source. The slow axis is collimated with high NA aspheric lens. The fast axis residual divergence is compensated by cylindrical lens. The pump radiation is focused into active element through end mirror. End mirror, Brewster prism, and output coupler form a ring cavity. Unidirectional hence single-frequency lasing is achieved by special AOM alignment using self-feedback mechanism [29].

The 980 nm diode laser is a commercial product of Amonics. It is a 980 nm bench-top FP laser source with model no. AFP-980-200-B-FA. Its output power is up to 196.3 mW, center wavelength is 976.707 nm and FWHM is 0.974 nm. The output power stability is <+/- 0.02 dB (8 hrs).
The electro-optic modulator is a fiber-optic-coupled, >16GHz lithium niobate modulator from EOSpace. Its model no. is AZ-0K1-20-PFA-SFA-106. Its insertion loss is 2.8dB, RF $V_{\pi}$ at 1GHz is 2.2 V, bias $V_{\pi}$ is 2.1V and extinction ratio is 22dB.

In our experiments, those two lasers were fed into a 2-by-1 combiner at the same time. Then they were fed into the fiber-optic-coupled, >16-GHz LiNbO$_3$ EO modulator at the same time. After the EO modulator, the optical beam was separated into two beams through a 3 dB fiber coupler. Following the fiber couple, the two beams went through two different bandpass filters, one for 980 nm and the other for 1064 nm. After the bandpass filters, only one wavelength beam traveled in each route. The 980 nm beam arrived at the Si photodiode and the 1064 nm beam reached the InGaAs photodiode. Tektronix TDS 6604 digital storage oscilloscope was used for the measurement.

The measured optical powers from two different wavelengths are shown in Figure 2.8(a). After deconvolution (where $V_{\pi}$ is 2.6V and $\phi$ is zero) by applying function (2) and (3), the signal was reconstructed by averaging the results from different wavelengths. The recovered signal from two different wavelengths closely matches the original signal as shown in Figure 2.8(b). The accuracy will be improved by using more wavelengths and that is the next step of this experiment.
Figure 2.8 (a) The modulated optical waveforms look completely different. (b) The deconvolution indicates that the reconstructed signal is very close to the modulation signal.
This demonstrates an EO measurement system that, using commercially available fiber optic and integrated optic components, sequentially modulates two optical frequencies and may be extended to multiple optical frequencies. In the proposed system, fiber lasers will be used as one of the optical sources and they will be introduced in Chapter 3.
Chapter 3. Fiber Lasers

Fiber lasers have drawn much attention in last decade due to the telecommunication boom. It consists of a pump source, a gain medium and a cavity. The gain medium is a rare-earth-doped glass fiber, which allows light to propagate without diffraction due to total internal reflection. In recent years, fiber lasers have been used in many other fields, like material processing, spectroscopy and medicine. There are some important advantages of fiber lasers over other types like semiconductor lasers, gas lasers and solid-state lasers and we choose fiber laser for the proposed electro-optic measurement system based on these benefits:

- High output power: its active region could be 10’s of meters long and provides very high optical gain.
- Compact size: Fiber lasers are compact compared to rod or gas lasers of comparable power, because the fiber could be bent and coiled to save space.
- Reliability: Fiber lasers exhibit high stability, extended lifetime, maintenance-free turnkey operation and immune to environmental changes.
- Ultra-short pulses: fiber lasers could have output pulses in the picoseconds or even femtosecond level and measurements based on the ultra-short pulse train could have higher resolution compared to diode lasers.

Further, mode-locked fiber lasers could largely be based on commercially available telecom components, which have been carefully developed for reliable long-term operation and have a moderate cost.

Depending on the mode-locking mechanism and pulse dynamics, fiber lasers can be classified in several ways.

Based on whether the mode-locking is activated by an electronic modulator, fiber lasers could be classified into active mode-locked lasers and passive mode-locked lasers. Actively mode-locked lasers have an electro-optic modulator or acousto-optic modulator in the laser cavity to generate periodic perturbations inside the cavity. The mode-locking condition is achieved when the perturbations are strong enough and synchronized with multiples of the fundamental frequency of the laser cavities. By contrast, passive mode-locked lasers have no electronic modulator inside the cavity. They use saturable absorbers to achieve mode-locking. A saturable absorber is an optical device that has an intensity dependent transmission. For passive mode-locking, an ideal saturable absorber absorbs low intensity light while transmit sufficiently high intensity light. In the laser cavity, assume a short pulse is already circulating in the laser resonator, when the pulse hits the saturable absorber each time, the saturable absorber saturates the absorption and hence temporarily reduces the losses. In the steady state, the laser gain could be saturated to a level that is just
sufficient for compensating the losses of the circulating pulse, whereas any light with lower intensity will experience losses when it hits the absorber at other times, as the absorber could not be saturated by this light. Since the light oscillates in the laser cavity, this repeated process leads to the amplification of the high intensity spikes and the absorption of the low intensity light. Finally, it leads to a train of pulses and mode-locking of the laser [30].

Based on the intra-cavity pulse dynamics, fiber lasers can also be classified into three groups: soliton lasers, stretched pulse lasers and similariton lasers. This classification is not used in this thesis.

### 3.1 Passive mode-locked lasers

Passive mode-locking is an all-optical nonlinear technique capable of producing ultra short optical pulses without requiring any active component, such as a modulator, inside the laser cavity. This characterization makes them especially suitable for low noise and compact applications.

There are two types of the saturable absorbers used in passive mode-locked lasers. One is artificial saturable absorbers, including Nonlinear Optical Loop Mirror (NOLM) and Polarization Additive-Pulse Mode locking (P-APM). The other is real saturable absorbers, such as semiconductor quantum-well Saturable Bragg Reflectors
(SBR) and Carbon Nanotubes (CNT) saturable absorbers. Several typical setups are explained in more detail below.

3.1.1 Nonlinear Optical Loop Mirror Mode-locked laser

A typical setup of nonlinear optical loop mirror mode-locked lasers is shown in Figure 3.1. The ‘figure-of-eight’ lasers [31-33] have nonlinear optical loop mirrors in the cavities as saturable absorbers. The cavity shown in Figure 3.1 has two fiber loops. The loop on the left has the output port of the laser and the isolator for single direction propagation. The loop on the right has the input port of the pump source and a piece of erbium-doped fiber. The laser light goes through the coupler in the middle from the left loop to the right loop, where it is split into two parts equally. One part goes clockwise back to the left loop and the other goes counter-clockwise to the right loop. There is little phase difference between the light waves traveling inside the right loop. But the isolator in the left loop introduces optical energy loss and thus the CW operation has a 50% loss here.

For pulsed operation, the two pulses have different nonlinear phase shifts due to the asymmetrical location of the gain fiber in the right loop. When the two pulses arrive at the coupler in the middle after a round trip in the right loop from each direction, the coupling ratio into each of the ports in the left loop depends on the phase difference the pulses pick up in the right loop [32]. As a result, the pulsed operation sends more energy to the port along the isolator direction at the coupler in
the middle and the fiber laser with this structure favors pulsed operation over CW operation.

Usually, fiber lasers using NOLMs produce pulses with duration around 100 fs. The advantage of using NOLMs to generate pulse trains is low timing jitter and low intensity noise. But there is one substantial drawback with NOLM lasers. Most of them could not initiate pulsation without extra help, like SBRs or moving mirrors. This feature is not welcome in practical applications.
3.1.2 Polarization Additive Pulse Mode-Locked Lasers

The Polarization Additive Pulse Mode Locking technique was first developed at MIT and many studies were published [34-41]. A typical structure of Polarization Additive Pulse Mode-Locked Lasers is shown in Figure 3.2 [37].

Assuming the laser initially operates in CW mode and a small pulse occurs due to a small perturbation in the cavity. The fiber in the cavity behaves as a Kerr medium and a birefringent medium at the same time. This causes the state of small pulse’s polarization to change with its instantaneous power along the time axis. It means there is a difference between the states of the polarization at the pulse’s peak and pulse’s wings. As a result, the pulse could be amplified in intensity by placing a polarization controller after the doped fiber section and aligning it with the state of
the polarization at the small pulse’s peak. After thousands of round trips in the cavity with gain and loss dynamics, the steady state could be reached and only pulsed operation survives in the cavity.

The Polarization Additive Pulse Mode Locked lasers have the advantage of self-starting pulse trains in practice and they react to the pulse instantaneously in the time domain and thus capable of generating ultra-short pulses.

The disadvantage of the Polarization Additive Pulse Mode Locked lasers is the gradual shift of the polarization state of the pulses inside the cavity, which could be introduced by changing temperature or mechanical stress of the fibers. This characteristic reduces the reliability of the mode-locking action. Fiber lasers in this class would fall out of mode-locking periodically and thus hard to be commercialized.

3.1.3 Saturable Bragg Reflector Mode-locked Lasers

Generally, a Saturable Bragg Reflector (SBR) consists of a semiconductor Bragg reflector and a single quantum well absorber layer near the surface [42-45]. A typical structure of fiber laser using SBR is shown in Figure 3.3 [46].
Figure 3.3 Schematic of the fiber laser cavity and structure of the SBR. [46]

The materials of the Bragg reflector have larger band gap energy and thus have no absorption in this area. The device lifetime would be increased with a suitable passivation layer on the top surface. A large modulation depth could be achieved by applying a thicker absorber layer. The modulation depth and the saturation fluence are determined by the optical intensity in the region where the saturable material is placed. The bandwidth and the chromatic dispersion of the SBR are determined by the structure of the Bragg reflector. The macroscopic parameters of SBR could be adjusted for different applications by varying the material composition and certain design parameters, such as operation wavelength, modulation depth, saturation fluence and recovery time.

The saturable absorber action is created by the inter-band transitions in the quantum well layer. When the quantum well layer absorbs the photons, it causes the
electrons jumping from the valence band to the conduction band. The thermalization relaxation within the conduction and valence band occurs quickly, about 50 to 100 fs. But the carrier recombination time is on the micosecond scale. To overcome this problem, traps are used to decrease the carrier recombination time in practice.

At low optical intensities, the level of electronic excitation is small and the absorption is unsaturated; at high optical intensities, electrons accumulate in the conduction band and thus the initial states for the absorbing transition are depleted although the final states are occupied, resulting in reduced absorption.

SBRs are broadly used in passive mode locking of fiber lasers. By carefully choosing the device and operation parameters, they could work for reliable self-starting mode locking. Different from the Polarization Additive Pulse Mode Locking, the state of the polarization is irrelevant in the mode locking process. As a result, the gradual shift of the polarization state, either by temperature drift or slow relief of the mechanical stress of the fibers, has no effect on the long term stability of the mode locking. This characteristic permits wide applications in industry.

Most SBRs demonstrate only moderate amounts of chromatic dispersion for reflected light, but dispersion could be engineered into a SBR via a multilayer structure [44]. Those dispersive SBRs could act as dispersion compensation element in the laser cavity besides working as a passive mode locker.

The disadvantage of SBRs is the long recovery time. The shortest recovery time for SBRs is about 1 to 2 ps. To achieve shorter pulses, more pulse dynamics are needed in SBR based fiber lasers.
Another disadvantage of SBRs is low tolerance to heat load and thus the incident optical power. The thermal and optical damage problem is a critical issue not only at high average power levels, but also with operation at high pulse repetition rates. SBRs in fiber laser cavity are required to have physical contact with the gain fibers, in order to maintain small footprints. But there may be thermal damages from the heat generated by short pieces of gain fiber besides the average signal power.

In conclusion, compared with active mode-locking, the technique of passive mode-locking allows the generation of much shorter pulses, essentially because a saturable absorber, driven by already very short pulses, can modulate the resonator losses much faster than any electronic modulator. However, passive mode-locking has two disadvantages. First, it is not synchronizable and the reproducibility is influenced by the characteristics of the absorber dye. Second, the decay time of the absorber affects pulse half-width and signal-to-noise ratio [47]. Considering the potential application of the proposed electro-optic sampling system, passive mode-locking is not a suitable choice due to these two drawbacks.

### 3.2 Active mode-locked lasers

Active mode-locking requires modulation of either the amplitude or the phase of the intracavity optical field at a frequency $f_m$ equal to (or a multiple of) the mode spacing $\Delta f$ [17]. There are four active mode-locking techniques: AM modulation, FM
modulation, synchronous pumping and optically modulated saturable absorption (OMSA) [48].

The principle of active mode locking by modulating the resonator losses is that the pulse could pass the modulator only when it has the minimum losses as shown in Figure 3.4. The wings of the pulse experience a little attenuation and thus lead to slight pulse shortening in each round trip. This pulse shortening effect is balanced by other effects in the cavity that tend to broaden the pulse, such as gain narrowing. Since the pulse duration relative to the pulse period is typically much smaller, this pulse-shortening effect of the modulator is reduced rapidly with shorter pulses.

Figure 3.4 Temporal evolution of optical power and losses in an actively mode-locked laser where one time unit is one round trip time, not actual time unit. [51]
In simple cases, the pulse duration achieved in the steady state could be calculated with the Kuizenga-Siegman theory [52]. For fast modulation in the GHz range, the pulse duration is in the picosecond range and weakly dependent on parameters like the strength of the modulation. This weak dependence is introduced by the fact that the pulse shortening effect of the modulator is less effective for shorter pulse durations. When the modulation frequency is the same, other effects that lengthen the pulse become more effective.

Active mode locking could also be achieved by a periodic phase modulation. The technique is called Frequency Modulation (FM) mode locking or phase modulation mode locking. FM mode-locking uses a modulator device based on the electro-optic effect. This device, when placed in a laser cavity and driven with an electrical signal, induces a small, sinusoidally varying frequency shift in the light passing through it. When the frequency of modulation is matched to the round-trip time of the cavity, some light in the cavity sees repeated up-shifts in frequency and some repeated down-shifts. After many repetitions, the up-shifted and down-shifted light is swept out of the gain bandwidth of the laser. The unaffected light is the one passing through the modulator when the induced frequency shift is zero and forms a narrow pulse of light [50]. Some FM mode-locked fiber lasers demonstrate instability. There is random hopping between two operation modes, where the pulses pass the modulator at both the minimum and the maximum phase delay. In some cases, this bistability can be removed by dispersive and nonlinear effects.
Synchronous pumping refers to the periodic modulation of a laser’s gain media at a repetition rate corresponding to a harmonic of the fundamental cavity frequency. The pump source for the laser is itself modulated; typically itself is another mode-locked laser. For stable operation, the round-trip time of the resonator must fairly precisely match the period of the modulator signal or some integer multiple of it, in order to let the circulating pulses pass the modulator at a time with minimum losses. Even a small frequency mismatch between the laser resonator and the drive signal could introduce a strong timing jitter or even chaotic behavior.

Synchronization between the modulator driver and the laser could be realized either by highly stable laser setup, or by means of a feedback circuit that automatically adjusts the modulation frequency or the length of the laser resonator. A widely used technique is called regenerative mode locking or mode locking via regenerative feedback [49]. In this technique, the modulator signal is not generated by a free-running or slightly corrected electronic oscillator, but is acquired from the detected intensity modulation of the pulse train itself. These techniques are especially crucial to achieve tunable pulse repetition rates, and usually applied to mode-locked fiber lasers and laser diodes.

Due to geometric constraints, it is difficult to achieve very high pulse repetition rates just by making the laser resonator very short. This problem could be solved by using harmonic mode locking. It has multiple pulses circulating in the laser resonator and the modulation frequency is an integer multiple of the round-trip frequency. A variation of the method applies the round-trip frequency times the ratio of two
integers as the modulation frequency. It is called rational harmonic mode locking [50].

Optically Modulated Saturable Absorption (OMSA), refers to a new technique developed in 2001, combines both AM modulation and synchronous pumping with Saturable Bragg Reflector (SBR) mode-locking together [53]. In this approach, a passively mode-locked laser using a SBR has its loss modulated. The difference between this loss modulation and conventional AM mode-locking is that the modulation is achieved through the application of a time varying optical signal which pumps the lasers SBR. This time varying pumping of the lasers SBR makes its loss not only intensity dependent but also time dependent. This allows one to align the pulses within the cavity as well as increase the laser’s repetition rate.

Compared to passive mode locking, active mode locking typically generates longer pulses, usually in picoseconds range. To achieve durations in the 100fs range, pulse trains coming out of the active mode-locked fiber lasers usually have to undergo nonlinear compressions. But this process could introduce phase fluctuations to the pulse train. In addition, special care is needed to ensure the low noise performance of the electronics in the laser cavity. Though electronic components present excellent noise characteristics such as timing jitter and relative intensity noise at low frequency range below mega-hertz range, they are inferior to the free running ultrafast optical oscillators at high frequencies.

On the other hand, active mode-locked fiber lasers could provide synchronization of the pulse trains with some electronic signal, or when many lasers need to be
operated in synchronism. Due to the nature of the proposed electro-optic sampling system, active mode-locked fiber lasers are good candidate to be the laser source of the proposed system. Based on all the characteristics of these different active mode-locking techniques, we choose AM mode-locking as the approach for the proposed system for its wide application and simple structure. The fiber laser used in the system is introduced in the following section.

### 3.3 Fiber laser used in the proposed electro-optic sampling system

The fiber laser used in the proposed electro-optic sampling system must be actively mode-locked. Though passive mode-locked fiber lasers could generate shorter pulses with a simpler structure, the repetition rate of the pulses is usually limited to the cavity’s fundamental-mode frequency and the electrical synchronization to the laser pulses is very difficult. On the other hand, actively mode-locked lasers have the advantage of low timing jitter, smaller chirp, and higher stability; its repetition rate is usually dependent on the modulation frequency applied to the active mode-locker [53]. In this section, we present the concept of an active mode-locked erbium-doped fiber laser with high stability and controllable pulse width.
The configuration of this active mode-locked fiber laser is shown in Figure 3.5. It consists of a 980-nm pump source, a 980/1550 wavelength-division multiplexer (WDM), a 7-m-long erbium-doped fiber, a 1550-nm-band 90:10 coupler, two polarization controllers (PC’s), one isolator, and a fiber-optic-coupled, >16-GHz LiNbO₃ EO modulator. The 980-nm pump laser has an output power of 126.7 mW. The 7-m-long erbium-doped fiber is pumped at 980 nm through the 980-nm/1550-nm WDM coupler. The isolator ensured unidirectional operation. The PC’s are used to optimize the polarization state of the cavity modes. The cavity is about 19.6 m long and has a fundamental repetition rate of about 10 MHz. The output of the laser system is 10% of the cavity energy coupled through the 90:10 coupler. The output of the fiber laser has a center wavelength at 1556.5 nm.
To achieve stability of this active mode-locked fiber laser, we examined the relationship between its pulse width and its harmonic frequencies. The pulse width is controllable under harmonic mode-locking. It is widely known that when the \( n \)th harmonic frequency of the EO modulator (\( nF \)) matches with the \( m \)th harmonic longitudinal-mode frequency of the fiber laser cavity (\( mf \)), the mode-locked laser operation takes place at the least common multiple frequency, which is also a harmonic of the cavity’s fundamental-mode frequency, i.e., \( f_{\text{harmonic}} = mf = nF \). In our experiment, we went one step further by applying radio frequency (\( rf \)) signal at different integer multiples of the fundamental frequency. The result is shown in Figure 3.6. The generated pulse width has a nonlinear, generally monotonically decreasing relationship with the applied \( rf \) modulation. This result could be explained by the transmittance function of the EO modulator. The EO amplitude modulator is sinusoidal, which has a narrower transmission window with higher frequency. In this case, increasing the modulation frequency decreases the time window for the transmission and therefore produces shorter pulses as demonstrated in Figure 3.7. Since ultra-short pulses are desired for general applications in fiber communication, high-harmonic modulation is preferred in those cases. In addition to controlling the \( rf \) on an EO modulator, shorter pulses could be achieved by adjusting the dc bias on the EO modulator and the PC’s, although not as efficiently as with high-harmonic mode-locking.
Figure 3.6 Controllable pulse width by harmonic mode-locking.

An rf frequency of ~2 GHz is needed to achieve 20-ps pulse widths.

Figure 3.7 The temporal width of the laser pulse is determined by the transmission window of the Mach-Zehnder modulator.
One set of the output of this actively mode-locked fiber laser, which is modulated at 509.246MHz, is shown in Figure 3.8 (a) and (b).

Figure 3.8 Output of the fiber laser modulated at 509.2464MHz.

(a) The generated pulse train. (b) The spectrum of the output.
In addition, particular output wavelength could be favored by adjusting the length of the erbium doped fiber in the laser cavity. As shown in Figure 3.9, the absorption and emission of erbium doped glass are acting differently in the 1500nm range. It exhibits higher gain around 1530nm and lower gain around 1555nm which are wavelengths channels in the telecommunication bands. In this laser layout, the pump source is a co-propagating pump. For erbium doped fibers with same concentration and based on Beer’s Law, a short fiber will have a large number of excited states through its entire length, which is less than the absorption length. On the other side, the long fiber will have most of the Er atoms in the front portion of the fiber in the excited state. Almost none of the Er atoms at the back part of the fiber in the excited state and it results in a smaller percentage of the total number of Er atoms in the excited state. As a result, the output pulses have longer wavelengths for longer fibers.

Figure 3.9 Particular wavelengths can be favored by adjusting the gain-length product, which is the product of the concentration of the doped material and the total length of the doped fiber. [51]
Different lengths of Erbium doped fibers were applied in the laser cavity and the resulting different wavelengths are shown in Figure 3.10. Since the output wavelengths are on the ITU 200-GHz grid (the most common frequency grid used for channel spacing in Dense Wavelength Division Multiplexing (DWDM) for fiber optic communication at wavelengths around 1550 nm and defined by ITU-T G. 694.1 (2002)) [54], the proposed electro-optical sampling system could use standard telecom components. The total cost of the system is significantly reduced too.

Figure 3.10 Wavelengths on the ITU 200-GHz grid make it possible to use standard telecom components.

Figure 3.11 shows the spectrum of two fiber lasers. One has a 2 meter long Erbium doped fiber in the cavity with output center wavelength at 1530nm; the other laser has a 7 meter long doped fiber in the cavity and its output center wavelength is at 1563nm which locate on the ITU 200-Ghz grid. Therefore, standard ITU-200 add/drop
module could be used for those fiber lasers. Since the total lengths of the cavity for
the two lasers are different, they have different modulation frequencies which are the
integer times of the fundamental frequency. The fundamental frequencies for the two
lasers are 9.98MHz and 7.49MHz respectively.

Figure 3.11 The spectrum of fiber laser with 2m and 6m long Erbium doped fibers respectively measured on Optical Spectrum Analyzer. However, since the standard ITU-200GHz channel has a width of about 0.5nm, the output pulse train of these two lasers would loss part of the power when go through WDM components.

The active mode-locked fiber laser shown in this section is proven to be highly reliable and has the advantage of synchronization, controllable pulse width and output power; besides, it is compact and provides high optical quality. The pulse width of the fiber lasers ranges from picoseconds to up to ~20 nS and could be adjusted to meet the BW of a MZ modulator. This laser is equivalent to one of the lasers needed to implement the experiment proposed by Yariv. We have shown that by varying the length of the gain medium, multiple lasers can be produced with different output wavelengths.
Chapter 4. Full Fiber Pulse Replicator

In this chapter, the second step of improving the SNR and DR of the proposed single-shot EO measurement system, the application of a full fiber pulse replicator, will be demonstrated. This technique is another important part of the proposed system and works together with the multi-wavelength EO sampling method to achieve better SNR and DR of the single-shot events. The original design of the full fiber pulse replicator is introduced in this chapter based on Prof. Donaldson, Prof. Marciane and Mr. Roides paper [55]. A shortened version is built for the proposed measurement system and presented at the end of this chapter.

The technique presented in this chapter uses an all-fiber-optic network to optically replicate pulses. Previous work has demonstrated a 3-bit improvement in the dynamic range (DR) for optical pulse shape measurements. These improvements in the dynamic range are difficult to realize with conventional oscilloscopes. This technique will work with conventional electronic analog-to-digital converters to preserve the highest commercially available temporal bandwidth, but also improve the SNR and DR by itself. For example, the commercial instruments have a Dynamic Range of 30 to 60 in single-shot mode at 10 GHz [56], the system introduced in this chapter could
achieve a Dynamic Range of about 1800 for an optical pulse and 60 for arbitrary electrical pulses that compare well with the state of the art [57]. The system is capable of processing pulses with durations of 0.1 to 10 ns, temporal features with bandwidths up to 12 GHz, and signal levels spanning three orders of magnitude.

The measurement system is shown in Figure 4.1. The shaped optical pulse is produced by an electro-optic modulator driven by a shaped electrical pulse. This modulator is a two-stage modulator. The first modulator utilizes a square electrical gate pulse to eliminate optical signal outside of the temporal duration of the electrical pulse since the replicator only supports the designed acquisition window. There would be interference among replicas if there is signal outside of this window. The electrical pulse to be measured is added on the second modulator. However, two separate modulators were used in the final system: one is the AOM functioned as the first modulator here and the other is a MZ modulator worked as the second modulator here. After the modulator, the optical pulse is amplified by a full fiber amplifier to make sure that each of the replicas has enough energy to overcome shot noise at the detector. The amplifier could also be placed before the electro-optic modulator but the noise from the laser itself would be replicated and would not average out. The original work mentioned the optical pulse shape distortion introduced by the amplifier in their system presented in Figure 4.1. In the proposed measurement system, an amplified photo detector was used instead. The DSC-R401 HG detector used in the proposed system offers a linear response to >+3 dBm optical input, 600m Vp-p of linear output voltage, 20 GHz of RF bandwidth and a conversion gain of 160 V/W.
The advantage of using amplified photodetector is that there is no Square-pulse Distortion introduced by the amplifier. However, since there is no charge amplification in the photodiode itself, the charge pulses are very small and the noise of the photodiode/preamplifier combination of this device may determine the performance of the device and prohibits the application of the device at very low energies.

Figure 4.1 The modulated pulse is amplified before being replicated and detected by a photodiode and digital oscilloscope. [55]

After the amplifier, the optical pulse goes into the full fiber optical replicator as shown in Figure 4.2. It consists of nine 2-by-2 fiber splitters. The optical pulse is produced by dividing its energy among 256 copies using 2-by-2 fiber-optic couplers. A series of 9 fused fiber couplers are spliced with 1, 2, 4, 8, ..., 256 ns differential delay fibers in between each stage. Each stage produces two pulse sets for input into the next stage. At m\th stage, one output is directly connected to the input of the following stage. The second output is connected to the second input of the following
stage with an optical fiber that has a propagation delay of 2m times the inter-pulse spacing. All the connections are made by fusion splicing, which joins two optical fibers end-to-end using heat. The first step is stripping, a procedure to prepare each fiber end for fusion by removing the coatings from the ends of each fiber. The fiber is then cleaved using the score-and-break method so its end face is perfectly flat and perpendicular to the axis of the fiber. The quality of each fiber end is inspected using a microscope. In fusion splicing, the two end faces of the fibers are aligned, then fused together. The bare fiber area is protected by a splice protector which is added on one of the fiber at the beginning and moved to the bare fiber area and heated to firmly cover that area.

The replicas should have identical amplitude, but the actual result is a characteristic distribution of the replicated amplitudes. This is due to the 0.6dB loss introduced by each fusion splicing. There are two fusion splices in every delayed leg of the replicator and thus causes the intensity to fall off with replica number. Also, the total length of the optical fiber before the replicator should be less than 30 meters to keep the stimulated Raman scattering (SRS) threshold low in the input fiber. This allows operation at about 70% of the saturation limit of the photodiode without SRS for nanosecond duration pulses. As soon as the pulses enter the replicator, there is an immediate decrease of the intensity and SRS is no longer a problem. The work presented in this chapter shows pulses with 12.5ns spacing, but the spacing varies with different applications. The output of the fiber replicator is shown in Figure 4.3 [55].
The standard deviation of the pulse optical power at each power level is used to determine the SNR. The signal is determined by taking identical measurements and averaging them; the noise is the standard deviation of the mean divided by the square
root of the number of points. The SNR is the ratio of those two values [59]. The cross correlation is used to align and average the pulses, and thus the SNR is improved. The details of the processing process are introduced in Chapter 5. As shown in Figure 4.4, the noise characteristics of the oscilloscope’s input amplifier dominate the SNR’s dependence on the signal level. The SNR has a linear relationship with the signal level below 20% of the signal peak. When SNR equals 1, the corresponding point represents the minimum credible signal that could be measured. The Dynamic Range is defined as the ratio of the peak to the signal level where the SNR is 1. For the recombined optical pulse out of the replicator, the DR is ~1800:1, giving an Effective Number of Bits (ENOB) of 10.8 at a time resolution of 25 ps, which is 50 times better than using a standard oscilloscope alone in the single-shot mode.

Figure 4.4 Based on the SNR, the optical pulse emerging from the 256× optical replicator has a DR of approximately 1800:1. The vertical lines indicate the SNR for signal levels that are listed as a percentage of the peak amplitude [55].
In addition to increasing the SNR of the signal, the optical replicator enhances the high-frequency response of the detected optical pulse beyond what can be achieved in a single measurement. The oscilloscope used in this measurement system has an analogue bandwidth of 12 GHz. The photodiode in the system has a flat response up to 18 GHz and a 3-dB cutoff frequency of 22 GHz [46]. Thus the measurement system could support frequencies up to 12 GHz. The Fast Fourier Transforms (FFT) could be used to convert the temporal data into a frequency response. Figure 4.5 shows the comparison of the magnitude of the FFT between a single optical pulse and the combined, averaged output from the fiber replicator. It shows that the FFT produces a frequency spectrum up to 20 GHz with a sampling window of 25 ps. The cutoff frequency is around 12 GHz. The measurement range above the cutoff frequency contains white noise only. The horizontal line is the noise floor limits for each curve. The single trace touches the noise floor at about 8 to 10 GHz. However, the averaged trace falls below the noise floor in the 12 to 15 GHz range.
The frequency dependent Signal-to-Noise-and-Distortion-Ratio (SINAD) could be deduced by dividing the replicated and the averaged FFT of the signal by high-frequency white noise limit given by the solid black line [58]. As a result, the SINAD is 1 at around 13 GHz, 3.55 around 10 GHz, and 4000 at DC.

This full fiber replicator is also capable of measuring electrical pulses besides optical ones with the addition of a high-bandwidth integrated-electro-optic modulator. A comparison of the measured SNR of the single shot input voltage by different methods is shown in Figure 4.6. It is clearly shown that the replicated optical method, or the fiber replicator has the highest SNR among the three methods.

Therefore, this replicator is a good choice to be added in the proposed EOS system to recover the SNR that substantially reduced by the EO modulator. Meanwhile, it could increase the DR of the system.
Figure 4.6 The measured SNR of the single-shot input voltage, inferred from the averaged optical output (red curve) is greater than that of the directly measured input voltage (blue curve). The solid red line is the ideal response of the EOM and governs the form of the SNR curve. The horizontal line represents an SNR of 1. [54]

A shorter version of the full fiber pulse replicator was constructed using five 3 dB couplers instead of nine in the original design. The structure of this version is shown in Figure 4.7 and its output is shown in Figure 4.8. The lengths of the fiber in each stage are 2.67m (13.36 nS), 5.16m (25.82 nS), 10.14m (50.73 nS) and 17.68m (88.46 nS) respectively.

Figure 4.7 A passive all-fiber optical pulse replicator produces a train of 16 optical pulses.
The fiber replicator used in the proposed system has slight variations from the one introduced in this chapter. The changes are made to match the characteristics of other equipment in the system but the basic features remain the same. This issue will be addressed in more detail in the next chapter.
Chapter 5. Experiment Setup and Results

The last four chapters introduced the motivation of this work, the background and prototype of this work and the fiber laser and full fiber pulse replicator used in this work respectively. In this chapter, the whole system will be presented step by step. It begins with the frame of the proposed system, followed by the testing of the components. The two-channel system will be demonstrated with the results in section 3 and the upgrade version of the two-channel system will be presented in section 4. In section 5, the fiber laser is applied as one of the laser sources. The application of the system on LLE DANTE will be included in section 6.
5.1 The framework of proposed Multi-wavelength Electro-optic Measurement Method

The framework of the proposed EO measurement system is shown in Figure 5.1. As demonstrated in the figure, multiple laser sources at different wavelengths go through the MZ modulators to measure the same electrical signal at the same time. The system shown in Figure 5.1 enables single-shot acquisition of electrical transients with enhanced signal to noise ratio. It also provides optical isolation between the detector and the electronic recording device. The isolation feature makes these systems particularly useful for large, low-repetition-rate, laser systems like OMEGA-EP at the University of Rochester that can generate single-shot, picosecond-scale events in an environment with high levels of EMI and ionizing radiation.

There are several important components of this system:

- EO modulators to encode the electrical signals on optical pulses providing high BW transmission over long cable lengths and optical isolation;

- Dense-Wavelength-Division-Multiplexing (DWDM) standards to serially combine several optical signals onto one photodiode;
Industry-standard, high-bandwidth oscilloscopes with 8-bit digitization; the long (ms), oscilloscope record lengths will record multiple copies of each signal and thus improving the SNR by averaging.

![Diagram of the multi-wavelength EO measurement system.](image)

Figure 5.1 The multi-wavelength EO measurement system.

There are many challenges to this work. For example, we have to simultaneously encode several high-power, low-noise, laser-diodes operating with different frequencies and serially combine those signals onto a single optical fiber and replicate those signals to achieve the advantages of single shot averaging without introducing interferometric beating. In order to meet those challenges, acousto-optic modulators will be used for each channel to avoid an additional MUX/DEMUX stage because it provides a timing window and optical signal outside of this window is eliminated;
and a thin film fiber multiplexer will be used to accommodate the limited availability of wavelengths.

There are two types of laser sources in the system. One is the fiber laser introduced in Chapter 3 which will be used in configurations described later in the chapter but initially diode lasers were used for their simplicity. The diode lasers are in a box fabricated by Optilab as shown in Figure 5.2.

![Figure 5.2 4-channel DFB Laser Source.](image)

The wavelengths were chosen to match a standard telecom MUX configuration. Table 5.1 shows the wavelength and maximum output power for each diode laser.

<table>
<thead>
<tr>
<th></th>
<th>Wavelength (nm)</th>
<th>Max Output (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LD1</td>
<td>1547.72</td>
<td>20</td>
</tr>
<tr>
<td>LD2</td>
<td>1552.52</td>
<td>20</td>
</tr>
<tr>
<td>LD3</td>
<td>1554.13</td>
<td>20</td>
</tr>
<tr>
<td>LD4</td>
<td>1557.36</td>
<td>60</td>
</tr>
</tbody>
</table>

Table 5.1 4-channel DFB Laser Source Output
The AOMs in the system work to generate pulsed laser beams from the CW diode lasers. They are based on the diffraction of light by a column of sound in a suitable interaction medium. The sound wave is produced by a piezoelectric transducer. Piezoelectric materials exhibit slight changes in physical size when voltage is applied to them. If the piezoelectric material is placed in contact with the acousto-optic material and a high-frequency oscillating voltage is applied to the piezoelectric material, it will expand and contract as the voltage varies. This in turn exerts pressure on the acousto-optic material and will launch an acoustic wave which will travel through the material. The frequency of the acoustic wave will be the same as the frequency of the applied voltage. The elasto-optic properties of the medium respond to the acoustic wave so as to produce a periodic variation of the index of refraction. A light beam incident on this disturbance is partially deflected in much the same way that light is deflected by a diffraction grating. No light is deflected unless the acoustic wave is present.

The reason to use pulsed laser beams is that in order to serially stack signals the measurement signals must have a finite temporal extent; also it avoids interference between signals in the replicator in the later part of the system.

To achieve the best performance of the Mach-Zehnder modulators, a 4-channel Bias Controller by NSTec is applied in the system. The bias control system uses the LD1 beam as the input to adjust the voltage applied to the DC ports of the MZ modulators to maintain the modulator bias at half-way between a maximum and a minimum transmission point on the transfer function curve- the quadrature point, since the
output voltage responsivity is maximum when the modulator is at the quadrature and only at quadrature are second-order distortion products minimized. There are two quadrature points on the transfer function curve: one located on the uprising part (Q+) and the other locates on the declining part (Q-). The Q- point was chosen considering the oscilloscope’s screen and which type of the signals are most likely to go off scale at each quadrature point. The layout of this Bias Controller is shown in Figure 5.3.

The LD1 was separated into two CW beams through a 3dB coupler and then added to the two channels by another 3dB coupler in each channel. The input fiber of MZ modulator is PM fiber and the output fiber is SM fiber. After the MZ modulator, the LD1 beam was picked out by WDM and fed into the bias controller as its input.

The front panel of the bias controller has SMA outputs for controlling the MZ DC bias and FC/APC input and output fiber connectors as shown in Figure 5.4.
The DWDM used in the system is an industry standard 8-channel DWDM by JDS Uniphase as shown in Figure 5.5 [60]. It provides adjacent DWDM channel isolation of minimum 22 dB, typical 30 dB; nonadjacent DWDM channel isolation of minimum 40 dB, typical 55 dB. Also, it provides expandability up to 8 channels per photodiode. The final output of those channels is multiplexed into one fiber. It was used in the proposed measurement system to combine the outputs of the two channels together and its output was the input of the full fiber replicator.
The full fiber replicator used in the proposed measurement system has a different layout compared to the one introduced in chapter 4. It has only 1 stage and thus replicates the pulse once. The length of the fiber in this stage is around 15 meters and capable of replicating 40 ns long pulses.

### 5.2 Test of Acousto-optic Modulators (AOMs) and Mach-Zehnder (MZ) modulators

The system was tested with one data channel and the MZ bias control channel active as shown in Figure 5.6. Laser Diode 1 is selected as the input of the Bias Controller. Polarization Controller is applied right after the laser output to make sure the light has the right polarization when enters the Polarization Maintaining (PM) fiber connecting the FC/APC connector on the laser source box and the Acousto-optic modulator (AOM).
Figure 5.6 The system testing diagram with one data channel and the MZ bias control channel active.

The first step is testing the Acousto-Optic Modulators (AOMs). An AOM uses the acousto-optic effect to diffract and shift the frequency of light using sound waves (usually at radio-frequency). The RF input to the AOM and the AOM optical output were measured. Although the cable lengths were not matched, the delay between the RF and optical pulses is consistent with a sound velocity of 5 mm/µs and on interaction point ~ 1 mm from where the acoustic signal is injected.

A comparison between the RF and the optical pulse from the AOM is shown in Figure 5.7. The manufacture specification for both the rise and fall times is 15 ns. However, the actual rise time of the optical pulse is 35 ns and the fall time is 50 ns, which are far longer than the manufacture specification. As presented in the figure, the RF seems to rise in about 12 ns. Therefore this slow response is not due to the RF driver.
Figure 5.7 The comparison between the RF and the optical pulse from the AOM.

The Electrical and Optical characteristics of the AOM are presented in Table 5.2. The letters in red, the rise and fall time and the contrast ratio, did not match our test results. The actual rise and fall time based on our measurement are 30 ns each.
Table 5.2. The AOM’s Electrical and Optical Characteristics.

<table>
<thead>
<tr>
<th>Parameter Sym. Condition</th>
<th>Min</th>
<th>Typ.</th>
<th>Max</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Wavelength $\lambda$</td>
<td>1530</td>
<td>1550</td>
<td>1570</td>
<td>nm</td>
</tr>
<tr>
<td>Input Optical Power (Average) PIN</td>
<td>1</td>
<td></td>
<td></td>
<td>W</td>
</tr>
<tr>
<td>Input Optical Power (Peak) PPEAK</td>
<td>500</td>
<td></td>
<td></td>
<td>W</td>
</tr>
<tr>
<td>On State Transmission TTRANS</td>
<td>45</td>
<td>50 %</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Optical Return Loss RLOPT Both input and output signals</td>
<td>40</td>
<td></td>
<td></td>
<td>dB</td>
</tr>
<tr>
<td>Polarization Extinction Ratio PER PM</td>
<td>17</td>
<td>20</td>
<td></td>
<td>dB</td>
</tr>
<tr>
<td>Rise Time tr 10% to 90% signal @1550nm</td>
<td>15</td>
<td></td>
<td></td>
<td>ns</td>
</tr>
<tr>
<td>Fall Time tf 90% to 10% signal @1550nm</td>
<td>15</td>
<td></td>
<td></td>
<td>ns</td>
</tr>
<tr>
<td>Contrast Ratio Cr</td>
<td>45</td>
<td>50</td>
<td></td>
<td>dB</td>
</tr>
<tr>
<td>RF Matching ZIN 50 $\Omega$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrical Return Loss RLRF -10 dB</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RF Peak Power PRF PK To achieve</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Contrast Ratio</td>
<td>3.5</td>
<td>4.0</td>
<td>4.5</td>
<td>W</td>
</tr>
<tr>
<td>RF Average Power PRF AVG</td>
<td>1.0</td>
<td>1.6</td>
<td></td>
<td>W</td>
</tr>
<tr>
<td>RF Center Frequency RFCF</td>
<td>165</td>
<td></td>
<td></td>
<td>MHz</td>
</tr>
</tbody>
</table>

To eliminate the possible reasons introduced by the testing system set-up, three measurements were carried out. The first one is using both a slow photodiode (FD80S7-F with response time ~150 ps) and a fast photodiode (DSC50S with response time 26 ps) to measure the optical output of the AOM. Based on the testing results, the rise and fall times are independent of photodiode used.

The second test is reducing the RF power into the modulator. The result is presented in Figure 5.8. It shows reducing the RF power does not change the rise or fall times but it does eliminate the droop seen at the photodiode.

The third test is measuring the contrast ratio by varying the repetition rate while keeping the pulse width fixed, where the Contrast ratio is
The result is shown in Figure 5.9.

\[
\frac{slop/\text{width}}{\text{intercept}} = \frac{0.309 \times 10^{-9} W}{130 \times 10^{-9} S} = \frac{1.2 \times 10^4}{204} = 40 dB
\]

Figure 5.8 Optical Response with different RF power on the MZ modulator.

Figure 5.9 The contract ratio by varying the repetition rate while keeping the pulse width fixed.
Based on the results of these three tests and the previous measurements, we could conclude that the rise and fall times of the AOM are independent of the photodiode used, RF power applied on the MZ modulator, the polarization of input light and the width of RF drive pulse. The real reason for the long rise and fall time is the manufacture design error. In order to accommodate this design error, the structure of the full fiber pulse replicator has to be changed to adapt wider optical pulses compared to original design. For the replicator used in the proposed measurement system, 1 stage instead of 4 stage layout was applied. As a result, it only replicates pulses for once, not three times. The single stage is the last stage of the originally designed replicator.

Next task is to explore the characteristic of the MZ modulators. We monitor the MZ modulator input, output and bias voltage for a 25 ns 5 V pulse into the RF port of the modulator. The result is shown in Figure 5.10. The input (blue curve) is a clean flattop optical pulse. The MZ modulator is biased at Q- so a positive RF pulse causes a decrease in transmission (the dip in black curve). The $V_{\pi}$ here is $\sim$3.7 V. The distance from Q- to minimum on the transfer curve is half of $V_{\pi}, 1.85$ V. The 5 V pulse is greater than 1.85 V so the dip becomes a rise as shown in Figure 5.10. Also, since the dip does not go to zero, there might be unpolarized light entering the MZ modulator. Different polarizations have different $V_{\pi}$ as they need different voltage for inducing a phase change of $\pi$ [30]. The red curve is the dithered DC bias and consistent over course of RF pulse. The period of 1 KHz dither ($\sim$1ms) is 10,000 times larger than the
temporal window (~100 ns as shown in blue curve), so the dither voltage is constant over the optical pulse.

![Figure 5.10 Input, Output and Bias Voltage of the MZ modulator.](image)

Also, the MZ modulator’s DC response curves at different wavelengths were compared and there is a consistent phase shift among the MZ DC response curves for different wavelengths as shown in Figure 5.11. Since half wave voltage \( V_{1/2} \) is a function of wavelength. To be specific, \( V_{1/2} = \frac{\lambda}{s} \), where \( \lambda \) is wavelength, \( s \) is electrode gap, \( n \) is optical refractive index, \( \gamma \) is electro-optic coefficient, \( \Gamma \) is electro-optic overlap coefficient and \( I \) is electrode length. For different wavelengths listed in Table 5.1, the corresponding \( V_{1/2} \) are 5.496 V for 1547.72 nm, 5.513 V for 1552.52 nm, 5.519 V for 1554.13 nm and 5.530 V for 1557.36 nm. Since different \( \lambda \) corresponds
to different Q-, we have to adjust the offset of Q- for the dither control box in order to stay in the desired operating region.

Figure 5.11 Phase shift among the MZ DC response curves at four different wavelengths.

We applied positive and negative going pulses to the MZ modulator’s RF ort while measuring the input and output optical pulses. The data is presented in Figure 5.12. The red portion of the rising edge is used for normalization as two different photo diodes were used and they share different responsivity. The normalization is done by using a scale factor, which is the ratio of one over the rising edges. For the negative going RF signal shown in Figure 5.12, the input signal of the photodiode has maximum power at 0.000855W and the output signal of the photodiode has maximum power at 0.000499W, with responsivity of the photodiode DSC50s at 0.8 A/W. If the MZ modulator worked at Q-, the negative going quadrature point, the
maximum signal for the negative RF pulse should be twice the input to the output. The results we got from Figure 5.12 shows that the operation point is not right at $Q_-$. A point by point mapping of the optical output to the RF input shows a roughly sinusoidal response with some glitches as demonstrated in Figure 5.13. This figure was obtained by combining multiple data sets with varying RF pulses. The RF pulses applied here were square pulses ranging from -2.02 V to 2.70 V, with corresponding measured optical signal shown in different colors. From Figure 5.13, we could see that the transfer curve changes slightly at different magnitudes of RF pulses. Normalizing to the input removed the glitches but some data sets seem to have an
offset in the response curve, as shown in Figure 5.14. Although the dither is constant over the course of the pulse, it varies from pulse to pulse. Assume that all pulse to pulse variations in the input to output ratio are due to changes in bias voltage, we could write the transfer function as

\[ T(f) = \frac{V_{out}}{V_{in}} \]

where \( V_{out} \) and \( V_{in} \) is known from manufacture. Rewriting the function in current format and ignoring \( K \) could give us:

\[ T(f) = \frac{V_{out}}{V_{in}} \]

and if \( V_{in} \), — — . Since we operate at Q-point, — — , and therefore — — . Thus we could get — — , or — — , which is the function used to normalize the output to input, from Figure 5.13 to Figure 5.14. This problem is eventually fixed by suspending dither during optical pulse.

![Figure 5.13 A point by point mapping of the optical output to the RF input.](image)
Figure 5.14 Point by point mapping curve is normalized to the input.

A sinusoidal fit to the transmission data establish the baseline voltage transfer function as shown in Figure 5.15.

Figure 5.15 A sinusoidal fit to the transmission data, where $V_{dc}$ is $\approx 0.095V$, is $\approx 3.431V$. 
5.3 Test of two channel EO sampling System

In this section, a two-channel EO sampling system is demonstrated. The system is shown in Figure 5.16. In this system, LD1 provides the input of the bias control to the DC ports of the two MZ modulators and is separated by WDMs from the two channels. LD3 and LD4 are the optical input of the two sampling channels and go through synchronized two AOM modulators to form optical pulse trains at 1554.13 nm and 1557.36 nm respectively. The RF signal is divided by a 4:1 splitter and adds on the RF ports of the two MZ modulators as the electrical signal to be sampled. The full fiber pulse replicator is not included in this system. The outputs of the two channels arrive at two detectors separately. The full fiber replicator was not used here, which is different from Figure 5.1.

Figure 5.16 Two-channel EO measurement system.
The RF signal added on the RF ports of the MZ modulators is CW sine wave at 10 different frequencies (from 33 MHz to 1 GHz) and 5 different amplitudes (from 400 MV to 2.2 V), generated by HP 8642B signal generator. The CW sine wave was chosen for this setup because this method of analysis facilitates comparison with other instruments whereas a particular pulse shape does not. Two sets of data are selected to present in this section. The outputs of the data are shown in Figure 5.17, where the RF signals are at 33 MHz but at different amplitudes. Figure 5.17 (a) has a RF signal at 33 MHz, 1.30 V; Figure 5.17 (b) has a RF signal at 33 MHz, 1.75 V.
The first step to process the data is to select the portion of the curve that carries the modulated signal. A flat top optical pulse was modulated here. The CW sine wave might pick up additional modulation from the optical pulse if it were beyond its flat portion. The selected parts are shown in Figure 5.18. Though the whole pulse was modulated, only the flat top portion was selected for further processing. The voltage in y-axis is the photodiode voltage, not the modulation one. However, not all the modulated part was selected. The portion close to the two edges of the optical pulse was cut off in order to exclude any distortion that might be induced by power fluctuations around the edge. Since the RF signal went through a 4:1 splitter to arrive at the two RF ports on the two channels, signal from the channel with smaller RF signal was amplified by 3.4436 times based on the actual measurement on the two RF
ports. As shown in Figure 5.18 (b), the red curve is not sinusoidal due to the overdriven MZ modulator.

Figure 5.18 The modulation part of the output signals.
The second step is to get the voltage transfer function. A sinusoidal fit to the transmission data will establish the baseline voltage transfer function. The transmission data is obtained by plotting RF signal vs. corresponding optical signal. The sinusoidal fit is achieved by using a function ‘lsqlin’ in Matlab [61]. This function solves constrained linear least-squares problems and returns three parameters of the sinusoidal fitting curve: \( A_0 \), \( V_0 \) and \( C_0 \) as shown in equation 6.

\[
T = A_0 \times \sin \left( \frac{\pi (V + V_0)}{V_\pi} \right) + C_0 \quad (6)
\]

We use equation 6 instead of equation 1 in the data processing in order to avoid the square calculation in the following step. The SINAD value is calculated by using difference between the sinusoidal fitting curve and the transmission data as the noise.

\[
SINAD = \frac{\text{RMS}(\sum_{i=0}^{n} \text{sinf}it^2)}{\text{RMS}(\sum_{i=0}^{n} (\text{sinf}it - \text{transmission})^2)} \quad (7)
\]

Where \text{RMS} means ‘root mean square’, \text{sinf}it means the data on the sinusoidal fitting curve, \text{transmission} means the corresponding data on the measured optical transmission curve. There are no specific fitting parameters used here, only the standard inputs were used for this function.

The third step is deriving the RF signal from the optical output signal. Based on function 6, the derived signal is:

\[
V = \frac{V_\pi}{\pi} \times \arcsin \left( \frac{T - C_0}{A_0} \right) - V_0 \quad (8)
\]
The fourth step is combining the results from the two channels together. The cubic smoothing spline interpolation method is applied here. The reason to use interpolation is to construct new data points within the range of a discrete set of known data points. The fundamental idea of this method is based on the engineer’s tool used to draw smooth curves through a number of points. This spline consists of weights attached to a flat surface at the points to be connected. A flexible strip is then bent across each of these weights, resulting in a smooth curve.

The mathematical spline is similar in principle. The points are numerical data in this case. The weights are the coefficients on the cubic polynomials used to interpolate the data. These coefficients ‘bend’ the line so that it passes through each of the data points without any erratic behavior or breaks in continuity. We use function ‘csaps’ in Matlab to execute this cubic smoothing spline interpolation work [62]. The results are presented in Figure 5.19 for each set of data.
Figure 5.19 The reconstructed RF signal from two channels.

We processed 50 sets of data using the same method. Based on industry standard, the characteristic of a system is presented by its SINAD vs. frequency curve. The results of this two-channel system are shown in Figure 5.20. At same frequencies, RF with different amplitudes corresponds to different SINAD values. When the MZ modulators are over driven, amplitudes at 1.75V and 2.2V in this case, the SINAD values are smaller than the data sets when RF signals have lower amplitudes. If the modulators were overdriven for LD4 channel, then LD3 were used to constrain LD4 to the correct $V_\pi$ interval of the transmission curve and the SINAD would be improved. Figure 5.20 (a) shows the SINAD value at different frequencies for LD4 channel only where Figure 5.20 (b) shows the whole system’s SINAD value at
different frequencies. Figure 5.20(b) has less clear trends due to the noise introduced by LD3 channel.

Figure 5.20 The SINAD corresponding to different frequencies of the two channel EO system.
5.4 Two channel EO sampling System with Replicator

In this section, the whole EO sampling system is introduced and its characteristics are demonstrated by testing results. Two types of RF signals are applied here. One type is the same with the RF signals used in last section, which is continuous sine wave generated by HP 8642B signal generator. The second type is single pulse, 1-cycle and 3-cycle, generated by Tektronix’s AFG 3252 Function generator to simulate the single shot event. We will focus on the second type RF signal in this section.

The system is shown in Figure 5.21. The whole EO sampling system is in a box. All the connections between the system and the supporting equipment, such as the bias control box and the laser source, are going through the connectors on the front panel of the box. The space inside the box is separated into two parts. The left part sits the electrical circuit providing the control and power to the acousto-optic modulators (AOMs). The right part holds all the fiber optic parts, like AOMs, wavelength-division multiplexing (WDMs), couplers, Mach-Zehnder (MZ) modulators and the replicator. Special shelves were made to fix all parts in the box.
Figure 5.21 The EO measurement system. (a) Front View. (b) Top View.
The schematic view of the system is shown in Figure 5.22. The system is a 2-laser/2-channel system and enables single-shot acquisition of electrical transients with enhanced signal to noise ratio. It also provides optical isolation between the detector and the electronic recording device if the electronic part of the system were separated from the optical components of the system. The isolation feature makes these systems particularly useful for large, low-repetition-rate, laser systems like OMEGA-EP at the University of Rochester that can generate single-shot, picosecond-scale events in an environment with high levels of EMI and ionizing radiation [13]. CW diode lasers were chosen as the laser sources in the system due to their low cost and simple operation. AOMs were installed right after the laser sources to produce pulses by producing a temporal gate passage for laser beams. The pulses are required to enable the use of the replicator, and the replicator has to work with a finite timing window in order to avoid the interference among replicated pulses. 1-by-2 splitter divides energy of LD1 and is followed by combiners. The two combiners are used following a 2-by-1 splitter to add the CW laser diode 1 into the two channels. One of the combiner, the 2-by-2 combiner had an extra output and this output was used as a monitor point. The LD1 (1547.72nm) beams goes through the MZ modulators in parallel with the pulsed beams (1554.13nm for LD3 and 1557.36nm for LD4) and then separated out by the WDM to feed into the bias control system. The bias control system uses LD1 beam as the input to adjust the voltage supplied to the DC ports of the MZ modulators to maintain the modulator transmission at half-way between a maximum and a minimum transmission point on the transfer function curve with a negative going
slope-the negative quadrature point, since the output fundamental signal strength is maximum when the modulator is at the quadrature and only at quadrature are second-order distortion products minimized. The MZ modulators are fiber-optic-coupled, >16-GHz LiNbO3 EO modulator from EOspace. An attenuator is installed before one of the RF ports on the MZ modulators so the two RF ports have signals with different amplitudes. The introduced difference makes the electrical signal locating on different region of the transfer function and the MZ modulator with the larger RF signal applied one could have distortion due to experiencing multiple fringes of the sinusoidal transfer function. If the distortion occurs, the distorted signal has higher resolution at the lower part of the curve while the signal from the other MZ modulator will have voltage higher resolution at the lower voltage region of the signal waveform. The final result will have higher resolution by selecting the best portion of both channels’. The dense wavelength division multiplexing (DWDM) functions as the coupler to combine the different channels into one optical fiber and the output goes to the fiber replicator directly.

There are two testing points in this section in order to capture the feature of the replicator. One testing point is before the replicator and the other is after the replicator as shown in Figure 5.22. The measurement before the replicator determines the input pulse and can be used to remove any noise or irregularities that would be common to the entire replica measured with the second detector.
As mentioned at the beginning of this section, there are two types of the RF signals added on the RF ports of the MZ modulators. The tests adding single pulse signal on the RF ports are introduced in details in this section. The first set of testing data was collected before the replicator. The first case used a single sinusoidal at a specific RF frequency. In the second case, a 3-cycle pulse was used as RF signal. The purpose to use 3-cycle pulse is to eliminate any possible distortion of the modulation signal that might be introduced by the electrical part of the system. All pulses are 50MHz and at 2.05V. Both the period of the single cycle and the 3-cycle pulse are shorter than the temporal measurement window defined by the AOM pulse. The collected data from the oscilloscope is shown in Figure 5.23. The modulation part of the optical signal measured on photo detector is presented in Figure 5.24. The same method as
introduced in section 5.3 is applied here to process the data. The results are demonstrated in Figure 5.25.

Figure 5.23 The simulated single-shot event EO sampling data. (a) 1-cycle RF signal added on the RF port of the MZ modulator. (b) 3-cycle RF signal added on the RF port of the MZ modulator. (The RF signal here is not sinusoidal signal, only half of it).
Figure 5.24. The modulation part of the signal after adjustment to align the interested parts together. (a) The 1-cycle case. (b) The 3-cycle case. (c) The middle pulse from the 3-cycle case was used to extract the RF signal and thus there is no major difference between the two cases. The sinfit here is fitting the 50% of a sinusoidal wave.
Figure 5.25 The processing results of the two cases.

(a) The results of the 1-cycle case, SINAD is 5.2205. (b) The results of the 3-cycle case, SINAD is 5.6362
There are eight sets of data collected before the replicator, four different amplitudes for each case. The SINAD vs RF amplitudes is plotted and shown in Figure 5.26. It is obvious that the 3-cycle case has slightly higher SINAD value when RF at all 4 different amplitudes. Some amplitudes exceed the $V_\pi$ threshold and others are not. This result confirms that there is pulse distortion introduced by the electrical part of the system, but the effect is quite small on lower frequencies. One exception is when the amplitude of the RF signal is at 4.0V, in other words, both channels are over driven as the RF signal is larger than $V_\pi$. The possible explanation is when the MZ modulator is over driven, the distortion introduced by the electrical power is enlarged.

![Figure 5.26 SINAD at different RF amplitudes for the Single shot event of the EO sampling system before the replicator.](image)

Figure 5.26 SINAD at different RF amplitudes for the Single shot event of the EO sampling system before the replicator. The depart of the results from two cases on the last point is probably due to the overdriven of MZ modulator at higher RF voltage, which causes different distortion on the transmission signal.
The second set of data was collected after the replicator. A one-step replicator is applied here due to the manufacture error of the AOMs. For this set of data, the first step is to average the two copies out of the replicator and the following steps are the same with previous data processing method. A 3-cycle single pulse case is presented here, as shown in Figure 5.27.

(a)

(b)
Figure 5.27. Two-channel EO sampling system with replicator. (a) optical output from the system. (b) Replicated pulses vs. RF. (c) Pulses after averaging where the RF signal was manually put negative for easy comparison. (d) The final extracted RF signal, SINAD is 11.8392.

To capture the characteristics of this one-step replicator, we compare the SINAD value of data sets collected before and after the replicator, while sharing same RF signal. The results are presented in Figure 5.28. From the graph we could see that the SINAD values are larger, about three times of the results with no replicator in the system, when the data sets were measured after the replicator. In theory, there should
be a square root of 2 improvements. However, since the replicator itself is not perfect in its structure (the 3dB couplers are not strictly 50/50), two more connectors used in the system and the insertion loss caused by fiber splicing, and the improvement introduced by this replicator is not exactly a square root of 2. Still, it proves that this replicator is a good choice to be added in the proposed EOS system to recover the SNR that substantially reduced by the EO modulator.

![Figure 5.28. SINAD value before and after the replicator.](image)

The second set of the data are using continuous sine wave as the RF signal as in section 5.3. There are fifteen data sets collected both before and after the replicator, with 5 different frequencies at 3 different amplitudes. Based on the industry standard, the characteristics of the two-channel EO sampling system, the SINAD vs. RF frequencies, are demonstrated in Figure 5.29. Basically the SINAD is constant at all frequencies with slightly decrease at frequencies above 2 GHz. Since only two channels were used, the results were not as good as directly measured RF signals. However, this proposed two-channel system contributes to constrain the $V_\pi$ jumps
and could be applied in places where direct measurement is not applicable. With more channels, the measurement accuracy could be improved and better SINAD would be expected than direct measurement.

Figure 5.29 SINAD corresponds to different RF frequencies for the 2-channel EO measurement system.

5.5 Application of the Two channel EO Measurement System on OMEGA

The application of the proposed system on OMEGA DANTE is a project called NIFDANTEEEO, a prototype of a data acquisition system for the NIF DANTE Diagnostic. Dante produces a time resolved X-ray spectrum of ICF targets by
monitoring at several vacuum photodiodes filtered to look at different wavelength ranges. The EO data acquisition enables isolation from EMI and ionizing radiation; long propagation lengths at high BW; multiplexing several channels onto a single photo detector; single shot averaging via optical replication and infinite data record lengths via high speed oscilloscopes. Besides, the EO acquisition system could be applied to all single point detectors on NIF or OMEGA.

The current NIF DANTE uses one or two digitizers per vacuum photodiode. The proposed EO system would record multiple X-ray diode signals on a single oscilloscope channel as shown in Figure 5.30.

![Figure 5.30 The proposed EO system on NIF DANTE.](image)

The NIF requirements for the EO data acquisition system are:

- The DR should be 10,000:1;
- The BW must be 6 GHz;
- Capable of providing long, high BW, low noise signal paths from the target chamber to the diagnostic mezzanine;
- The system must provide over-voltage protection for the detection electronics;
- The system should use 4 rather than 72 oscilloscopes;
- The system could allow capture of signals as long as 200 ns;

The NIFDANTEEEO system uses the techniques employed by Gamma Reaction History MZ system along with other techniques mentioned in the previous chapters to meet the requirements. To be specific:

- Pulse carving cw lasers to allow temporal multiplexing;
- Optical replicator for single-shot averaging to improve the SNR and DR;
- Encoding each MZ channel onto separate optical wavelengths;
- Combining multiple MZ channels with Dense-Wavelength-Division-Multiplexing (DWDM) telecom components;
- Using secondary wavelengths for MZ bias control;
- Using dither suppression circuitry on the MZ bias controllers;

In LaCave, one DANTE channel was recorded with our two-channel EO system with a one-step replicator. The measurement is shown in Figure 5.31.
The data from the 50 mW (LD4) channel gives good agreement with DANTE but the 20 mW (LD3) channel had too much digitizing noise from the scope to give a good match as shown in Figure 5.32.

The best fit of the measured DANTE signal to NIFDANTEO closely matches the calibration value of $V_\pi$ at 3.05V and $V_\Phi$ of 4.5V, as shown in Figure 5.33. The RMS difference, the square root of the arithmetic mean of the squares of the difference, of the two curves in Figure 5.33 is 0.54164.
Figure 5.32 Measurements from the two channels. (a) The 50 mW (LD4) Channel. (b) The 20 mW (LD3) Channel.

Figure 5.33 The DANTE signal (red) vs. The measured signal by NIFDANTEEO (black).
5.6 Two channel EO sampling System with Fiber Laser as one laser source

In the previous sections, the proposed EO sampling system uses diode lasers as laser source. One drawback of using diode lasers, or CW lasers, is the limited time resolution by the characteristics of the oscilloscope. Even a 45-GHz scope could not resolve 2 ps features [63]. However, the time resolution can be improved by injecting mode-locked ultra-short pulses. We will discuss the application of the fiber laser in the proposed EO system in this section. The system setup is shown in Figure 5.34. In this setup, one of the diode lasers, LD3 was replaced by fiber laser introduced in the end of chapter 3.

![Figure 5.34 The application of fiber laser in the proposed EO sampling system.](image-url)
The number of sampling points for the fiber laser channel is decided by the modulation frequency. First, we selected 58.7589 MHz as the modulation frequency of the fiber laser as it is the closest harmonic frequency to the RF signal’s frequency and capable of synchronizing the laser pulses and the RF signals. The system output is shown in Figure 5.35. The RF signal added on the system is the same with previous experiments, 1-cycle pulse with pulse period at 50 MHz, amplitude of 2.05V. From Figure 5.35 we could see that there is only one optical pulse at the modulation part of the sampling window provided by AOMs.

![Injection of Mode-locked Pulses](image)

Figure 5.35 The system output when modulation frequency of the fiber laser is 58.7589.

To increase the sampling points, we increased the modulation frequency of the fiber laser up to 156.69 MHz in order to get three times more sampling points. Based on the Nyquist Sampling theory [64], the original signal could be adequately
reconstructed from the sampling signal with higher than 2 times the original frequency, here it is 100 MHz. Therefore, only 159.69 MHz instead of up to 2 GHz was selected since higher frequency is not needed here. At this frequency, the output optical pulse train of the fiber laser has period of 27.06 nS, pulse width at 2.14 nS. The system output, the modulation part of the signal, the corresponding RF signal and the final result are presented in Figure 5.36~5.39. As shown in Figure 5.39, the reconstructed signal has a close match with the RF signal (a square wave), though the shape of the fiber laser pulses were included in the results as the pulses were around 2 nS wide and not negligible.

Figure 5.36 The system output when modulation frequency of the fiber laser is 156.69 MHz.
Figure 5.37 The modulation part of the optical signal.

Figure 5.38 The corresponding RF signal.

Figure 5.39 The reconstructed signal based on the processing results from the two channels.
The original design of the proposed system is to use synchronized actively mode-locked fiber lasers to produce the multi-wavelength sampling pulse train as mentioned in [23]. To get different fiber lasers synchronized, the total cavity lengths of the lasers have to be same with each other in order to share the same modulation frequency. The required accuracy of the length for lasers in 1550 nm range is < 1.5 cm, which could not be reached by the equipment available in LLE. In order to demonstrate the case with more sampling points, the system output was repeatedly collected for several times. The system output was averaged and then processed. Two sets of data are presented in Figure 5.40 and 5.41, which are averaged by two and three data sets respectively. Since the original signals are the average of more than one measurement, the resolution is lower compared to the direct measured signal. Also, the fiber laser signal appears to be double or triple pulsed due to this averaging process.
Figure 5.40 Using the average of two data sets to process data.

(a) Average of two data sets. (b) The modulation part of the averaged data. (c) The final result.
Figure 5.41 Using the average of three data sets to process data.
(b) Average of three data sets. (b) The modulation part of the averaged data. (c) The final result.
From the two examples shown in Figure 5.40 and 5.41, we could see that the reconstructed signal was improved with the increased sampling points from the fiber laser channel. This affirms us that higher resolution could be achieved by using closely aligned ultra-short multi-wavelength optical pulse train.

However, the major obstacle to get the Multi-wavelength measurement pulse train is the synchronization of different fiber lasers. As mentioned above, special instruments are required in order to reach accuracy of ~1.5cm for laser’s cavity length. Another way to get the laser synchronized is to put a device with tunable optical length into the laser cavity, a phase modulator for example. There are other devices that have controllable optical length. But those options were not attempted due to funding limitations.

In conclusion, actively mode-locked fiber lasers could be used as laser source for our proposed EO sampling system and higher resolution than using only diode lasers could be achieved by using multiple synchronized fiber lasers.
Chapter 6. Conclusion and future work

In this thesis, I presented a detailed study of a multi-wavelength electro-optic sampling system, which includes the two-wavelength experiment, the active mode-locked fiber laser, the all fiber replicator and the testing of the whole system. The experiment results presented in chapter 5 proves that the system viable and can probably meet its design goals.

There are several future directions relating to the work presented here and could be explored in the future. First, the synchronization of fiber lasers. A couple possible solutions are discussed in section 5.6. There might be other ways to solve the problem, like using only one fiber laser with WDM to shift wavelength in some channels and it is a good topic for future studies. Second, the replicator used in the demonstrated system has one step and replicate the pulses for once only. This is a revised design in order to accommodate the AOMs with unexpected long rise and fall times. Once the problem with the AOMs is solved by the producer, we could use four-step replicator to get more copies of the pulses and thus improve the SNR and DR. Also, Erbium Doped Fiber Amplifier (EDFA), an optical repeater device that is used to boost the intensity of optical signals, could be included in the system to
amplify the optical replicas out of the full fiber replicator. Depends on the characteristics of the EDFA to be used, the system would have higher SNR. The drawback of this application is that laser noise is also amplified, which could not affect the optical signal. Third, the demonstrated two-channel system could be upgraded to more channels very easily. For conventional WDM systems, up to 8 channels could be established in the 3rd transmission window (C-Band) around 1550nm; for dense WDM systems, typically up to 40 channels at 100 GHz spacing or 80 channels with 50 GHz spacing are used.

For the application of the proposed system, there are many areas quite suitable for this system. With the development of commercial available pulsed fiber lasers and CW diode lasers, the whole system could be more compact and thus resulting in more flexible use. However, commercial fiber lasers are expensive though they provide picoseconds long output pulses and therefore we could expect to achieve picoseconds level resolution. The diode lasers are not expensive and easy to operate, but they need additional modulations to produce pulses and the pulse width is highly dependent on the modulators.

As mentioned in chapter 1, this system is particularly useful for single-shot measurements, where the high DR and SNR of optical pulse insures that the inferred electrical pulse shape has a higher SNR than an electrical pulse directly measured with a conventional electronic oscilloscope. The optical isolation makes the system well-suited to environments with high levels of EMI. The system could be used in
non-single shot events too. In those cases, the results could be further improved by averaging results from different shots.
References


