High bandwidth optical coherent transient true-time delay
by Randy Ray Reibel

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Physics
Montana State University

Abstract:
An approach to reaching high bandwidth optical coherent transient (OCT) truetime delay (TTD) is described and demonstrated in this thesis. Utilizing the stimulated photon echo process in rare-earth ion doped crystals, such as Tm3+:YAG, TTD of optical signals with bandwidths > 20 GHz and high time bandwidth products > 104 are possible. TTD regenerators using OCT's have been demonstrated at low band-widths (< 40 MHz) showing picosecond delay resolutions with microsecond delays. With the advent of high bandwidth chirped lasers and high bandwidth electro-optic phase modulators, OCT TTD of broadband optical signals is now possible in the multi-gigahertz regime.

To achieve this goal, several theoretical and technical aspects had to be explored. Theoretical discussions and numerical simulations are given using the Maxwell-Bloch equations with arbitrary phase. These simulations show good signal fidelity and high (60%) power efficiencies on echoes produced from gratings programmed with linear frequency chirps. New approaches for programming spectral gratings were also examined that utilized high bandwidth electro-optic modulators. In this technique, the phase modulation sidebands on an optical carrier are linearly chirped, creating an analog to the common linear frequency chirp. This approach allows multi-gigahertz true-time delay spectral grating programming. These new programming approaches are examined and characterized, both through simulation and experiment.

A high bandwidth injection locked amplifier, based on semiconductor diode lasers, had to be developed and characterized to boost optical powers from both electro-optic phase modulators as well as chirped lasers. The injection locking system in conjunction with acousto-optic modulators were used in high bandwidth TTD demonstrations in Tm3+:YAG. Ultimately, high bandwidth binary phase shift keyed probe pulses were used in a demonstration of broadband true-time delay at a data rate of 1 GBit/s. The techniques, theory, and demonstrations described in this thesis can also be applied to high bandwidth optical signal processing and arbitrary waveform generation using optical coherent transient phenomena.

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ABSTRACT

An approach to reaching high bandwidth optical coherent transient (OCT) true-time delay (TTD) is described and demonstrated in this thesis. Utilizing the stimulated photon echo process in rare-earth ion doped crystals, such as Tm^{3+}:YAG, TTD of optical signals with bandwidths > 20 GHz and high time bandwidth products $> 10^4$ are possible. TTD regenerators using OCT's have been demonstrated at low bandwidths (< 40 MHz) showing picosecond delay resolutions with microsecond delays. With the advent of high bandwidth chirped lasers and high bandwidth electro-optic phase modulators, OCT TTD of broadband optical signals is now possible in the multi-gigahertz regime.

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A high bandwidth injection locked amplifier, based on semiconductor diode lasers, had to be developed and characterized to boost optical powers from both electro-optic phase modulators as well as chirped lasers. The injection locking system in conjunction with acousto-optic modulators were used in high bandwidth TTD demonstrations in Tm^{3+}:YAG. Ultimately, high bandwidth binary phase shift keyed probe pulses were used in a demonstration of broadband true-time delay at a data rate of 1 GBit/s. The techniques, theory, and demonstrations described in this thesis can also be applied to high bandwidth optical signal processing and arbitrary waveform generation using optical coherent transient phenomena.

CHAPTER 1

INTRODUCTION TO HIGH BANDWIDTH OPTICAL COHERENT TRANSIENTS

The goal of this thesis is to describe and demonstrate an approach to reaching high bandwidth optical coherent transient (OCT) true-time delay. True-time delay (TTD) is useful in a number of potential applications including phased array antenna systems, arbitrary waveform generation and correlators. This chapter presents an introduction to this research topic including a brief overview of stimulated photon echoes (SPE). The potential usefulness of photon echoes in these high bandwidth systems is examined and an overview of how to reach these bandwidths is shown. An overall description and the organization of this thesis is also given.

Introduction To Research Topic

In Merriam-Webster's Online Collegiate Dictionary the word echo has the definition: *the repetition of a sound caused by reflection of sound waves* [1]. Most all of us are familiar with the effect of an acoustic or reflection echo. Whether we were in a large auditorium, outside near a building or inside some room, an echo is the repetition of our words caused by a reflection of the sound waves from some surface. Echoes are unique in that they mimic or repeat the words of the person who uttered them although often the echo is fainter or a less intense sound. The amount of time

it takes before an echo reaches an observer is directly proportional to the distance the observer is from the surface that has reflected the sound. Thus by changing the distance to the reflecting surface an echo's time delay can be varied. In much the same way, a photon echo, generated from an OCT process, follows these traits, however, the waveform is no longer an acoustic wave but an electromagnetic wave. The photon echo is not created by reflection from a surface, it is instead created by a complex physical process in an optically absorbing material. In certain situations the photon echo waveform will exactly mimic the original electromagnetic waveform, however with less intensity and a variable time delay. These characteristics are similar to the acoustic echo and are what gives rise to the name *photon echo*. But the photon echo is much more than a simple reflection from a surface and the OCT processes that govern it are truly unique and can be used as a powerful optical processing tool for a variety of applications.

One such application for the photon echo is as a component that can control, steer and adaptively beamform phased array antennas. Phased array antennas, steered with conventional electronics, currently perform a variety of tasks and find application to both military and civilian markets. These systems make use of the wavelike properties of electromagnetic radiation to "steer" beams without ever physically moving the antenna. The significant benefits of such systems over conventional radar systems were quickly noticed and several phased array radar systems became operational in the 1960's [2]. The operational premise of such a system is shown in figure 1. These

arrays can be used to transmit or receive a variety of waveforms. The array antenna is a collection of RF emitters, each emitting its individual electromagnetic field. In the far field, the electromagnetic fields of each emitter sum to form the overall beam pattern from the antenna array.

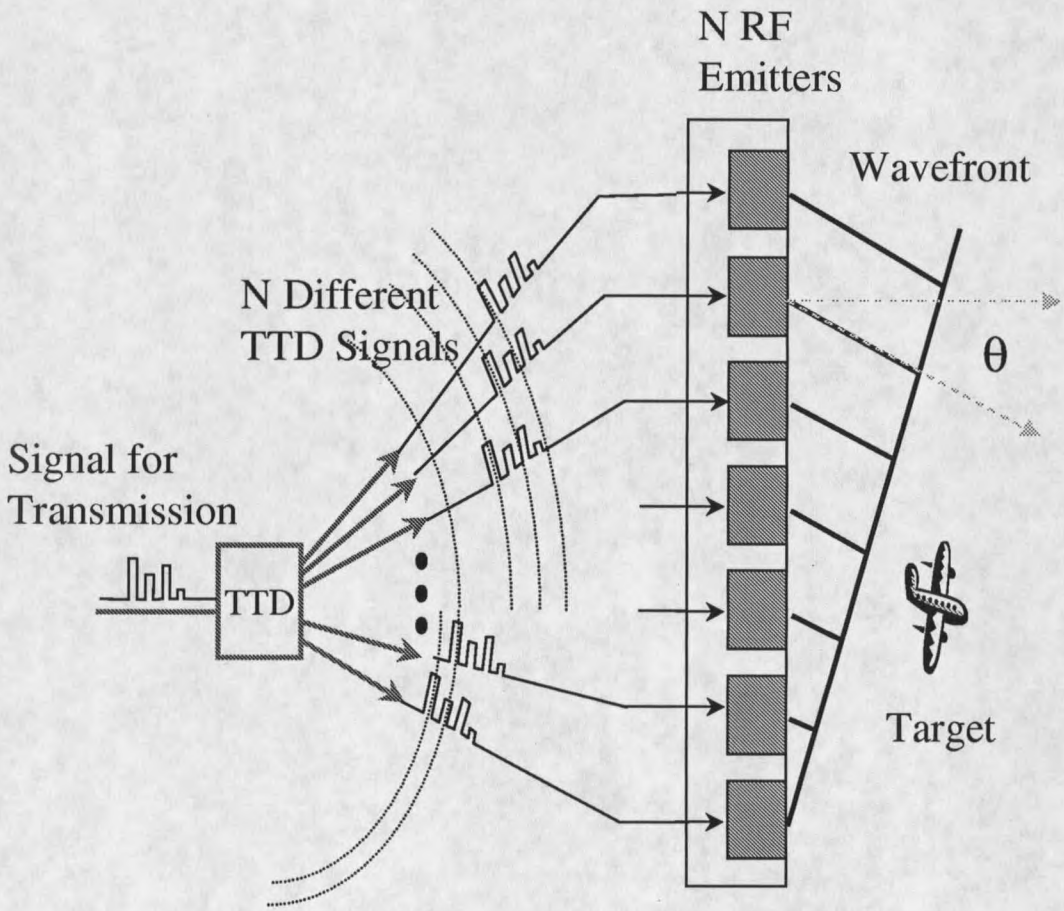

Figure 1. The operational design of how a phased array system works.

This overall beam pattern in the far field is known as the antenna beam lobe. This lobe can be controlled or steered utilizing the wave-nature of electromagnetic fields. If the time delay from each emitter to a spatial location away from the array can be controlled, the signal at that spatial location can be made to constructively or destructively interfere with the field produced at that location from other emitters. In the far field, the delay imparted to the electromagnetic fields from each emitter allows the beam lobe to be steered as shown in figure 1. Thus, the time delay of the electrical signals becomes the key component to the operation of a phased array radar. In narrow band (nearly single frequency) antenna arrays, the time delay of an electrical signal need not be *true* time delay. Instead, the electrical signal can be simply phase shifted. A single frequency sinusoidal waveform that is phase shifted is equivalent to one that is time delayed. Thus, simple electronic phase shifting devices could be used to steer the antenna, assuming the waveform is close to a single frequency sinusoidal waveform (narrow band) or, in other words, has a low fractional bandwidth (bandwidth divided by carrier). As the bandwidth deviates from narrowband an equal phase shift no longer translates directly to an equal time delay of the whole waveform. Essentially, different frequency components getting the same phase shift from the phase shifter, have a time delay, τ_D, that can be written as

$$\tau_D(\omega_m) = \phi/\omega_m. \tag{1.1}$$

Here ϕ is the constant phase shift imparted by the phase shifting device, and ω_m is

a frequency component of the broadband signal. If the fractional bandwidth of the signal is large, one can see that different ω_m's will experience different time delays, τ_D. This causes signals with significant bandwidths to behave improperly when steered with phase shifting devices. This imparts what is known as beam squint on the main lobe of the radiation field emitted from the array elements. Since delay and angle are related in a phased array, beam squint essentially means the steering of different frequency components of the signal into different angular directions. This angular spread, $\Delta\theta$, is given by

$$\Delta\theta = -\frac{B}{\omega_{RF}}\tan(\theta) \tag{1.2}$$

Here, B is the bandwidth of the signal, ω_{RF} is the carrier frequency of the radar (giving a fractional bandwidth B/ω_{RF}), and θ is the steering angle of the main lobe [3]. As can be seen, the angular deviation is a linear function of the fractional bandwidth, giving large angular deviations of frequency components for large fractional bandwidths. It should be noted that the angular size of the antenna beam lobe gets smaller with more antenna elements. Thus, if a large phased array radar (with high fractional bandwidths) uses phase shifters to control the time delay, beam squint will be a significant problem [4].

In order for a system of antenna elements to properly steer signals with large fractional bandwidths, the elements must impart a true-time delay (TTD) on the signals. TTD means that each frequency component of the signal for a given emitter gets the same time delay rather than the same phase shift. Thus, eqn. (1.1) can be

rearranged as

$$\phi(\omega_m) = \omega_m \tau_D. \tag{1.3}$$

In a TTD system it is τ_D that typically remains constant (per element), and thus the phase shift needed will change according to the given frequency component, ω_m. Producing broadband TTD waveforms is the main emphasis of this thesis.

There have been many proposals for optical TTD control of an RF signal. These include but are not limited to delaying optical signals via different optical delay lines or creating delays by frequency shifting the optical carrier in a highly dispersive optical fiber [3]. In the first approach, several different techniques have been envisioned but all follow the same principle. That principle is that one would choose the time delay for the optical signal by switching the optical pulse into an appropriate delay line. One suggestion is to use several different length optical fibers to give various different delays. Unfortunately, as the number of array elements grows, the switching network for such a system becomes increasingly complex as does the amount of fiber needed. For the second approach, simply by changing the frequency of the optical carrier a different delay can be chosen because the index of refraction for that frequency has changed. In this case, it is the number of distinctive frequency channels that can be achieved by the optical source that limits the resolution of the delays to less than 1 part in 1000 [3]. Along with this, a tunable diode laser and fiber must be used for each element of the array. Again, this results in an increasing complexity and cost as the number of array elements is increased. These systems also have no ability to

control the phase, number, or weight of these delays, and thus adaptive beamforming or jammer nulling can not be done with such systems.

It has been suggested that the SPE process can be used to create the TTD needed to avoid beam squint in a phased array radar or communication system [5]. Instead of using an electronic phase shifter, the photon echo would be used to create TTD. The properties of OCT's are such that the photon echo can theoretically delay signals with tens of gigahertz bandwidths over delays of microseconds with picosecond resolutions. The delays can be programmed on the fly or preprogrammed. The storage capabilities of OCT's enable several different delays to be stored spatially in the OCT medium providing more than a million different delays all within a single compact crystal. This along with the ability to individually control the delay of each frequency component makes OCT's an attractive basis for steering a phased array antenna, especially ones requiring adaptive beamforming and jammer nulling.

In order to create a stimulated photon echo, an inhomogeneously broadened absorber (IBA), such as a rare-earth ion doped crystal, is used. Because of the special properties of IBA's, a time delay between two incident brief programming pulses is stored as a spectral grating within the medium. This grating can be probed sometime later by another incident brief pulse. The medium is then coherently stimulated and produces a stimulated photon echo with the delay that was stored in the spectral grating. In the linear regime, this process is not limited to just temporally brief probe pulses. Any arbitrarily shaped incident probe pulse can be delayed assuming

the bandwidth of the spectral grating is larger than the bandwidth of the probe.

OCT's have previously been demonstrated as TTD devices giving microsecond delay times and picosecond resolutions [6]. Various methods including brief pulse programming and chirped pulse programming have been explored to produce TTD spectral gratings [7]. However, almost all previous demonstrations were over a limited bandwidth (typically 40 MHz) and did not reach the ideal goal of showing TTD with multi-gigahertz bandwidths. This thesis extends TTD demonstrations to the gigahertz bandwidth, along with developing more practical OCT techniques to program multi-gigahertz TTD.

Programming and probing broadband spectral gratings is not an easy task. In order to program an efficient spectral grating, a significant amount of optical energy must be transferred to the medium. Unfortunately, if brief pulses are used to program these broadband gratings, their temporal lengths must be extremely short (on the order of 100 picoseconds) to achieve large bandwidths. Producing these types of brief pulses is not easy, requiring the use of mode-locked lasers with amplification. These systems are impractical because of their cost, power inefficiencies and size. And, even though powerful pulsed lasers exist with tremendous power per pulse (~GW), producing efficient broadband spectral gratings with these lasers has proven challenging. The intensities required are near or exceed the damage threshold of OCT crystals. Processes such as accumulation of spectral gratings, where less powerful programming pulses are repeatedly applied to the medium, must be used in order to produce

efficient gratings.

Another way to produce a spectral grating in an OCT media is through the use of linear frequency chirped pulses [7]. Linear frequency chirps (LFC's) ramp their instantaneous frequency linearly as a function of time. Through the proper choice of chirp bandwidth and chirp duration, a power limited laser can program much more efficient TTD spectral gratings, as compared to brief pulses from the same laser. High bandwidth (> 20 GHz) LFC's are now a possibility due to the recent advances in chirped external cavity diode lasers (CECDL's) [8, 9].

Broadband signals are also inherently harder to detect because of noise issues. The level of thermal noise detected increases as the square root of the bandwidth. Thus, this thermal noise limits the detection of broadband echoes. Poor echo efficiencies also contribute to these detection problems. Recently, photon echoes with greater than unit efficiency have been suggested and observed for certain situations using optically thick samples [10, 11]. Unfortunately, the direct results from these research efforts are not applicable to TTD. This thesis examines the efficiencies of photon echoes for the situation of TTD for both brief pulse programming and LFC programming in optically thick crystals. Another problem is that these broadband RF signals must be imparted to the optical carrier, TTD, and subsequently converted to RF signals. The TTD optical signals must be detected in a fashion that allows detection of the encoded broadband signals. Various methods of modulation and detection are explored. It is also shown that the spectral grating itself can be utilized in making more efficient

detection methods for optically encoded broadband signals.

Another reason previous demonstrations were limited to low bandwidths (40 MHz) was the lack of suitable high bandwidth modulators to create probe signals. Advancements in high bandwidth, affordable electro-optic modulators (EOM's) makes the encoding of high bandwidth electronic signals onto optical carriers easier. Unfortunately, at the wavelength with which most of our work is done (793 nm) these EOM's are optical power limited due to photorefractive damage. The maximum output powers are 1 to 2 orders of magnitude lower than that required to produce detectable broadband photon echoes. In order to overcome this power limitation, a suitable amplifier for high bandwidth signals was developed using EOM's and an injection locked amplifier.

Overview of Thesis

This thesis details the possible approaches for creating high bandwidth TTD along with the problems and solutions. As stated above TTD applications such as phased array radars and communication systems will benefit from this research. But, as with any type of science, there are other unexpected benefits from the research and other applications to which this research can be applied. The desire to bring OCT's into the high bandwidth regime is a continuing struggle, one that is ongoing with new developments and twists everyday. This thesis is a snapshot of the past three years detailing the steps and barriers that had to be overcome before high bandwidth TTD

could be realized. What follows is a brief description of the chapters found within this thesis.

In chapter 2, the theoretical framework needed for this thesis is developed and presented. This includes a detailed overview of the stimulated photon echo process and the linear filter theory that predicts the dynamics of this process in certain regimes. An outline of other approaches to predictive solutions is given for various conditions. Chapter 2 also includes a discussion on the Maxwell-Bloch equations including arbitrary phases of the field. This mathematical approach, combined with simulation, allows quantitative predictions of the OCT phenomena covered in this thesis. Specifically, high efficiency TTD is studied for thick crystals utilizing linear frequency and linear phase chirps. Aspects such as delay resolution and signal fidelity are also examined with this simulator.

Chapter 3 presents the important practical considerations for reaching high bandwidth TTD using the stimulated photon echo process. A discussion of phase modulated signals created from high bandwidth EOM's is given. Spectral filtering effects caused by the medium as well as programmed spectral gratings are examined for these high bandwidth signals. It is shown that detection schemes utilizing these spectral filters can be more efficient than conventional detection schemes. Experimental parameters and material details are discussed as well as problems related to temporally long probe pulses. Simulations are performed for optically thick samples, showing that expected echo efficiencies using chirped programming can reach 60%.

The chapter also examines the aspects of accumulation and continuous programming and continuous processing, which are relevant to this thesis.

Chapter 4 shows how to amplify broadband signals from the power limited EOM's using an injection locking system. The needed theoretical framework for injection locking is detailed as well as experimental demonstrations of the amplifier. The benefits of such a system include ease of use and gains of more than 20 dB. However, using injection locking with semiconductor diode lasers has inherent challenges that will be discussed.

Through experimental demonstrations, problems related to high bandwidth linear frequency chirped programming were uncovered that called for modifying the previous approach to linear frequency chirp programming. Chapter 5 presents the modification of the linear frequency chirped programming method. The modification was to temporally overlap two frequency offset linear frequency chirps. Both low bandwidth demonstrations and high bandwidth demonstrations (using a CECDL) are presented. The tuning linearity of this method is examined as well as the efficiency of programmed gratings for TTD versus bandwidth scaling. Results from accumulation using this new method are also presented.

Finally, a novel technique for programming TTD gratings into an OCT medium using the broadband EOM's is presented in chapter 6. By using an EOM in conjunction with the injection locked amplifier, one can create multi-gigahertz gratings in the OCT media. This novel technique relies upon linear sideband chirping (LSC) and in

chapter 6 this approach is detailed. Experimental TTD results of both data and CW waveforms, which are delayed over several hundreds of nanoseconds, are presented. Data rates of 1 Gbit/s and bandwidths of 1 GHz are achieved. The tuning linearity and the resolution of this method are also analyzed.

CHAPTER 2

THEORETICAL OVERVIEW OF OPTICAL COHERENT TRANSIENTS

A basic overview of OCT's followed by the development of the coupled Maxwell-Bloch equations is given in this chapter. The basic operation of OCT's in the linear regime (energetically weak pulses) can be understood from a simple conceptual framework using a Fourier transform approach. In optically thin media, one can invoke the undepleted pump approximation that assumes the output electric field is proportional to the polarization of the thin medium. Using this approximation, the output electric field is a linear transform of the input pulses. While this is useful in describing the output from the medium, the assumptions invoked mean working in a regime of poor power efficiencies. By including the effects of propagation, where the polarization acts back on the field, highly efficient photon echoes can be created in optically thick media [10, 12, 13, 11]. To do this, the Maxwell wave equation must be used in conjunction with the optical Bloch equations that describe the dynamics of the medium. Expressions that can be solved analytically for certain cases have been shown [13] for the coupled Maxwell-Bloch equations (assuming energetically weak pulses or temporally brief pulses). The analytic solutions found were compared with direct numerical integrations of the Maxwell-Bloch equations and were found to be in good agreement [13]. However, the previous approaches to solving the propagation

effects of the medium did not allow for arbitrary phase and frequency for the input pulses [10, 12, 13]. The phase can not be ignored for pulses that are linearly chirped such as those used in this thesis. Here, a derivation for the Maxwell-Bloch equations is given for arbitrary phase and frequency. These equations are then used as the basis for a Maxwell-Bloch simulator that can predict the output of pulses with arbitrary phase and frequency in an optically thick regime. This allows analysis of the echo power efficiency for linear frequency chirped programming pulses.

Optical Coherent Transients And The Photon Echo

Properties Of OCT Media

In order to begin a discussion on the photon echo, it helps to understand some of the basic properties of the medium in which photon echoes can take place. Photon echoes have been observed in various kinds of media ranging from inorganic rare-earth-ion-doped crystals, such as Tm^{3+}:YAG [14], to gases of heated materials, such as barium or sodium heated in an oven [15], and even to amorphous systems of large organic molecules [16]. All of these materials, as varied as their physical makeup is, contain similar physical properties, which allow them to produce the photon echo.

First, like any optical phenomena, there must be an optical transition between two atomic levels in the material of interest. This allows a given atom within the medium to become excited, by absorbing a photon. Once an atom is in an excited state, it can leave the excited state through either spontaneous emission or stimulated

emission. The spontaneous emission decay rate Γ_e, gives rise to an exponential decay of the upper state with lifetime, $T_1 = 1/2\pi\Gamma_e$. The upper state lifetime is important in the photon echo process, as it determines the lifetime of the upper state spectral grating.

For the photon echo process, there is a fundamental limit to the amount of time delay that can be created. This limit arises due to the coherence lifetime or irreversible dephasing time in the crystal. This lifetime is given as $T_2 = 1/\pi\Gamma_H$, where Γ_H is the homogeneous linewidth. In an inorganic crystal, this individual atomic linewidth is created due to perturbations such as lattice phonon coupling, nuclear and electron spin couplings as well as the overall population decay rate. It is known as the "homogeneous" linewidth because the broadening is experienced equally by all atoms within the medium. For demonstrations in Tm^{3+}:YAG, Γ_H is mostly dominated by phonon coupling and is thus heavily dependent upon temperature [17]. Typical homogeneous linewidths for rare-earth ion doped crystals used in this thesis are tens of kilohertz, but have been measured to be as narrow as 122 Hz [18].

Another broadening mechanism, called inhomogeneous broadening, exists within these crystals. Due to imperfections within a rare-earth ion doped crystal, the local environment of a given ion can be perturbed resulting in a different resonant frequency for the ion. Since the perturbations add randomly, the inhomogeneous line typically has a Guassian lineshape. Because the inhomogeneous broadening plays such a critical role in OCT phenomena these materials are often referred to as inhomogeneously