Letter of Intent for Ultra-short Xray Pulse Measurements at LCLS

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Abstract

Most of the experiments planned for LCLS will require accurate measurements of xray pulse temporal history, including pulse shape and relative timing with optical lasers. These requirements are particularly daunting given the recent demands for shorter pulse-widths (< 50 fs), some of which are discussed at the LCLS workshop[1]. This LOI addresses a novel approach to these measurements. There are two main elements: a new xray detection technology which converts the xray temporal history into an amplitude modulated optical probe beam and a high-speed recording technique that records this modulated optical probe beam, in a single-transient format.

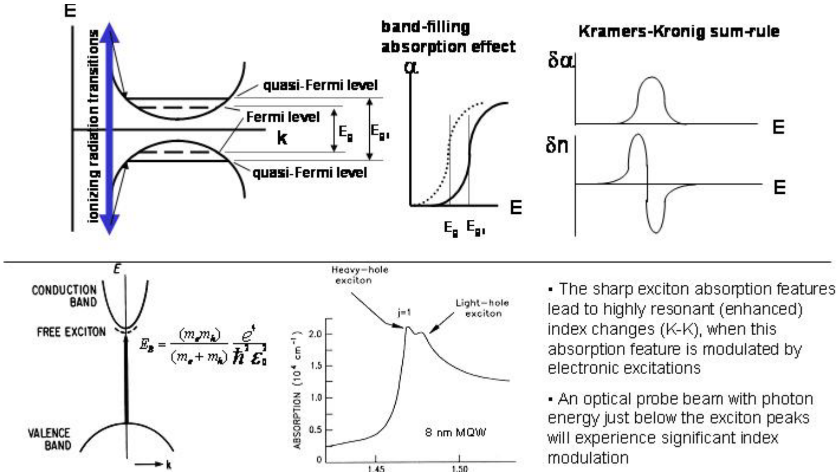
Conversion of the xray temporal history into the optical domain is accomplished in a semiconductor (e.g., GaAs). The xrays produce a modulation of the material's dielectric function which is then sensed by the phase modulation of the optical probe beam. Through interferometry this phase modulation is converted into an amplitude modulation of the optical probe beam. With the xray information in the optical domain, both pulse shape information and cross-timing with other lasers is more readily accomplished.

Our approach to the optical recording element is to use "temporal imaging" to "stretch" the temporal duration of the short optical pulse, in a very high-fidelity manner. The resulting optical pulse is "magnified" in time, resulting in a slower pulse which can then be measured and recorded with more conventional means optical techniques, such as optical streak cameras.

Background

Detection: Xray to optical conversion

We note that the optical index modulation in our detector shares most of the electron dynamics inherent in many semiconductor-based nonlinear all-optical switches (see Ironside [2] for an excellent review, as well as Garmire[3]). In this field the fundamental goal is the development of all-optical switches and gates that allow one optical beam to "switch" or gate the transmission of a second optical beam. In our radiation detector, the radiation beam plays the role of the optical pump in the all-optical switch. The primary mechanisms for these semiconductor devices are so-called "resonant" nonlinearities.. The major mechanisms are illustrated in Figure 1.



- The sharp exciton absorption features lead to highly resonant (enhanced) index changes (K-K), when this absorption feature is modulated by electronic excitations
- An optical probe beam with photon energy just below the exciton peaks will experience significant index modulation

Figure 1. Radiation absorption creates electron-hole pairs that modulate the absorption spectrum; causality (Kramers-Kronig) necessarily implies a change in the real part of the index, as well.

Here we see in the top portion of the figure the production of e-h pairs can shift the optical absorption spectrum through band-filling, which in turn will modulate the optical index spectrum. The bottom portion of the figure illustrates how exciton features alter the bandstructure and lead to very sharp features in the absorption spectra. These excitons represent very weakly bound electron-hole pairs. The combination of the weak binding and sharp absorption features, lead to an absorption spectrum that can be very sensitively modulated by the presence of free carriers, generated by xrays. Thus exciton bleaching/screening is likely the mechanism responsible for low xray intensity modulation, while bandfilling could provide additional dynamic range at high xray fluences. Park, et.al. [4] is an example of early work that demonstrates, for the case of optical pumping, the sensitivity enhancements due to the resonant nature of exciton bleaching and the enhancing effects of quantum-confinement.

In the all-optical switching field, these effects have been demonstrated, repeatedly, to have very fast rise times (<100 fs, limited by measurement resolutions) and if the material is grown or prepared with enough mid-gap energy levels (that act as very efficient carrier recombination centers) the fall times will also be very fast (< 250 fs), see ref. [5].

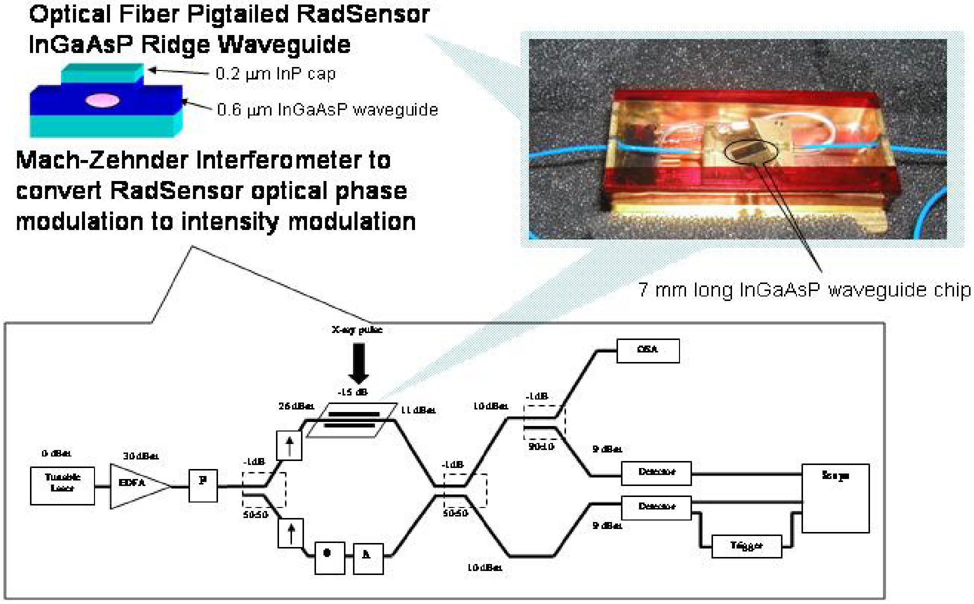


Figure 2. Ridge waveguide RadSensor pigtailed package and Mach-Zehnder Balanced Bridge interferometer, fielded at SSRL.

We recently demonstrated that xrays induce a similar optical index modulation [6]. We successfully processed ridge waveguide detector devices in InGaAsP material and packaged these with fiber optic pigtails on the input and output. To facilitate the measurement of xray driven optical index and absorption modulation we built a fiber-optic balanced-bridge Mach-Zehnder interferometer, and sophisticated closed-loop control systems to control the operation, see figure 2. We used optical detectors and amplifiers to convert the optical signal into the electrical domain. Oscilloscopes and RF spectrum analyzers were used to record the resulting electrical signals. We are calling this type of radiation detector “RadSensor”.

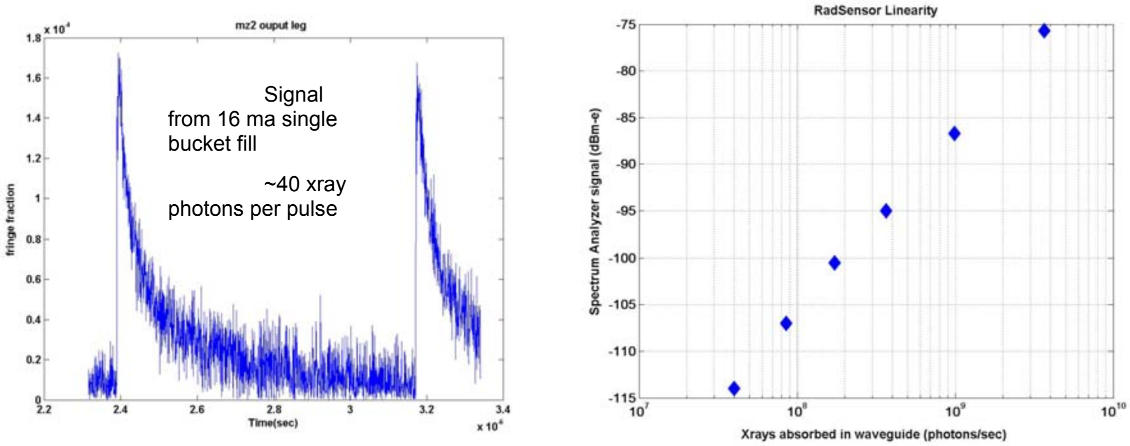


Figure 3. The left panel shows the RadSensor response using oscilloscope recording. The right panel shows RadSensor response using the RF spectrum analyzer to record data. All data taken using 8.9 kev xrays from beamline 10-2 at SSRL.

This system was fielded in January and in March on Beamline 10-2 at SSRL. We used a calibrated ion chamber to record total xray fluence, while using a calibrated xray CCD imager to record the xray spatial footprint. A diamond PCD detector was also used to record the xray temporal history. Figure 3 shows some of the many experimental results obtained. The oscilloscope trace shows the output from one of the Mach-Zehnder legs in response to xray pulses spaced in time by 781 ns (the storage ring period), for the January run. Each xray pulse was of a fluence that resulted in the aborption of 40 xray photons into the thin active region of this detector. The optical detector output was divided by the peak-to-peak fringe voltage, thereby converting the output to "fringe-fractions", to enable calculation of the index change, and performance projections to other detector geometries.

The right panel in figure 3 shows results of a dynamic range study using the RF spectrum analyzer recordings of the optical detector outputs. The xrays were attenuated using Al filters while the ion chamber was used to record the xray fluences. These data display a response that is very close to linear, over the two-decades of xray fluence measured.

The rise-times illustrated in figure 3 were limited recording system and xray pulse-width, however, the times are expected to be <100 fs, similar to the optical switching rise-times. The fall-times for these xray induced signals were long, because the material was not prepared with the necessary density of carrier trapping centers. However, this can be done, as with the optical switching case, and fall-times approaching 100 fs have been demonstrated. Work on this detector approach continues at LLNL under internal funding, with the emphasis on implementing high-speed xray imagers and reducing the temporal response to <100 fs. Various approaches to optical reflection modulation, using the same index modulation techniques, are also being investigated.

Recording: Temporal Imaging

Our approach to recording the modulated optical signal uses temporal imaging. Temporal imaging is based on a space-time duality between how a beam of light spreads due to diffraction as if propagates in space and how pulses of light disperse (spread) as they propagate through dispersive media, such as grating systems or optical fiber, Fig. 4. Since the equations describing narrow-band dispersion have the same mathematical form as those for paraxial diffraction, dispersion can perform the role of diffraction in the temporal equivalent to an imaging system. There is also a one-to-one analogy between the quadratic spatial phase modulation produced by a lens and imparting of a quadratic temporal phase (equivalent to a linear frequency chirp). Any process that can impart this temporal phase profile can act as the time domain equivalent of a lens in space. We have chosen to implement a time lens through sum-frequency generation of a broadband-chirped optical pump with the input signal in a nonlinear crystal because of the improved resolution it produces. Analogous to its spatial counter part, a system that can expand (or compress) arbitrary temporal waveform is produced by cascading dispersive propagation, time lens modulation, and further dispersive propagation, in the proper balance according to the temporal imaging condition $1/\phi_1'' + 1/\phi_2'' = 1/\phi_f''$, where ϕ_1'' is the input group delay dispersion (GDD), ϕ_2'' is the output GDD, and ϕ_f'' is the focal GDD, respectively. The output waveform is then a temporally scaled replica of the input waveform with a magnification $M = -\phi_2''/\phi_1''$. The theory of these temporal imaging systems has been analyzed [7]

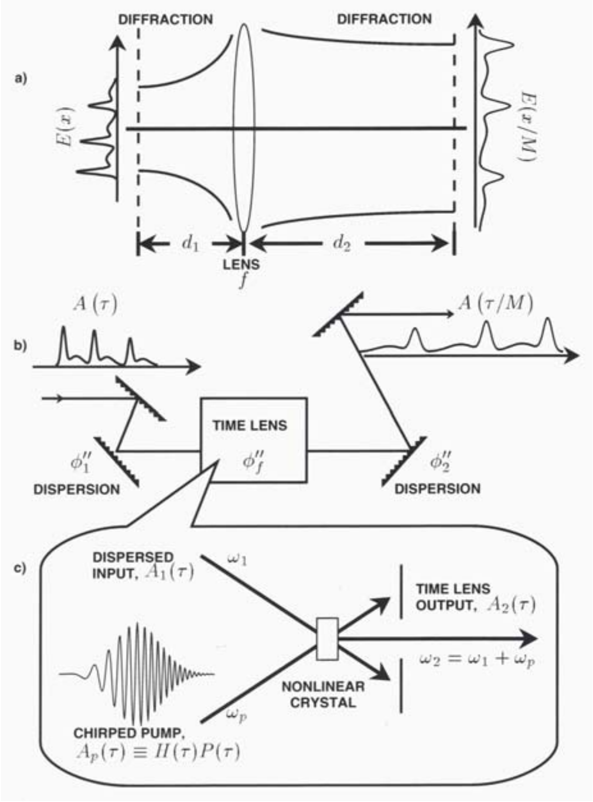


Figure 4. A comparison of a) spatial and b) temporal imaging systems. A c) time lens is produced by mixing the input signal with a chirped optical pump pulse.

An optical temporal imaging system has been constructed and tested at LLNL, and its performance is discussed in ref. [8,9]. That system was a large tabletop free space proof-of-principle system. It was the first and only system to demonstrate 103x temporal magnification with ~200 fs resolution, while simultaneously converting the output signal to its second harmonic (830 nm to 415 nm in that case). Higher order spectral phase in the dispersive delay lines that cause aberrations in the system were studied. Some of these distortions[10] were corrected; others could not because of their technical difficulty and budgetary constraints at that time. A new system with still higher performance is currently being developed at LLNL, under internal funding.

Proposal for Ultrashort Xray Measurements at LCLS.

We propose to combine these two techniques: xray-to-optical conversion and temporal imaging to develop a versatile high-performance measurement system for the routine characterization of sub-100 fs xray pulses. The baseline system would consist of a RadSensor xray detector, a time-lens, and an optical streak camera. Other system configurations are also being considered.

We estimate that the R&D effort will require approximately $400K to $800K of DOE funding. This amount which is directed at LCLS specific requirements will be leveraged by continued funding at LLNL for NIF-related instrumentation development and radiation detection for home-land security. We estimate the final instrument cost to be in the range of $1M to $2M.

We look forward to submitting a full proposal for this work in the near future.

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