Some Ideas for Photonic Approaches to LCLS timing, jitter, and xray temporal history measurements

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A system for fast single-transient radiation measurements

Single shot x-ray recorder for complex arbitrary waveforms. Sub-ps resolution and greater than THz instantaneous bandwidth.
Ionizing Radiation particle, energy $E$

Volume of III-V semiconductor... other materials may be possible

optical probe beam: we control power, $\lambda$, phase, pulsed or cw

e-h pair production leads to local index change $\sim 10^{-1}-10^{-2}$

$\rho_{e-h}(r, t; E) \rightarrow \delta n(r, t, \lambda; E)$

$\rho_{e-h}$ and $\lambda$ dependence

$\delta n_{opt}(\lambda) = C \left[ \frac{\rho_{e-h} / \rho_{sat}}{1 + \rho_{e-h} / \rho_{sat}} \right] \left[ \frac{\Gamma}{1 + \Gamma^2} \right]$

$= CF(\rho)G(\lambda); \quad \Gamma = \frac{\bar{\lambda} - \lambda_{edge}}{\delta \lambda}$

Index change increases with $\rho_{e-h}$

- Why III-V semiconductors?
  - Huge base of research in all optical switching for telecom applications
  - Established device technology
  - Index change depends on $\rho_{e-h}$
  - $\sim 100$ fs temporal response
  - Typical all-optical switching results

- Ionizing radiation is the analog to the optical pump, index modulation physics the same
- The use of the optical probe is ideal for high-energy radiation particle detectors and high-speed operation: relatively high material volume required (no transport limitations)
Results from the all-optical switching field show fast response


(a) As grown; (b) annealed

(d) MQW, 1/e fall time = 250 fs

(f) System response

- These devices are the optically-pumped analog of RadSensor.
- We expect similar temporal responses using appropriate epitaxial growth or neutron-damaged epi
To probe index change: Interferometry
Mach-Zehnder and Fabry-Perot compared

\[ \frac{\delta p}{P_0} = \frac{\pi L \langle \delta n \rangle}{\lambda} \]

Fringe-fraction

\[ \frac{\delta p}{P_0} = 2 \frac{F}{\lambda} \langle \delta n \rangle L \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tau )</td>
<td>( \tau_p )</td>
</tr>
<tr>
<td>for ( L = 3.4\text{mm}, n = 3.5 )</td>
<td>for ( F = 10, \lambda = 1550\text{nm}, n = 3.5 ) and ( L = 20\mu\text{m} )</td>
</tr>
<tr>
<td>( \approx 40\text{ps} )</td>
<td>( \approx 0.74\text{ps} )</td>
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- Sensitivity will be determined by how small a fringe-fraction we can measure (1-2% is reasonable); better sensitivity => higher fringe fraction
- The sensitivity of the FP is essentially that of the MZ, multiplied by \( 2F/\pi \)
Our First RadOptic Effect Demonstration Was at SSRL

We have measured the single-xray photon phase-shift to be

\[ \delta \phi = 2.0 \times 10^{-4} \text{ radians} \]

@ 8.9 kev and 70 nm from the bandedge.
RadSensor Linearity

- RadSensor response appears fairly linear over 2 decades
- Note that lower amplitude signals correspond to single xray photon events (9 keV)
Now We Are Focused on Imager Development in FY04

X-ray image

Monolithic RadSensor Reflection Modulation Array--Fabrication would be at the wafer level using well-established techniques used for VCSELs--10^6 pixels achievable

Optical Probe Beam

Optical Replica of X-ray image

Beam-splitter

Expanded View of individual pixel-Vertical Cavity RadSensor (VCRS)

III-V semiconductor

\[ \Delta n \text{ active region} \]

III-V substrate

Mirror

DBR mirror

Optical aperture

optical carrier wave

modulated optical output

AR coating

The cavity geometry is not only convenient for imagers it also allows for a sensitivity enhancement ~ cavity finesse

R&D Challenges:
- Optimizing sensitivity
- epi for “thick” cavity (eventually)
- epi with short e-h pair lifetime (fast)
- containing scattering (if necessary)
Optical phase shift from localized radiation excitation

\[ \delta \phi_{\text{rad}} = \frac{2\pi s_{\text{rad}}^3}{\lambda A_{\text{mode}}} F(\rho_{\text{rad}}) G(\lambda) \]

If \( \rho_{\text{rad}} \ll \rho_{\text{sat}} \) then, \( F(\rho_{\text{rad}}) \rightarrow \frac{\rho_{\text{rad}}}{\rho_{\text{sat}}} \)

\[ \rho_{\text{rad}} = \frac{N_{\text{rad}}}{s_{\text{rad}}^3} ; N_{\text{rad}} = \frac{E_{\text{rad}}}{E_0} ; \]

\[ E_0 = \frac{15}{5} E_{\text{gap}} + E' \approx 3.15 \text{ ev} \]

(For InGaAsP with \( E_{\text{gap}} = 0.857 \text{ ev} \))

\[ \delta \phi_{\text{rad}} = \frac{2\pi}{\lambda} \frac{s_{\text{rad}}^3}{A_{\text{mode}}} \langle \delta n \rangle ; \quad (\text{Eq. 1}) \]

\[ \langle \delta n \rangle = \frac{s_{\text{rad}}^2}{A_{\text{mode}}} \delta n ; \quad (\text{Eq. 2}) \]

\[ \delta \phi_{\text{rad}} = \frac{2\pi}{\lambda} \frac{s_{\text{rad}}^3}{A_{\text{mode}}} \delta n ; \quad (\text{Eq. 3}) \]

\( \delta n = \text{index change in excitation volume} \)

\[ \delta n = CF(\rho_{\text{rad}}) G(\lambda) \quad (\text{Eq. 4}) \]

From Nonlinear optical theory

This inhomogeneity will also lead to scattering... being quantified in Kallman's LDRD

Excitation volume cancels

From SSRL data we have (with \( A_{\text{mode}} = 4 \mu\text{m}^2 \))...

\[ \frac{C}{\rho_{\text{sat}}} = 1.2 \times 10^{-6} \mu\text{m}^3 \]
RadSensor phase modulation is xray irradiance dependent

Since the areas cancel, the signal is only dependent on xray irradiance

signal is independent of pixel size… very different from conventional detectors
RadSensor Optical System fielded at USP

Xrays

Cavity mirrors

Probe ~1550 nm

GRIN lens

Fiber circulator

Optical fiber

High-speed optical detector

Tunable probe

Scope

Cavity RadSensor Proto Package
First Single-Transient, Cavity RadSensor Data

RadSensor USP Layout

- 100 mJ, 100 fsec, 800 nm
- Off-axis paraboloid
- Fold mirror
- PIN diodes
- Cu target
- RadSensor device
- Fiber to optical subsystem

- Standard Si X-ray PIN diodes were used to monitor the x-ray output for each shot
- This shot had only Be filter
- Be and Cu filters were used to define and narrow x-ray spectrum later

New geometry works with system-limited risetime
Temporal Imaging Explained by Analogy to Spatial Imaging

Spatial Imaging

Group Delay Dispersion (GDD):

\[ \phi'' = \sum_n \xi_n \beta_n'' = \frac{d^2 \phi(\omega)}{d\omega^2} \mid \omega = \omega_0 \]

Focal GDD

\[ \phi_f'' = \frac{-1}{d\omega/d\tau} \]

Resolution

\[ \delta \tau_{\text{in}} \approx \frac{.44}{\Delta f_{\text{pump}}} \]
It Works But Old System Had Many Problems
(from DNT LDRD 98-ERD-027)

Past System Setup

- VERY LARGE free space system
  - Filled 5 x 12 ft optical table
- Many mechanical stability problems
- Not practical for imaging

Streak Camera Single-Shot Recording

- Two pulse test pattern, changed in 670 fs steps
- 68.8 ps changes at output, demonstrated M=+103 magnification
- Fundamental problem was low efficiency, producing poor Dynamic Range (DR)

A Practical Instrument Requires a Complete Redesign
(Introducing new challenges)

(See backup slides for additional past results and publications from LDRD 98-ERD-027)
Proposed Development of Robust Guided Wave System

- New Challenges:
  - Noise due to Amplified Spontaneous Emission
  - Aberrations due to higher order dispersion terms and possible self phase modulation
  - Polarization Mode Dispersion
  - Packaging of nonlinear crystal with fiber input & output

- ~ 250 fs resolution
- Dynamic Range > 100
- Practical record length (100ps – 1 ns)
- Compact and Robust
RadSensor/Time lens approach to xray pulse measurement

Phase matching condition: \[ \frac{V_{\text{probe}}}{c} = \sin \alpha = \frac{1}{n} = \frac{1}{3.5} \rightarrow \alpha = 16.6^\circ \]

For slow-recovery material (integrating detector), signal can be differentiated to obtain pulse shape.
Fast recovery material will probably yield better dynamic range

\(~100 \text{ fs temporal resolutions are possible}\)
Potential RadSensor Based Cross-timing Scheme

Phase matching condition:

\[
\frac{V_{\text{probe}}}{c} \sin \alpha = \frac{1}{n} = \frac{1}{3.5} \rightarrow \alpha = 16.6^\circ
\]

**Cross-timing ~ 100 fs is possible using just the rising edge of the RadSensor signal**
We have

- demonstrated that x-rays can be produce an optical phase modulation for detection purposes, that should scale to $< 1\text{ps}$.
- investigated the x-ray sensitivity as a function of wavelength separation from the band-edge...$1.0 \times 10^{-4}$ fringe-fractions/x-ray photon is best measured
- Measured the linearity over 2 decades of x-ray fluence.
- Developed model in reasonable agreement with measurements
- Recently demonstrated single-shot results with new cavity geometry

We plan to:

- Improve the sensitivity using optimized cavity structures (USP experiments)
  - Goal is single x-ray photon sensitivity
- make fast devices and characterize temporal response ($<\text{ps}$)
- Develop imaging versions
- Develop companion optical recording technologies (Time lens/streaker)

**We believe these approaches are capable of 100 fs temporal resolution and reasonable dynamic range**

*Questions: Lowry3@LLNL.gov*
Backup slides
Our device design model is aimed at optimizing sensitivity

Model output

\[ \frac{\delta P_{Rx}}{P_{Rx}^0} = \frac{1}{R(\phi)} \frac{dR}{d\phi} \delta \hat{\phi}(\lambda)_{rad} \]

The “Contrast Ratio” is maximized for optimum detector sensitivity

Model inputs

\[ n = H\left( E_{gap}, \lambda \right) \]

The linear index is a function of material composition which is directly related to the energy gap. We use empirically derived polynomial expressions from Amman and Buus

\[ \delta \hat{\phi}(\lambda)_{rad} = \frac{2\pi}{\lambda} \frac{C}{\rho_{sat}} \frac{1}{A_{mode}} \frac{E_{rad}}{E_0} G(\lambda) \]

The resonant nature of the nonlinearity implies close to the bandedge is good, more phase shift

\[ \alpha = \alpha_g \exp\left[ \frac{hc}{\lambda - E_{gap}} / \frac{E_{urb}}{E_{urb}} \right] \]

The Urbach absorption tail is higher, closer to the bandedge, thus close to the bandedge is bad

We are exploring the device design parameter space: mirror reflectivities, thickness, wavelength offset to quantify the trade-offs to maximize sensitivity
Design model examples for sensitivity optimization

Model inputs

“Materials Physics”

Cavity physics; predicted responsivity

5% contrast for a single xray photon at 8 keV, this should be detectable

The model also outputs cavity results in 3D (vs. wavelength and thickness)...

Model implemented in Matlab adapted from codes developed by John Heebner
Summary of RadSensor sensitivity data

- Scatter in data is primarily due to polarization instability in the interferometer caused by packaging induced birefringence in the RadSensor—higher values probably more accurate.
- We should see more resonant enhancement. Trap-filling effects may be causing the as measured “normal fill-pattern” fringe-fractions to be preferentially saturated (x10 xray photons/SPEAR period).
We considered several cavity design approaches to mitigate risk

Epi-DBR-thin cavity

- Pros:
  - Very VCSEL-like know how to produce high-quality laser cavities
  - Material in the cavity is only InGaAsP

- Cons:
  - MOCVD shutdown forced reliance on vendors—no takers
  - Difficult to match resonances to probe range (10 µm OK)

Etched-back, thin cavity

- Pros:
  - We have control over final cavity thickness and mirror reflectivities

- Cons:
  - Cavity trimming (not quite working)
  - Membrane is fragile and stressed

Thick cavity

- Pros:
  - Robust (thick)
  - Relatively easy to make

- Cons:
  - Cavity includes InP and InGaAsP
  - Difficult to get good effective finesse
  - Impossible to get fast response

To meet our USP fielding schedule we had to go with the thick cavity
First generation RadSensor Cavities Presented Challenges

Cavity resonances showing thermal drift

- Finesse is very poor (~1)
- Measured using ASE from EDFA
- Drift went away when optical input power was lowered to ~ 0 dBm
- We suspected this would be a problem–locking circuit not ready for this fielding… will be next time

Temporary cavity drift solution:

Map detector voltage vs. phase by varying wavelength and modulating light on/off – Optical receiver is ac-coupled

Detector Voltage (Volts) vs. Phase shift (Radians)
Typical Results Compared to Prediction from SSRL derived empirical constants

These data used Be and Cu filters to narrow xray spectrum

Detector Voltage

Optical Phase

\[ \Delta \phi_{\text{predicted}} = \psi \left( 1 - \exp(-\mu d) \right) \frac{2\pi}{\lambda} \frac{C}{\rho_{\text{sat}}} \frac{E_{\text{rad}}}{E_0} G(\lambda) \]

\[ = (60 \text{ xrays/}\mu\text{m}^2) \left( \frac{2\pi}{1.55 \text{ \mu m}} \right) (1.2 \times 10^{-6} \text{ \mu m}^3) \left( \frac{8.05 \text{ keV}}{3.15 \text{ eV}} \right) (0.04) = 0.030 \text{ radians} \]

Reasonably good comparison between SSRL experiments and USP… please note– these are very preliminary results, analysis still underway