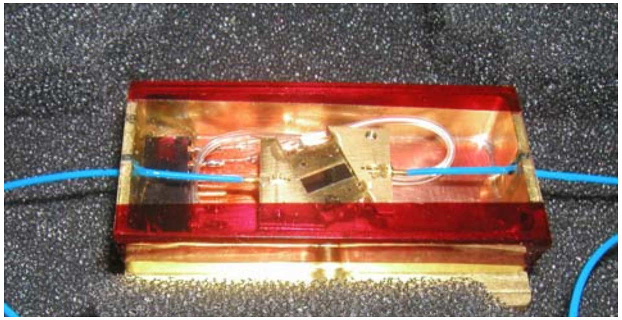
Some Ideas for Photonic Approaches to LCLS timing, jitter, and xray temporal history measurements



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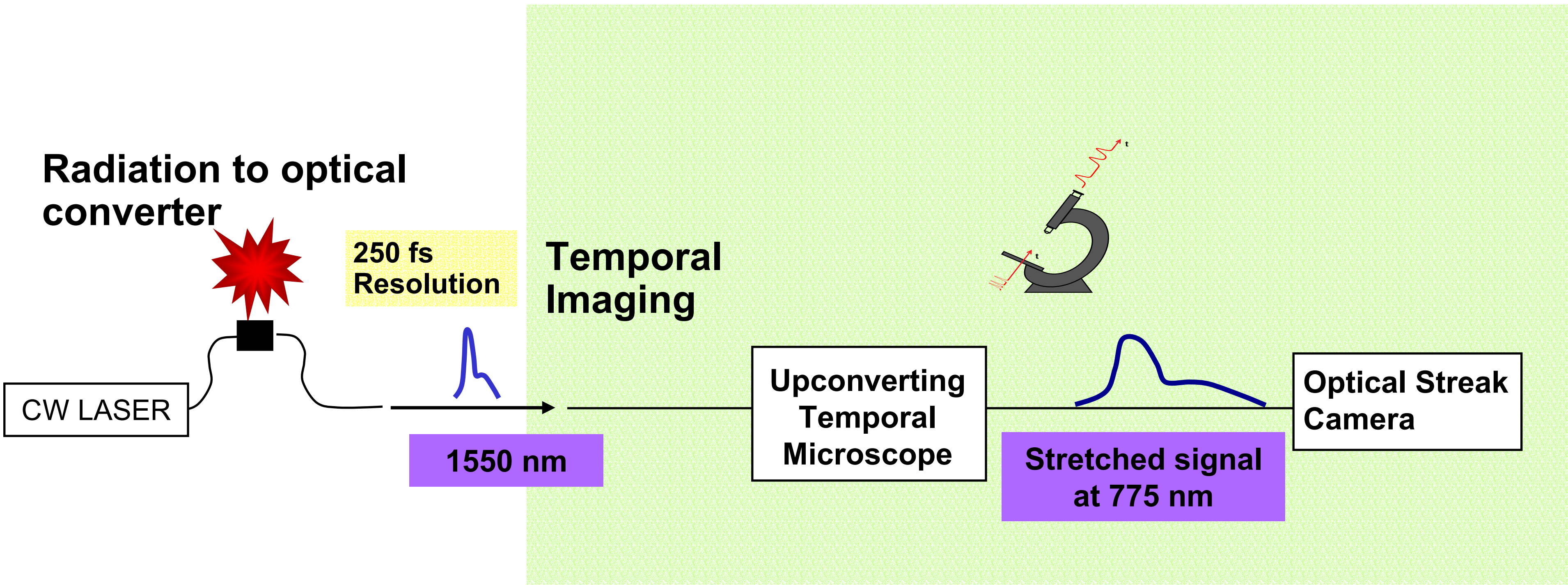
Lawrence Livermore National Laboratory

Presented to XFEL 2004

7/28/04

*** Lowry3@LLNL.gov**

A system for fast single-transient radiation measurements



Radiation to optical converter

250 fs Resolution

Temporal Imaging

CW LASER

1550 nm

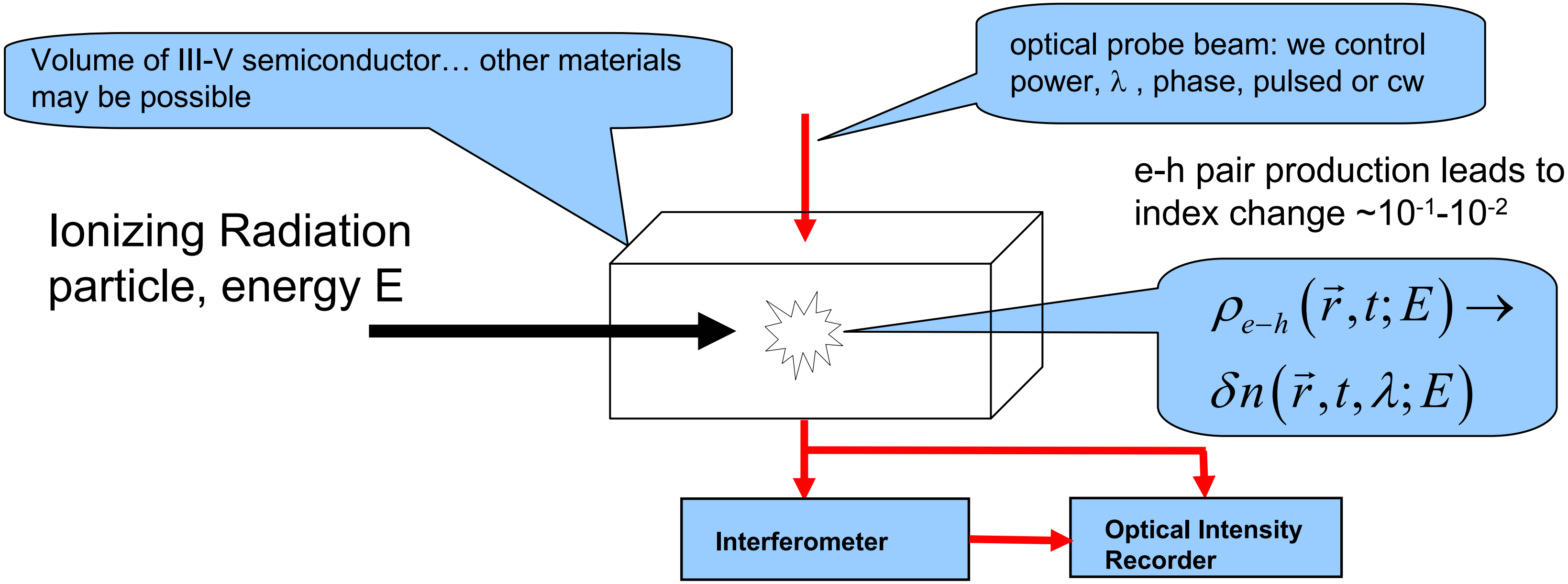
Upconverting Temporal Microscope

Stretched signal at 775 nm

Optical Streak Camera

Single shot x-ray recorder for complex arbitrary waveforms. Sub-ps resolution and greater than THz instantaneous bandwidth.

Radoptic Effect Radiation Detection



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

optical probe beam: we control power, λ , phase, pulsed or cw

Ionizing Radiation particle, energy E

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

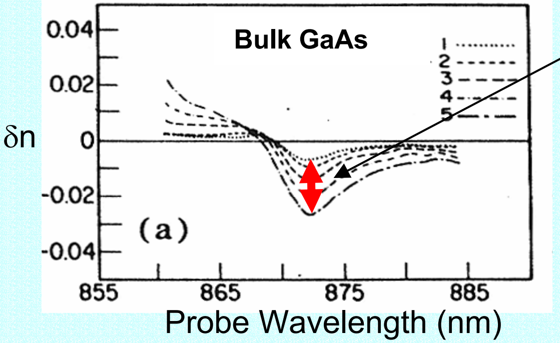
$$\rho_{e-h}(\vec{r},t;E) \rightarrow \delta n(\vec{r},t,\lambda;E)$$

Interferometer

Optical Intensity Recorder

- Why III-V semiconductors?
  - Huge base of research in all optical switching for telecom applications
  - established device technology
  - index change depends on ρ_{e-h}
  - ~100 fs temporal response
  - typical all-optical switching results

Data from: Park, et. al. Appl. Phys. Lett. 52 (15), pp 1201-1203



Index change increases with ρ_{e-h}

ρ_{e-h} and λ dependence

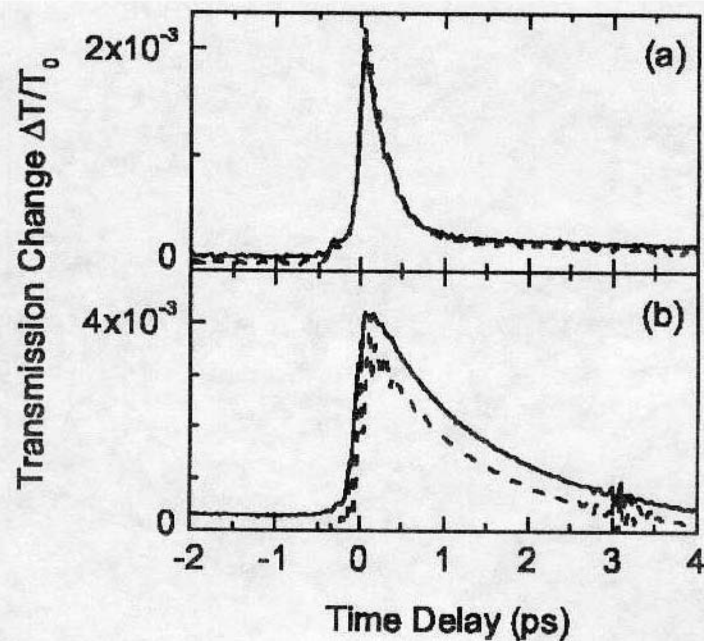
$$\delta n_{opt}(\lambda) = C\left[\frac{\rho_{e-h}/\rho_{sat}}{1+\rho_{e-h}/\rho_{sat}}\right]\left[\frac{\Gamma}{1+\Gamma^2}\right]$$

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

- 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)

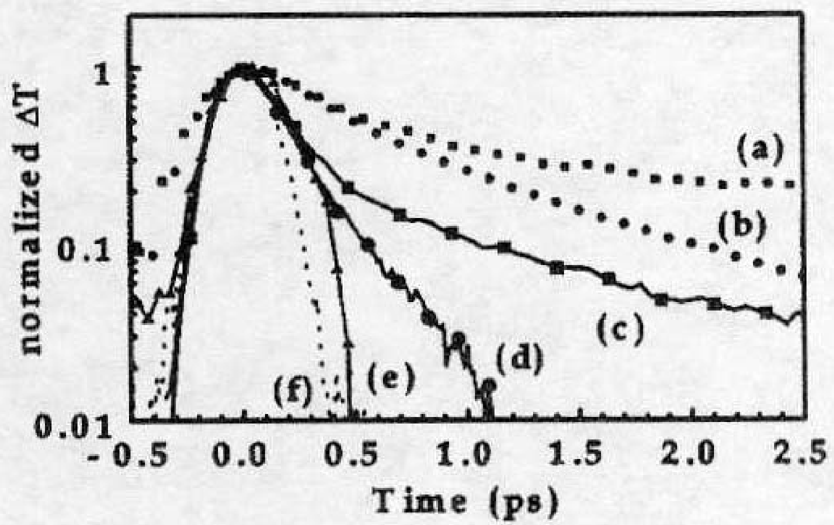
Results from the all-optical switching field show fast response

K. Biermann, et.al., ***Ultrafast optical nonlinearity of low-temperature-grown GaInAs/AlInAs quantum wells at wavelengths around 1.55 μm,*** Appl. Phys. Lett., 80 (11), pp1936-1938 (2002)



(a) As grown; (b) annealed

T. Okuno, et. al., ***Femtosecond response time in beryllium-doped low-temperature-grown GaAs/AlAs multiple quantum wells,*** Appl. Phys. Lett. 79 (6), pp 764-766 (2001)

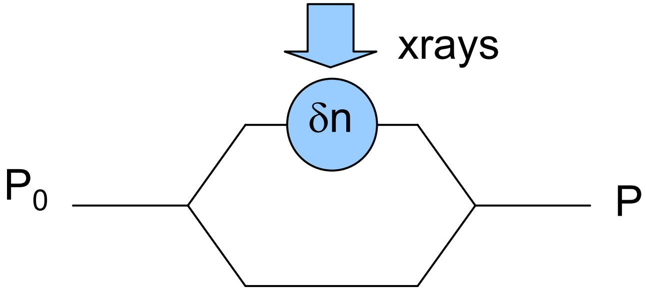


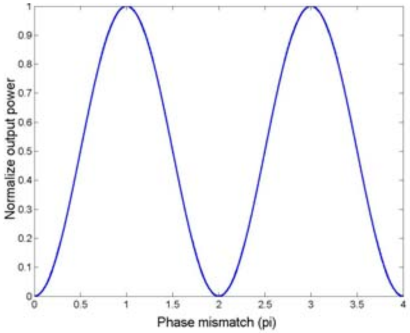
(d) MQW, 1/e fall time = 250 fs

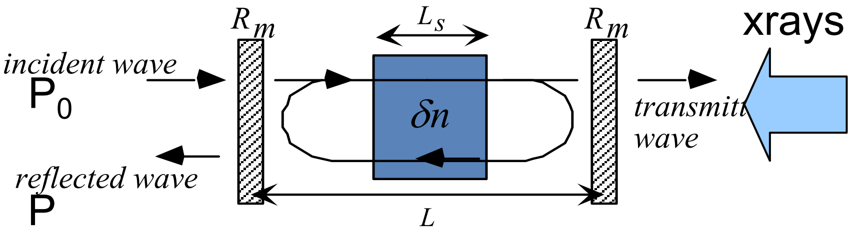
(f) System response

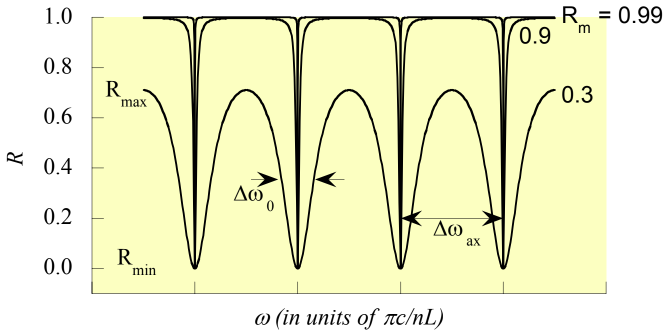
- These devices are the optically-pumped analog of RadSensor.
- We expect similar temporal responses using appropriate epitaxial growth or neutrondamaged epi

To probe index change: Interferometry
Mach-Zehnder and Fabry-Perot compared









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

Fringe-fraction

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

$$\tau = \frac{nL}{c} \approx 40\,ps$$

for L = 3.4mm, n = 3.5

Time-response

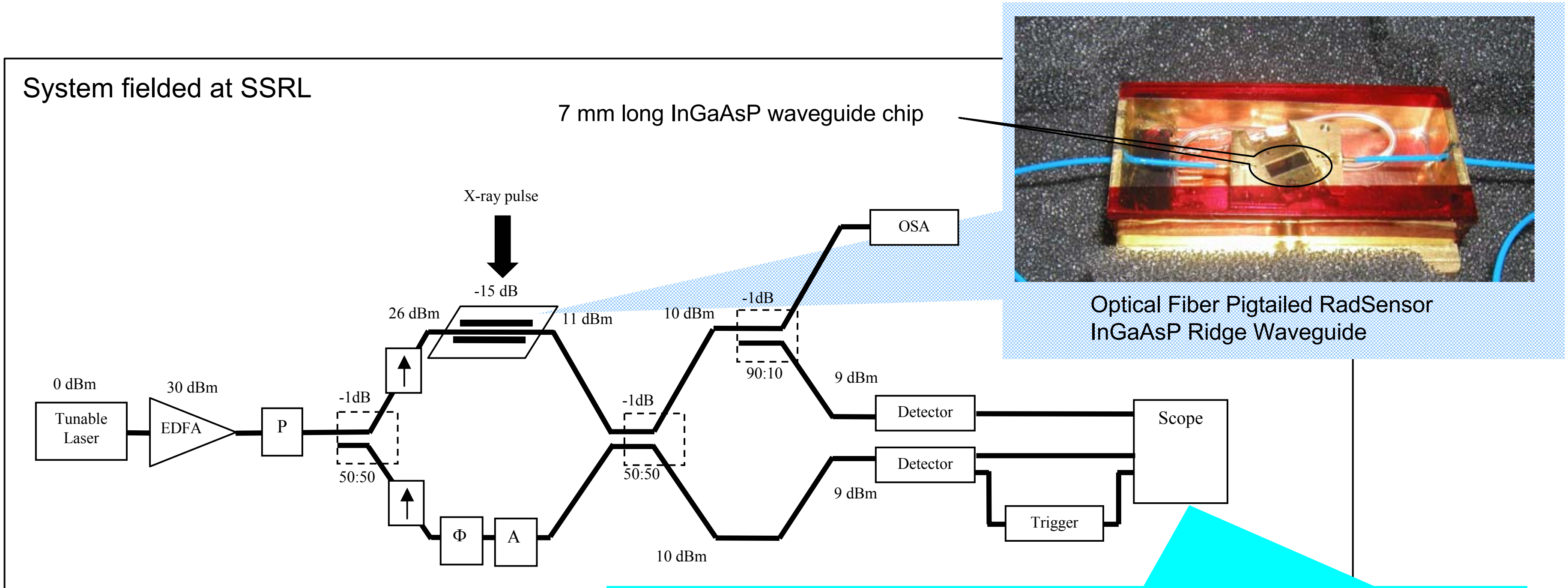
$$\tau_p = \frac{nL}{\pi c} F \cong 0.74\text{ps}$$

for $F = 10$, λ = 1550nm, n = 3.5 and $L = 20\,\mu m$

- 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/π

Our First RadOptic Effect Demonstration Was at SSRL

System fielded at SSRL



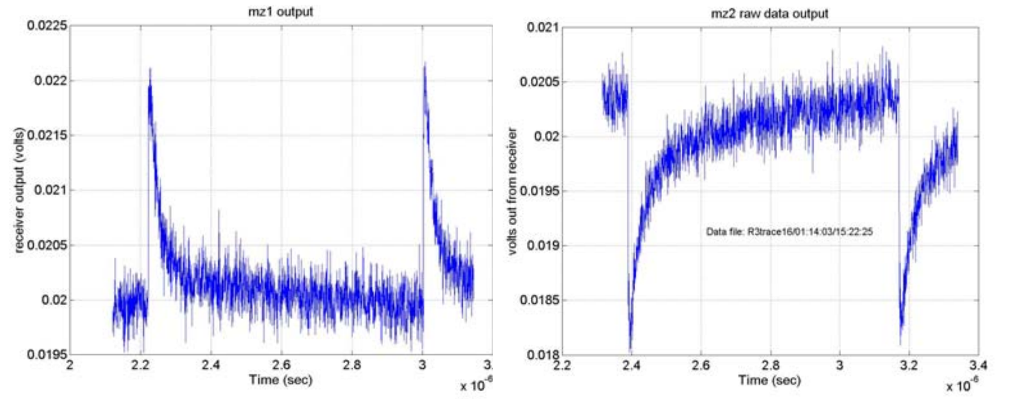
7 mm long InGaAsP waveguide chip

Optical Fiber Pigtailed RadSensor
InGaAsP Ridge Waveguide

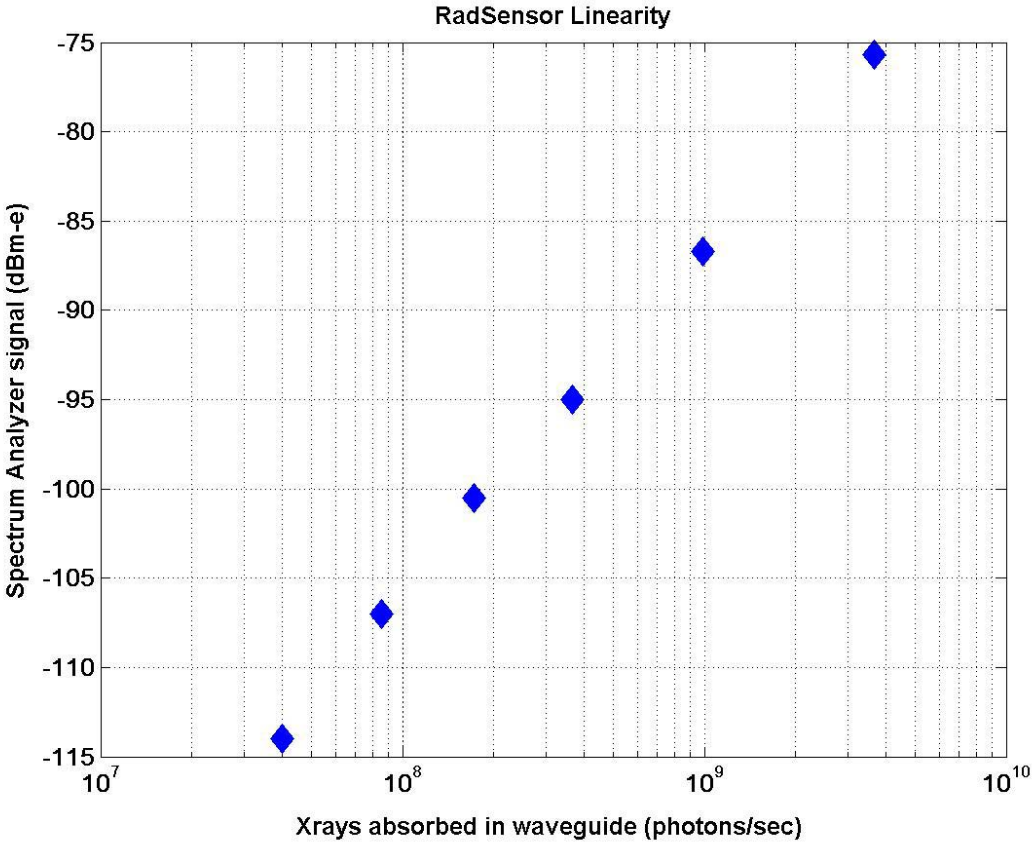
We have measured the single-xray photon phase-shift to be

$\delta\phi = 2.0\times10^{-4}$ radians

@ 8.9 kev and 70 nm from the bandedge.

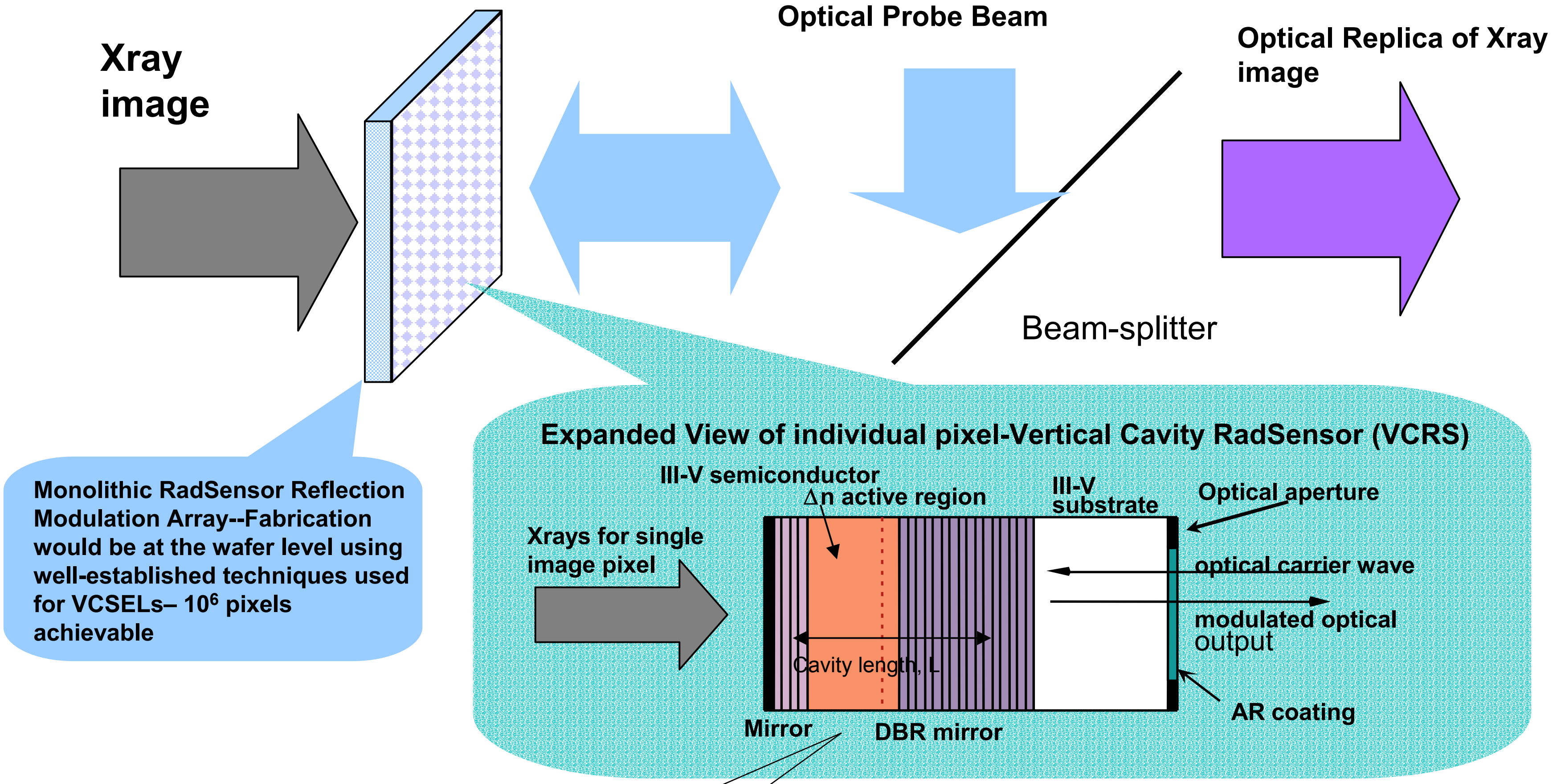


RadSensor Linearity



- 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



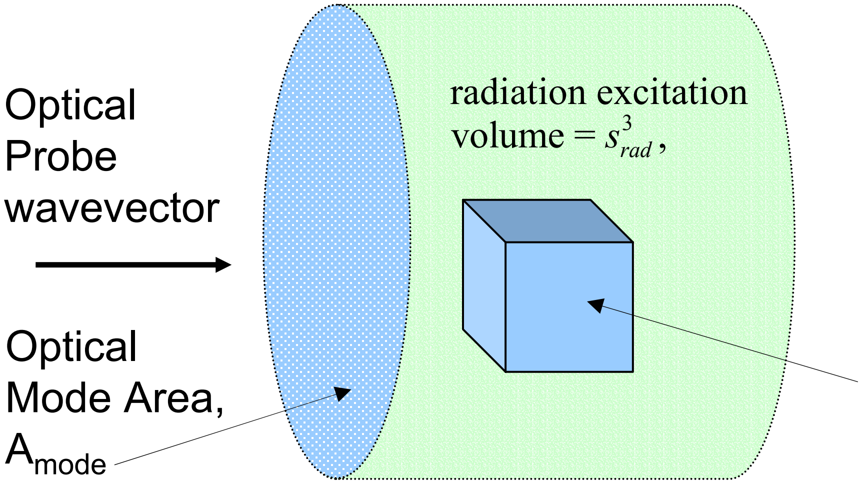
Monolithic RadSensor Reflection Modulation Array--Fabrication would be at the wafer level using well-established techniques used for VCSELs– 10^6 pixels achievable

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



$$\delta\phi_{rad} = \frac{2\pi s_{rad}}{\lambda}\langle\delta n\rangle; \quad \text{(Eq. 1)}$$

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

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

$\delta n =$ index change in excitation volume

$$\delta n = CF(\rho_{rad})G(\lambda) \qquad \text{(Eq. 4)}$$

From Nonlinear optical theory

This inhomogeneity will also lead to scattering…

being quantified in Kallman's LDRD

$$\delta\phi_{rad} = \frac{2\pi C}{\lambda}\frac{s_{rad}^3}{A_{\mathrm{mode}}}F(\rho_{rad})G(\lambda)$$

If $\rho_{rad} \ll \rho_{sat}$ then, $F(\rho_{rad}) \rightarrow \dfrac{\rho_{rad}}{\rho_{sat}}$

$$\rho_{rad} = \frac{N_{rad}}{s_{rad}^3}; N_{rad} = \frac{E_{rad}}{E_0};$$

$$\mathrm{E}_0 = \frac{15}{5}E_{gap} + E' \approx 3.15 \text{ ev}$$

(for InGaAsP with E_{gap} =0.857 ev)

$$\delta\phi_{rad} = \frac{2\pi}{\lambda}\frac{C}{\rho_{sat}}\frac{\cancel{s_{rad}^3}}{A_{\mathrm{mode}}}\left(\frac{E_{rad}/E_0}{\cancel{s_{rad}^3}}\right)G(\lambda)$$

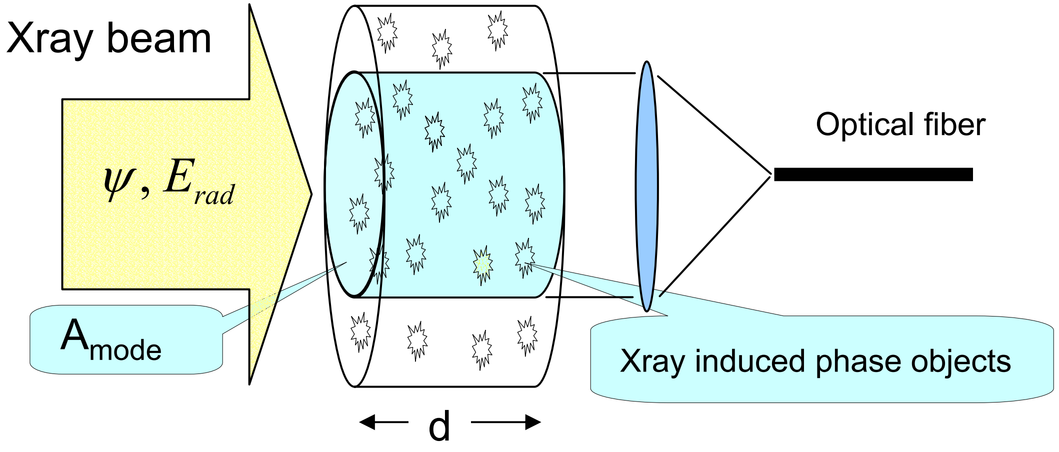
Excitation volume cancels

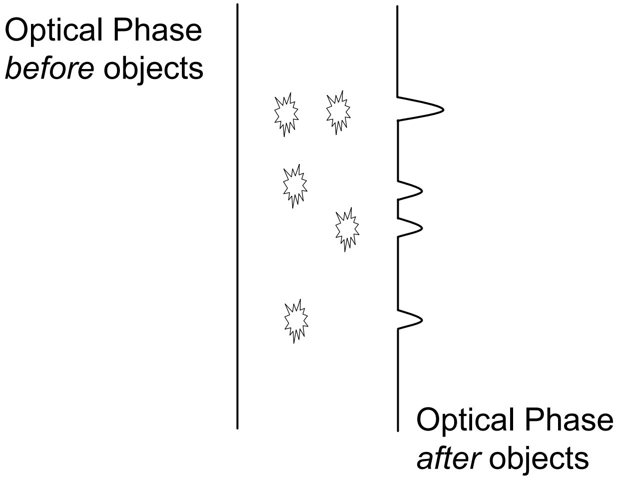
$$\delta\phi_{rad} = \frac{2\pi}{\lambda}\frac{C}{\rho_{sat}}\frac{1}{A_{\mathrm{mode}}}\frac{E_{rad}}{E_0}G(\lambda)$$

From SSRL data we have (with $A_{\mathrm{mode}} = 4\ \mu\mathrm{m}^2$) …

$$\frac{C}{\rho_{sat}} = 1.2\times10^{-6}\ \mu\mathrm{m}^3$$

RadSensor phase modulation is xray irradiance dependent





$$\Delta\phi = N_x \delta\phi;$$

$$\delta\phi = \frac{2\pi}{\lambda}\frac{1}{A_{\text{mode}}}\frac{C}{\rho_{sat}}\frac{E_{rad}}{E_0}G(\lambda); \quad \frac{C}{\rho_{sat}} \text{ calibrated from FY03 SSRL data}$$

N_x = # of xrays absorbed in mode volume= $\psi A_{\text{mode}}(1-\exp(-\mu d))$

ψ = xray irradiance (# xrays/μm^2) into cavity volume

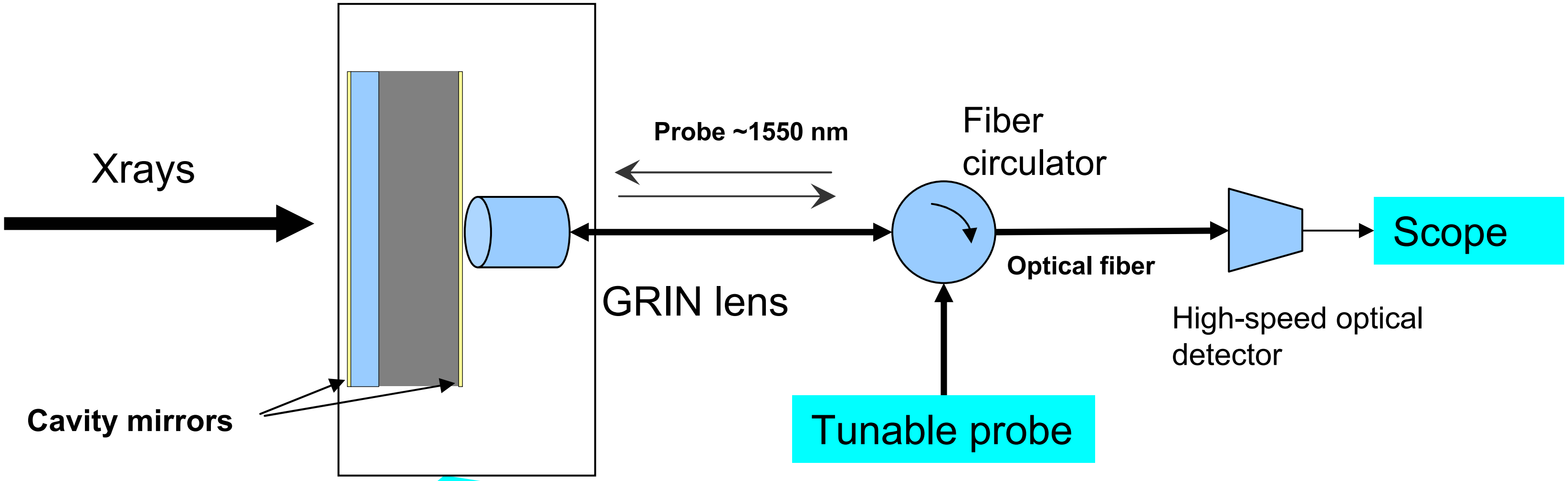
$$\Delta\phi = \psi \cancel{A_{\text{mode}}}\left(1-\exp(-\mu d)\right)\frac{2\pi}{\lambda}\frac{1}{\cancel{A_{\text{mode}}}}\frac{C}{\rho_{sat}}\frac{E_{rad}}{E_0}G(\lambda)$$

$$\Delta\phi = \psi\left(1-\exp(-\mu d)\right)\frac{2\pi}{\lambda}\frac{C}{\rho_{sat}}\frac{E_{rad}}{E_0}G(\lambda)$$

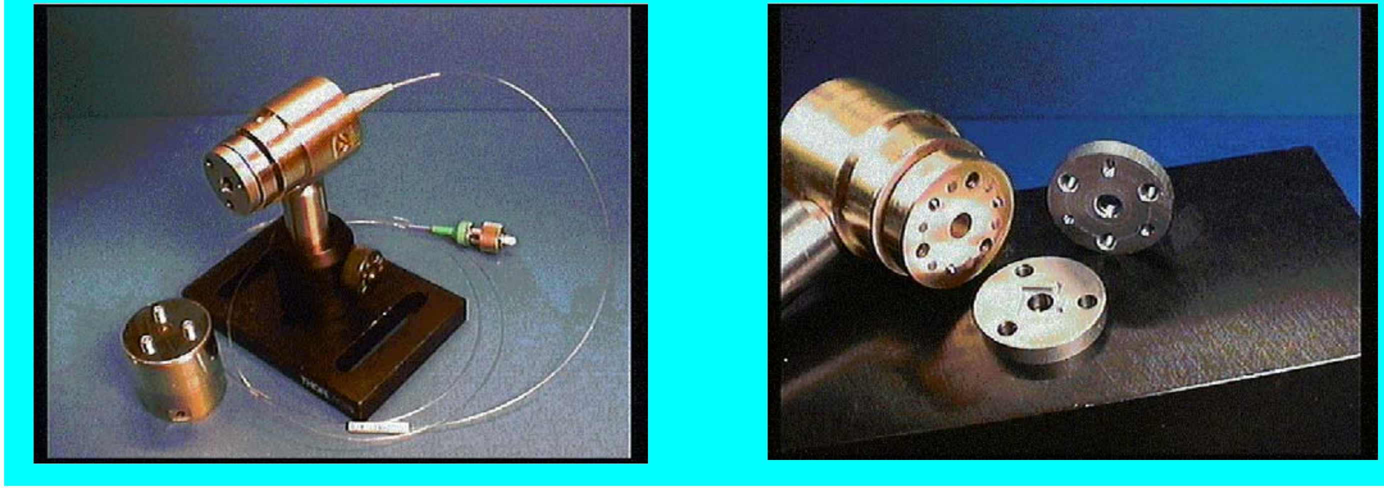
Since the areas cancel, the signal is only dependent on xray irradiance

signal is independent of pixel size… very different from conventional detectors

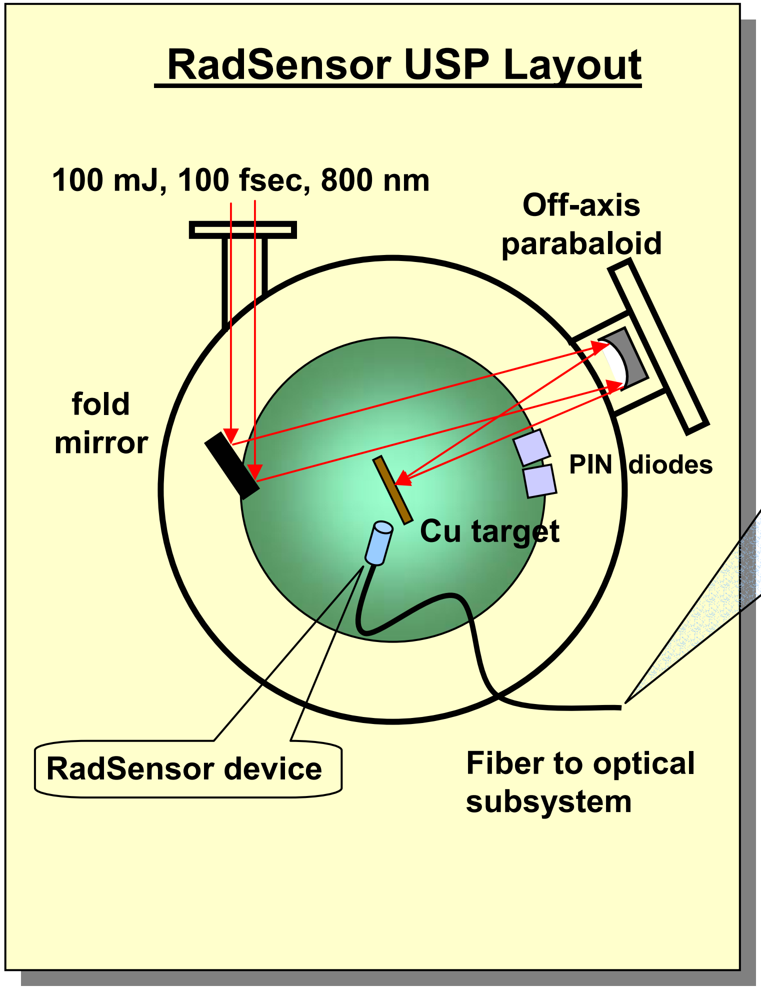
RadSensor Optical System fielded at USP

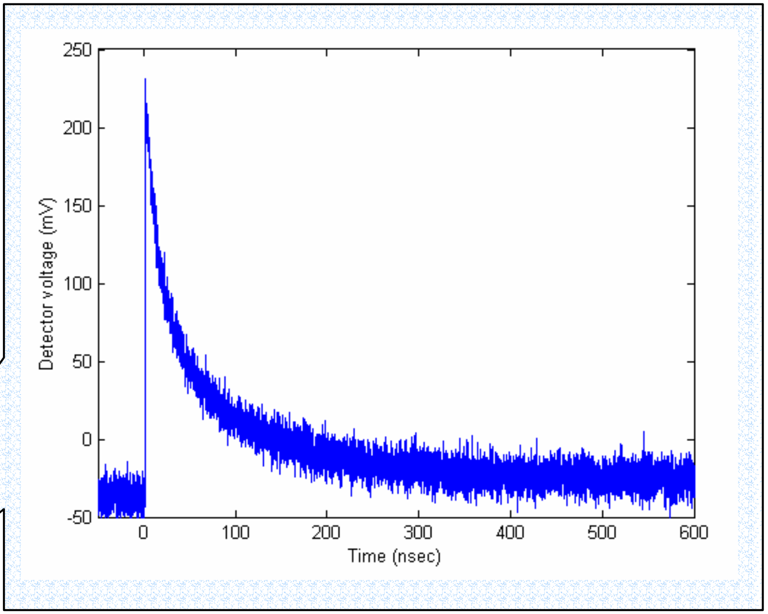


Cavity RadSensor Proto Package



First Single-Transient, Cavity RadSensor Data



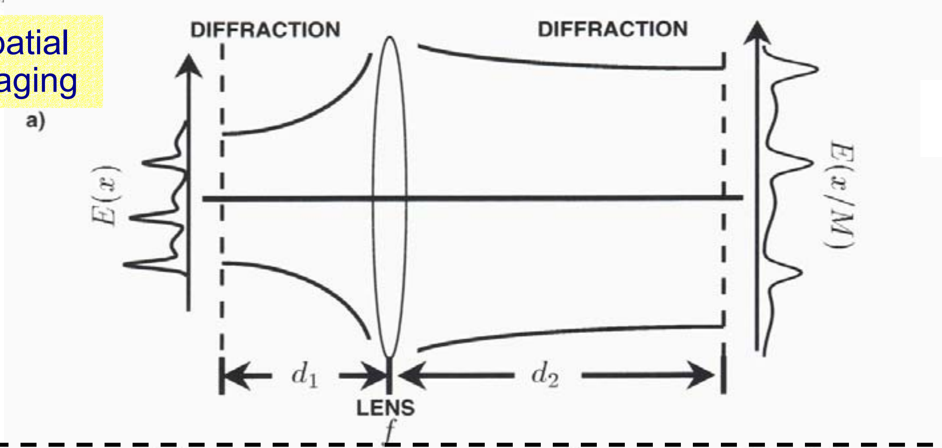


- Standard Si Xray PIN diodes were used to monitor the xray output for each shot
- This shot had only Be filter
- Be and Cu filters were used to define and narrow xray spectrum later

New geometry works with system-limited risetime

Temporal Imaging Explained by Analogy to Spatial Imaging

Spatial Imaging



Imaging Condition

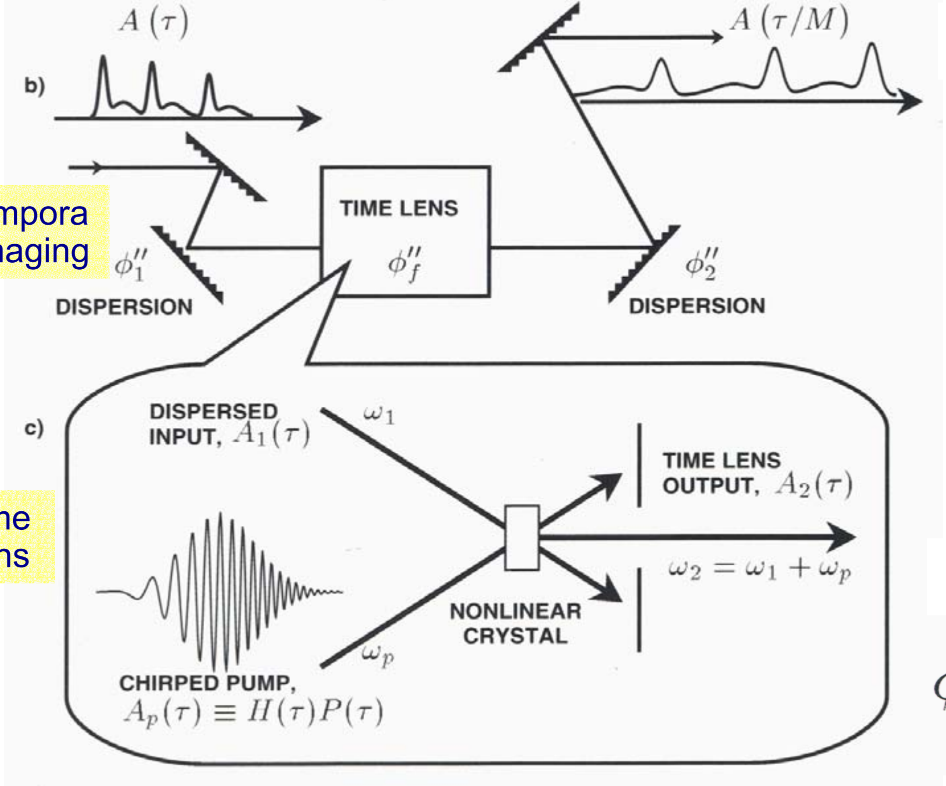
$$\frac{1}{d_1} + \frac{1}{d_2} = \frac{1}{f}$$

Magnification

$$M = -\frac{d_2}{d_1}$$

Temporal Imaging

Time Lens



Imaging Condition

$$\frac{1}{\phi''_1} + \frac{1}{\phi''_2} = \frac{1}{\phi''_f}$$

Magnification

$$M = -\frac{\phi''_2}{\phi''_1}$$

Group Delay Dispersion (GDD):

$$\phi'' = \sum_n \xi_n \beta''_n = \left.\frac{d^2\phi(\omega)}{d\omega^2}\right|_{\omega=\omega_0}$$

Focal GDD

$$\phi''_f \equiv \frac{-1}{d\omega/d\tau}$$

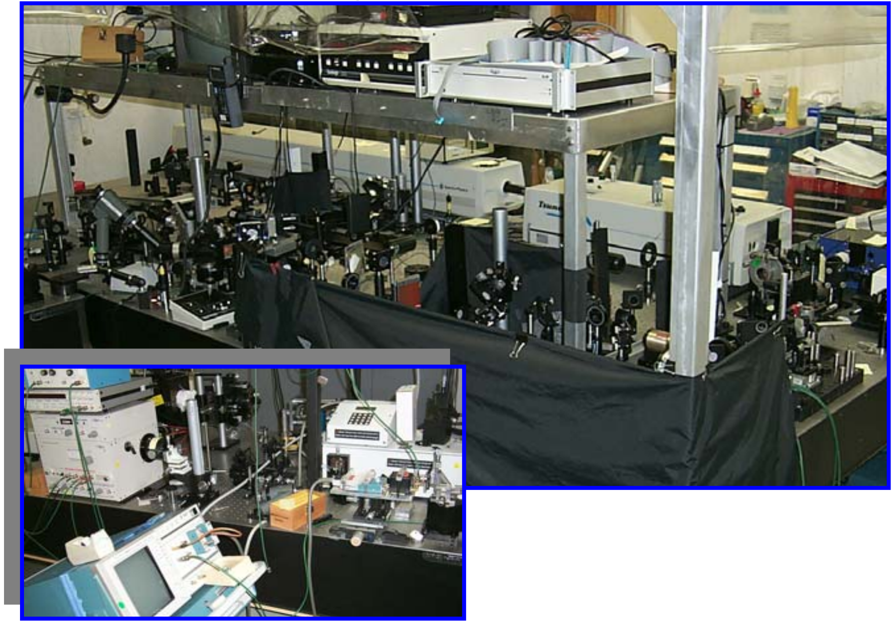
Resolution

$$\delta\tau_{\text{in}} \approx \frac{.44}{\Delta f_{\text{pump}}}$$

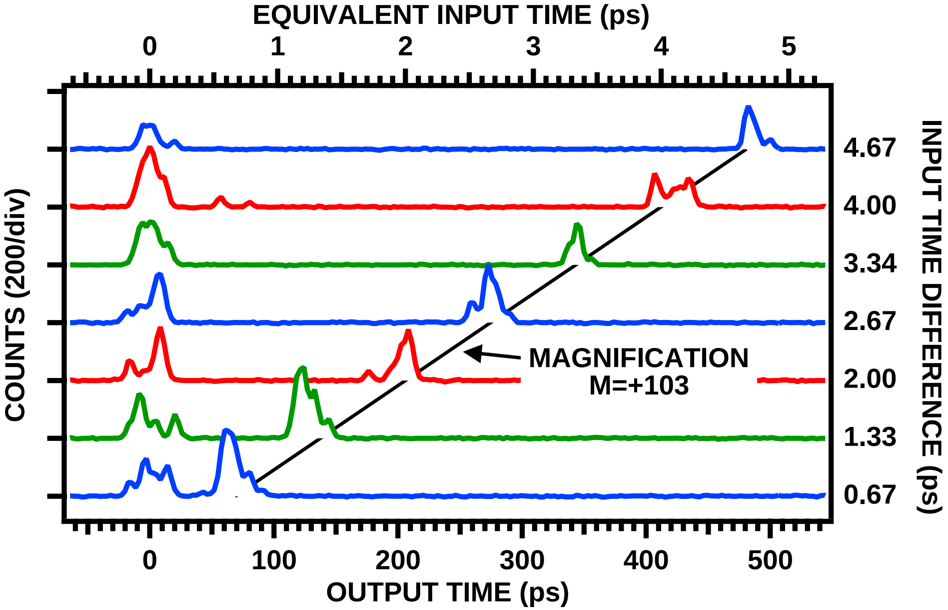
It Works But Old System Had Many Problems

(from DNT LDRD 98-ERD-027)

Past System Setup



Streak Camera Single-Shot Recording



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

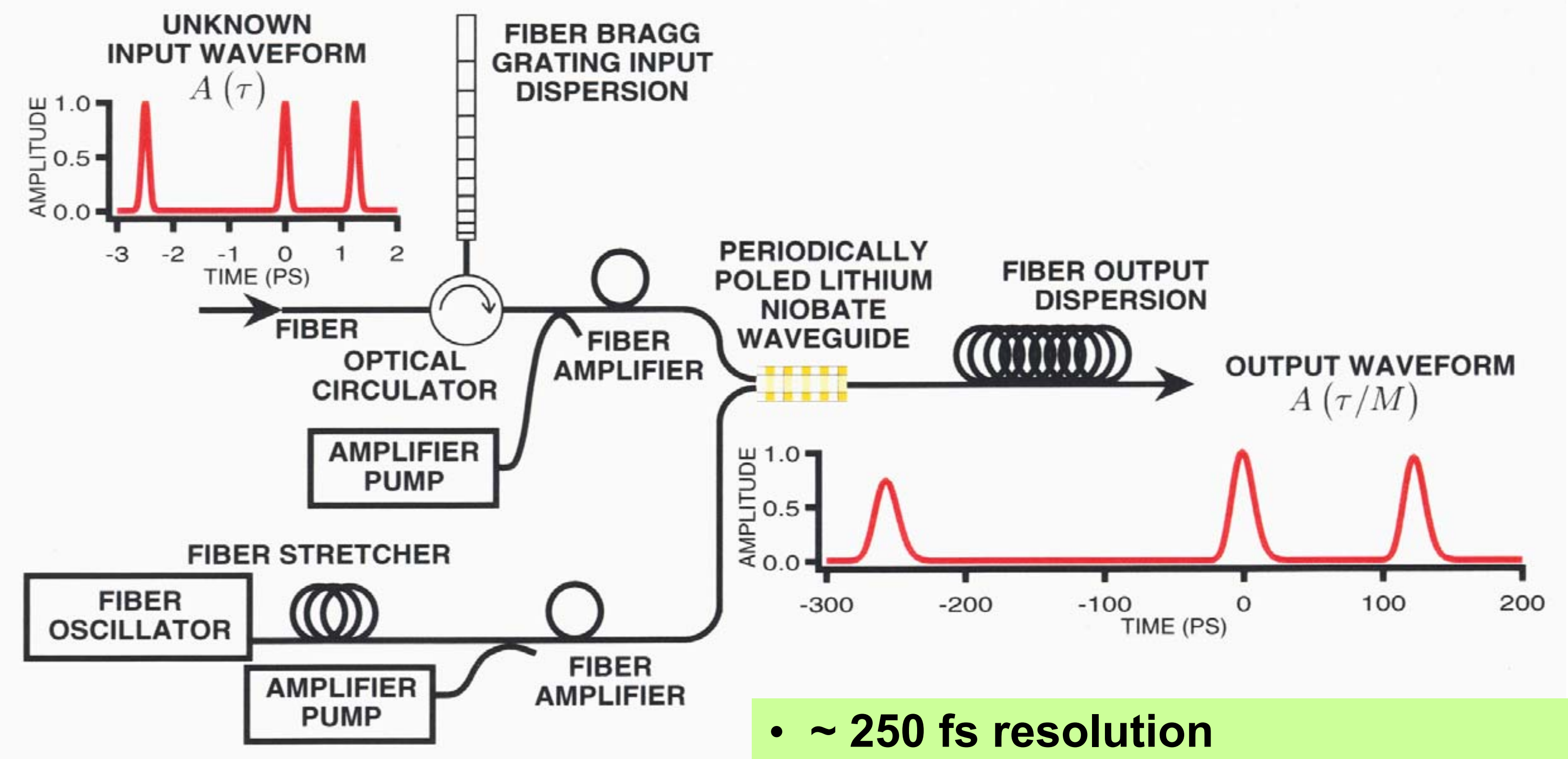
- **Two pulse test pattern, changed in 670 fs steps**
- **68.8 ps changes at output, demonstrated M=+103 magnification**
- **Fundamental problem *was* low efficiency, producing poor Dynamic Range (DR)**

A Practical Instrument Requires a Complete Redesign

(Introducing new challenges)

(See backup slides for addition past results and publications from LDRD 98-ERD-027)

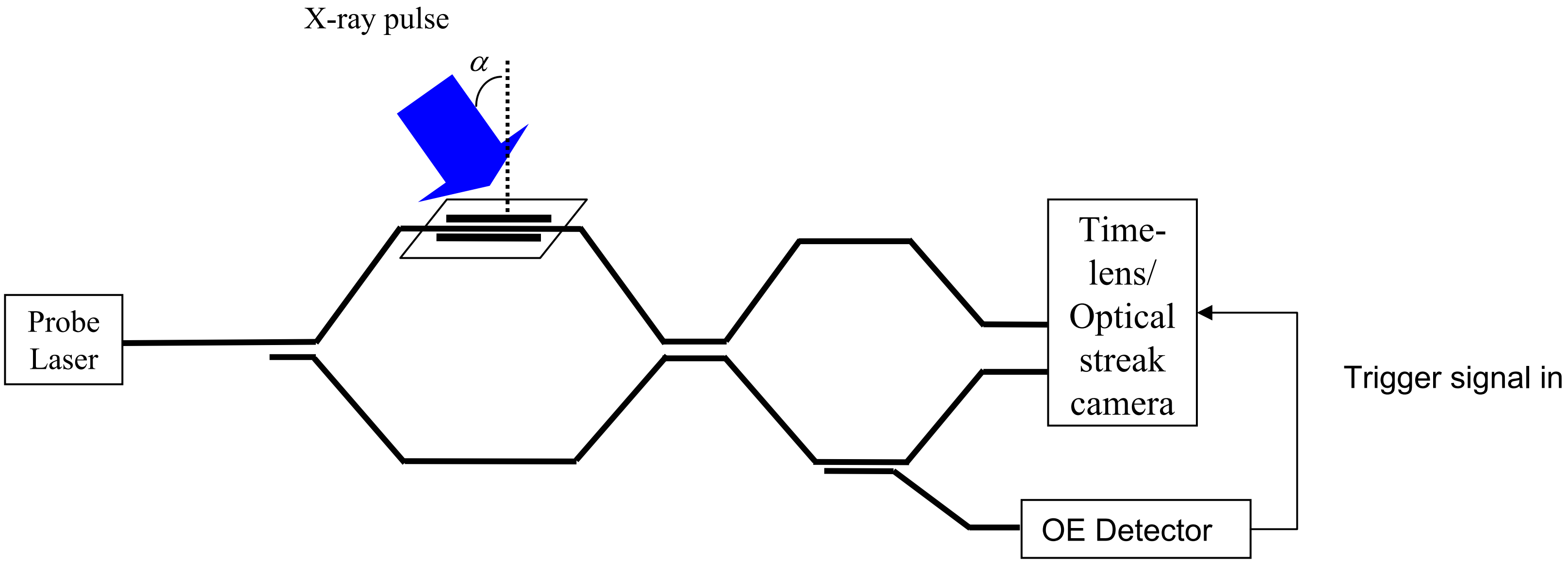
Proposed Development of Robust Guided Wave System



- **~ 250 fs resolution**
- **Dynamic Range > 100**
- **Practical record length (100ps – 1 ns)**
- **Compact and Robust**

- **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**

RadSensor/Time lens approach to xray pulse measurement



Phase matching condition:

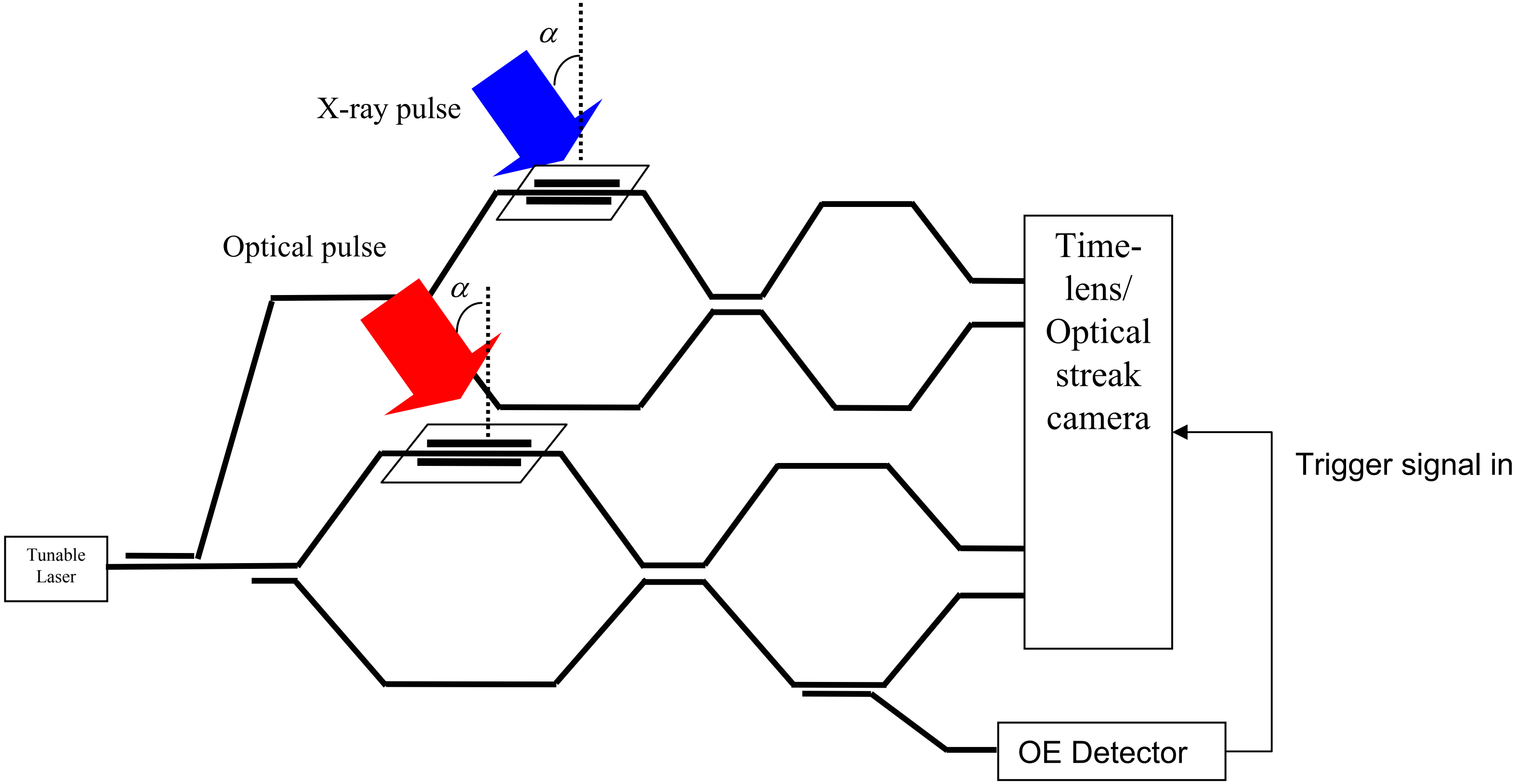
$$\frac{\mathrm{v}_{\mathrm{probe}}}{\mathrm{c}} = \sin\alpha = \frac{1}{n} = \frac{1}{3.5} \rightarrow \alpha = 16.6^{\circ}$$

For slow-recovery material (integrating detector), signal can be differentiated to obtain pulse shape.

Fast recovery material will probably yield better dynamic range

~100 fs temporal resolutions are possible

Potential RadSensor Based Cross-timing Scheme



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

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

Conclusions and future work

- We have
  - demonstrated that xrays can be produce an optical phase modulation for detection purposes, that should scale to < 1ps.
  - investigated the xray sensitivity as a function of wavelength separation from the band-edge…1.0x10-4 fringe-fractions/xray photon is best measured
  - Measured the linearity over 2 decades of xray 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 xray photon sensitivity
  - make fast devices and characterize temporal response (<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

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

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

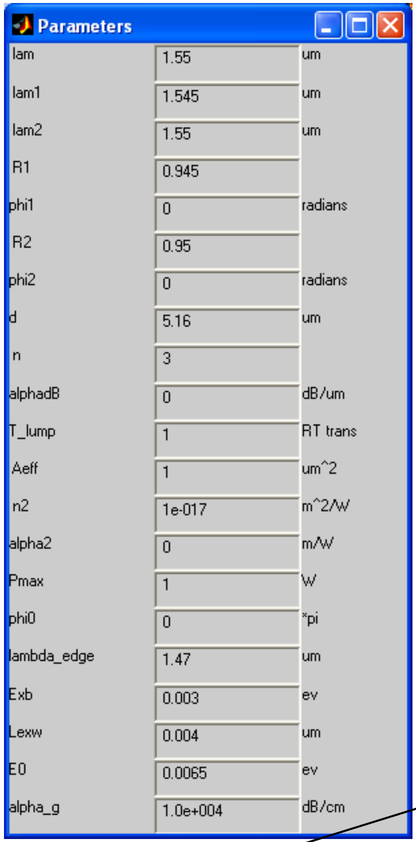
$$\alpha = \alpha_g \exp\left[\frac{hc/\lambda - E_{gap}}{E_{urb}}\right]$$

The Urbach absorption tail is higher, closer to the bandegde, 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

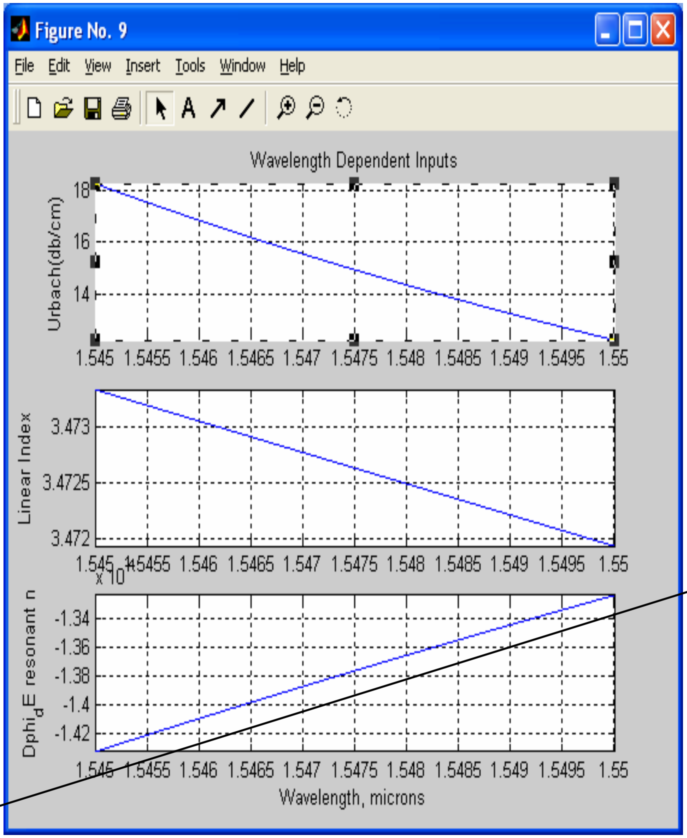
Model inputs



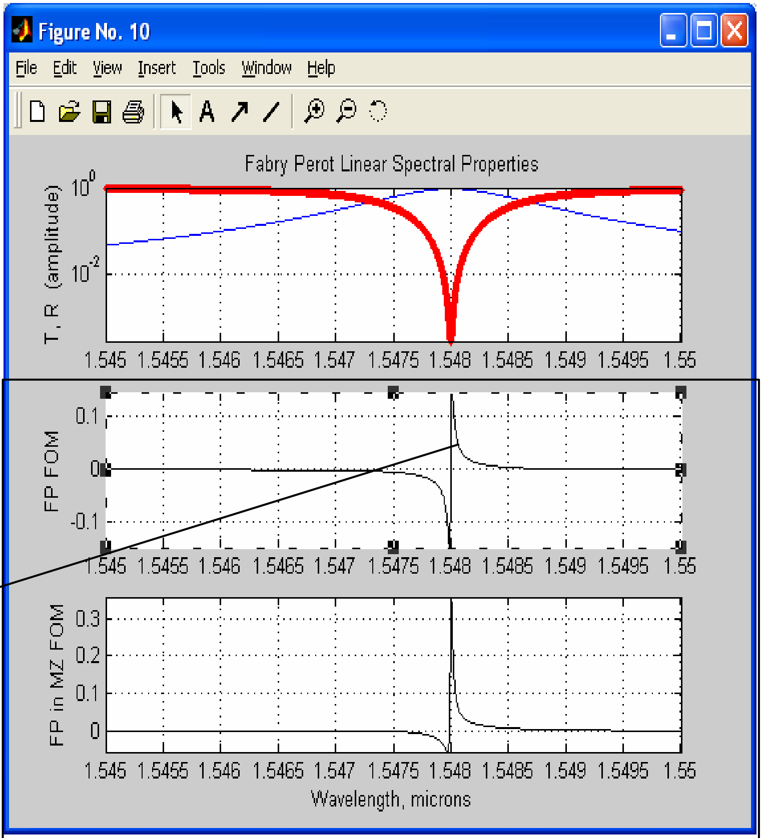
Parameters

lam	1.55	um
lam1	1.545	um
lam2	1.55	um
R1	0.945	
phi1	0	radians
R2	0.95	
phi2	0	radians
d	5.16	um
n	3	
alphadB	0	dB/um
T_lump	1	RT trans
Aeff	1	um^2
n2	1e-017	m^2/W
alpha2	0	m/W
Pmax	1	W
phi0	0	*pi
lambda_edge	1.47	um
Exb	0.003	ev
Lexw	0.004	um
E0	0.0065	ev
alpha_g	1.0e+004	dB/cm

“Materials Physics”



Cavity physics; predicted responsivity

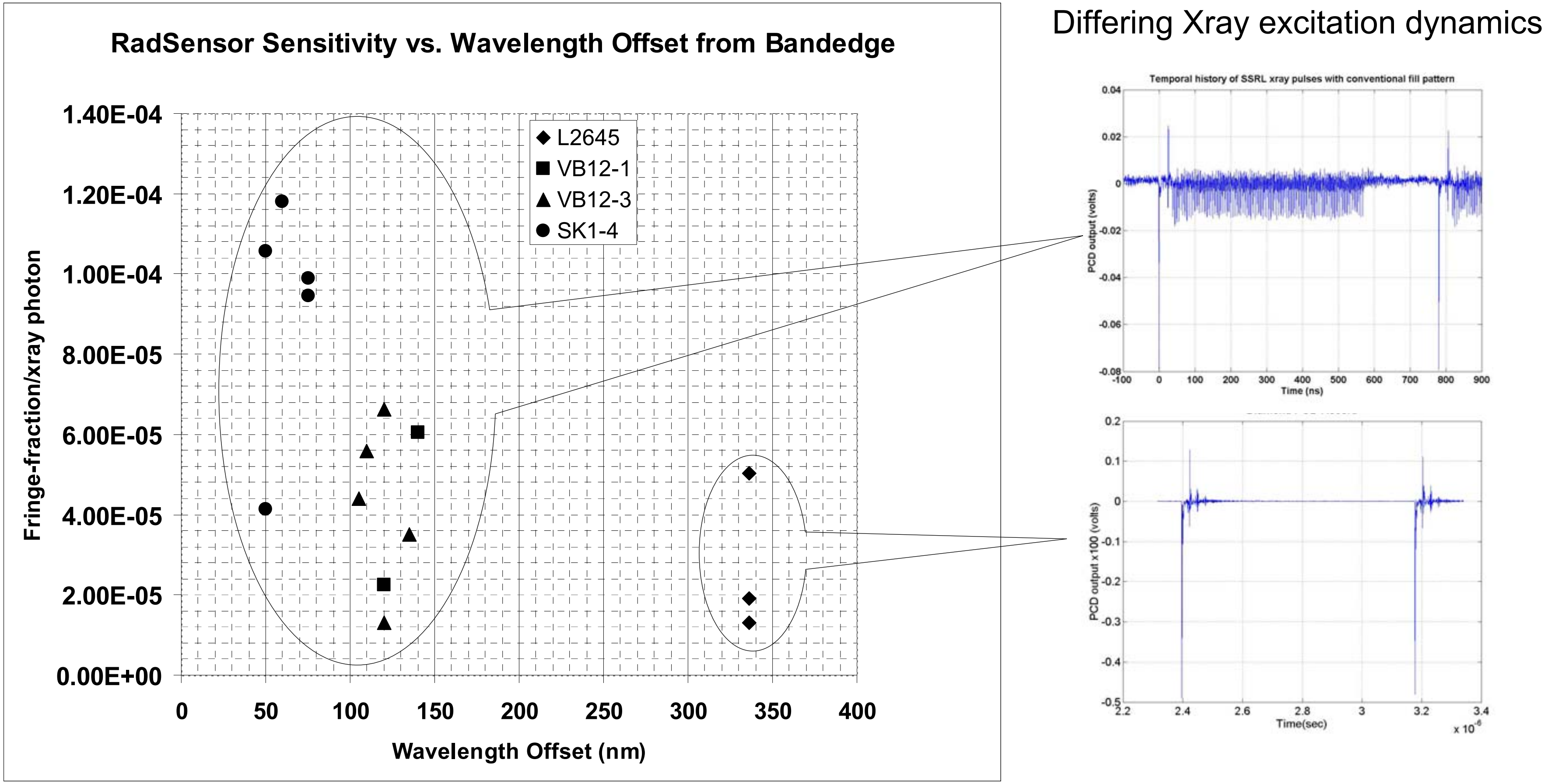


5% contrast for a single xray photon at 8 keV, this should be detectable

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

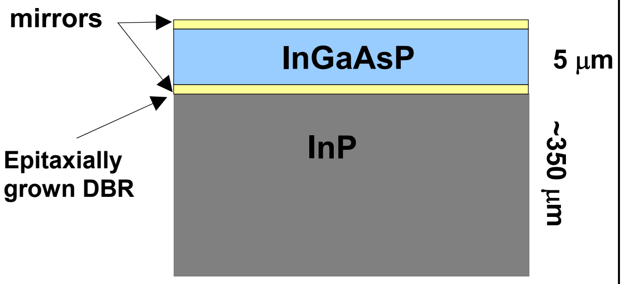


Differing Xray excitation dynamics

- 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



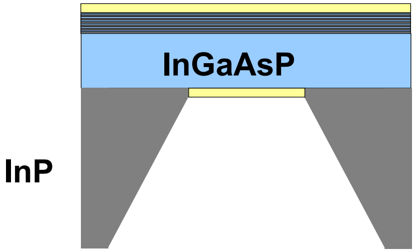
Pros:

- **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



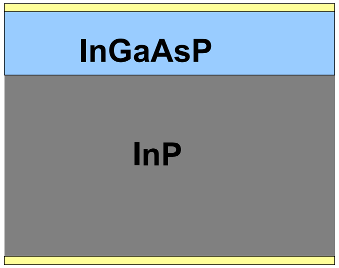
Pros:

- **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**

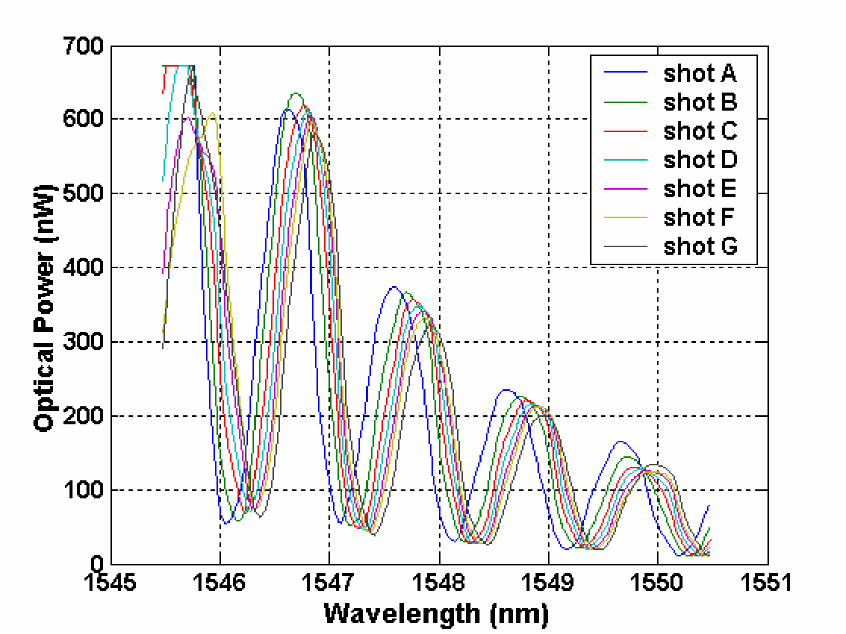
Cons:

- **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

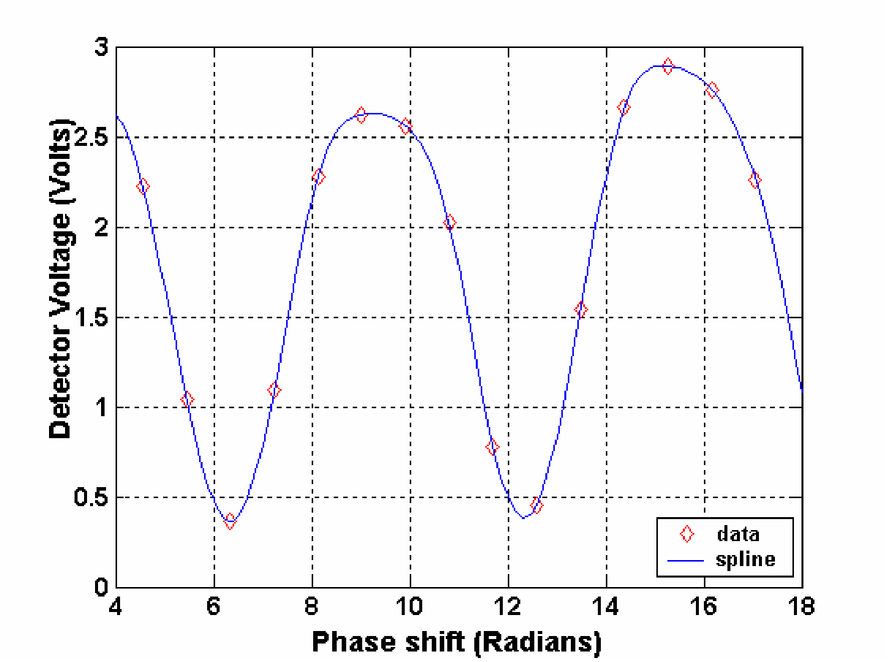


- Finesse is very poor (~1)
- Measured using ASE from EDFA
- Drift went away when optical input power was lowered to ~ 0 dBm
- We suspected this would be a problem– locking circuit not ready for this fielding… will be next time

Temporary cavity drift solution:

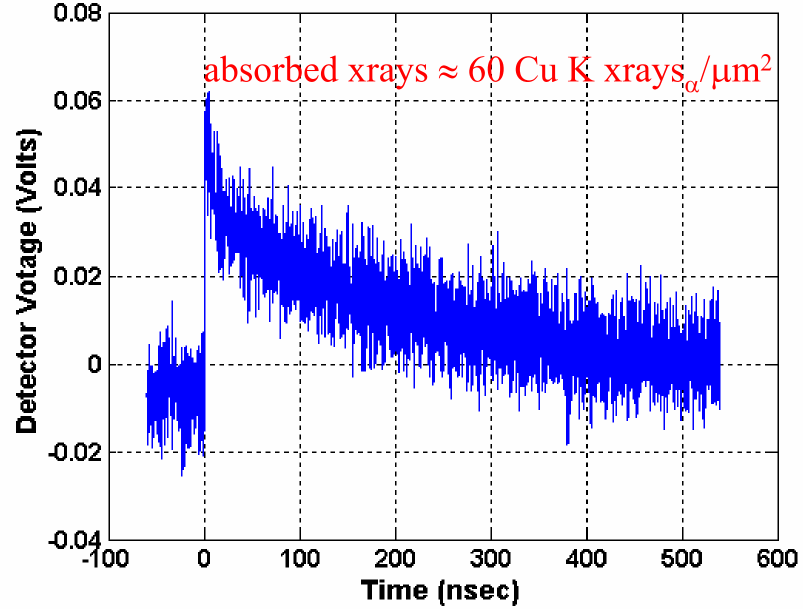
Map detector voltage vs. phase by varying wavelength and modulating light on/off – Optical receiver is ac-coupled

Detector Voltage (Volts) vs. Phase shift (Radians)



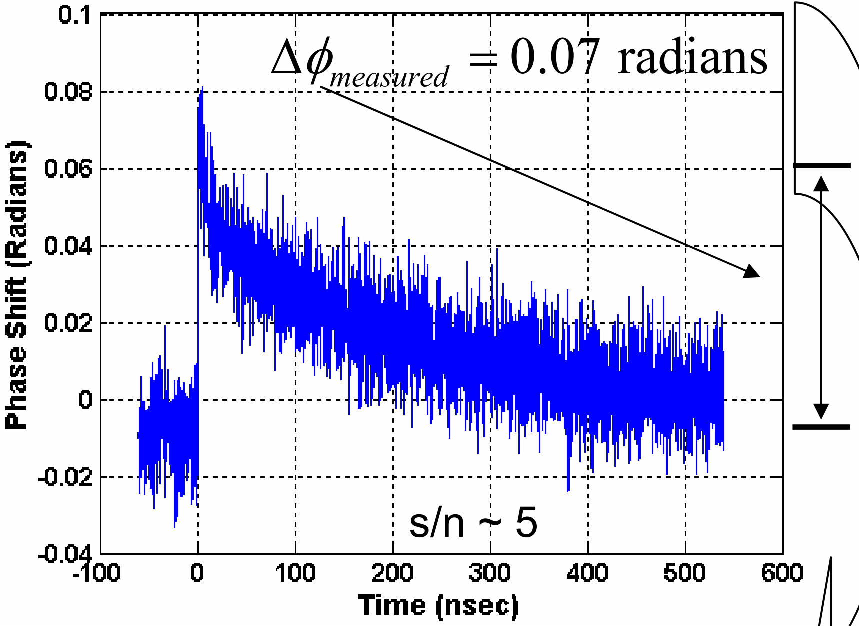
Typical Results Compared to Prediction from SSRL derived empirical constants

These data used Be and Cu filters to narrow xray spectrum



Detector Voltage

absorbed xrays ≈ 60 Cu K xrays$_\alpha$/μm^2



Optical Phase

$\Delta\phi_{measured} = 0.07$ radians

s/n ~ 5

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

$$= (60\ \text{xrays}/\mu\text{m}^2)\left(\frac{2\pi}{1.55\ \mu\text{m}}\right)\left(1.2\times10^{-6}\ \mu\text{m}^3\right)\left(\frac{8.05\ \text{keV}}{3.15\ \text{eV}}\right)(0.04) = 0.030\ \text{radians}$$

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