RESMIQ
Regroupement Stratégique
en Microsystèmes du Québec

SEMINAR

Wednesday, March 24th 2010 at 13h00

UQAM, President-Kennedy Bldg., Rm. Pk-4610

201, President-Kennedy av.

Progress in integrated optical sources and all-optical processing devices

Dominik Pudo

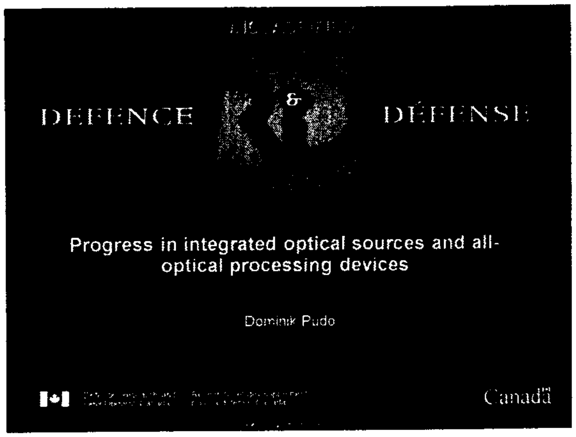
Defence research scientist, DRDC Valcartier

50 years after the invention of the first laser, the evolution of photonic technologies increasingly involves an inherent drive towards more compact, integrated, and energy-efficient solutions. Such miniaturization efforts allow them to be considered for applications in which size, weight and power constraints were so far a key limiting factor. This presentation will illustrate new advances in the development of compact optical technologies through two distinct examples.

The first part will focus on the development and demonstration of integrated optical clocks. These represent a critical enabling technology for frequency metrology and ultrafast sampling applications as they alleviate the need for a low noise electronic microwave driver. Moreover, integrating these devices effectively allows them to act as a reference clock in a variety of portable or low-footprint applications. Here compact fibre, and silica-waveguide lasers generating femtosecond pulses with GHz repetition rates are demonstrated.

The second example illustrates the concept of integrated all-optical signal processing, a fundamental building block for what is known as the vision of a photonic chip. Again, a key benefit of developing such a capability lies in the potential development of very compact, low optical power devices, in addition to paving the way towards increasingly sophisticated photonic processors. In this project, a silicon photonic crystal was used to provide slow-light enhanced reduction amplitude noise on a 10 Gbps data stream.

Dr. Dominik Pudo received the B.Eng. and Ph.D. degrees in electrical engineering from McGill University in 2003 and 2007 respectively under the supervision of Prof. Lawrence R. Chen. Initially, he focused on novel configurations of fibre lasers, following which he extensively studied the fundamentals and novel applications of the temporal Talbot effect in fibre optics. Applications involved clock recovery as well as the generation of high repetition rate pulse trains. Dr. Pudo was also a visiting researcher at the Universidad Politécnica de Valencia (Spain) further pursuing his theoretical analysis of noise and timing jitter mitigation in high speed data signals using the Talbot self-imaging effect. His experience with highly nonlinear fibres, as well as in integrated signal processing in photonic crystals, was acquired during his stay at the University of Sydney (Australia) in 2005 and 2008. Dr. Pudo completed his postdoctoral fellowship at the Massachusetts Institute of Technology (USA), working on integrated femtosecond lasers. Since 2009, he is working as a defence research scientist at DRDC Valcartier. He has published over thirty journal papers and conference proceeding articles and is the recipient of numerous fellowships and awards.



DEFENCE & DÉFENSE

Progress in integrated optical sources and all-optical processing devices

Dominik Pudo

Canadä

The big picture

Courtesy of the Centre for Ultrahigh-bandwidth Devices for Optical Systems. University of Sydney

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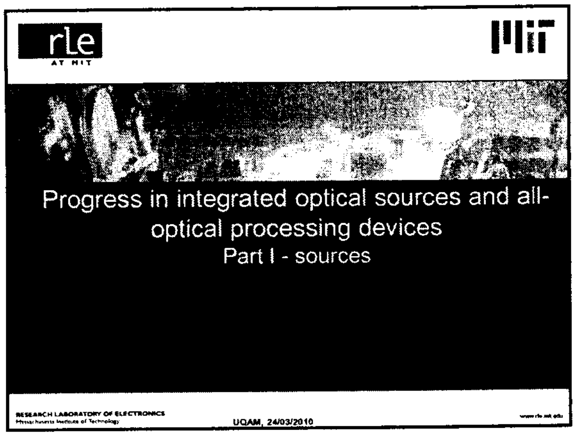


rle AT MIT

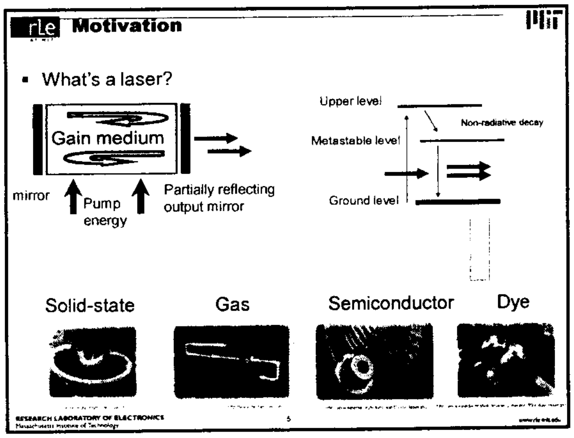
Progress in integrated optical sources and all-optical processing devices

Part I - sources

Outline

1. **Background and motivation**
2. Part I: Integrated optical laser clock
    1. Why?
    2. How?
    3. Results?
3. Part II: Integrated optical processing chip
    1. Why?
    2. How?
    3. Results?

Motivation

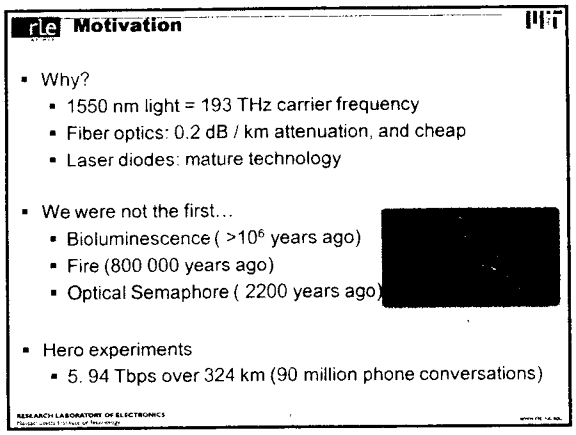


- What's a laser?

Solid-state Gas Semiconductor Dye

Motivation

- Photonics is more than data transmission…..



Motivation

- Why?
  - 1550 nm light = 193 THz carrier frequency
  - Fiber optics: 0.2 dB / km attenuation, and cheap
  - Laser diodes: mature technology
- We were not the first…
  - Bioluminescence ($>10^6$ years ago)
  - Fire (800 000 years ago)
  - Optical Semaphore (2200 years ago)
- Hero experiments
  - 5. 94 Tbps over 324 km (90 million phone conversations)

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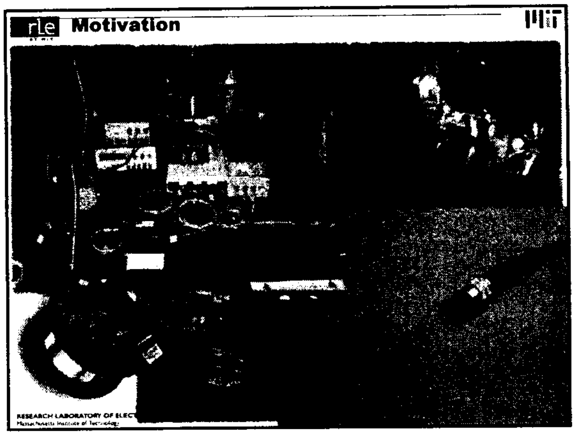
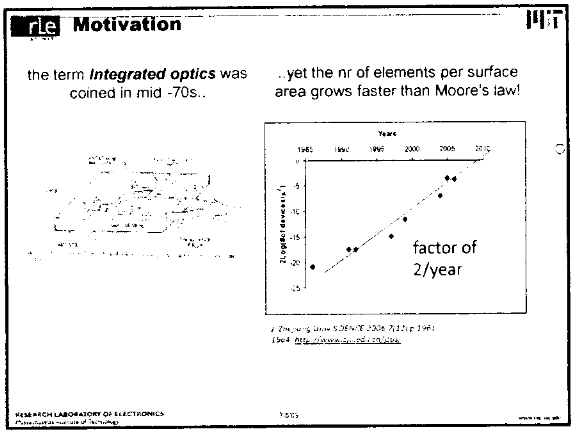


Motivation



Motivation

the term ***Integrated optics*** was coined in mid -70s..

..yet the nr of elements per surface area grows faster than Moore's law!

J. Zhejiang Univ SCIENCE 2006 7(12) p 1961 1964 http://www.zju.edu.cn/jzus

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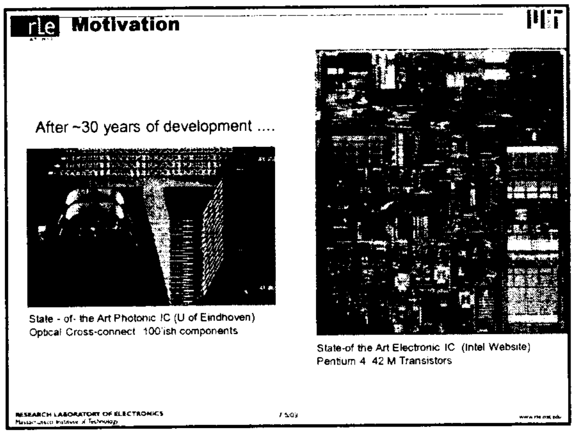

Motivation

After ~30 years of development ....

State - of- the Art Photonic IC (U of Eindhoven)
Optical Cross-connect 100'ish components

State-of the Art Electronic IC (Intel Website)
Pentium 4 42 M Transistors

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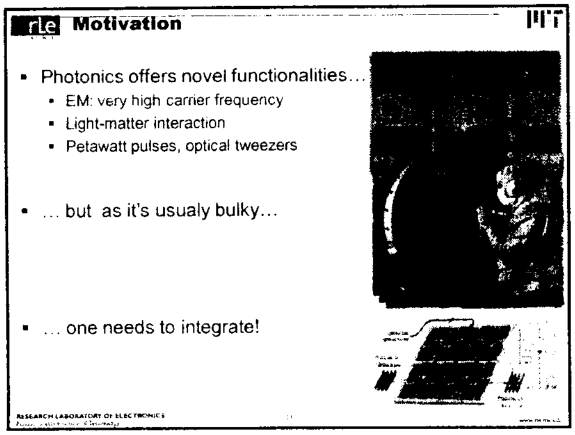

Motivation

- Photonics offers novel functionalities…
  - EM: very high carrier frequency
  - Light-matter interaction
  - Petawatt pulses, optical tweezers
- … but as it's usualy bulky…
- … one needs to integrate!

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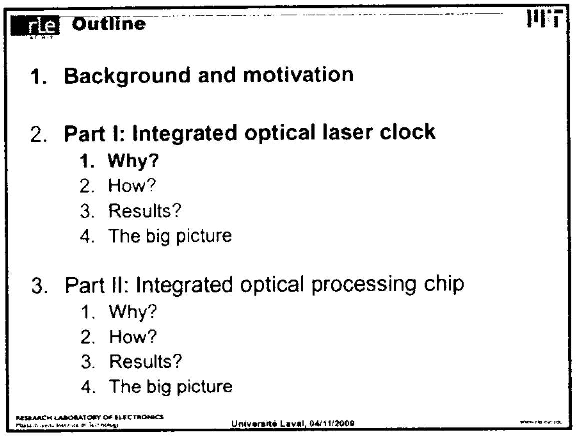

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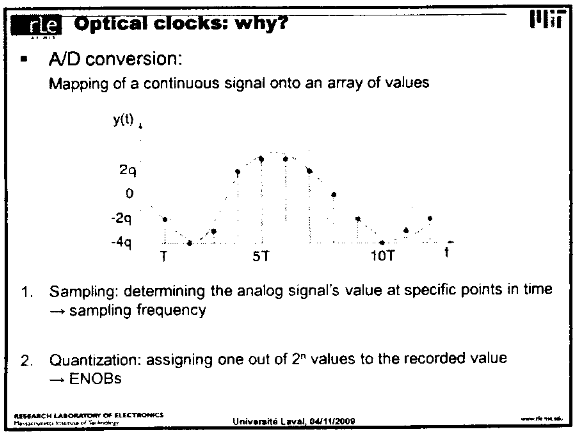
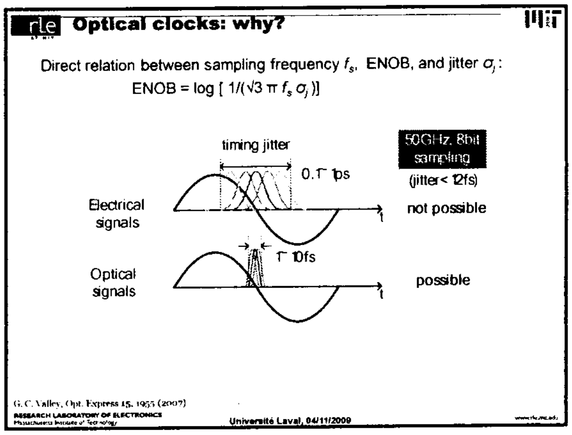


Optical clocks: why?

- A/D conversion:
  Mapping of a continuous signal onto an array of values

1. Sampling: determining the analog signal's value at specific points in time
   → sampling frequency

2. Quantization: assigning one out of 2^n values to the recorded value
   → ENOBs



Optical clocks: why?

Direct relation between sampling frequency f_s, ENOB, and jitter σ_j:

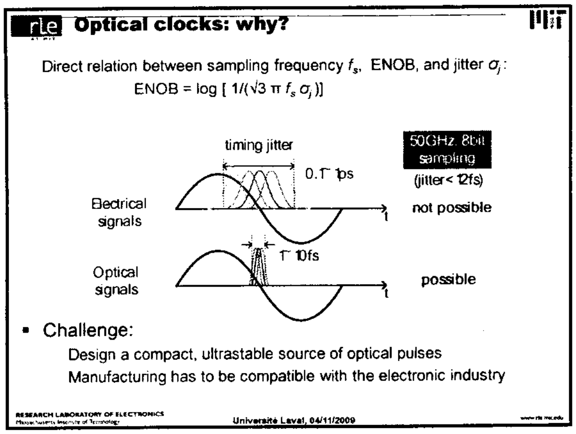
$$\text{ENOB} = \log [1/(\sqrt{3}\, \pi\, f_s\, \sigma_j)]$$

50GHz, 8bit sampling
(jitter< 12fs)

Electrical signals: not possible

Optical signals: possible

G. C. Valley, Opt. Express 15, 1955 (2007)



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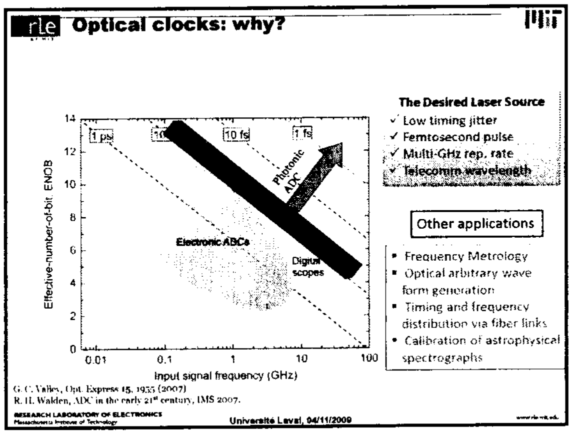
50GHz, 8bit sampling
(jitter< 12fs)

Electrical signals: not possible

Optical signals: possible

- Challenge:
  Design a compact, ultrastable source of optical pulses
  Manufacturing has to be compatible with the electronic industry

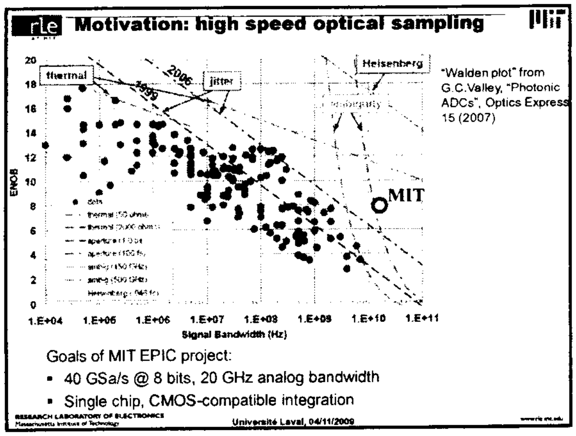


Optical clocks: why?

The Desired Laser Source
- ✓ Low timing jitter
- ✓ Femtosecond pulse
- ✓ Multi-GHz rep. rate
- ✓ Telecomm wavelength

Other applications
- Frequency Metrology
- Optical arbitrary wave form generation
- Timing and frequency distribution via fiber links
- Calibration of astrophysical spectrographs

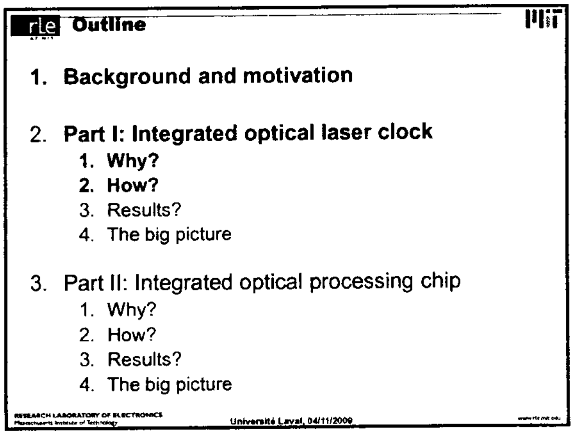
G. C. Valley, Opt. Express 15, 1955 (2007)
R. H. Walden, ADC in the early 21st century, IMS 2007.



Motivation: high speed optical sampling

"Walden plot" from G.C.Valley, "Photonic ADCs", Optics Express 15 (2007)

Goals of MIT EPIC project:
- 40 GSa/s @ 8 bits, 20 GHz analog bandwidth
- Single chip, CMOS-compatible integration



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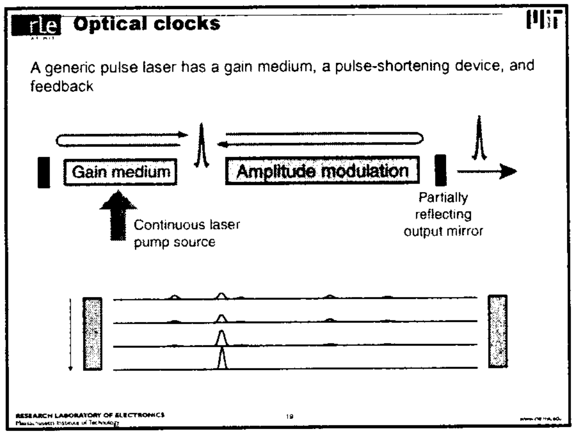
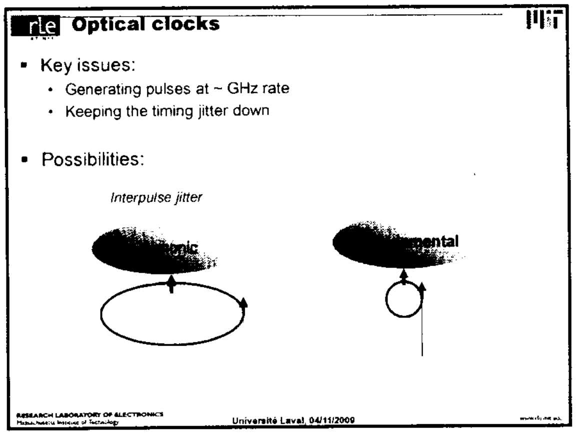


Optical clocks

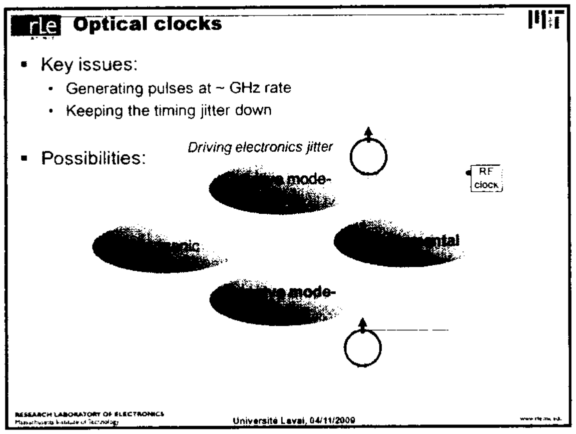
A generic pulse laser has a gain medium, a pulse-shortening device, and feedback



Optical clocks

- Key issues:
  - Generating pulses at ~ GHz rate
  - Keeping the timing jitter down
- Possibilities:

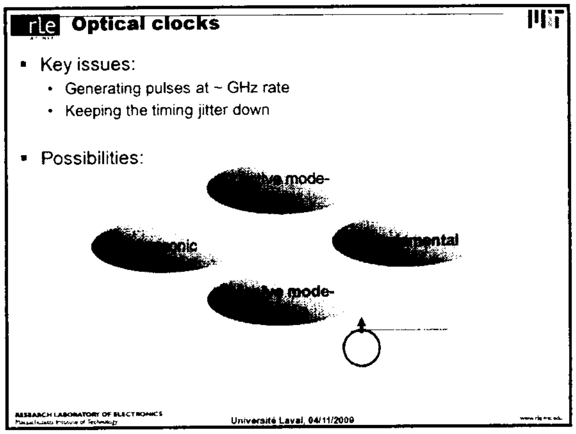
Interpulse jitter



Optical clocks

- Key issues:
  - Generating pulses at ~ GHz rate
  - Keeping the timing jitter down
- Possibilities:

Driving electronics jitter



Optical clocks

- Key issues:
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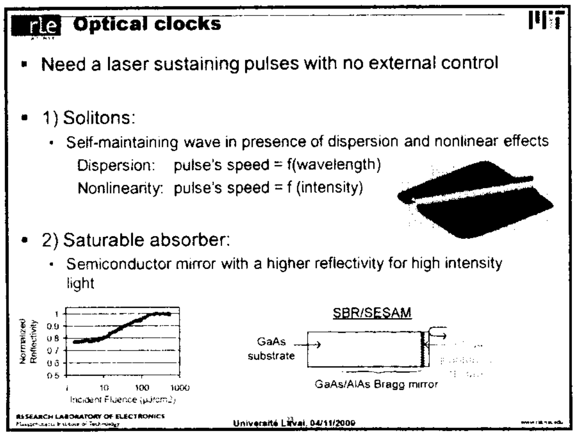
  - Keeping the timing jitter down
- Possibilities:

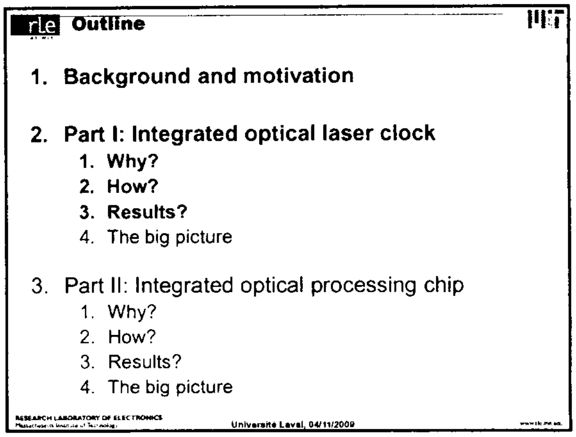


Optical clocks

- Need a laser sustaining pulses with no external control
- 1) Solitons:
  - Self-maintaining wave in presence of dispersion and nonlinear effects

    Dispersion: pulse's speed = f(wavelength)

    Nonlinearity: pulse's speed = f (intensity)
- 2) Saturable absorber:
  - Semiconductor mirror with a higher reflectivity for high intensity light



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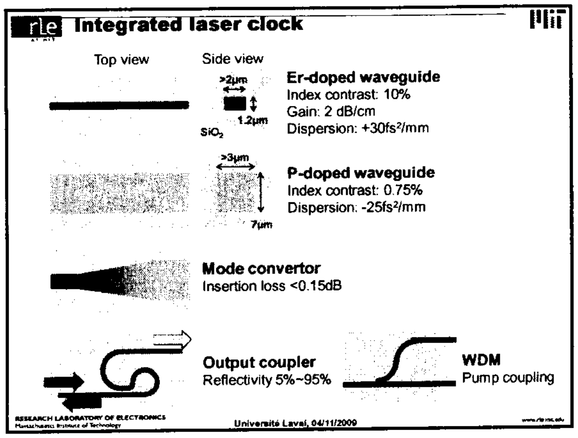

Integrated laser clock

Er-doped waveguide
Index contrast: 10%
Gain: 2 dB/cm
Dispersion: +30fs²/mm

P-doped waveguide
Index contrast: 0.75%
Dispersion: -25fs²/mm

Mode convertor
Insertion loss <0.15dB

Output coupler
Reflectivity 5%~95%

WDM
Pump coupling

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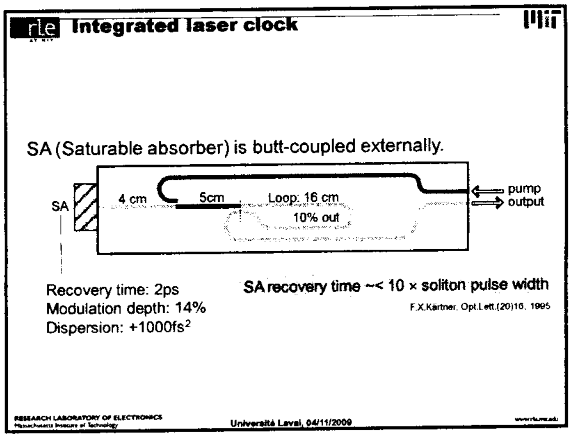

Integrated laser clock

SA (Saturable absorber) is butt-coupled externally.

Recovery time: 2ps
Modulation depth: 14%
Dispersion: +1000fs²

SA recovery time ~< 10 × soliton pulse width

F.X.Kärtner, Opt.Lett.(20)16, 1995

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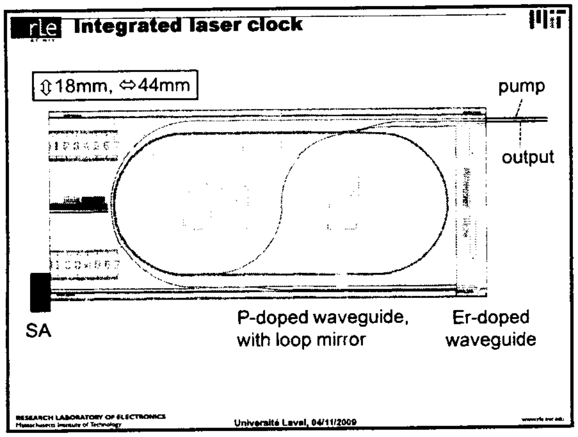

Integrated laser clock

⇕18mm, ⇔44mm

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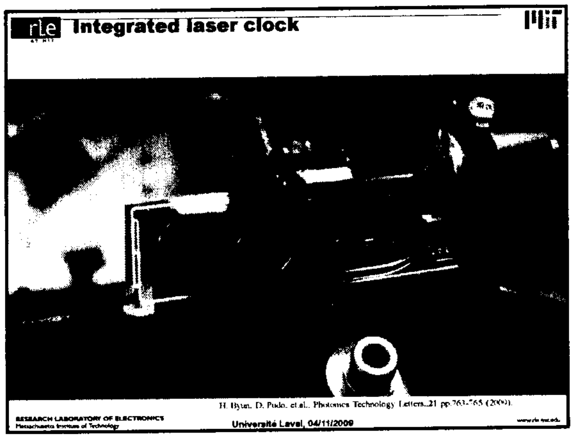

Integrated laser clock

H. Byun, D. Pudo, et.al., Photonics Technology Letters,21 pp.763-765 (2009).

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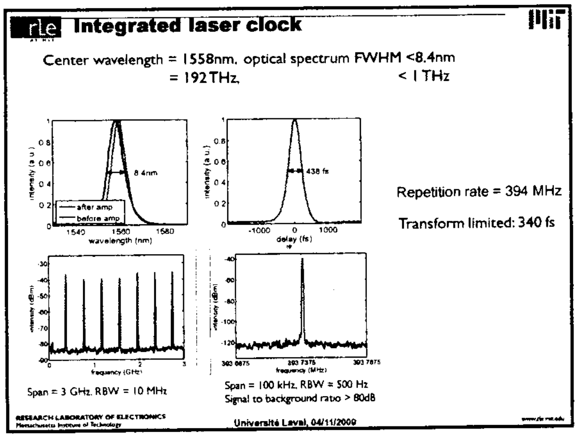

Integrated laser clock

Center wavelength = 1558nm, optical spectrum FWHM <8.4nm
= 192THz, < 1 THz

Repetition rate = 394 MHz

Transform limited: 340 fs

Span = 3 GHz, RBW = 10 MHz

Span = 100 kHz, RBW = 500 Hz
Signal to background ratio > 80dB

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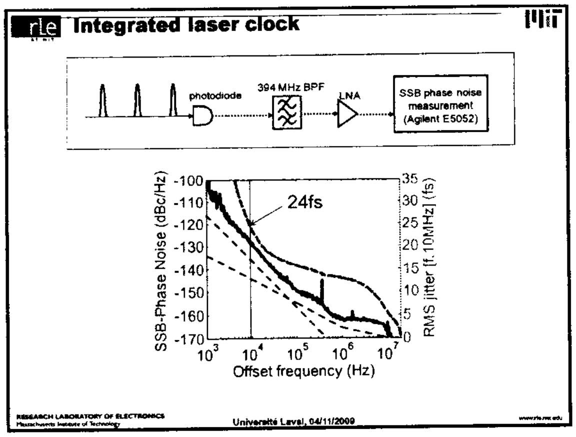

Integrated laser clock

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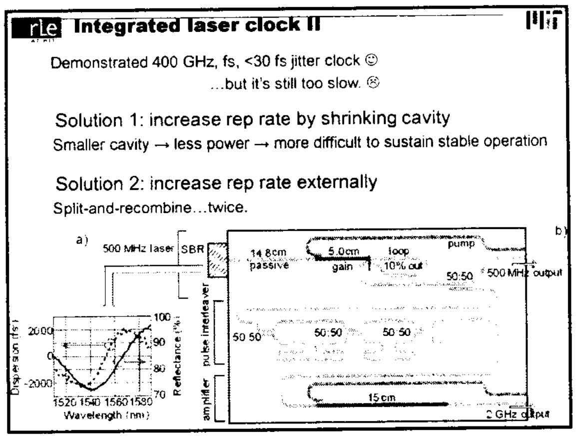
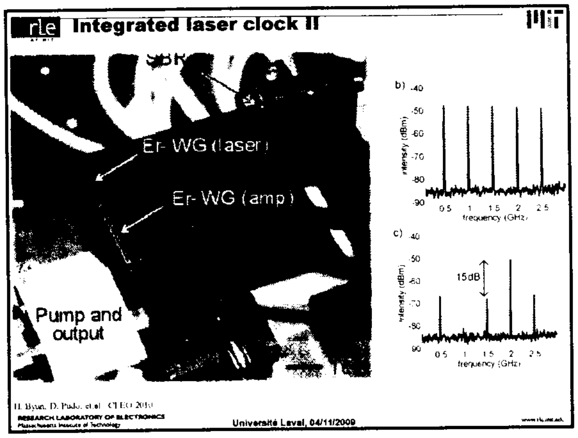


Integrated laser clock II

Demonstrated 400 GHz, fs, <30 fs jitter clock ☺
...but it's still too slow. ☹

Solution 1: increase rep rate by shrinking cavity
Smaller cavity → less power → more difficult to sustain stable operation

Solution 2: increase rep rate externally
Split-and-recombine...twice.



Integrated laser clock II

H. Byun, D. Pudo, et al. CLEO 2010

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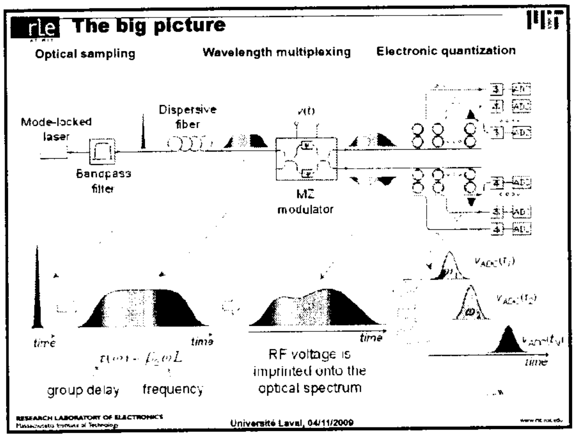

The big picture

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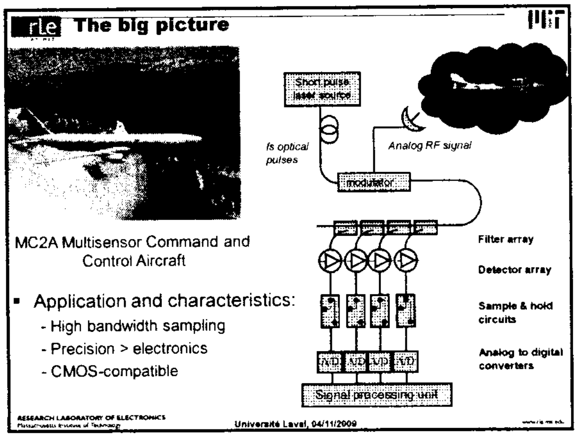

The big picture

MC2A Multisensor Command and Control Aircraft

- Application and characteristics:
  - High bandwidth sampling
  - Precision > electronics
  - CMOS-compatible

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The big picture

- Stable short pulse optical sources are key for next gen. sampling
  - femtosecond timing jitter required
  - Repetition rates above a GHz
- CMOS compatibility needed for low cost
  - Limits the host glass and materials
  - Benefits from the maturity of semiconductor industry
  - Integration required for robustness

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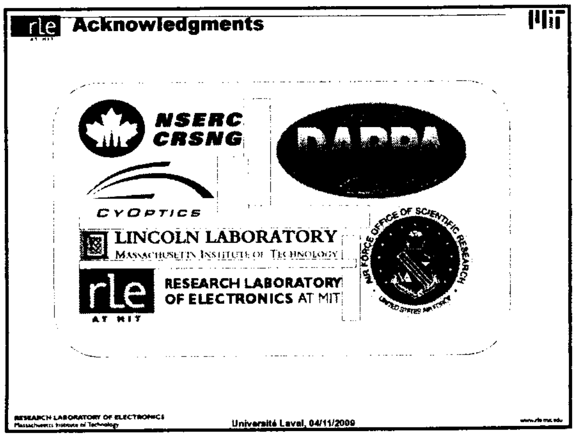

Acknowledgments

NSERC
CRSNG

DARPA

CYOPTICS

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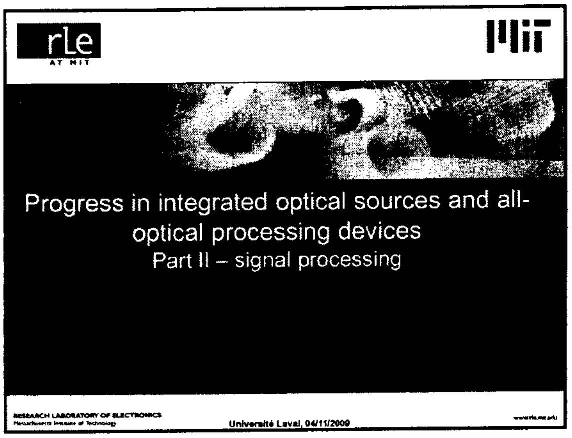

Progress in integrated optical sources and all-optical processing devices

Part II – signal processing

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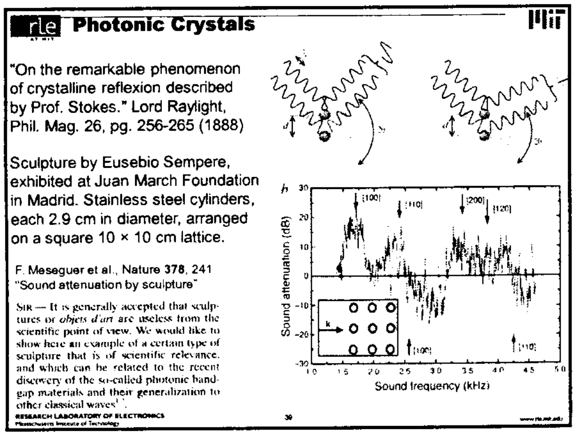

Photonic Crystals

"On the remarkable phenomenon of crystalline reflexion described by Prof. Stokes." Lord Raylight, Phil. Mag. 26, pg. 256-265 (1888)

Sculpture by Eusebio Sempere, exhibited at Juan March Foundation in Madrid. Stainless steel cylinders, each 2.9 cm in diameter, arranged on a square 10 × 10 cm lattice.

F. Meseguer et al., Nature **378**, 241
"Sound attenuation by sculpture"

SIR — It is generally accepted that sculptures or *objets d'art* are useless from the scientific point of view. We would like to show here an example of a certain type of sculpture that is of scientific relevance, and which can be related to the recent discovery of the so-called photonic band-gap materials and their generalization to other classical waves[1].

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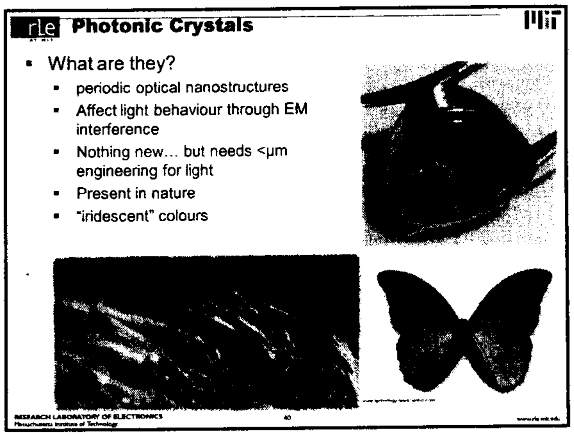

Photonic Crystals

- What are they?
  - periodic optical nanostructures
  - Affect light behaviour through EM interference
  - Nothing new… but needs <μm engineering for light
  - Present in nature
  - "iridescent" colours

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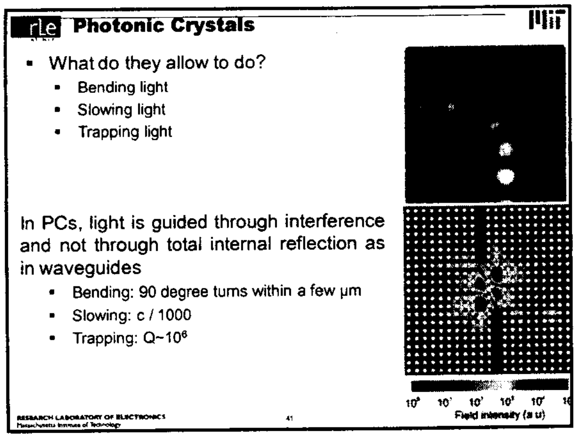

Photonic Crystals

- What do they allow to do?
  - Bending light
  - Slowing light
  - Trapping light

In PCs, light is guided through interference and not through total internal reflection as in waveguides

- Bending: 90 degree turns within a few μm
- Slowing: c / 1000
- Trapping: Q~10^6

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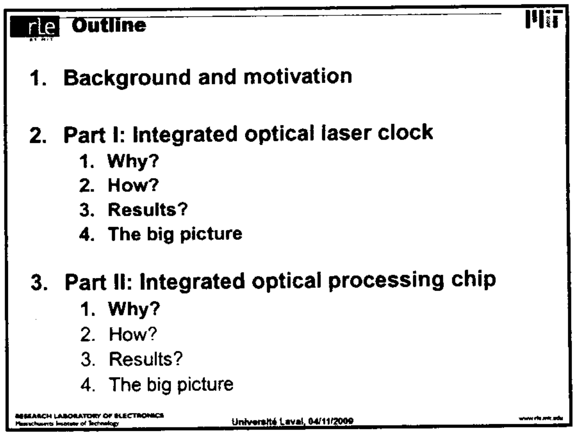

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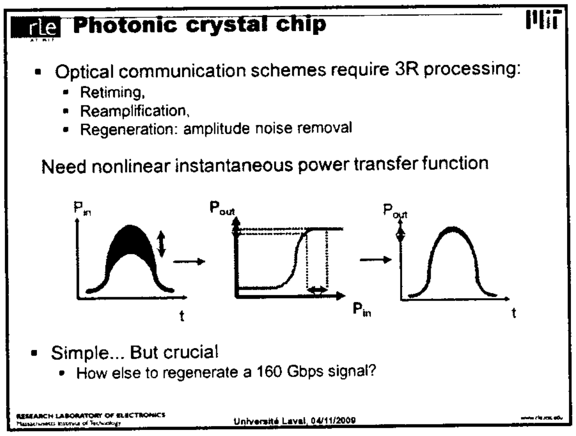
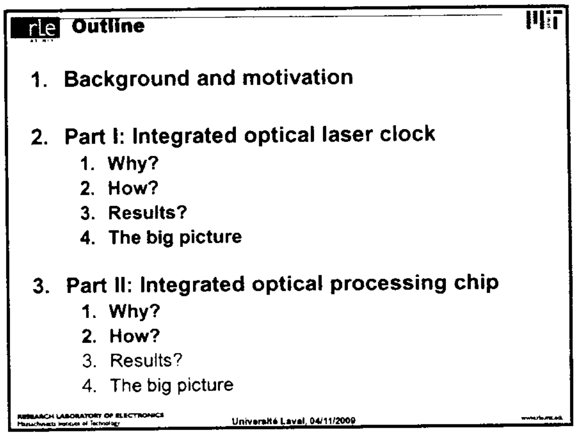


Photonic crystal chip

- Optical communication schemes require 3R processing:
  - Retiming,
  - Reamplification,
  - Regeneration: amplitude noise removal

Need nonlinear instantaneous power transfer function

- Simple... But crucial
  - How else to regenerate a 160 Gbps signal?



Outline

1. Background and motivation
2. Part I: Integrated optical laser clock
   1. Why?
   2. How?
   3. Results?
   4. The big picture
3. Part II: Integrated optical processing chip
   1. Why?
   2. How?
   3. Results?
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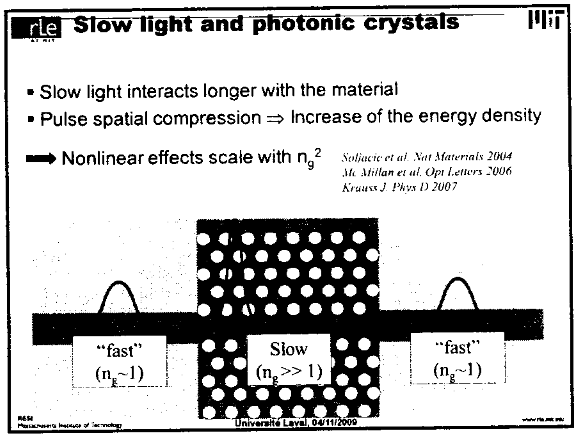
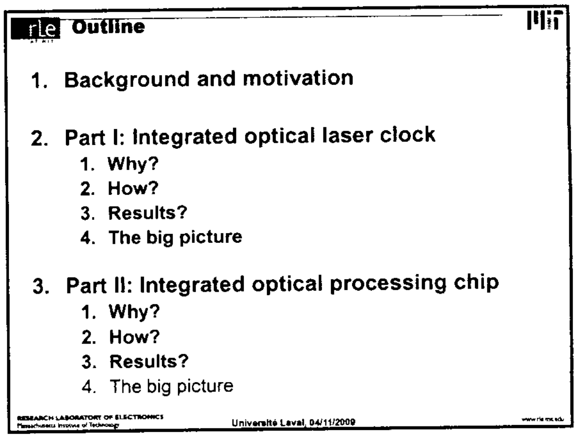


Slow light and photonic crystals

- Slow light interacts longer with the material
- Pulse spatial compression ⇒ Increase of the energy density

➡ Nonlinear effects scale with n_g^2

Soljacic et al. Nat Materials 2004
Mc Millan et al. Opt Letters 2006
Krauss J. Phys D 2007



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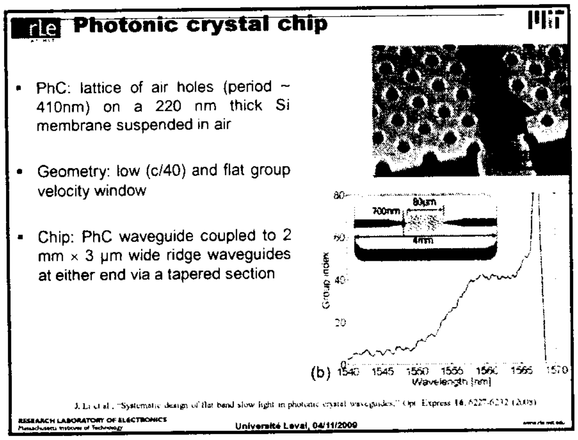
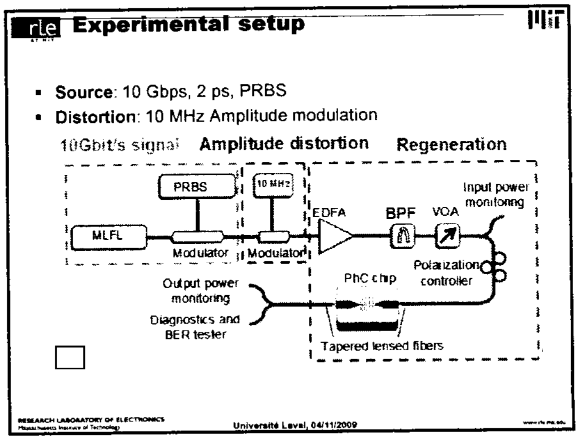


Photonic crystal chip

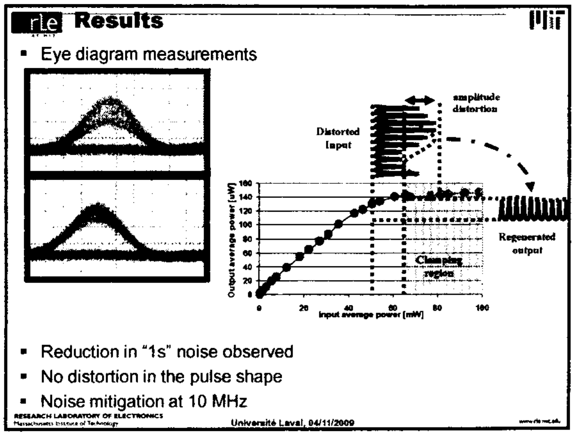
- PhC: lattice of air holes (period ~ 410nm) on a 220 nm thick Si membrane suspended in air
- Geometry: low (c/40) and flat group velocity window
- Chip: PhC waveguide coupled to 2 mm × 3 μm wide ridge waveguides at either end via a tapered section

J. Li et al., "Systematic design of flat band slow light in photonic crystal waveguides," Opt. Express 16, 6227-6232 (2008)



Experimental setup

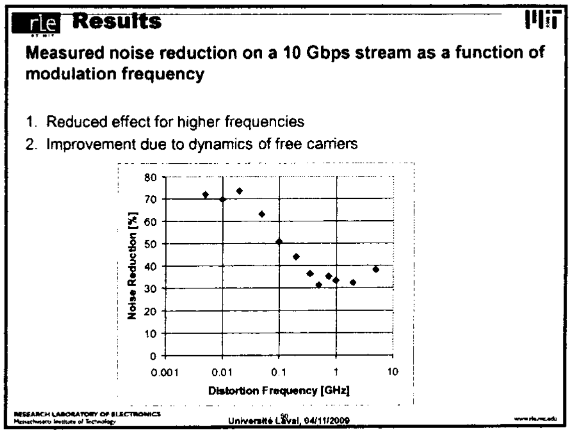
- **Source**: 10 Gbps, 2 ps, PRBS
- **Distortion**: 10 MHz Amplitude modulation



Results

- Eye diagram measurements

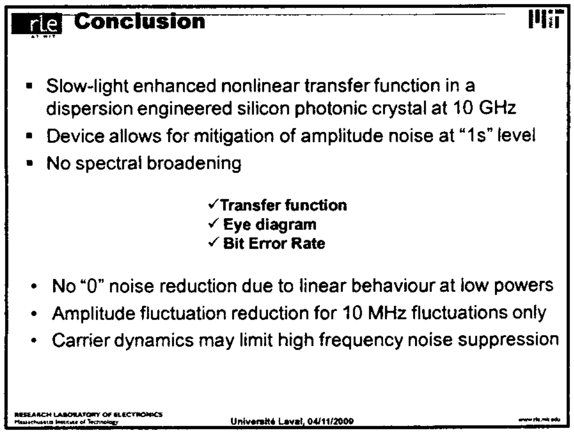
- Reduction in “1s” noise observed
- No distortion in the pulse shape
- Noise mitigation at 10 MHz



Results

Measured noise reduction on a 10 Gbps stream as a function of modulation frequency

1. Reduced effect for higher frequencies
2. Improvement due to dynamics of free carriers

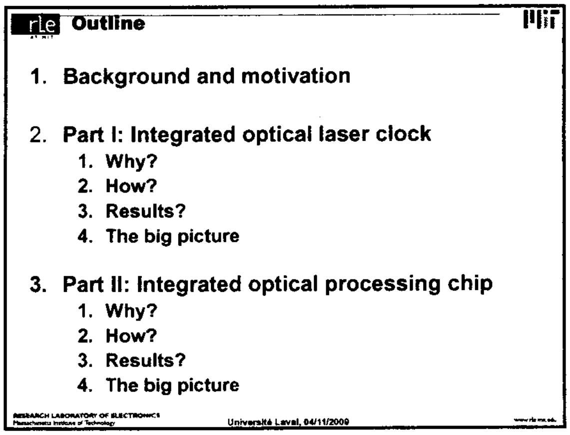


Conclusion

- Slow-light enhanced nonlinear transfer function in a dispersion engineered silicon photonic crystal at 10 GHz
- Device allows for mitigation of amplitude noise at “1s” level
- No spectral broadening

✓Transfer function
✓ Eye diagram
✓ Bit Error Rate

- No “0” noise reduction due to linear behaviour at low powers
- Amplitude fluctuation reduction for 10 MHz fluctuations only
- Carrier dynamics may limit high frequency noise suppression



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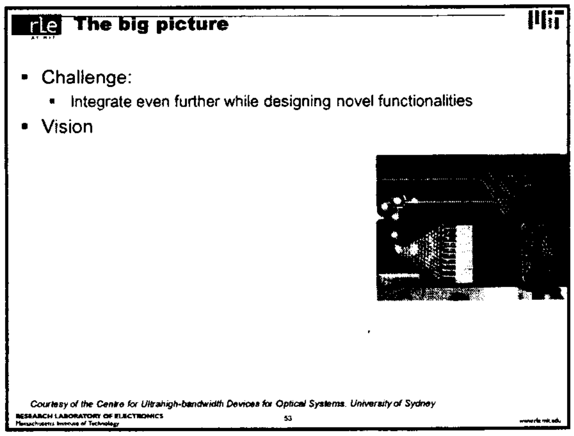
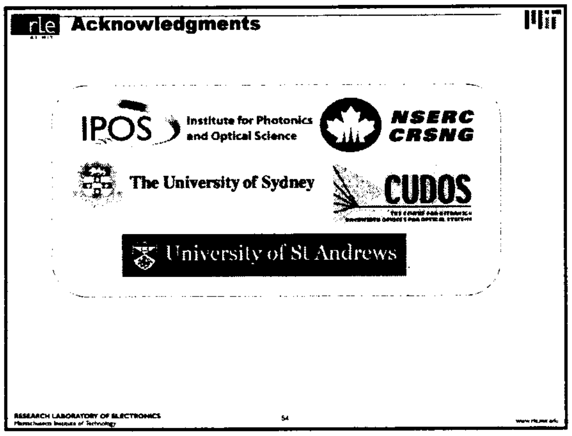


The big picture

- Challenge:
    - Integrate even further while designing novel functionalities
- Vision

Courtesy of the Centre for Ultrahigh-bandwidth Devices for Optical Systems, University of Sydney



Acknowledgments

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CUDOS
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