PHOTONICS RESEARCH GROUP

NONLINEAR OPTICS IN A-SI-ON-INSULATOR AND INGAP-ON-INSULATOR WAVEGUIDE CIRCUITS

Utsav D. Dave

GHENT UNIVERSITY

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NONLINEAR OPTICS IN <SOMETHING…> AND <SOMETHING…> <SOMETHING…>

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NONLINEAR OPTICS IN <MATERIAL PLATFORM 1> AND <MATERIAL PLATFORM 2> <SOMETHING…>

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NONLINEAR OPTICS IN <MATERIAL PLATFORM 1> AND <MATERIAL PLATFORM 2>

<DEVICE/SYSTEMS>

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NONLINEAR OPTICS IN <MATERIAL PLATFORM 1> AND <MATERIAL PLATFORM 2> <DEVICE/SYSTEMS>

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NONLINEAR OPTICS IN A-SI-ON-INSULATOR AND INGAP-ON-INSULATOR

<DEVICE/SYSTEMS>

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- **Photonics Research Group** (INTEC, Ugent) and the ERC grants MIRACLE and InSpectra grants for financial support
- **LPN**, Paris for collaboration in processing of the InGaP waveguide circuits
- **ULB**, Brussels for collaboration in nonlinear experiments in InGaP waveguide circuits
- **Thales**, Paris, for providing the III-V material as well as providing feedback for nonlinear experimental results

OUTLINE

1. Nonlinear optics
2. … in a-Si:H-on-insulator platform
3. … in InGaP-on-insulator platform
4. Future perspectives

1. Nonlinear optics

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OUTLINE

1. Nonlinear optics

   1.1 What is it?

   1.2 Historical developments

   1.3 SOI platform

2. … in a-Si:H-on-insulator platform

3. … in InGaP-on-insulator platform

4. Future perspectives

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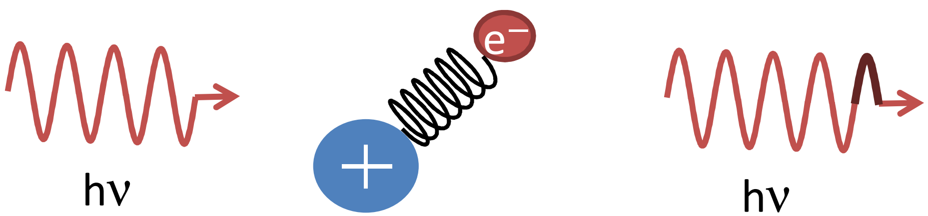
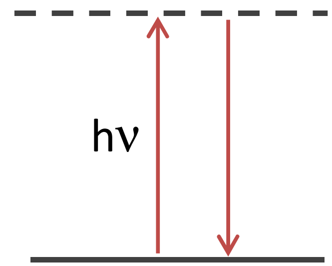
1.1 What is it?

THE *LINEAR* RESPONSE TO LIGHT

Atom-light interaction



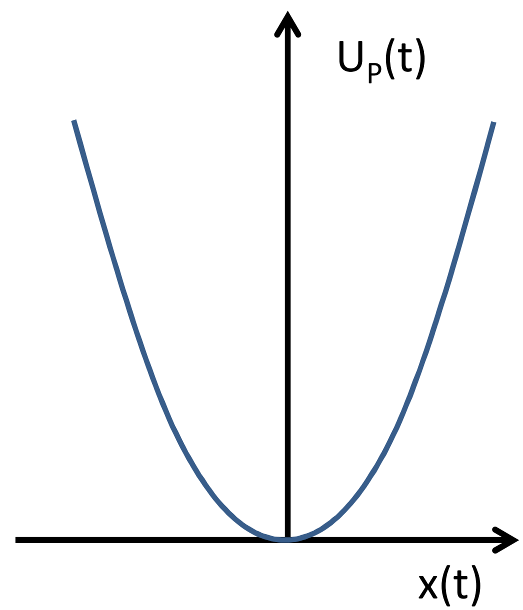


Refractive index: phase delay

$$m\frac{d^2}{dt^2}\mathrm{x}(t)+m\gamma\frac{d}{dt}\mathrm{x}(t)+m\omega_0^2\,\mathrm{x}(t)=-eE\cos(\omega t)$$

Total Force   Damping term   "Spring" term   Driving term

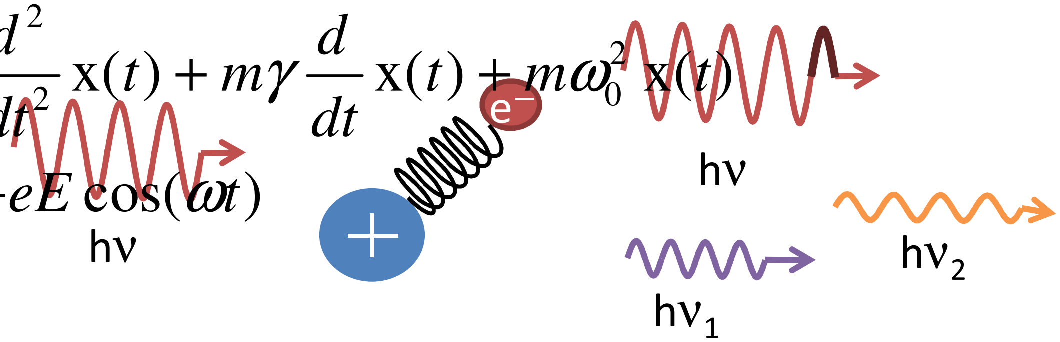
$$P(\mathrm{t})=-eNx(t) \qquad U_P(\mathrm{t})=\frac{1}{2}m\omega_0^2x^2(t)$$

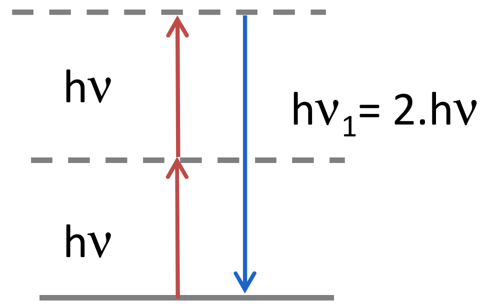


THE *NONLINEAR* RESPONSE TO LIGHT

Nonlinear response of dielectric materials

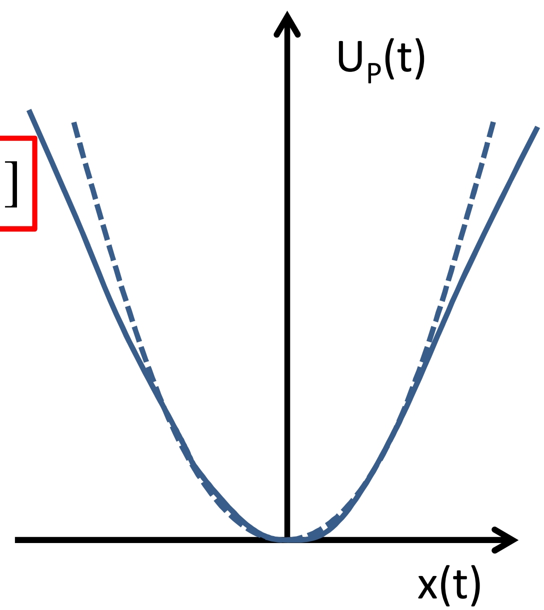
$$m\frac{d^2}{dt^2}x(t) + m\gamma\frac{d}{dt}x(t) + m\omega_0^2 x(t) = -eE\cos(\omega t)$$





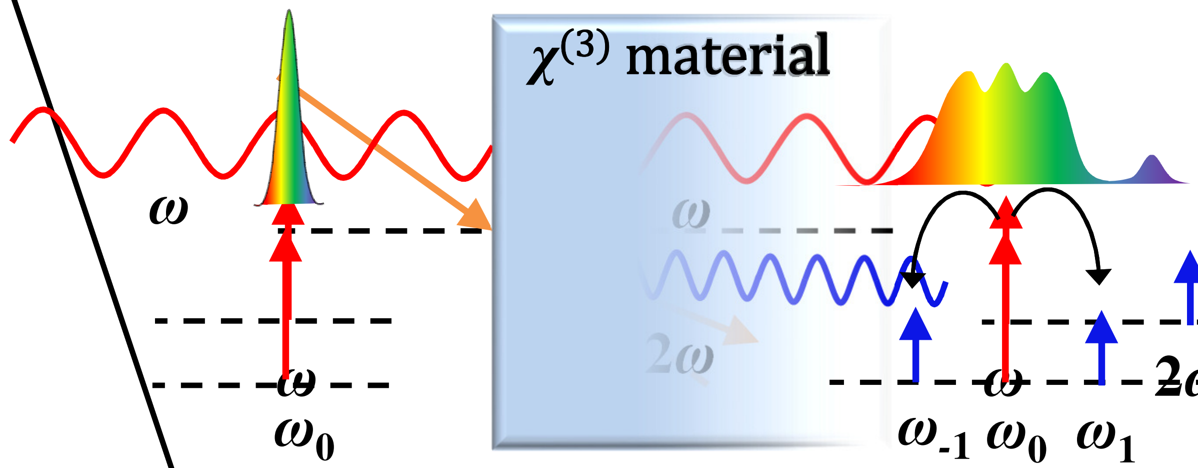
$$m\frac{d^2}{dt^2}x(t) + m\gamma\frac{d}{dt}x(t) + [m\omega_0^2 x(t) + bx^2(t) + cx^3(t) + \ldots] = -eE\cos(\omega t)$$

Nonlinear terms of 2nd, 3rd order…



DIFFERENT NONLINEAR PROCESSES

$$P = \chi^{(1)}E + \chi^{(2)}EE + \chi^{(3)}EEE + \dots$$



Linear optics:
Refractive index

Second-order effects:
- **Electro-optic effect**
- **Sum/difference frequency generation**

Third-order effects:
- **Self-phase modulation**
- **Supercontinuum generation**
- **Four-wave mixing**

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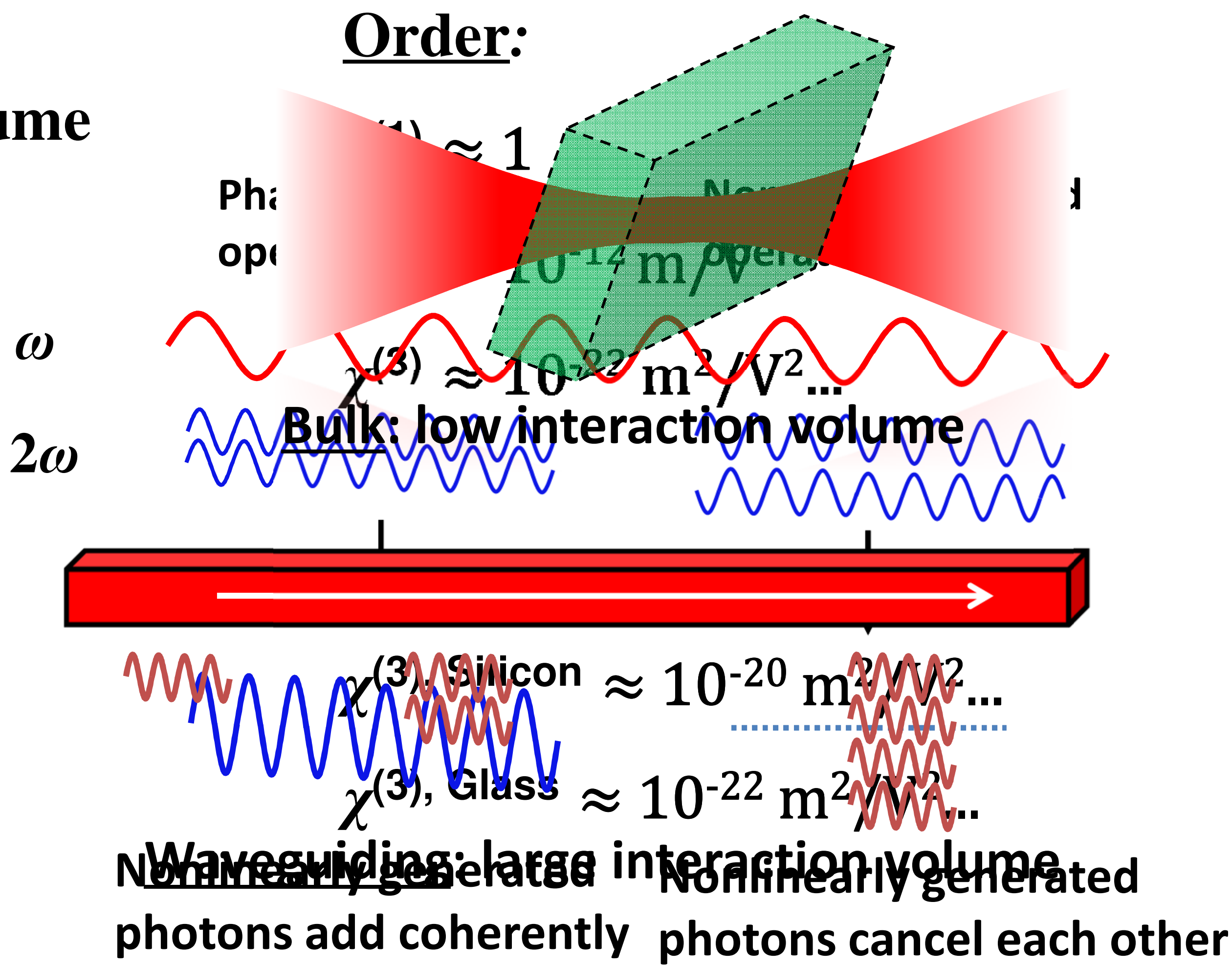
THE EFFICIENCY OF NONLINEAR PROCESSES

1. **The strength of the nonlinear response**
2. **Light intensity**
3. **Interaction volume**
4. **Phasematching**



OUTLINE

1. Nonlinear optics

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   1.3 SOI platform

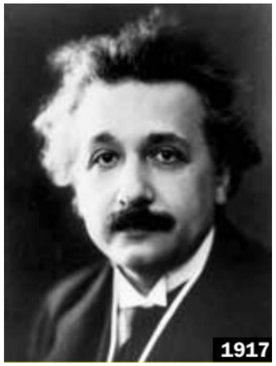
2. … in a-Si:H-on-insulator platform

3. … in InGaP-on-insulator platform

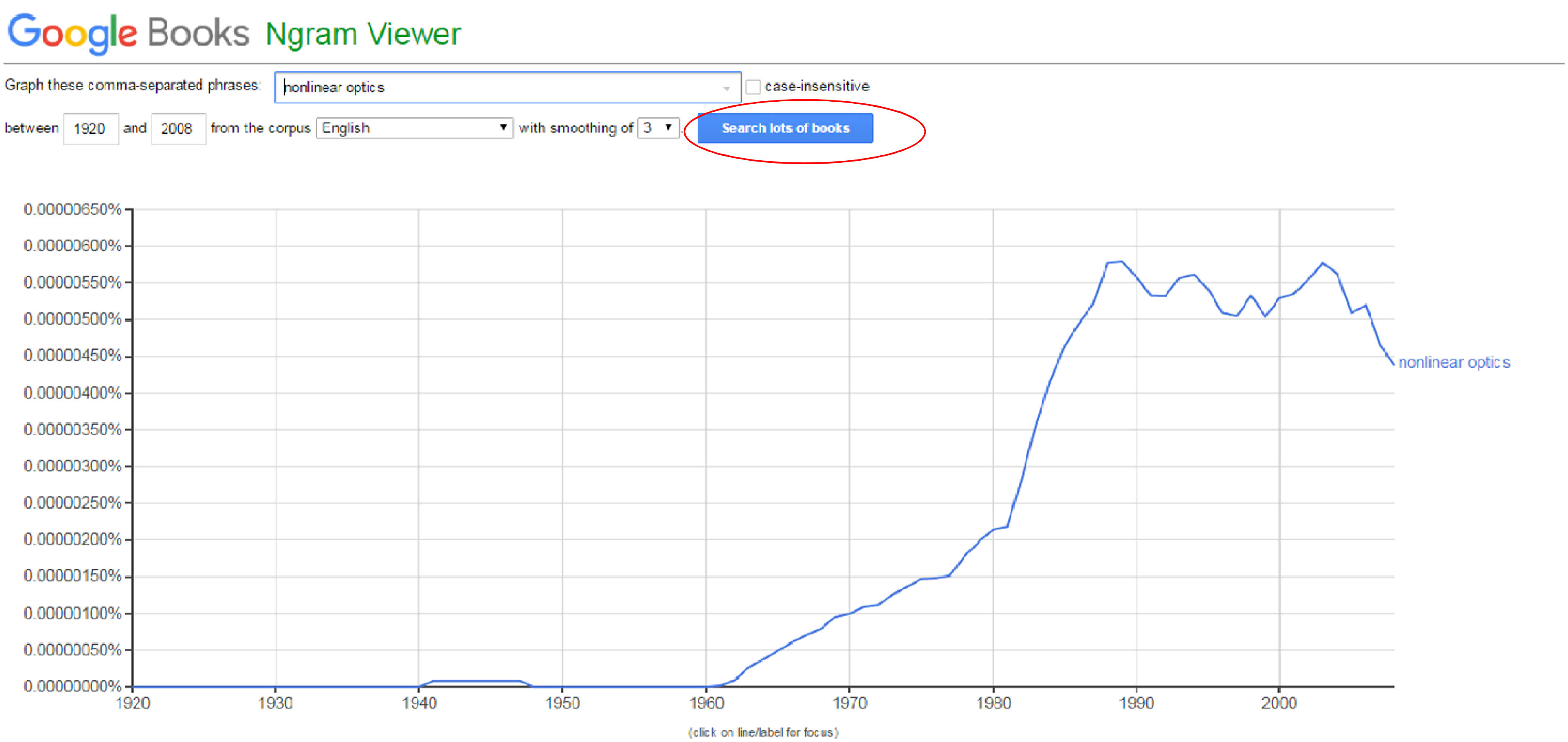
4. Future perspectives

1.2 HISTORICAL DEVELOPMENTS

<u>1917</u>: Einstein's theory on stimulated emission



Google Ngram Viewer



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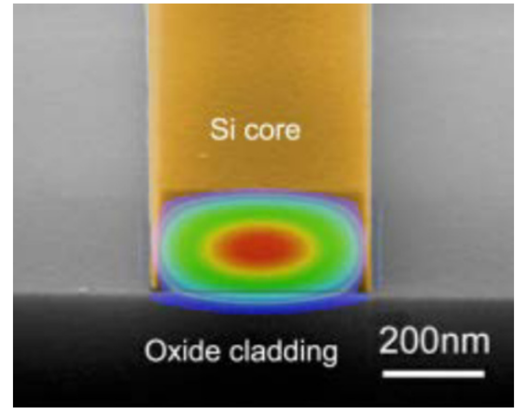
1.3 SOI PLATFORM

NONLINEARITY OF THE SOI PLATFORM

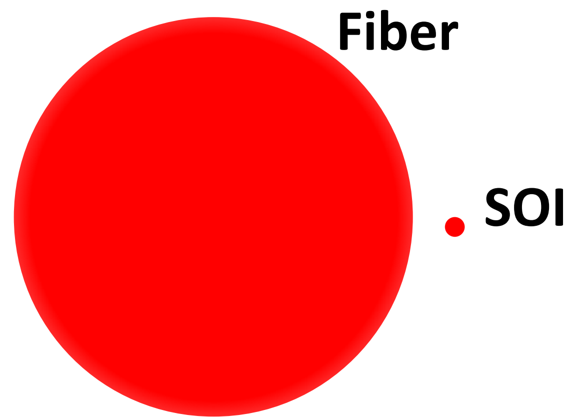
- Silicon-on-insulator (SOI)



- SOI vs SMF-28 fibers as a nonlinear platform

- **$\chi^{(3)}$ (x 100 silica)**
- **Effective area (/ 1000)**

➡ **$\gamma_{SOI} = \gamma_{fiber}$ x 100000 !**



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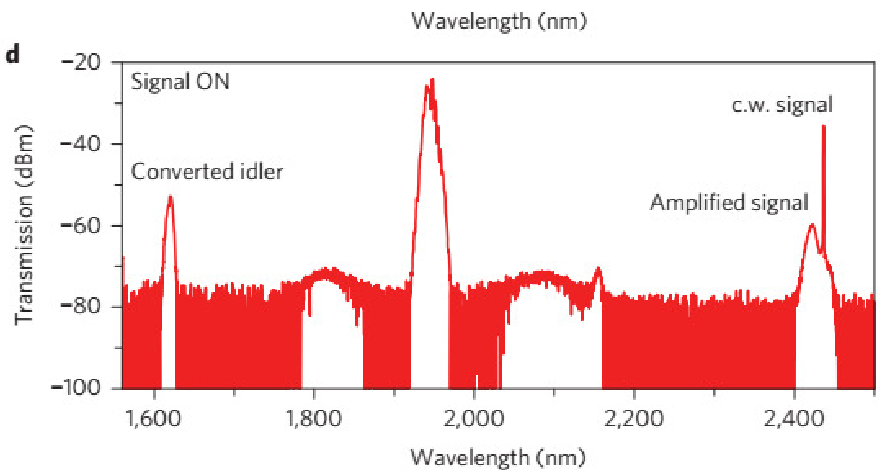
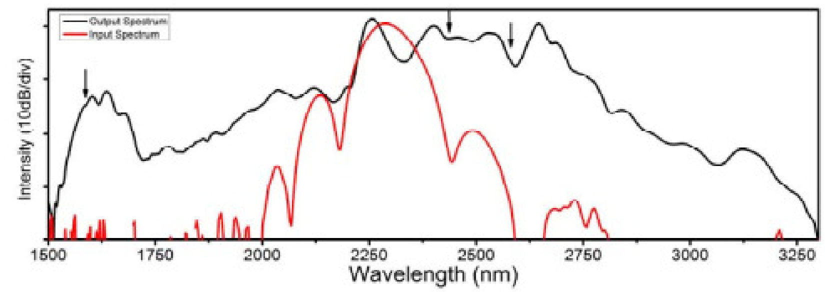
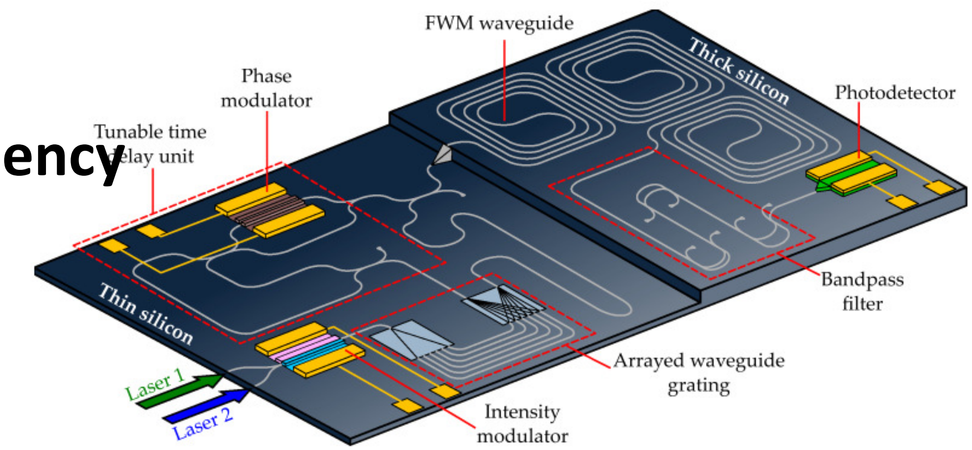
NONLINEAR PROCESSES IN SOI PLATFORM

Going to the mid-infrared

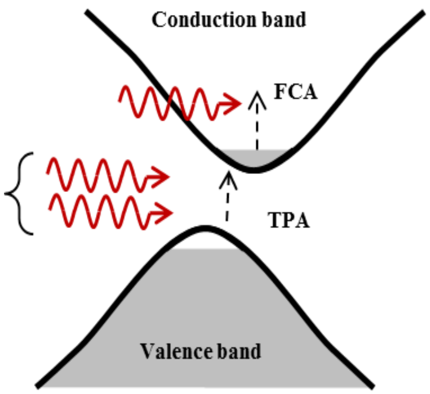




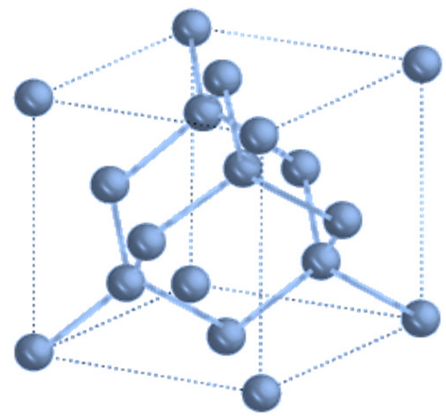
Microwave frequency measurement



DEFICIENCIES OF SOI AS A NONLINEAR PLATFORM



(a) Nonlinear losses > nonlinear gain



(b) Centrosymmetry => $\chi^{(2)} = 0$

<u>Solutions</u>?

(1) Work beyond TPA wavelength, sweep out carriers, ultrashort pulses…

(2) <u>Other materials</u>: large bandgap materials

(1) Strain/surface $\chi^{(2)} = 0$

(2) <u>Other materials</u>: non-centrosymmetric crystal structure

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OUTLINE

1. Nonlinear optics
2. … in a-Si:H-on-insulator platform
3. … in InGaP-on-insulator platform
4. Future perspectives

2. NLO in a-Si-on-insulator platform

Outline

1. Nonlinear optics

2. … in a-Si:H-on-insulator platform
   - 2.1 Why amorphous silicon?
   - 2.2 Nonlinear loss measurement
   - 2.3 Supercontinuum generation (ps-regime)

3. … in InGaP-on-insulator platform

4. Future perspectives

2.1 WHY AMORPHOUS SILICON?

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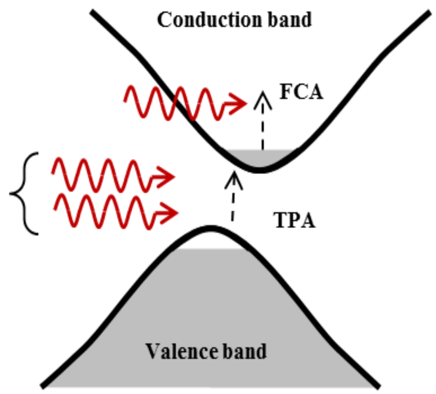
WHY AMORPHOUS SILICON?

But, also, good quality! :D

$$!



(a) Nonlinear losses > nonlinear gain

CMOS-compatibility

Solutions?

(1) Work beyond TPA wavelength, sweep out carriers, ultrashort pulses…

(2) Other materials: large bandgap materials → **Amorphous silicon!**

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OUTLINE

1. Nonlinear optics

2. … in a-Si:H-on-insulator platform

   2.1 Why amorphous silicon?

   2.2 Nonlinear loss measurement

   2.3 Supercontinuum generation (ps-regime)

3. … in InGaP-on-insulator platform

4. Future perspectives

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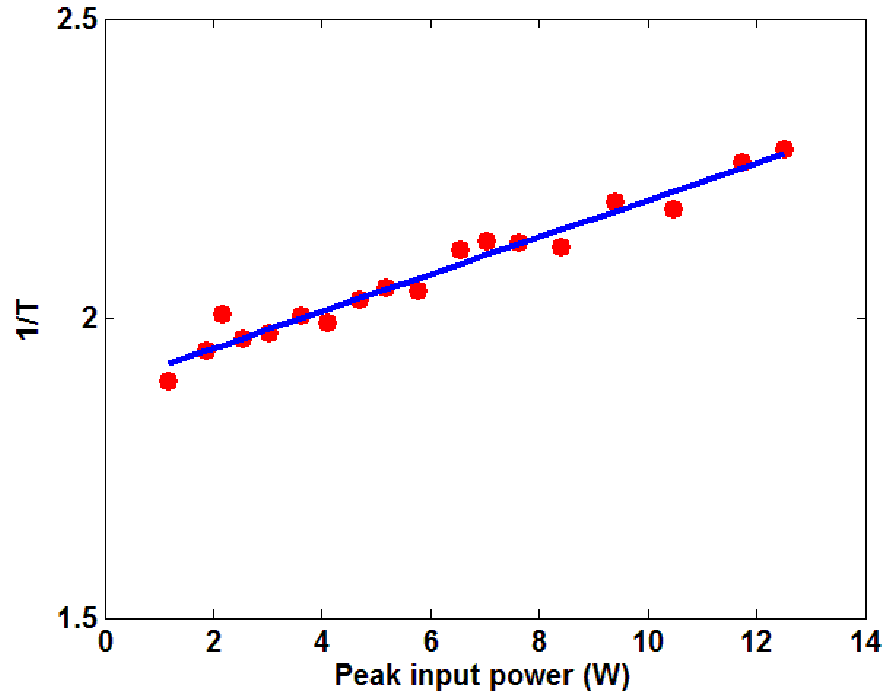
2.2 NONLINEAR LOSS MEASUREMENT

Nonlinear loss – transmission measurement

<u>Pulsed source</u>:
1.24 ps
26 MHz
1950 nm

$$T_{NL}^{-1} = \frac{I(0,t)}{I(L,t)} = \frac{1 + \alpha_{tpa} I(0,t) L_{eff}}{e^{-\alpha_{lin} L}}$$



Two-photon absorption loss:

$$\alpha_{\text{a-Si}} = 0.045\ \text{cm/GW}\ [1950\ \text{nm}]$$
$$\alpha_{\text{c-Si}} = 0.500\ \text{cm/GW}\ [1550\ \text{nm}]$$

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OUTLINE

1. Nonlinear optics

2. … in a-Si:H-on-insulator platform

   2.1 Why amorphous silicon?

   2.2 Nonlinear loss measurement

   2.3 Supercontinuum generation (ps-regime)

3. … in InGaP-on-insulator platform

4. Future perspectives

2.3 SUPERCONTINUUM GENERATION (PS-REGIME)

SUPERCONTINUUM GENERATION

<u>Mechanism for supercontimuum generation</u>:

Modulation instability sidebands

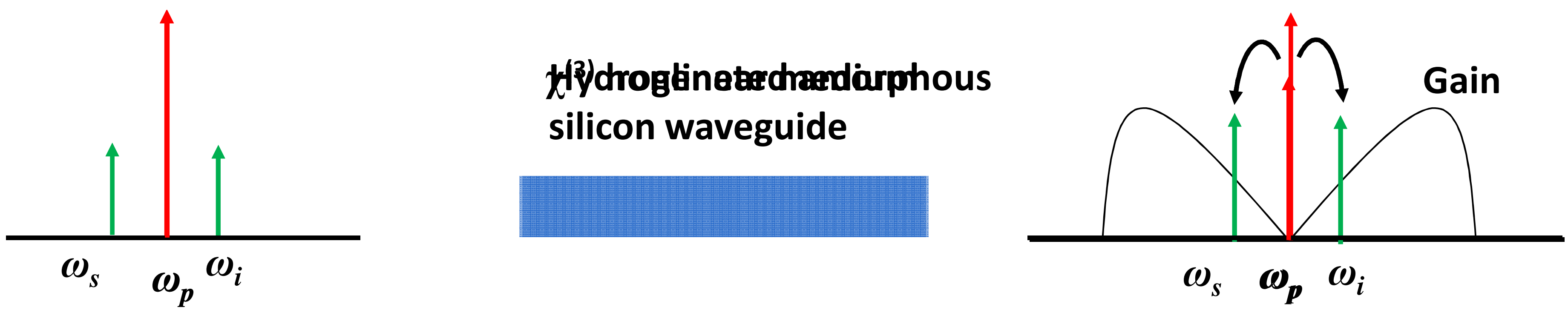
Four coupled wave equations:

$$\frac{dA_1}{dz} = iRe(\gamma)\left[\left(|A_1|^2 + 2|A_2|^2 + 2|A_3|^2 + 2|A_4|^2\right)A_1 + 2A_2^* A_3 A_4 e^{i\Delta k_{lin} z}\right]$$

$$\frac{dA_2}{dz} = iRe(\gamma)\left[\left(|A_2|^2 + 2|A_3|^2 + 2|A_4|^2 + 2|A_1|^2\right)A_2 + 2A_1^* A_3 A_4 e^{i\Delta k_{lin} z}\right]$$

$$\frac{dA_3}{dz} = iRe(\gamma)\left[\left(|A_3|^2 + 2|A_4|^2 + 2|A_1|^2 + 2|A_2|^2\right)A_3 + 2A_1 A_2 A_4^* e^{-i\Delta k_{lin} z}\right]$$

$$\frac{dA_4}{dz} = iRe(\gamma)\left[\left(|A_4|^2 + 2|A_1|^2 + 2|A_2|^2 + 2|A_3|^2\right)A_4 + 2A_1 A_2 A_3^* e^{-i\Delta k_{lin} z}\right]$$

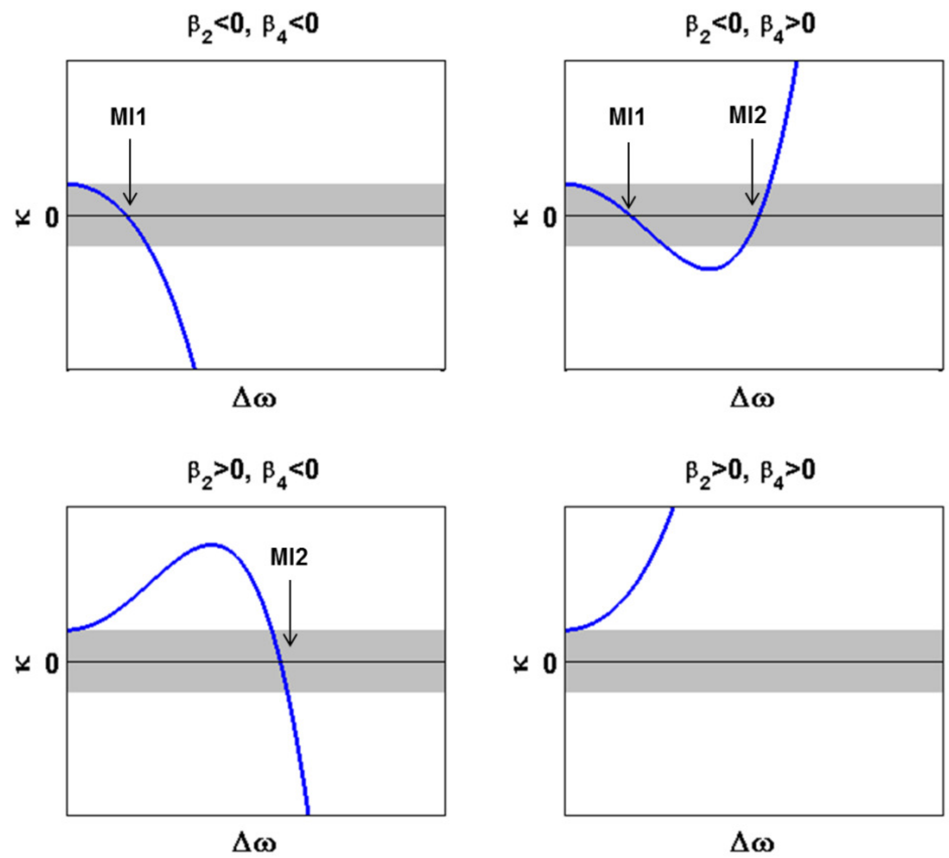


WHERE IS THE GAIN AVAILABLE?

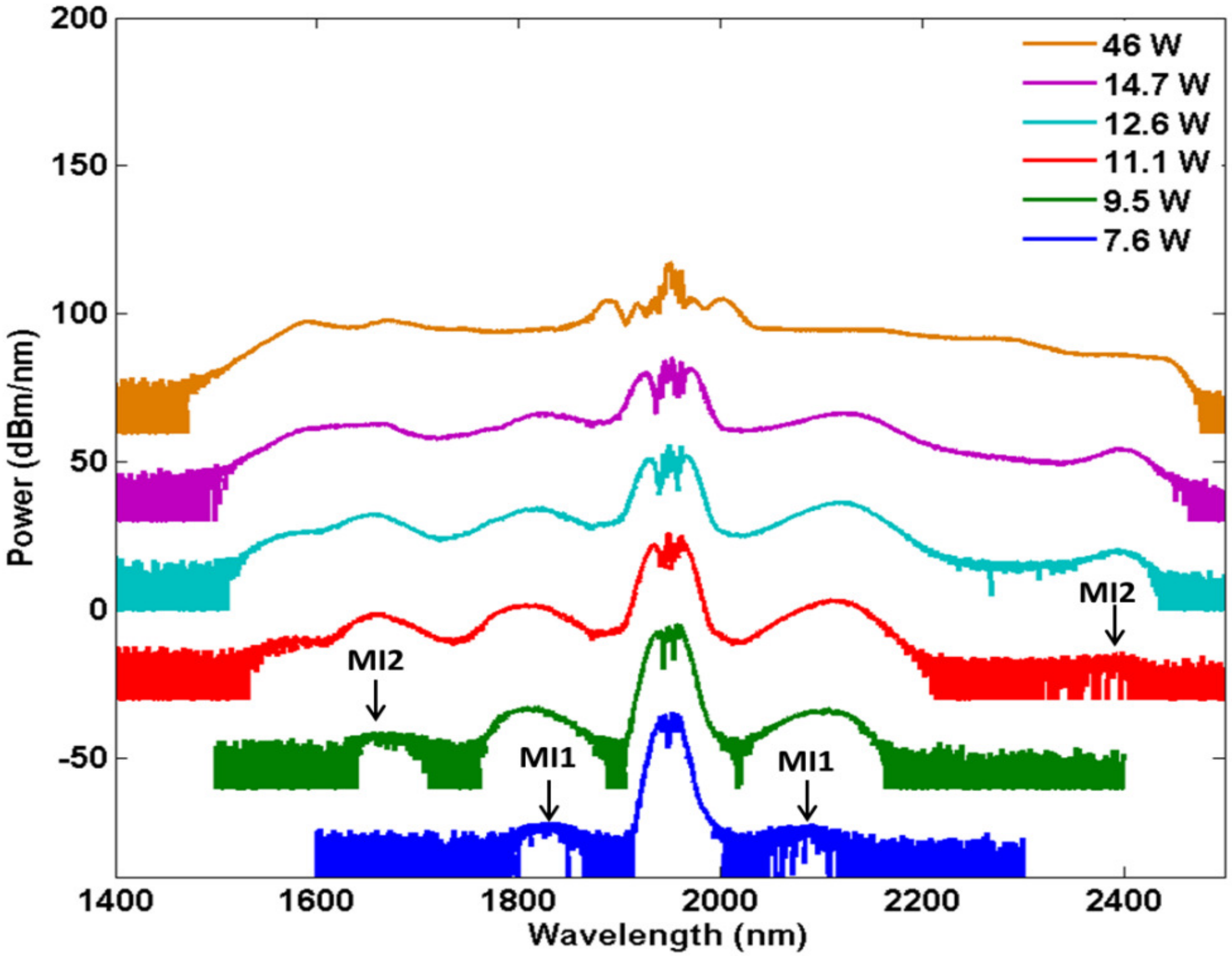
$$\kappa = \beta_2(\omega_0)\Delta\omega^2 + \frac{\beta_4(\omega_0)}{12}\Delta\omega^4 + 2\gamma P$$

= 0

Multiple gain bands possible!



SUPERCONTINUUM GENERATION (PS-REGIME)



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Outline

1. Nonlinear optics
2. … in a-Si:H-on-insulator platform
3. … in InGaP-on-insulator platform
4. Future perspectives

3. NLO IN INGAP-ON-INSULATOR PLATFORM

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OUTLINE

1. Nonlinear optics
2. … in a-Si:H-on-insulator platform
3. … in InGaP-on-insulator platform
   - 3.1 Why InGaP?
   - 3.2 Fabrication overview
   - 3.3 Nonlinear loss (3PA)
   - 3.4 Four-wave mixing
   - 3.5 Supercontinuum generation
   - 3.6 Second order nonlinearity
4. Future perspectives

3.1 WHY InGaP?

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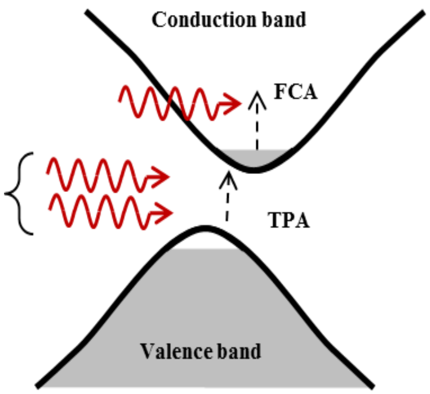
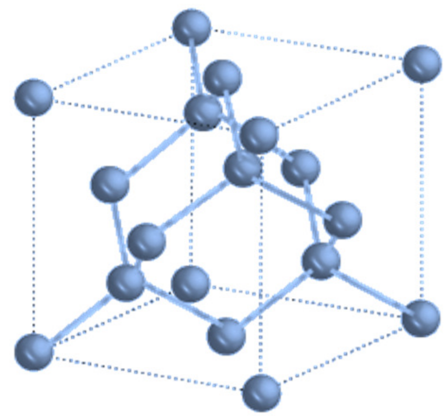
DEFICIENCIES OF SOI AS A NONLINEAR PLATFORM



(a) Nonlinear losses > nonlinear gain



(b) Centrosymmetry => $\chi^{(2)} = 0$

Solutions?

(1) Work beyond TPA wavelength, sweep out carriers, ultrashort pulses…

(2) Other materials: large bandgap materials

(1) Strain/surface $\chi^{(2)} = 0$

(2) Other materials: non-centrosymmetric crystal structure

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OUTLINE

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3. **… in InGaP-on-insulator platform**
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4. Future perspectives

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3.2 Fabrication

Overview

Materials for On-chip NLO

Metric / Material	Index contrast	Losses	Transparency range	Bandgap	$\chi^{(3)}$ nonlinearity	$\chi^{(2)}$ nonlinearity
SiO_2 fiber	V. Low	V. Low (0.1 dB/km)	Vis-2.5 um	Large	Weak	No (bulk)
Si_3N_4-on-oxide	Low	Moderate < 1dB/cm	Vis-7(4)um	Large	Moderate	No (bulk)
Si-on-insulator	Large	Moderate ~ 1 dB/cm	1.1 to 8(4) um	1.1 eV	Strong	No (bulk)
Amorphous silicon	Large	Moderate ~ 1 dB/cm	1.1 to 8(4) um	> 1.1 eV	Strong	No (bulk)
III-V-on-insulator	Large	Moderate-high (1-10 dB/cm)	~Vis-MIR	1.7 eV	Strong(er)	Yes, strong

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FABRICATION FLOW OVERVIEW

- Substrate preparation (SOI/SiN/"plain")
- Bonding
- Substrate removal
- E-beam Patterning
- Etching

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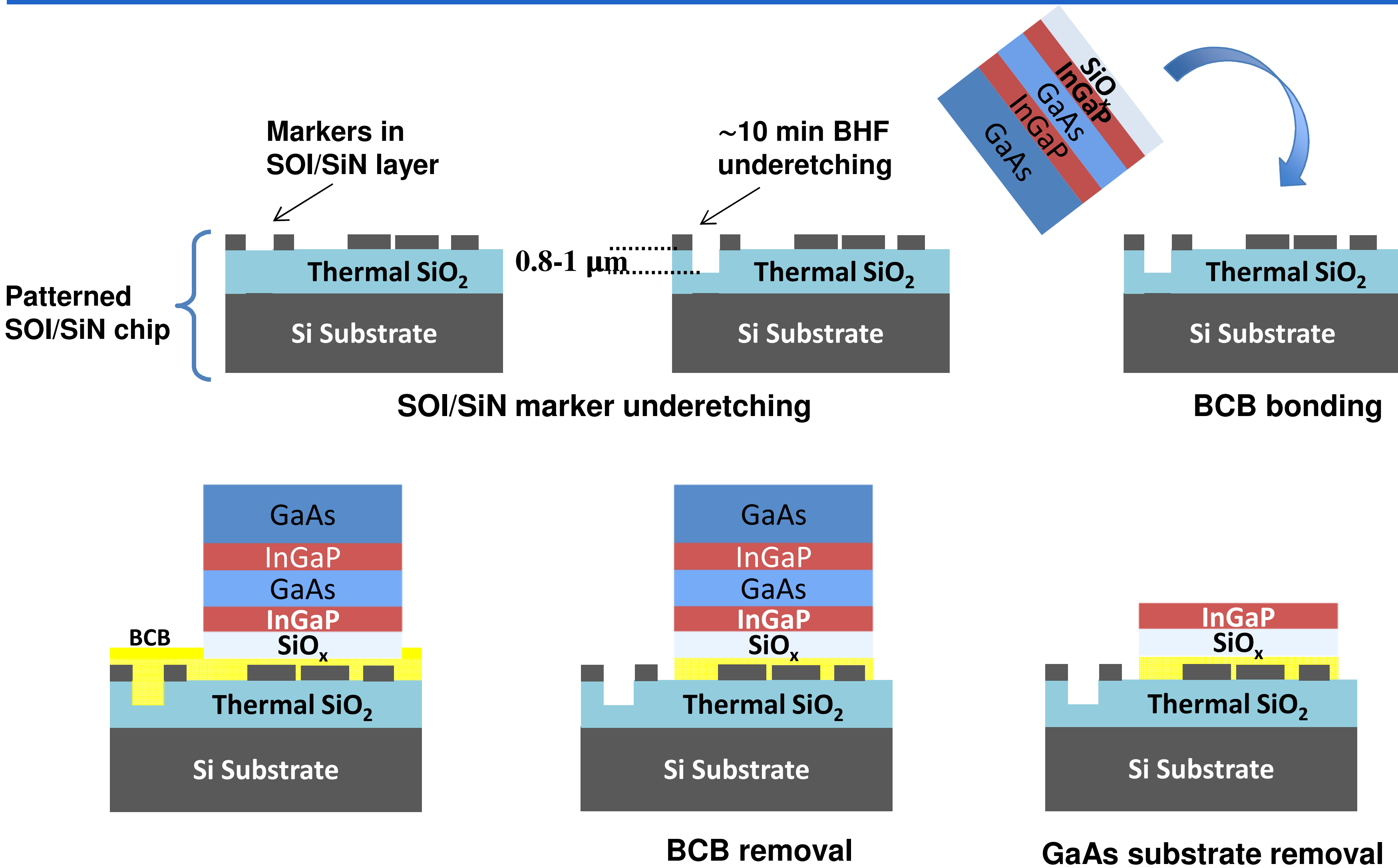
LABORATOIRE DE PHOTONIQUE ET DE NANOSTRUCTURES

FABRICATION FLOW



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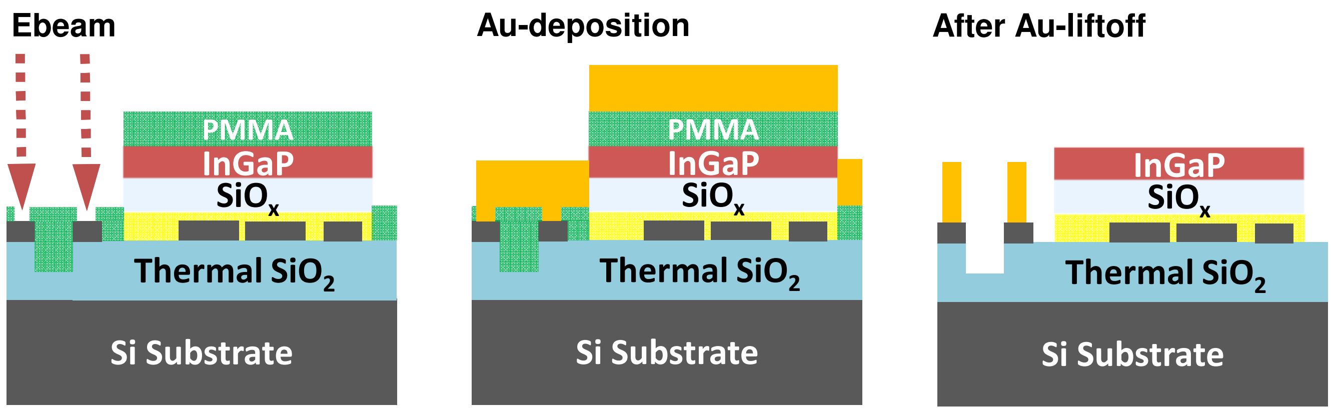
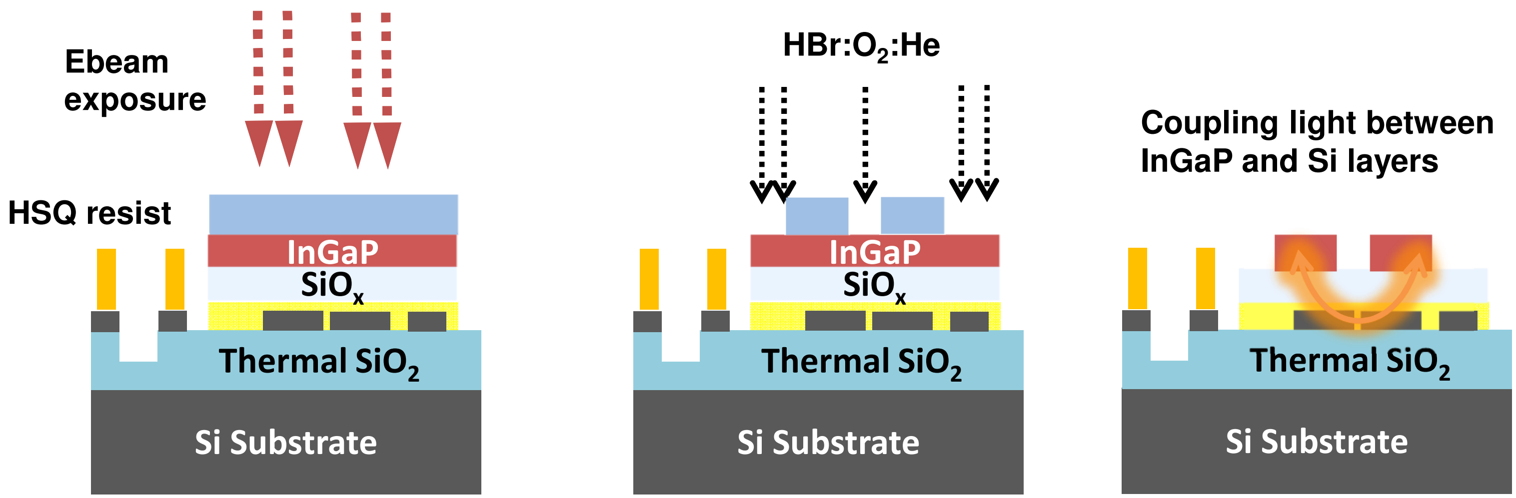
Integration to SOI/SiN



Gold marker definition in SOI/SiN layer



Ebeam patterning using Au-markers

ICP Etching of patterns

Final integrated chip

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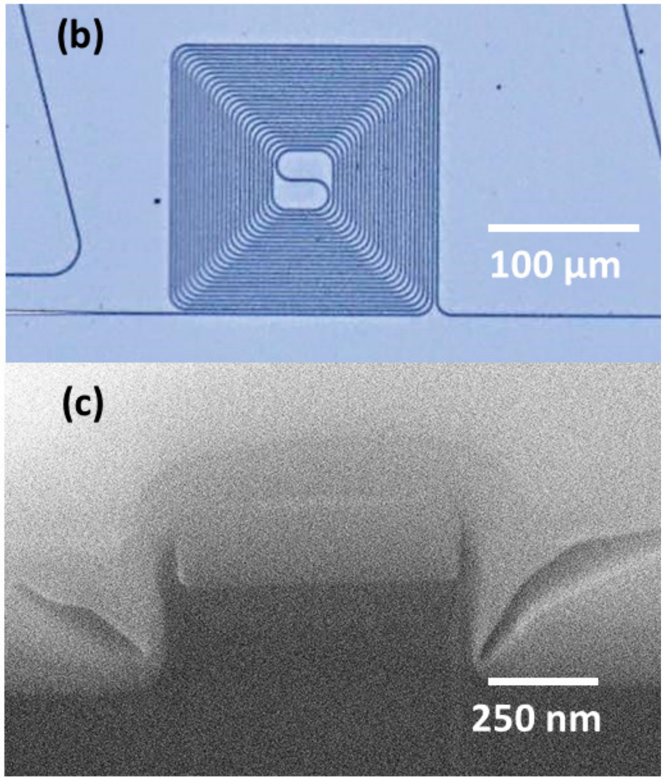
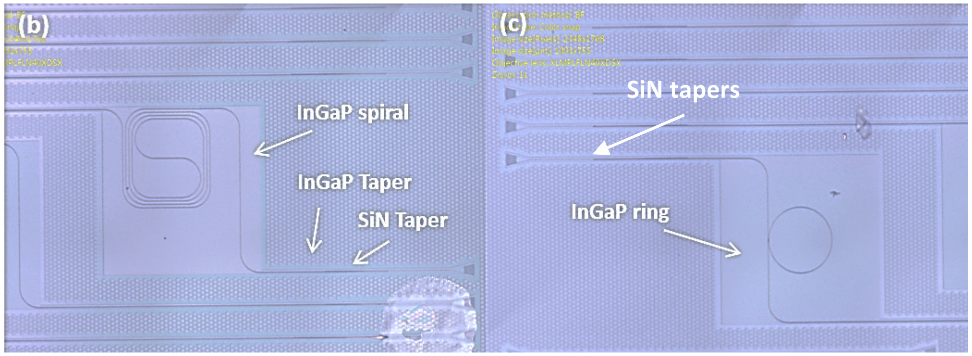
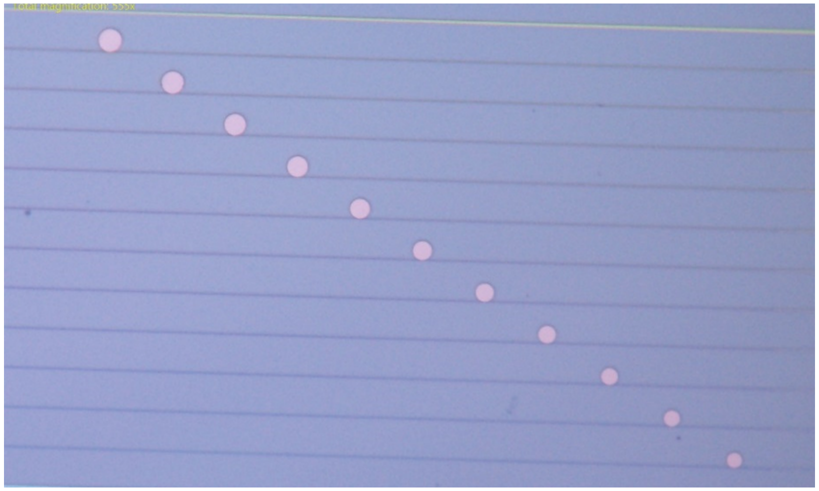
SOME FABRICATED STRUCTURES







OUTLINE

1. Nonlinear optics
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3. … in InGaP-on-insulator platform

    3.1 Why InGaP?

    3.2 Fabrication overview

    3.3 Nonlinear loss (3PA)

    3.4 Four-wave mixing

    3.5 Supercontinuum generation

    3.6 Second order nonlinearity

4. Future perspectives

3.3 Nonlinear loss (3PA)

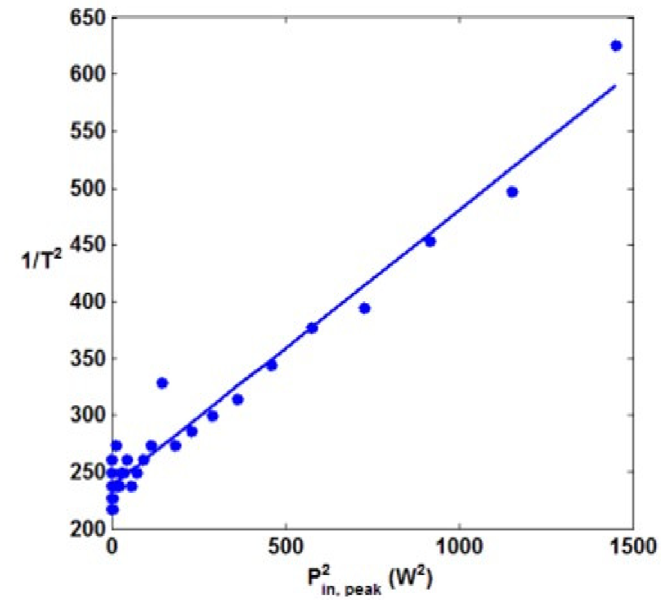
Determination of α_{3pa}:

Pulsed source:

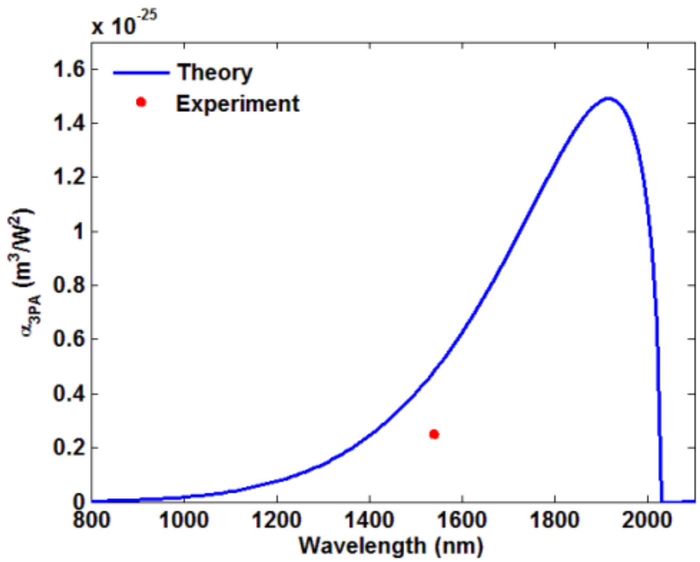
2.8 ps

10 MHz

1540 nm



$$\frac{1}{T^2} = \frac{P_{in}^2}{P_{out}^2} = \frac{2\,\alpha_{3pa} L_{3eff}}{A_{5eff}^2\, e^{-2\alpha_{lin}L}} P_{in}^2 + \frac{1}{e^{(-2\alpha_{lin}L)}}$$



Thus: no TPA, only very weak 3PA at 1550 nm!

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   3.1 Why InGaP?

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   3.4 Four-wave mixing

   3.5 Supercontinuum generation

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4. Future perspectives

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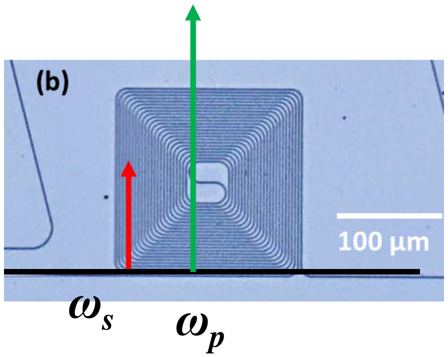
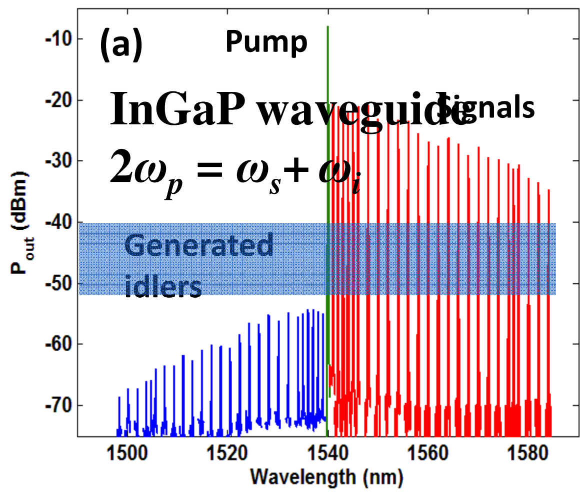
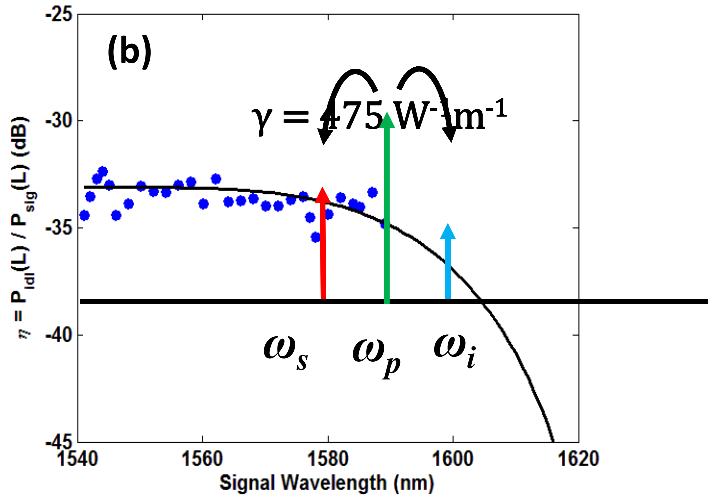
3.4 Four-wave mixing

Four-wave mixing

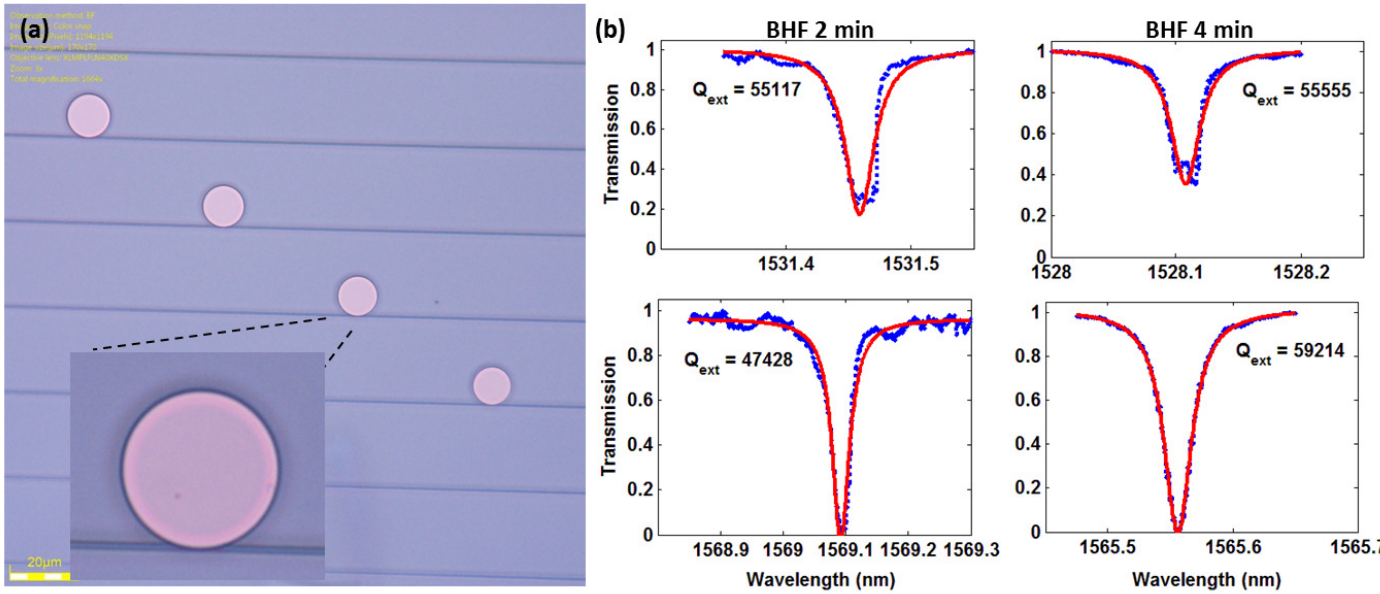


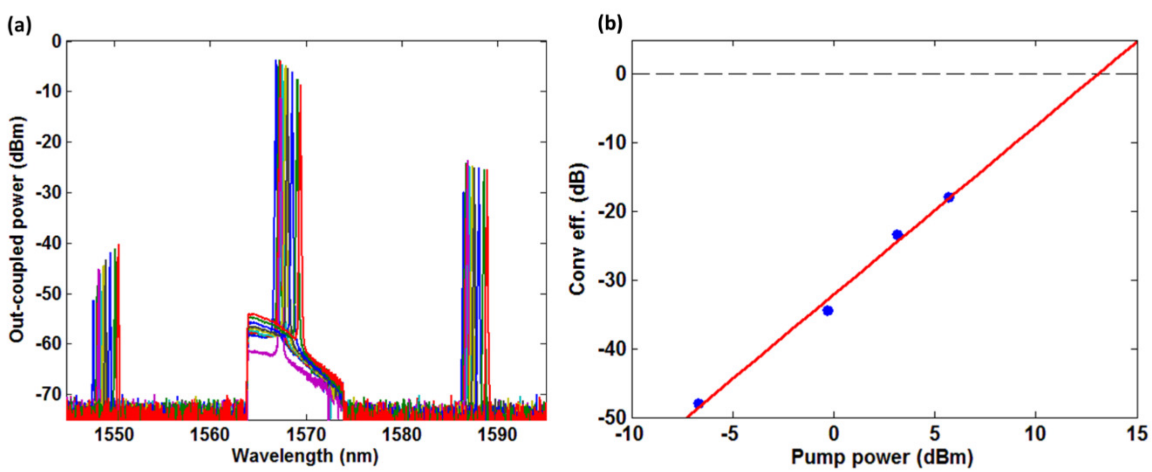




Material platform	γ (/W/m)
SOI	400 (but, saturation due to TPA/FCA)
SiN	7
AlGaAs-on-AlGaAs	82
InGaP-on-insulator	475

FWM in InGaP-on-SOI microdisks





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3.5 SUPERCONTINUUM GENERATION (FS-REGIME)

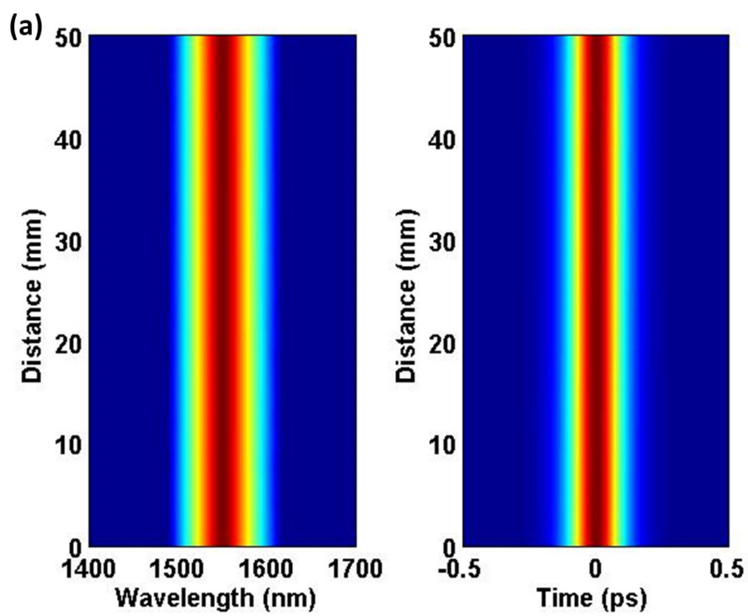
Coherent Supercontinuum Generation

Ideal Soliton case: only β_2, no HOD, 3PA etc.

NLSE: $$i\frac{\partial \tilde{U}}{\partial \xi} = sgn(\beta_2)\frac{\partial^2 \tilde{U}}{\partial T^2} - N^2|\tilde{U}|^2\tilde{U} = 0 \qquad N^2 = \frac{L_D}{L_{NL}} = \frac{\gamma P_0 T_0^2}{|\beta_2|}$$

Fundamental Soliton: $$\tilde{A}(\tau, z) = A_0 sech(\tau/\tau_0)e^{i\kappa z}; |A_0|^2 = \frac{-\beta_2}{\gamma\tau^2}; \kappa = \frac{1}{2}\gamma|A_0|^2$$

!



$N = 1$ $N = 2$

Reality vs Ideal

How the envelope evolves along the waveguide

Second-order dispersion

Higher-order dispersion terms

GNLSE:

$$\frac{\partial A}{\partial z} = -i\frac{\beta_2}{2}\frac{\partial^2 A}{\partial t^2} + \ldots - \frac{\alpha_{lin}}{2}A + \left(1 + \frac{i}{\omega_0}\frac{\partial}{\partial t}\right)\left(iRe(\gamma)|A|^2 - \frac{\alpha_{3pa}}{3A_{5eff}^2}|A|^4\right)A$$
$$- \frac{\sigma}{2}(1 + i\mu)N_c A$$

Linear loss

Nonlinear gain

$$\frac{dN_c}{dt} = \frac{\alpha_{3pa}}{3h\nu_0}\frac{|A|^6}{A_{eff}^3} - \frac{N_c}{\tau_{recomb}}$$

Nonlinear loss (3PA)

Carriers! (loss + dispersion)

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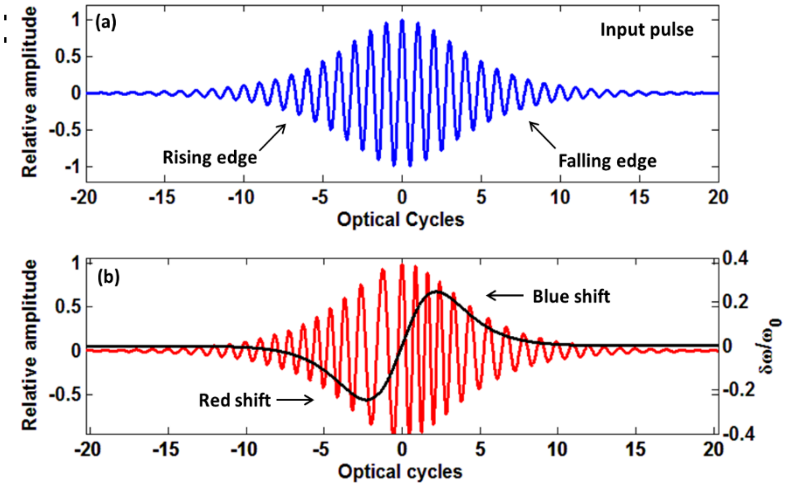
SUPERCONTINUUM GENERATION MECHANISM

Supercontinuum generation in the *fs*-regime:



1. Self phase modulation

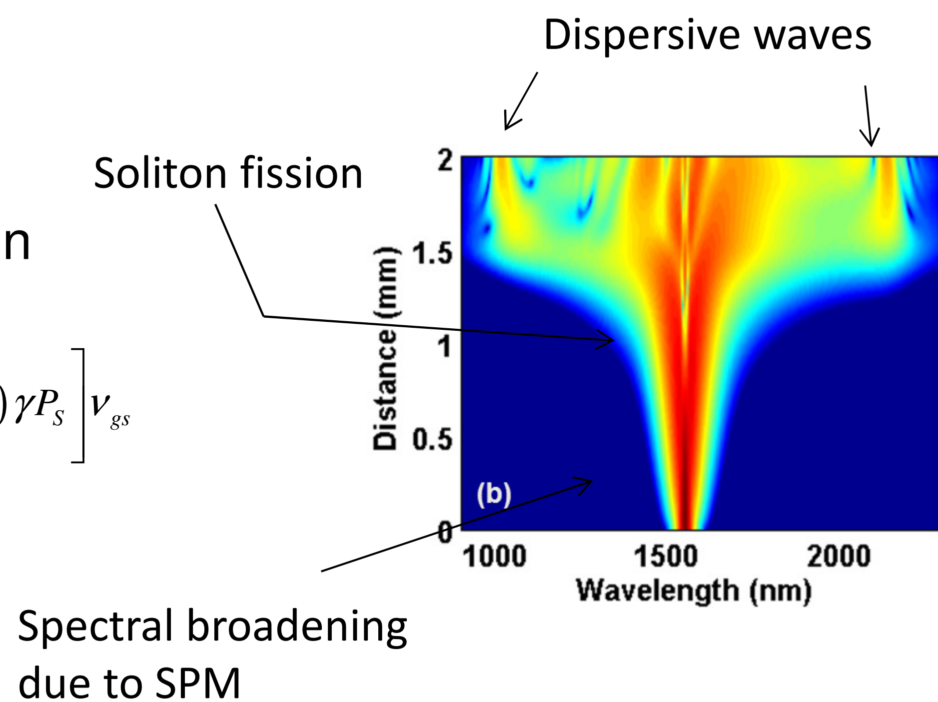
$$n(t) = n_0 + n_2 I(t)$$

2. Soliton fission

$$N = \sqrt{\frac{\tau^2 \gamma P}{|\beta_2|}} \qquad \gamma = \frac{k_0 n_2}{A_{eff}}$$

3. Dispersive wave generation

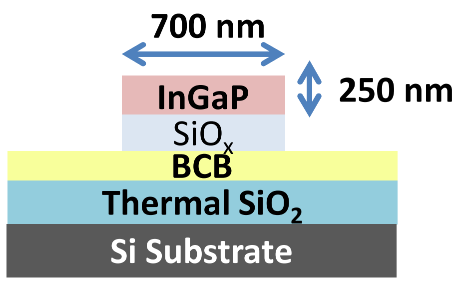
$$\omega_{DW} = \left[\beta(\omega_{DW}) - \beta(\omega_S) + \frac{\omega_S}{v_{gs}} - (1 - f_R)\gamma P_S \right] v_{gs}$$

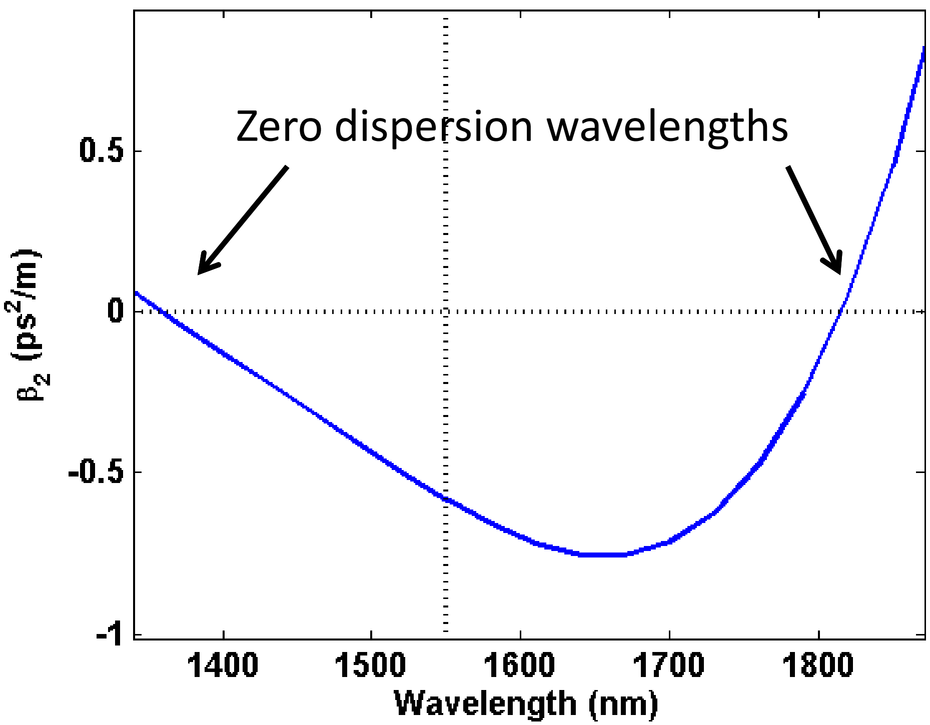


SUPERCONTINUUM GENERATION: THEORY

Dispersive wave (DW) generation: waveguide design with dispersion engineering

$$\omega_{DW} = \left[\beta(\omega_{DW}) - \beta(\omega_S) + \frac{\omega_S}{v_{gs}} - (1 - f_R)\gamma P_S \right] v_{gs} \qquad \gamma = \frac{k_0 n_2}{A_{eff}}$$





2 zero-dispersion points

= 2 dispersive waves

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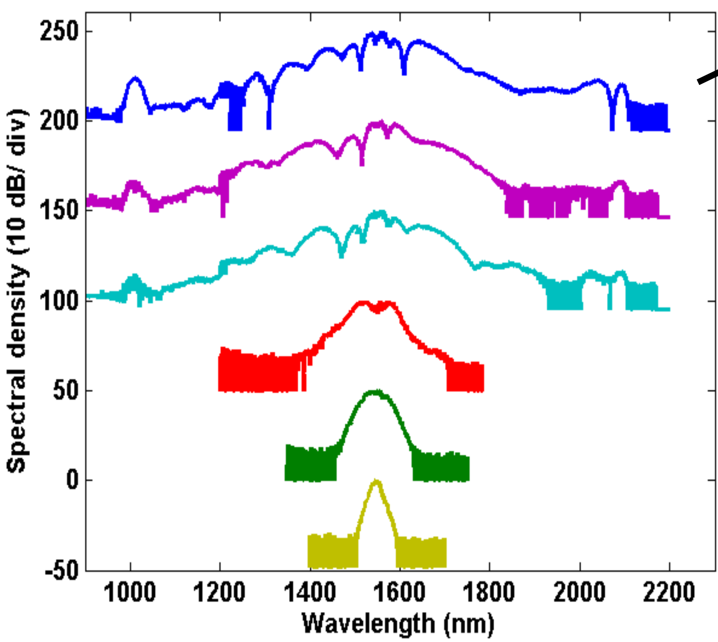
SUPERCONTINUUM GENERATION: EXPERIMENT

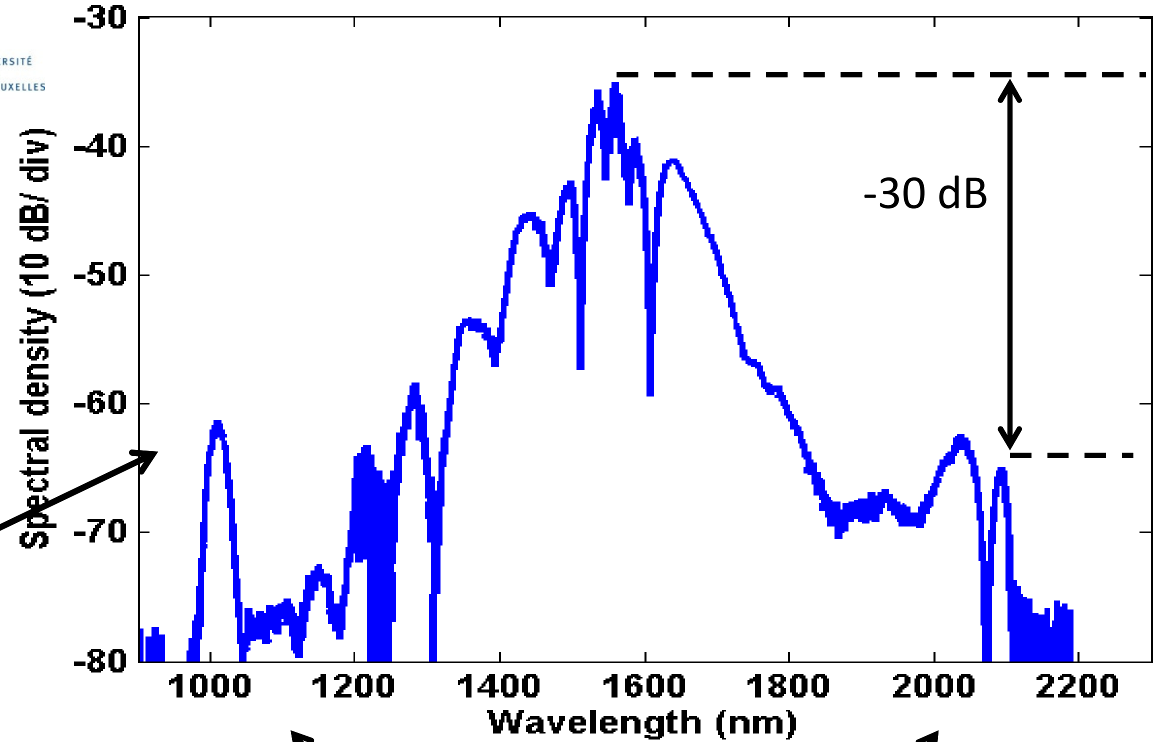
Pump pulse:

1550 nm

10 W peak power,

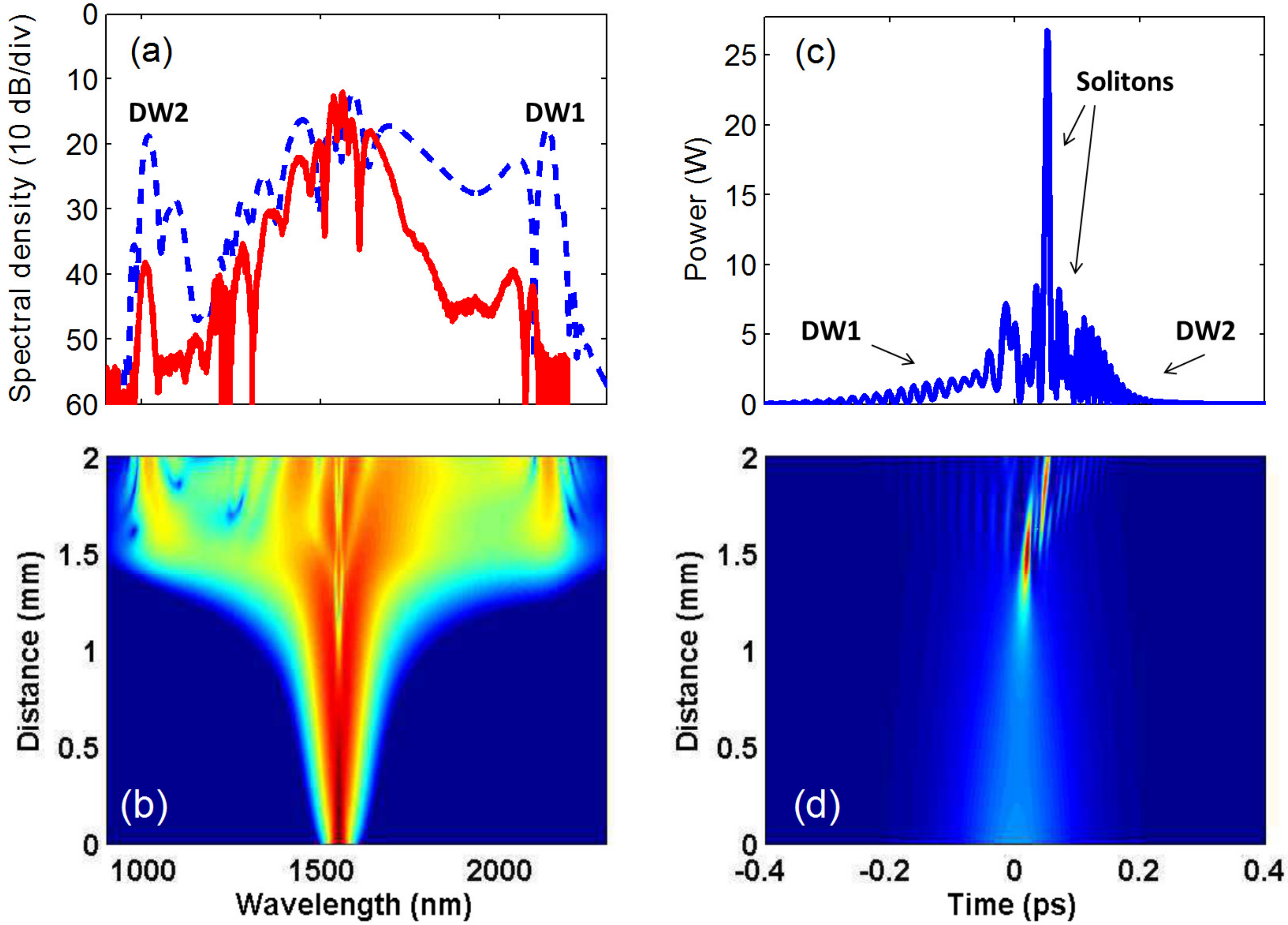
170 fs FWHM





Dispersive waves at 1000 nm and 2100 nm

Comparison to simulations



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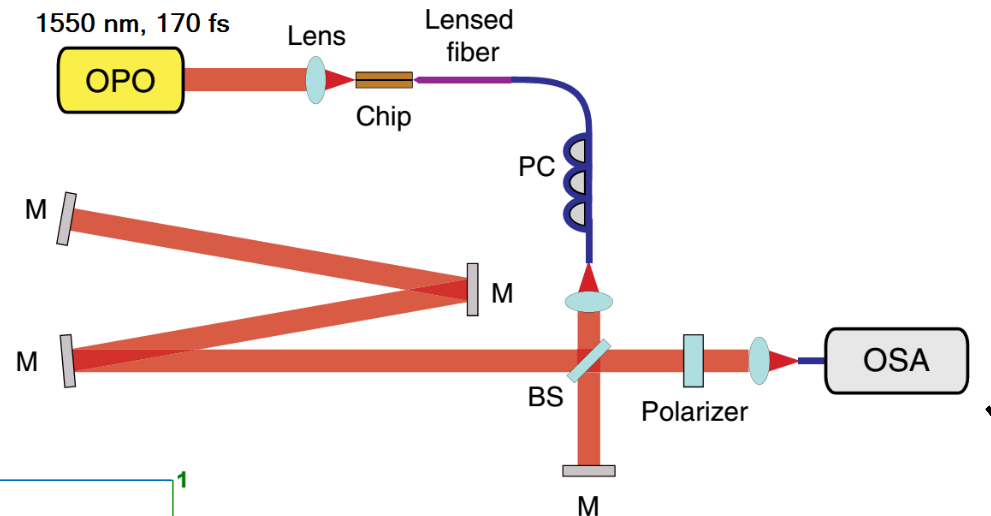
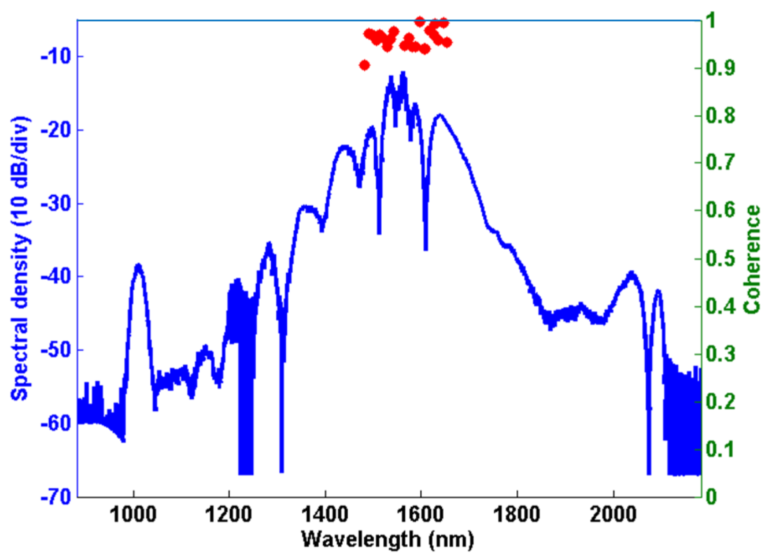
SUPERCONTINUUM GENERATION: COHERENCE

The coherence measurement setup

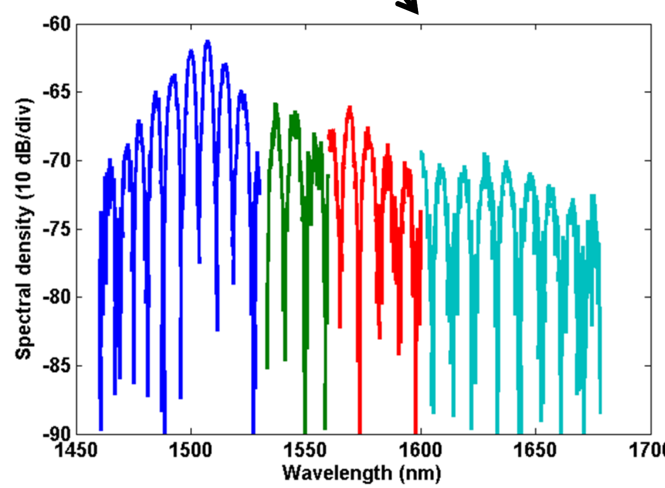




Coherence measurement

$$g_{12}^{(1)}(\lambda) = \frac{\langle E_1^*(\lambda)E_2(\lambda)\rangle}{\sqrt{\langle|E_1(\lambda)|^2\rangle\langle|E_2(\lambda)|^2\rangle}}$$

$$V(\lambda) = \frac{2\sqrt{I_1(\lambda)I_2(\lambda)}}{I_1(\lambda)+I_2(\lambda)}|g_{12}^{(1)}(\lambda)|$$



Interference fringes

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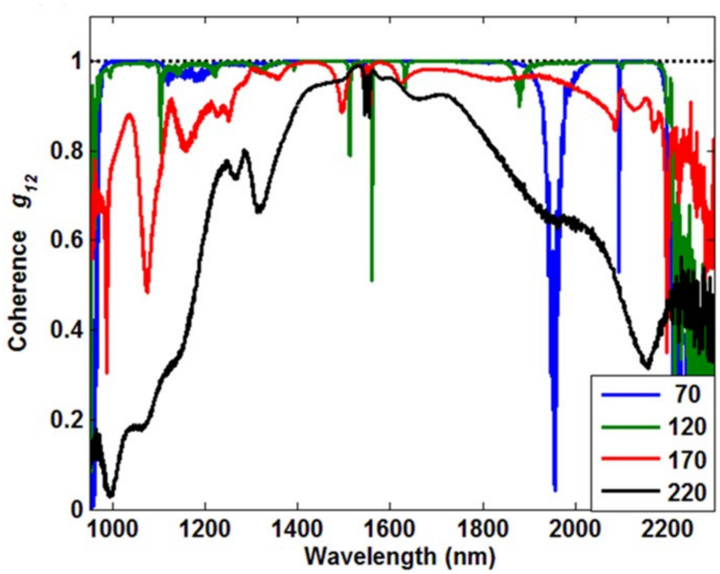
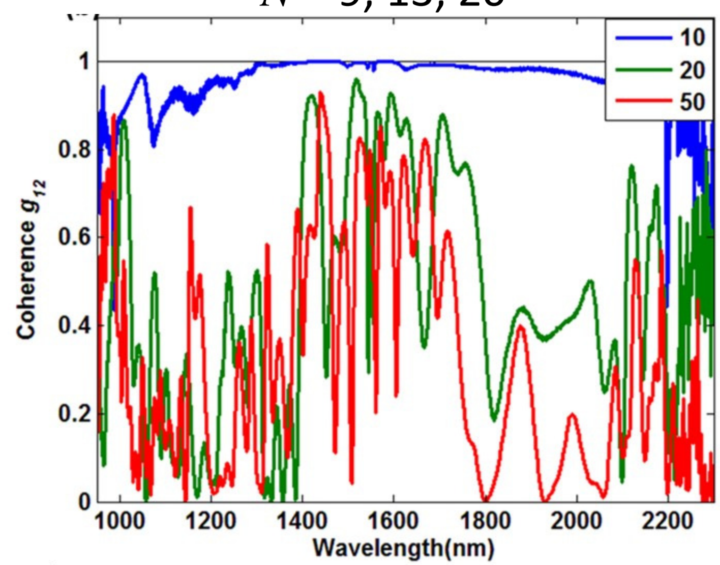
Coherence properties

N = 4, 6, 9, 11



N = 9, 13, 20



	SOI	InGaP
Bandwidth (octaves)	0.56	1.1
Pulse energy (pJ)	50	1
Coherence	Yes* (P_{peak} capping by TPA)	Yes (by limiting soliton no.)
Self-referencing [$\chi^{(2)}$]	No*	Yes*

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3.6 SECOND ORDER NONLINEARITY

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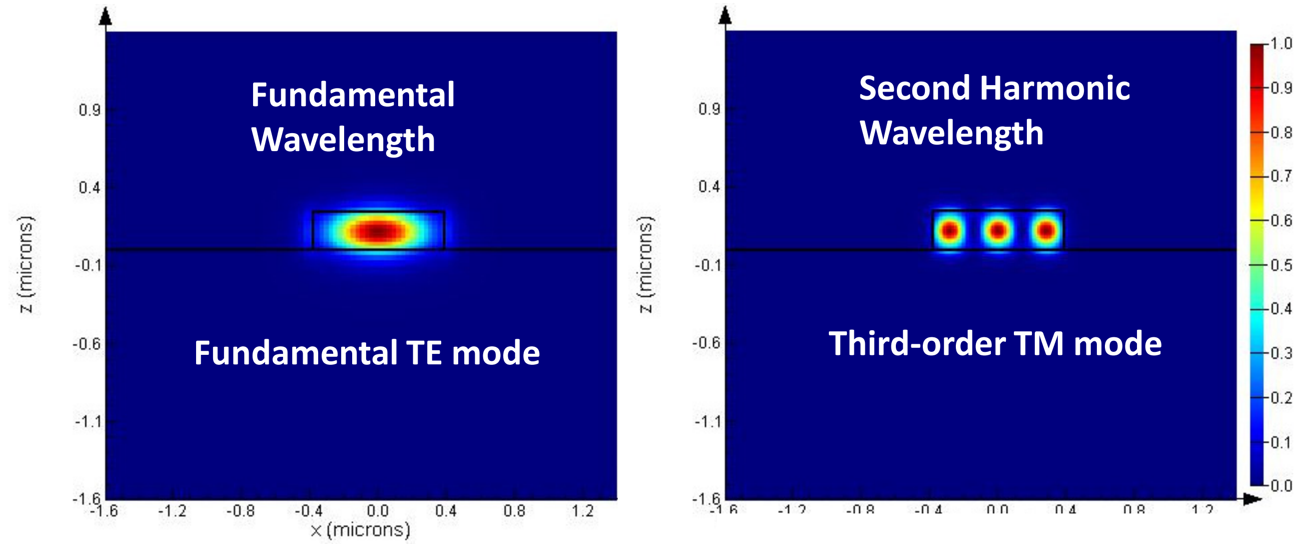
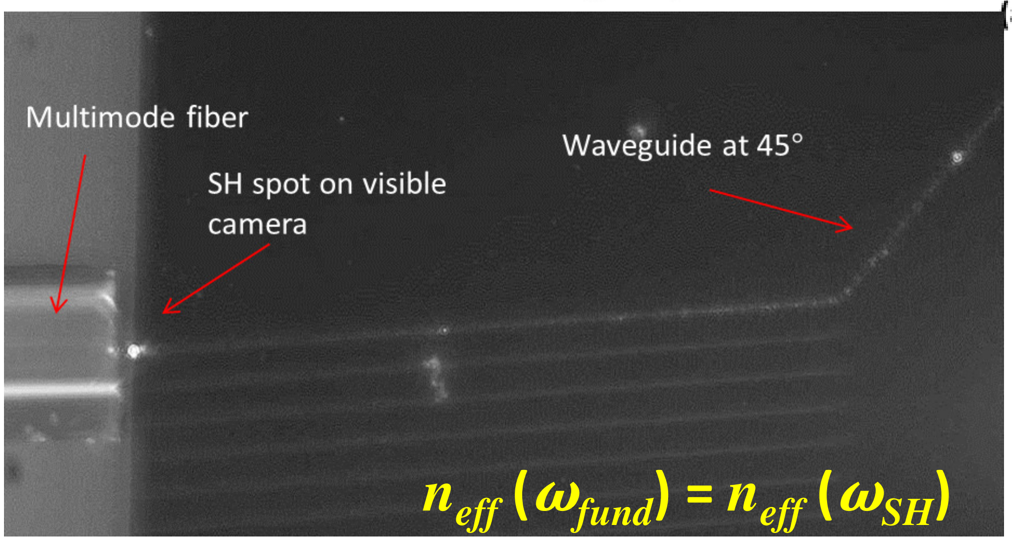
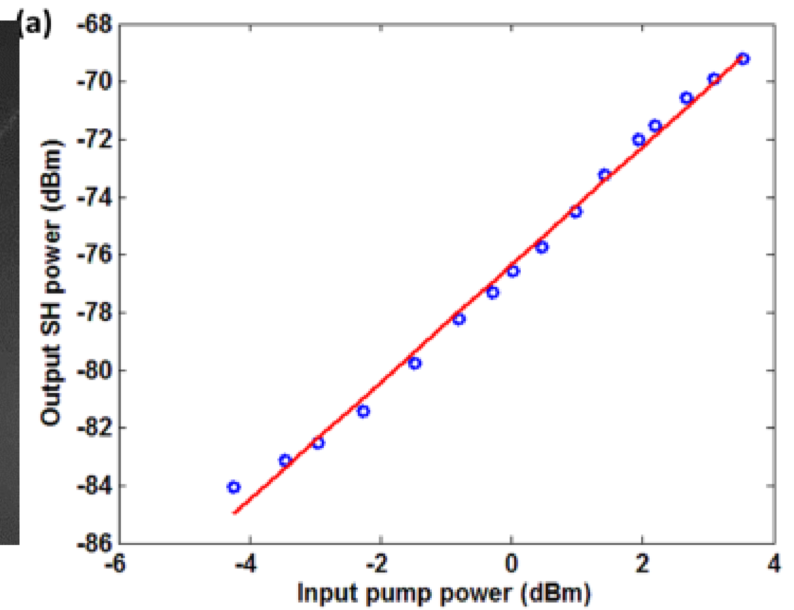
Second-order nonlinearity

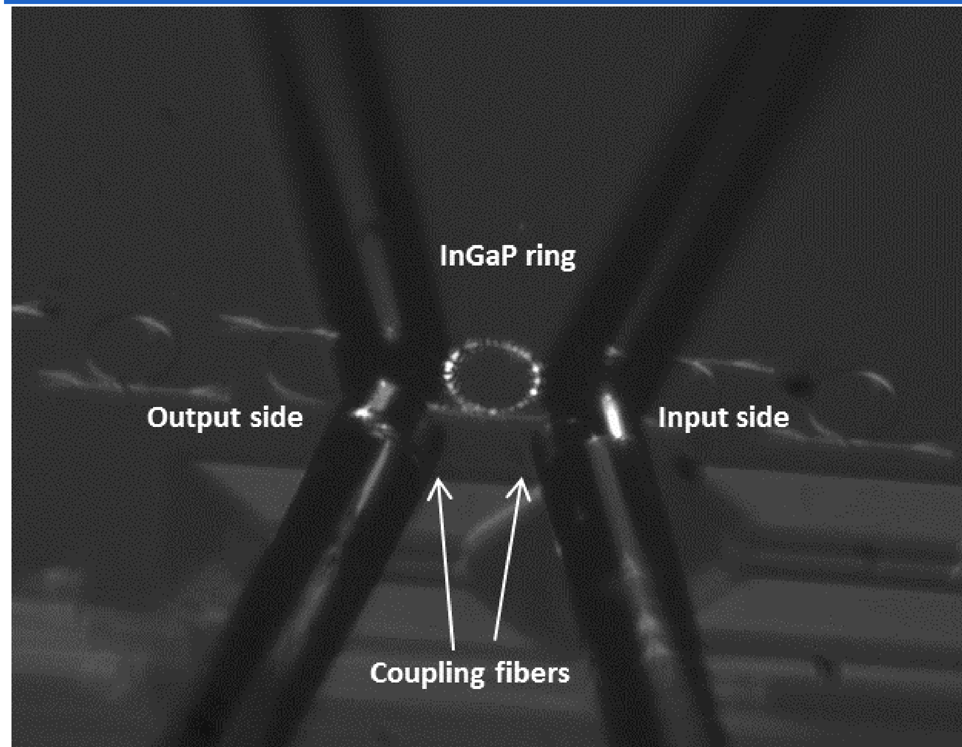


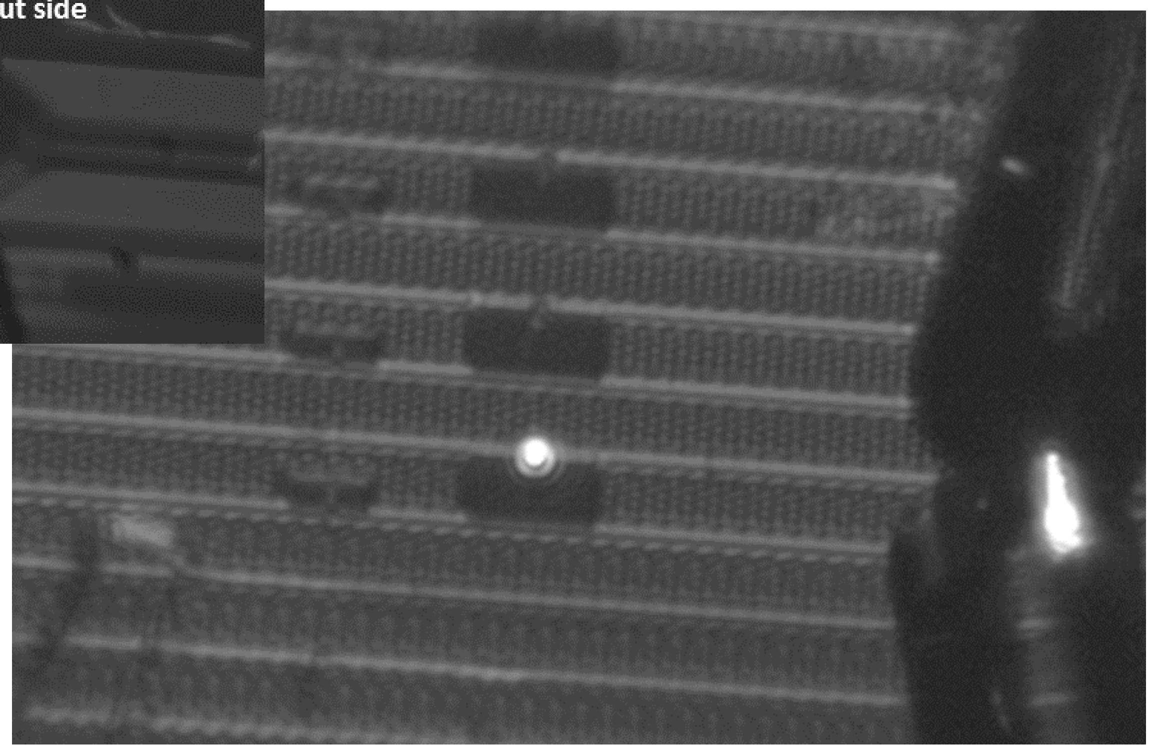


$$n_{eff}(\omega_{fund}) = n_{eff}(\omega_{SH})$$

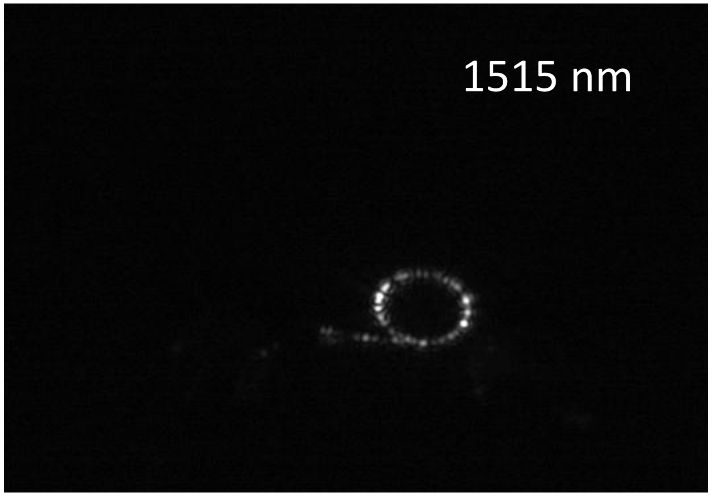


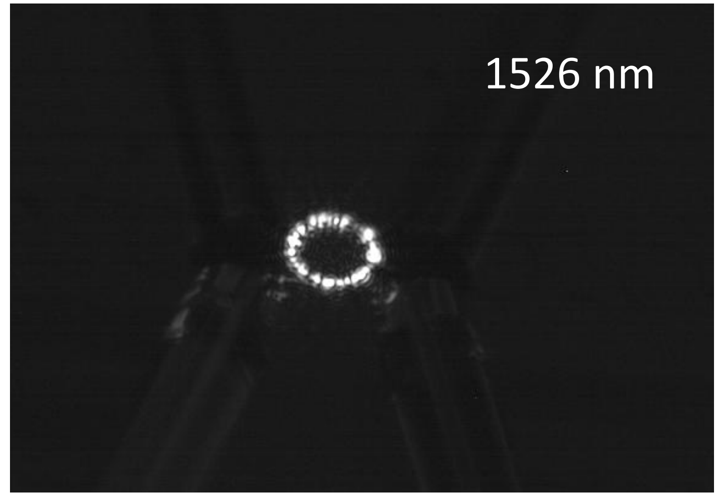
SHG IN RESONATORS

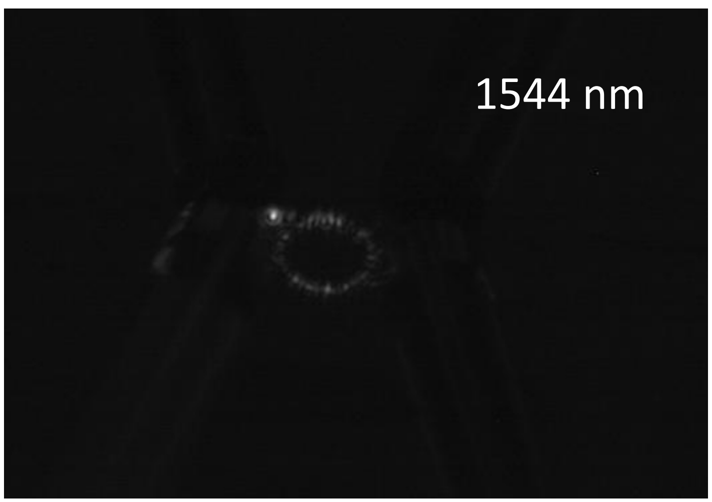


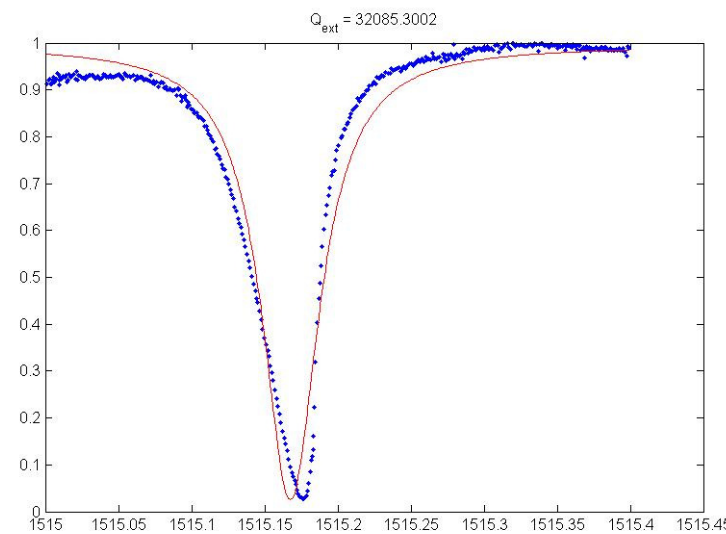


SHG IN RESONATORS









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OUTLINE

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4. Future Perspectives

WHAT NEXT?

- Moving beyond the proof-of-principle experiments in the InGaP-OI platform, improve performance (losses)
- Integration with on-chip lasers, comb generation, f-to-2f, *etc.*
- Second-order applications such as DFG
- Exploit full potential of all the nonlinearities
- Extend platform to other similar materials

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CONCLUSIONS

- Nonlinear optical platforms for overcoming deficiencies of SOI were investigated

- Hydrogenated amorphous silicon was shown to be useful in the mid-IR range

- InGaP-on-insulator platform was built
  – Fabrication process developed
  – Linear and nonlinear characterizations performed
  – Applications like SCG, SHG and integration were shown


THANK YOU ALL!

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