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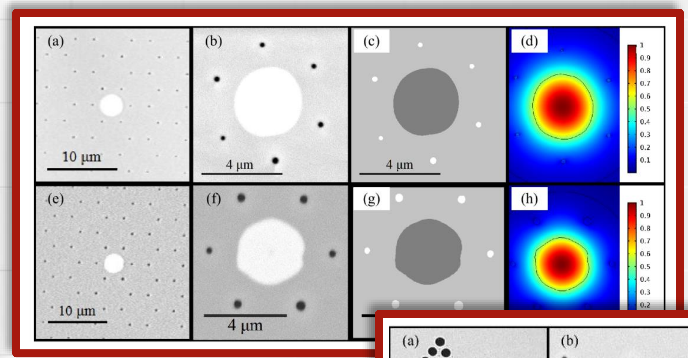
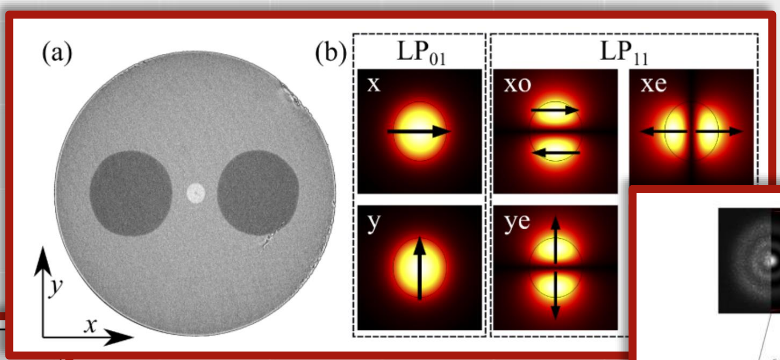
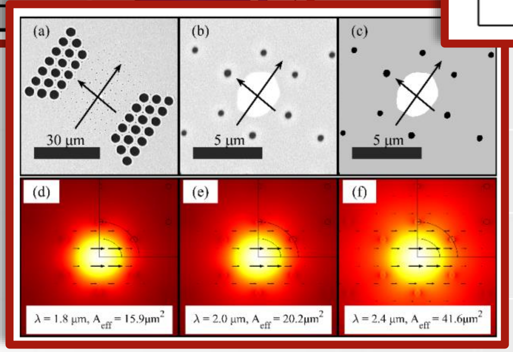
LasIonDef - Wrocław 2024

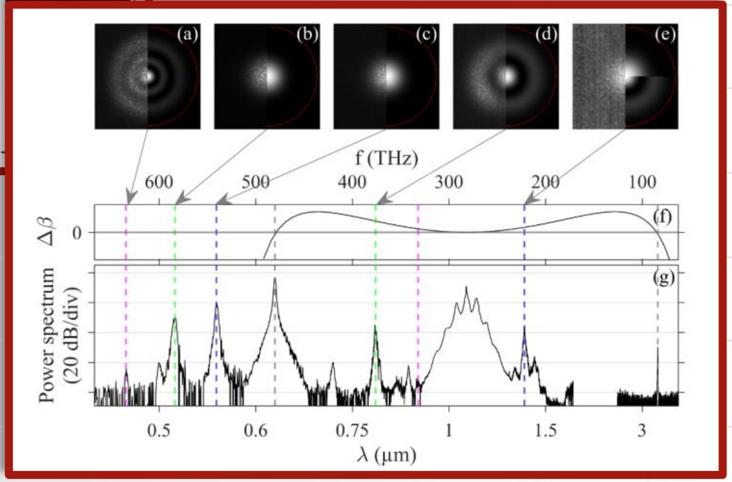
Nonlinear phenomena in few-mode optical fibers

LasIonDef









Karol Tarnowski
Wrocław University of Science and Technology
Faculty of Fundamental Problems of Technology
Department of Optics and Photonics
23.02.2024

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HR EXCELLENCE IN RESEARCH

Evaluated by IEP INSTITUTIONAL EVALUATION PROGRAMME www.iep-qaa.org

Outline

Introduction	• Description of frequency conversion processes in optical fibers
Single mode propagation	• All-normal dispersion supercontinuum
Birefringent fibers	• Polarized all-normal dispersion SC
Few mode fibers	• Intermodal-vectorial four wave mixing • Far-detuned frequency conversion + intermodal four wave mixing

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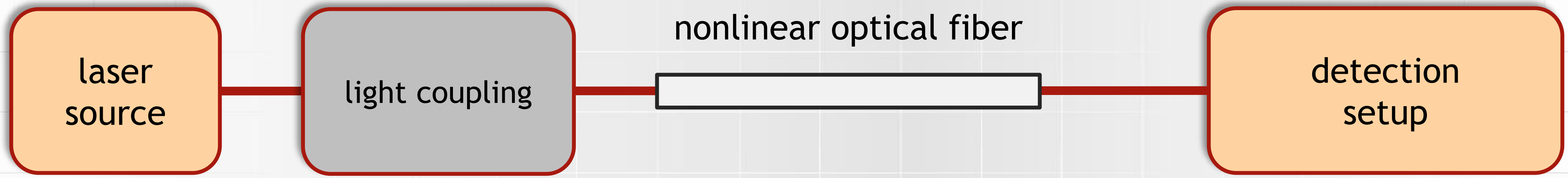
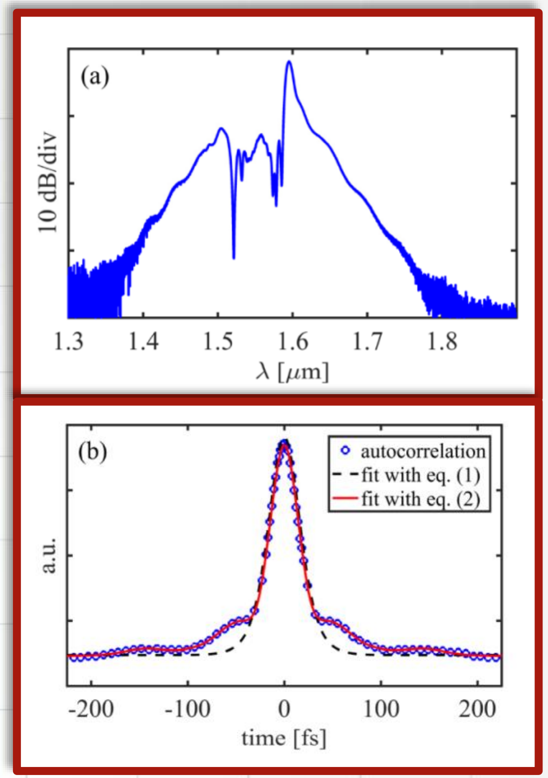
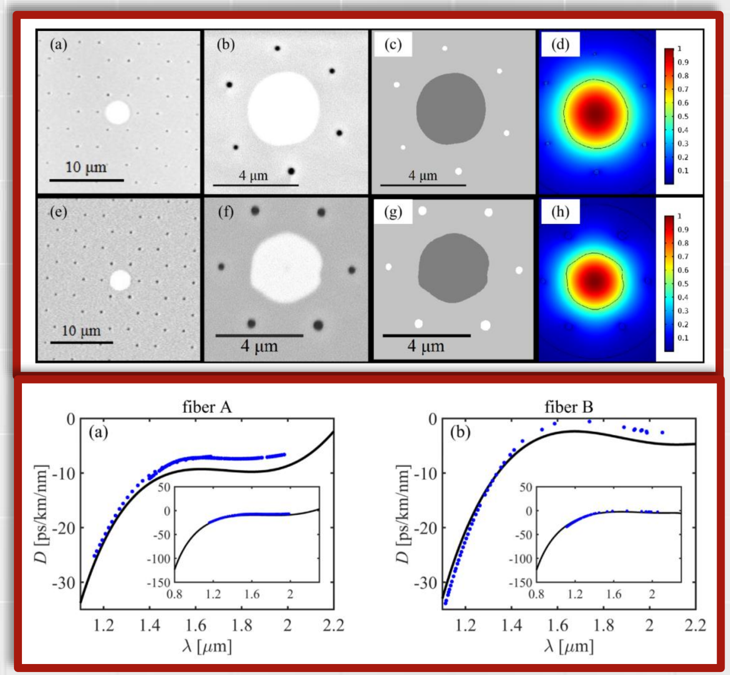
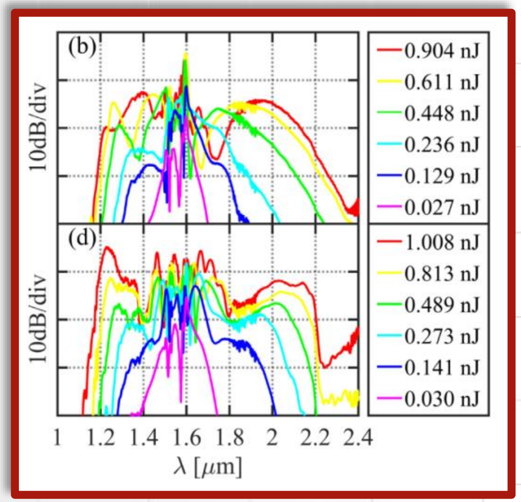
Typical experimental setup

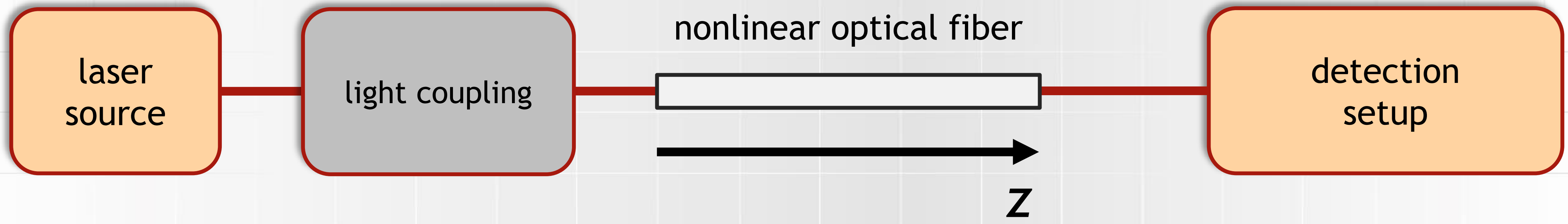








Numerical experiment



$$A(0,T)=\mathcal{F}^{-1}\left\{\tilde{A}(0,\Omega)\right\}$$
$$\tilde{A}(0,\Omega)=\mathcal{F}\left\{A(0,T)\right\}$$

$$\frac{\partial A}{\partial z}=D(A)+N(A)$$

$$I(\Omega)$$
$$I(T)$$
$$S(\Omega,T)$$

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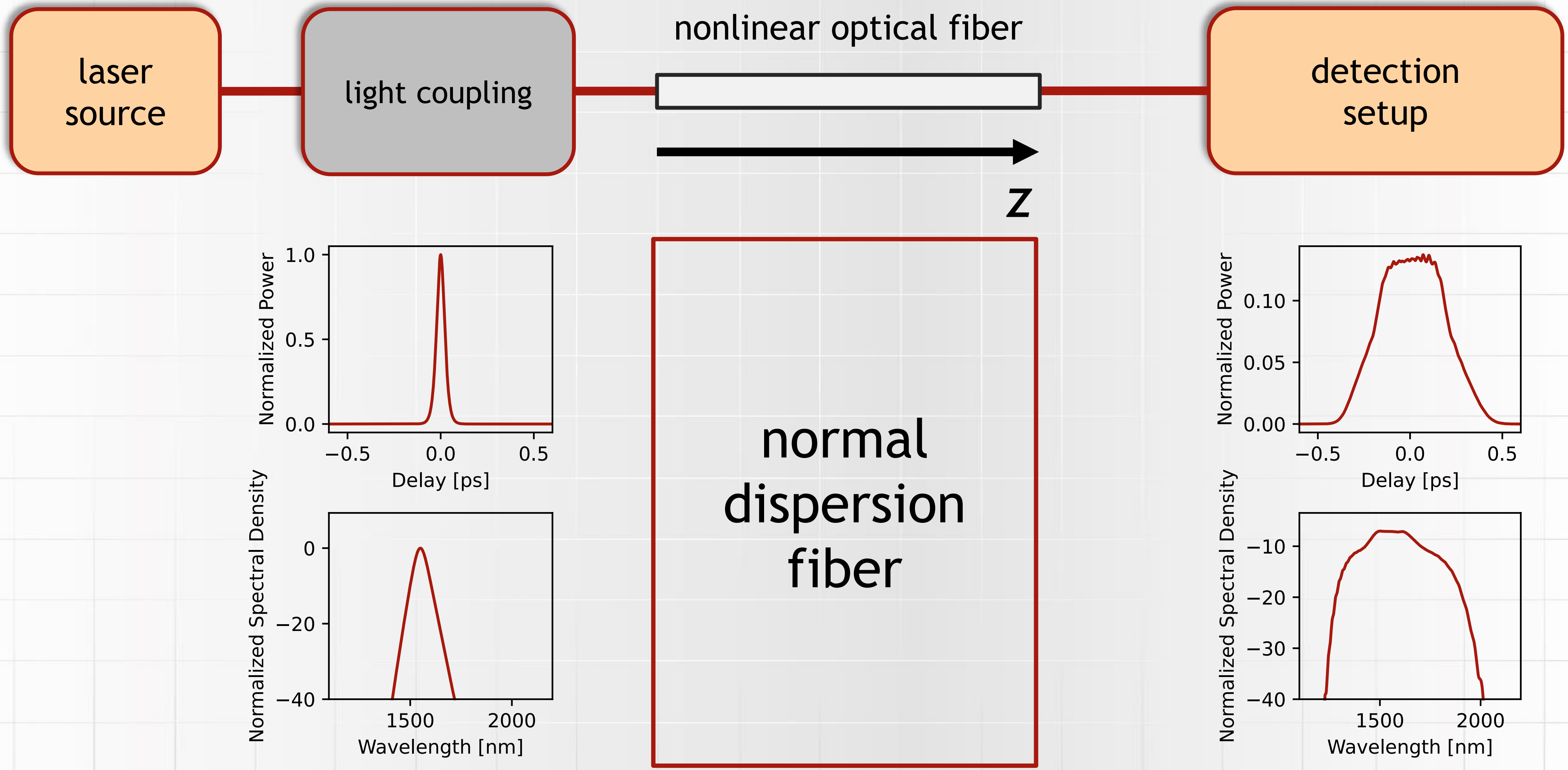
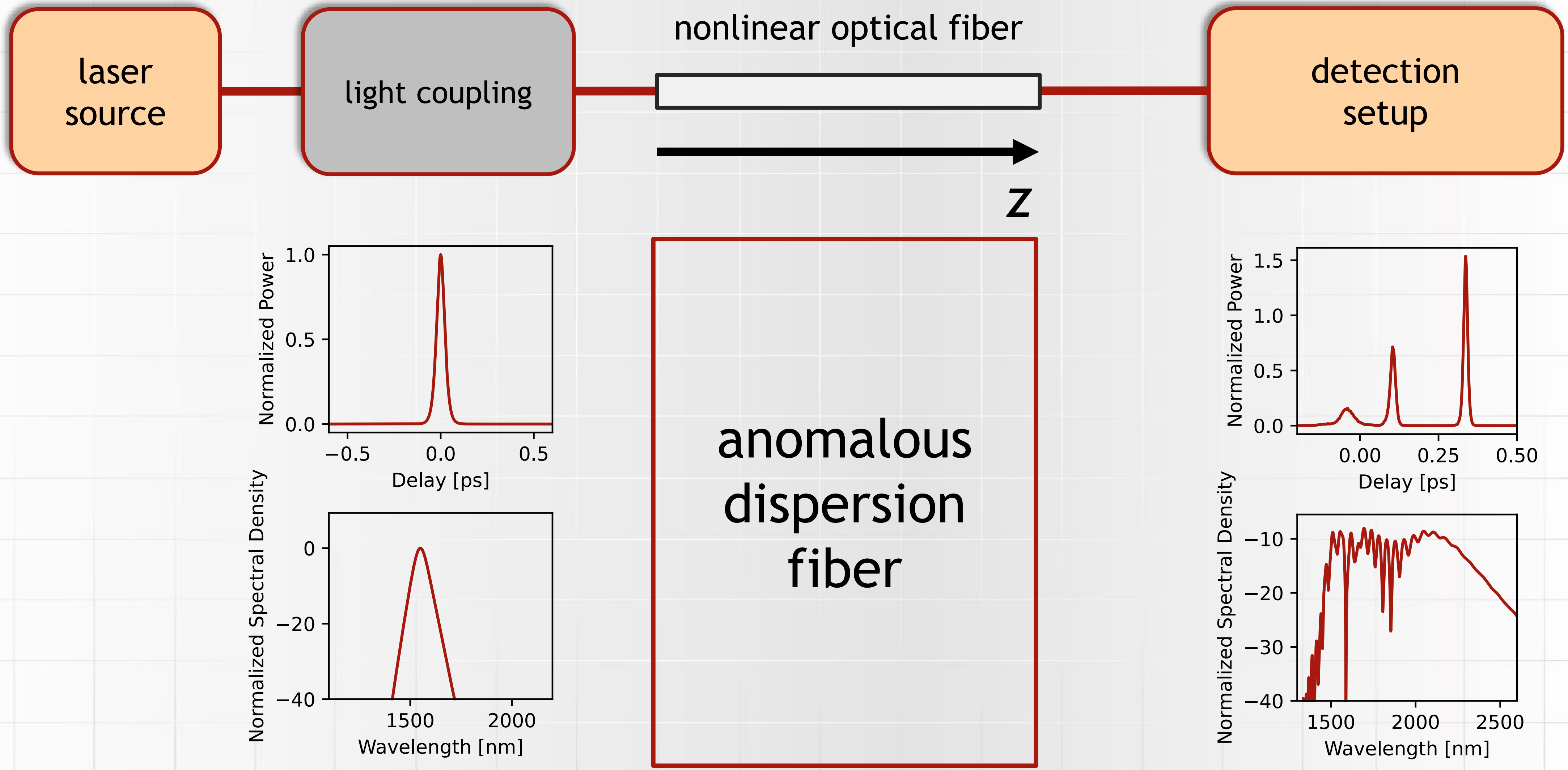
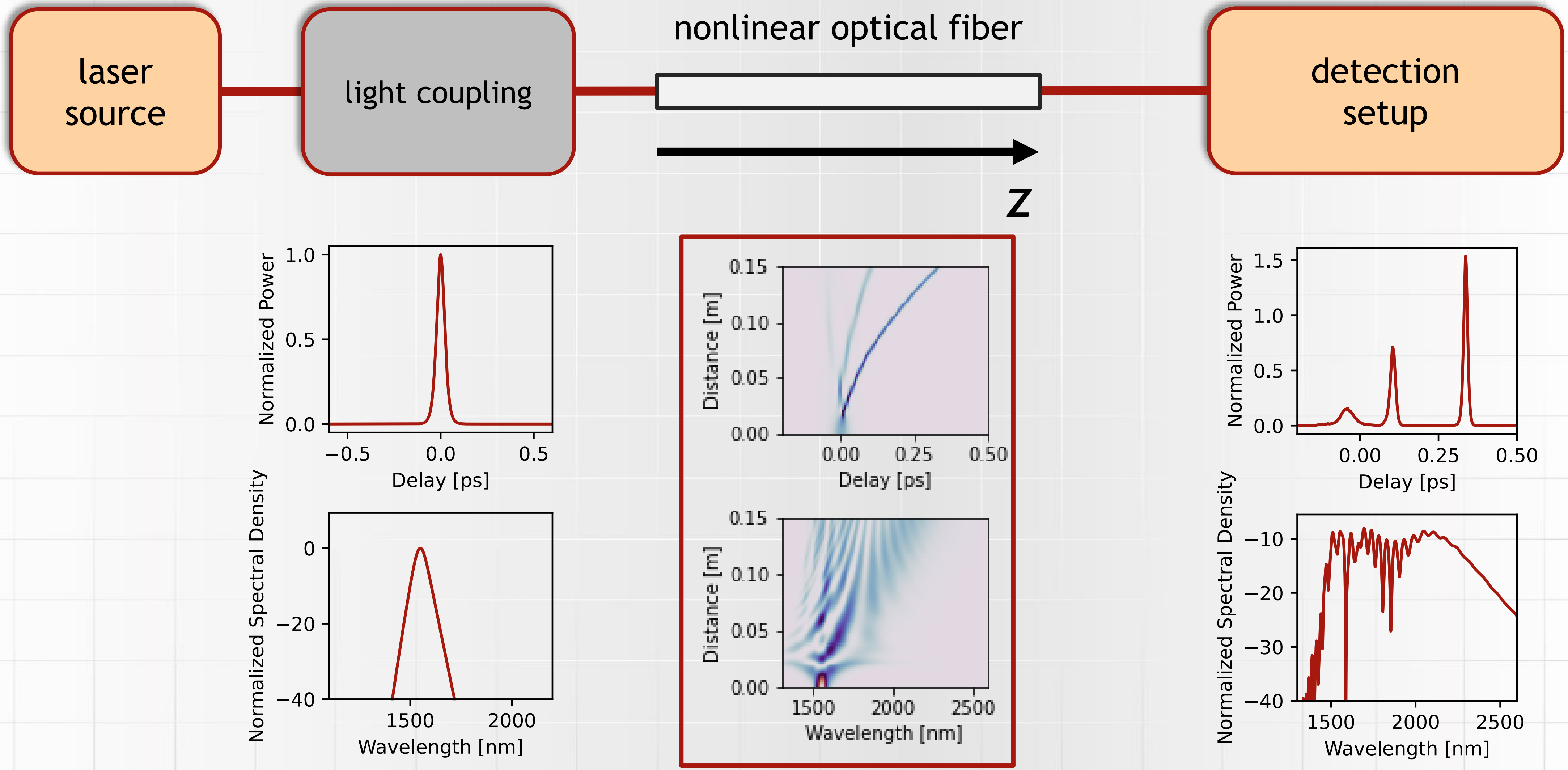
Numerical experiment



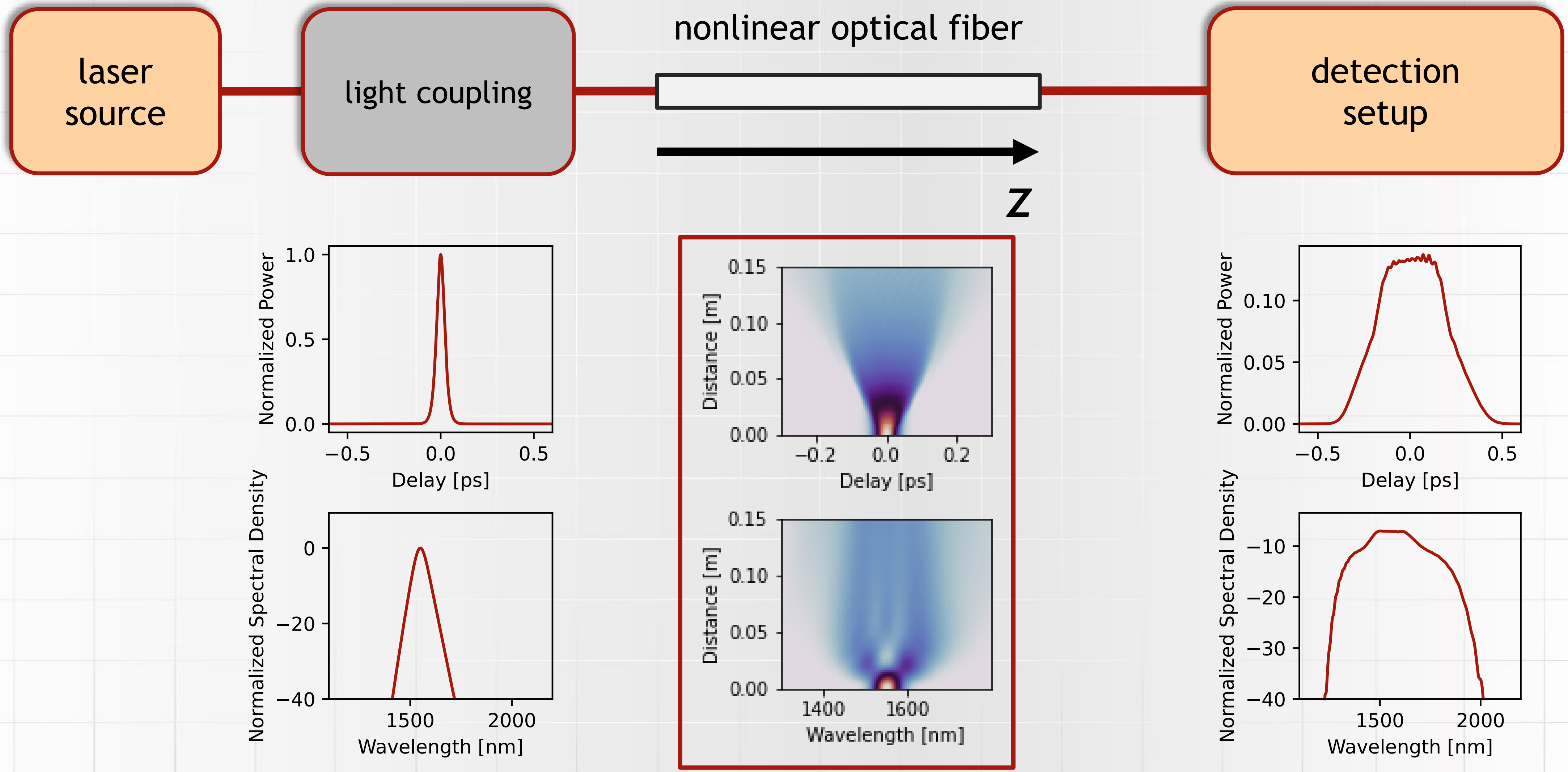
Numerical experiment



Numerical experiment



Numerical experiment



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Nonlinear Schrödinger equation

Generalized nonlinear Schrödinger equation

$$\frac{\partial A}{\partial z} = \underbrace{-\frac{\alpha}{2}A + i\sum_{n=1}^{\infty}\frac{i^n\beta_n}{n!}\frac{\partial^n A}{\partial t^n}}_{D(A)} + \underbrace{i\gamma A\int_0^{\infty}R(t')\left|A(z,t-t')\right|^2 dt'}_{N(A)}$$

Nonlinear Schrödinger equation

$$\frac{\partial A}{\partial z} = \left(-\frac{i\beta_2}{2}\frac{\partial^2}{\partial t^2} + i\gamma\left|A\right|^2\right)A$$

$$i\hbar\frac{\partial}{\partial t}\Psi = \left(-\frac{\hbar^2}{2m}\nabla^2 + V\right)\Psi$$

Frequency conversion

Optically induced change in the refracitve index

- self-phase modulation (SPM)
- cross-phase modulation (XPM)
  - same mode – different wavelengths
  - same mode – orthogonal polarizations
  - different modes
- modulation instability (MI)
- four-wave mixing (FWM)

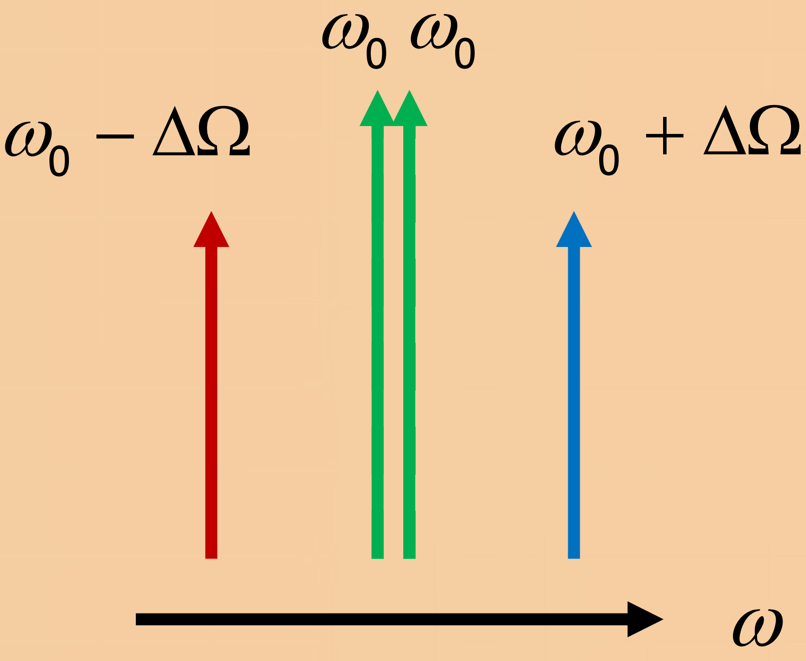
Inelastic scattering

- stimulated Raman scattering (SRS)

Frequency conversion

Optically induced change in the refracitve index

- SPM
- XPM
- MI
- degenerated FWM



Frequency conversion

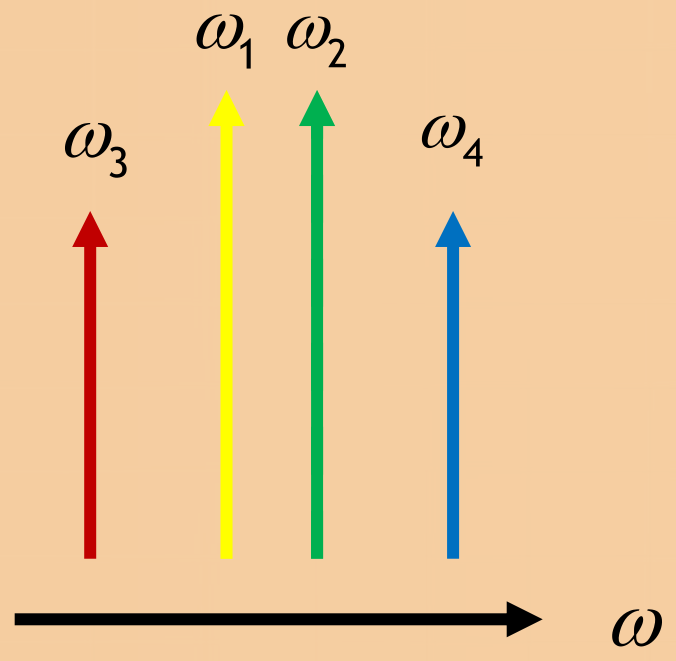
Optically induced change in the refracitve index

- four-wave mixing

$$\omega_1 + \omega_2 = \omega_3 + \omega_4$$

$$\beta_1 + \beta_2 = \beta_3 + \beta_4$$

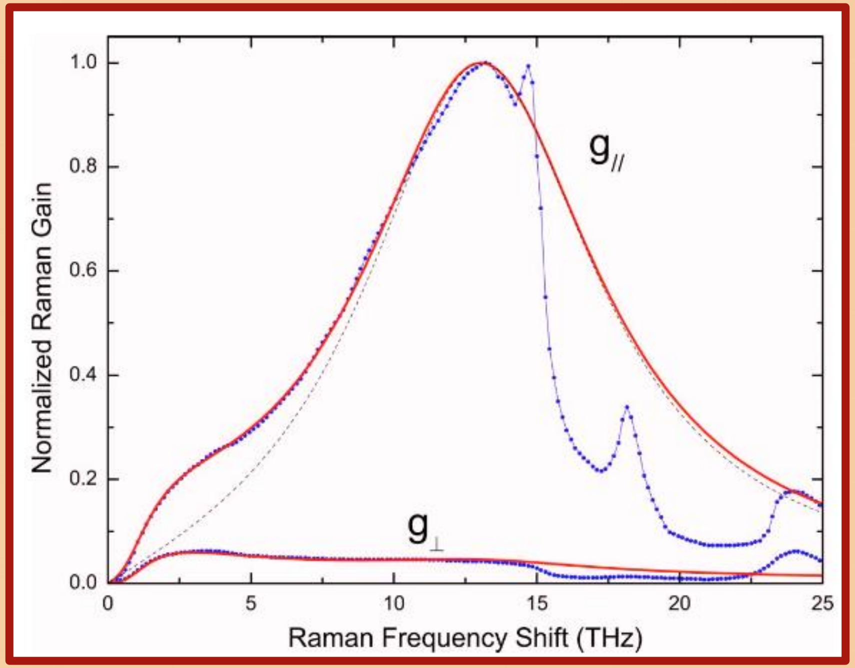
$$\beta_1 + \beta_2 = \beta_3 + \beta_4 + \Delta k_{NL}$$

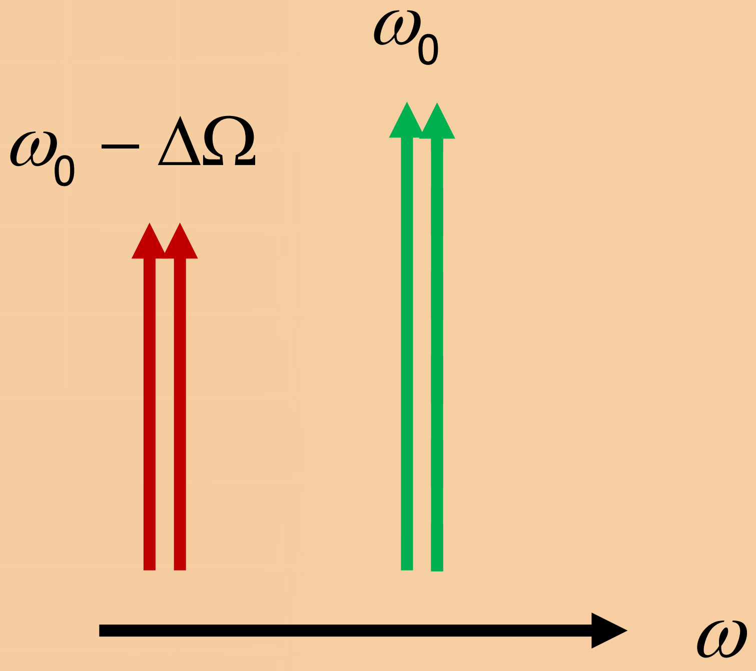


Frequency conversion

Inelastic scattering

- stimulated Raman scattering (SRS)



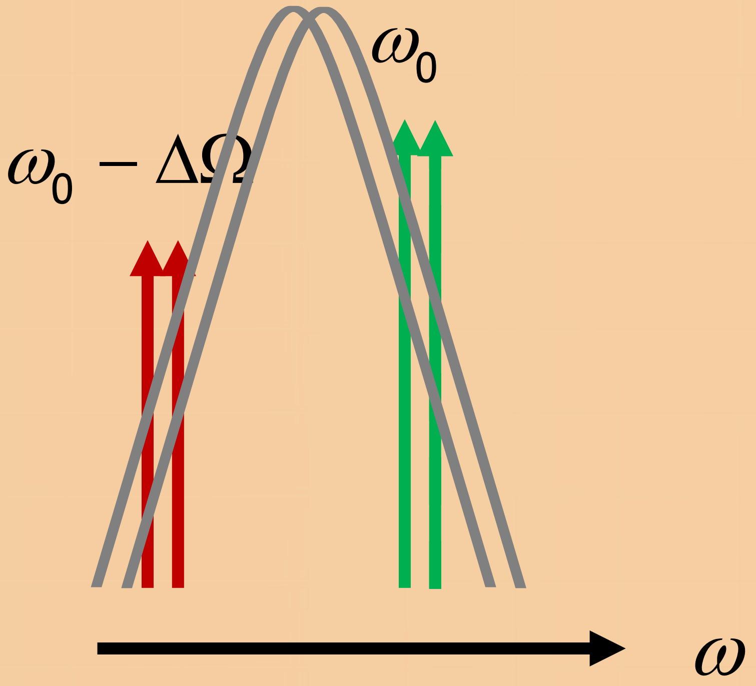


Q. Lin, G. P. Agrawal, Optics Letters, 31(21): 3086 (2006)

Frequency conversion

Inelastic scattering

- Intrapulse Raman scattering (SRS)



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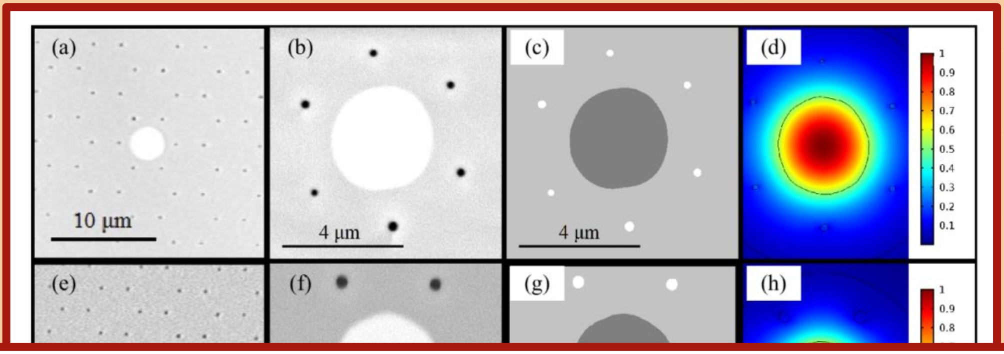
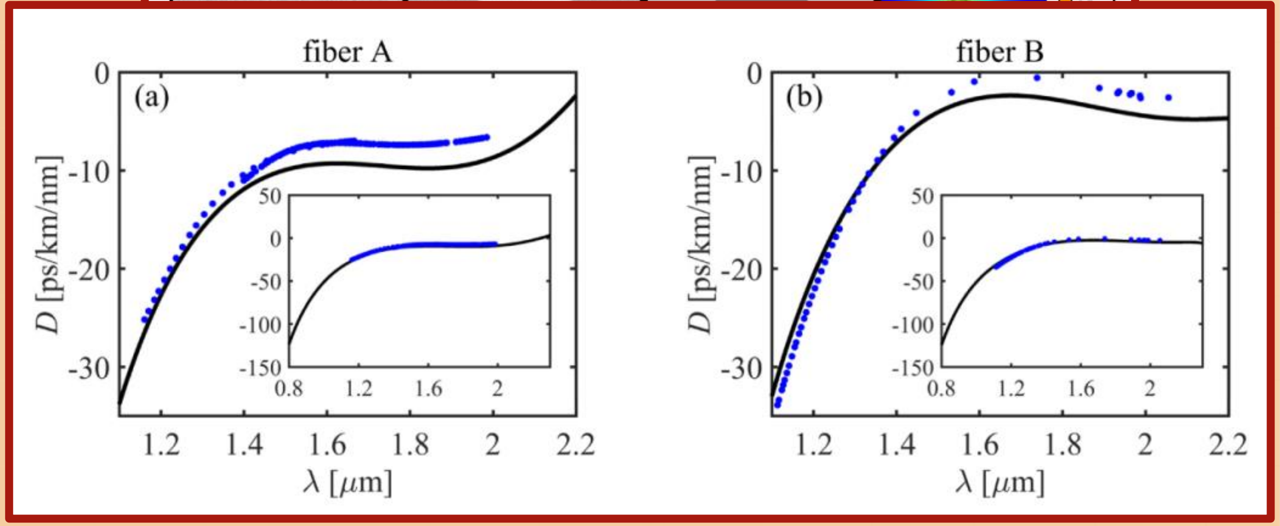
All-normal dispersion SC

Nonlinear microstructured fiber with normal dispersion

- design
- fabrication
- characterization
- supercontinuum generation





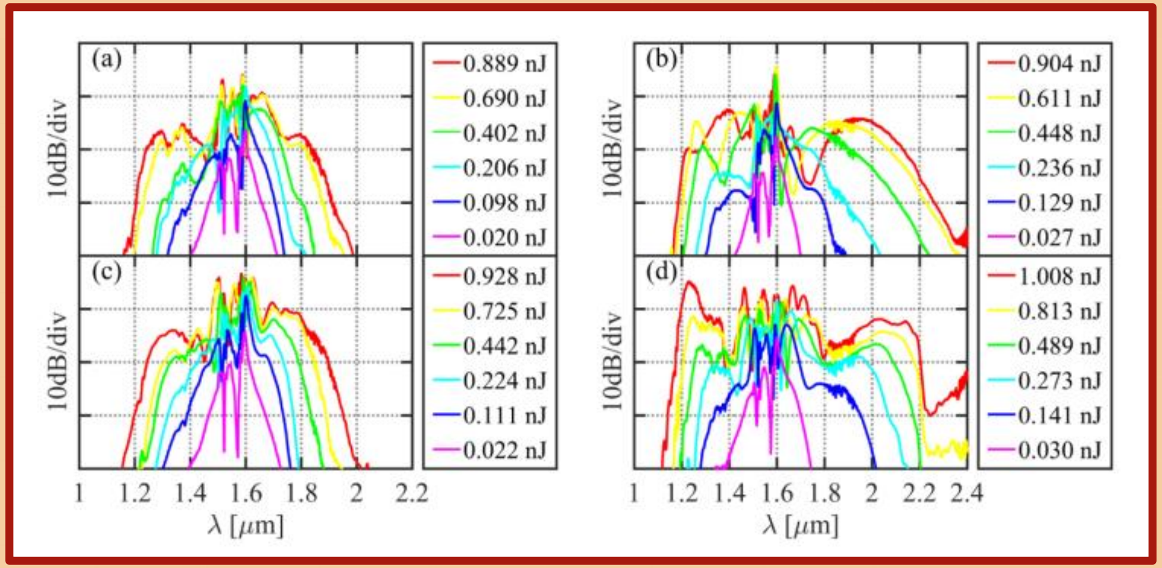
Optics Express, 24(26): 30523 (2016)

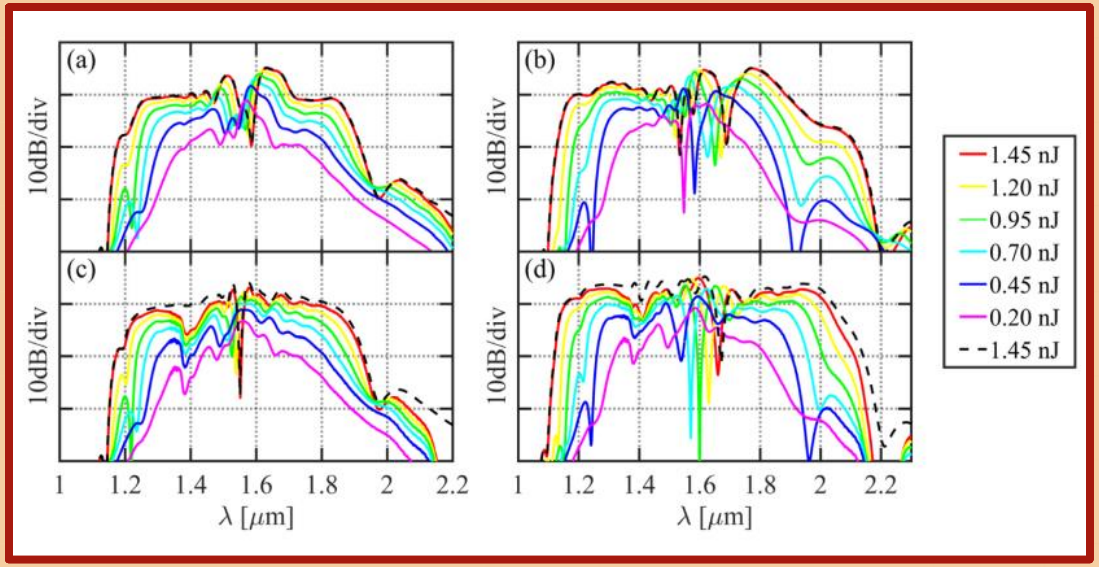
All-normal dispersion SC

Nonlinear microstructured fiber with normal dispersion

- Broad and coherent SC generated in an all-normal dispersion fiber

23-fs pumping





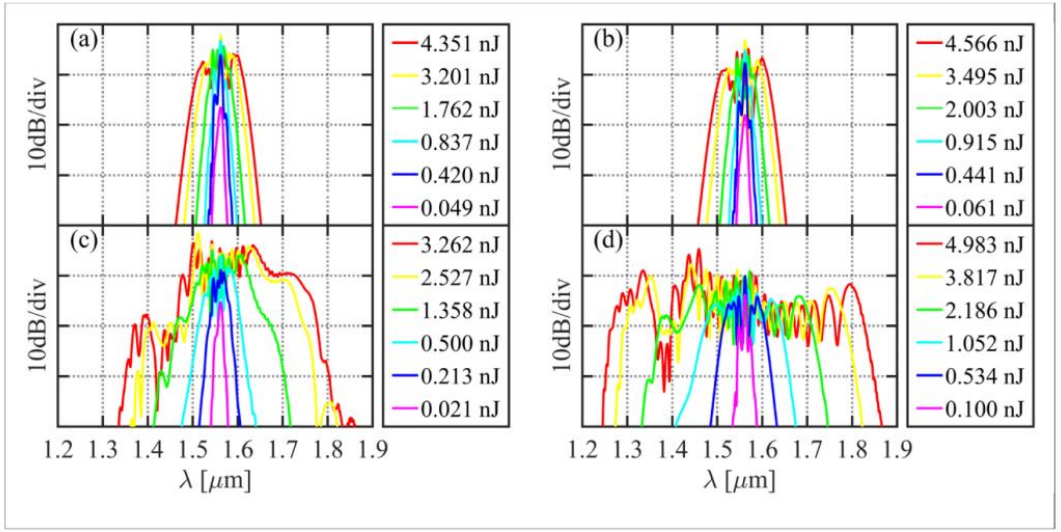
Optics Express, 24(26): 30523 (2016)

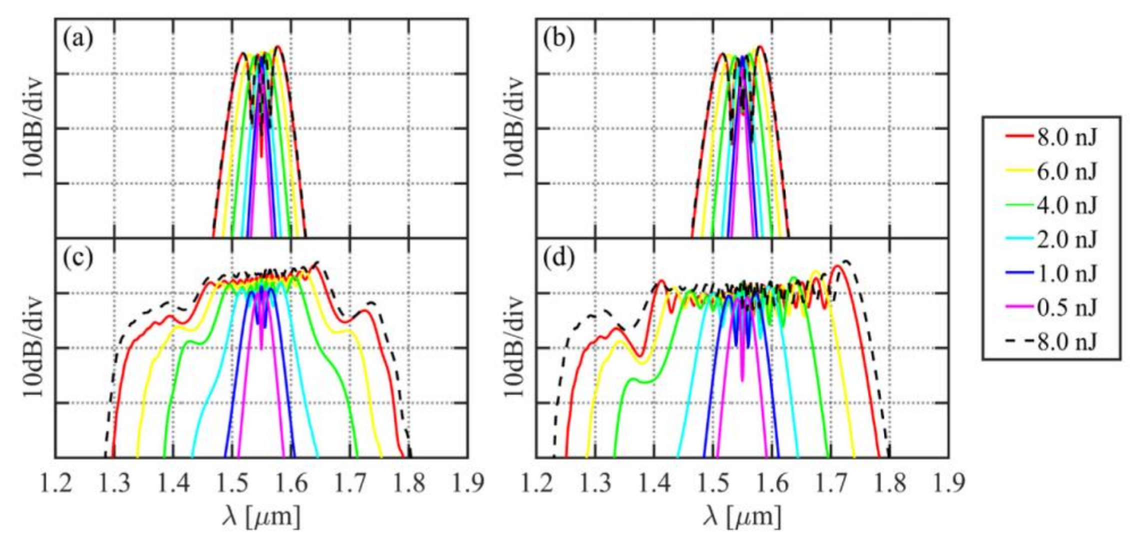
All-normal dispersion SC

Nonlinear microstructured fiber with normal dispersion

- Broad and coherent SC generated in an all-normal dispersion fiber

460-fs pumping





Optics Express, 24(26): 30523 (2016)

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Birefringent fibers

Coupled nonlinear Schrödinger equations

$$\tilde{C}_x = \sqrt[4]{\frac{A_{\text{eff}}(\omega)}{A_{\text{eff}}(\omega_0)}}\tilde{A}_x, \quad \tilde{C}_y = \sqrt[4]{\frac{A_{\text{eff}}(\omega)}{A_{\text{eff}}(\omega_0)}}\tilde{A}_y$$

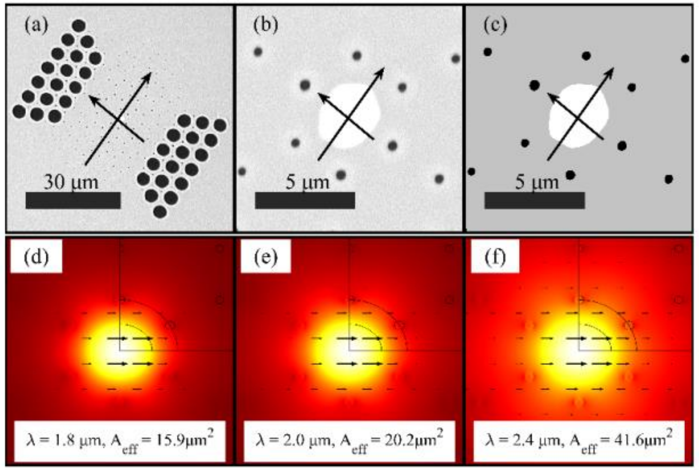
$$\frac{\partial \tilde{C}_x}{\partial z} = D_x\left(\tilde{C}_x\right) + \\ +i\frac{n_2 n_0 \omega}{c n_{\text{eff}}\sqrt{A_{\text{eff}}(\omega) A_{\text{eff}}(\omega_0)}} \cdot \mathcal{F}\left\{\left(\left|C_x\right|^2 + \frac{2}{3}\left|C_y\right|^2\right)C_x + \frac{1}{3}C_y^2 C_x^* \exp\left(-2i\Delta\beta z\right)\right\}$$

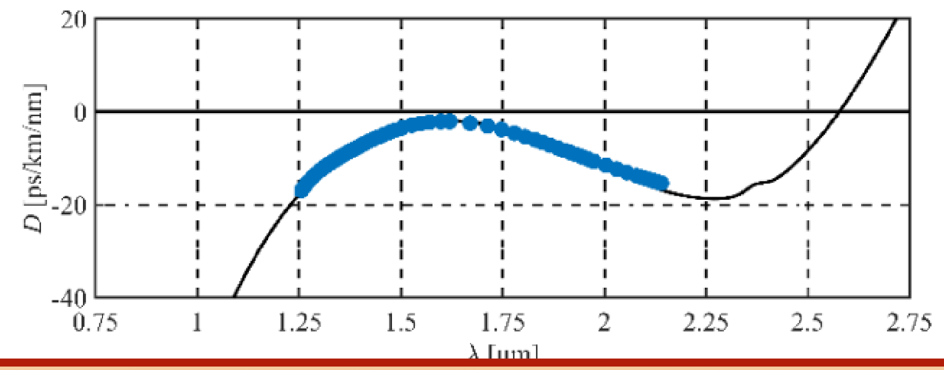
$$\frac{\partial \tilde{C}_y}{\partial z} = D_y\left(\tilde{C}_y\right) + \\ +i\frac{n_2 n_0 \omega}{c n_{\text{eff}}\sqrt{A_{\text{eff}}(\omega) A_{\text{eff}}(\omega_0)}} \cdot \mathcal{F}\left\{\left(\left|C_y\right|^2 + \frac{2}{3}\left|C_x\right|^2\right)C_y + \frac{1}{3}C_x^2 C_y^* \exp\left(+2i\Delta\beta z\right)\right\}$$

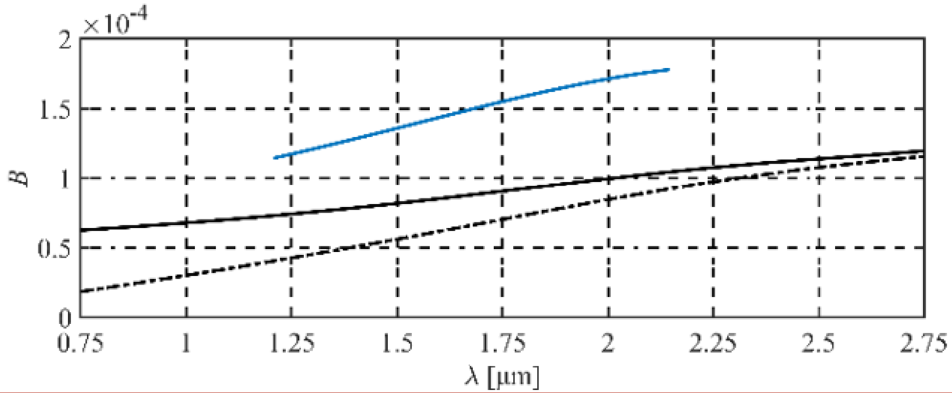
Polarized all-normal SC

Nonlinear birefringent microstructured fiber with normal dispersion

- design
- fabrication
- characterization
- supercontinuum generation





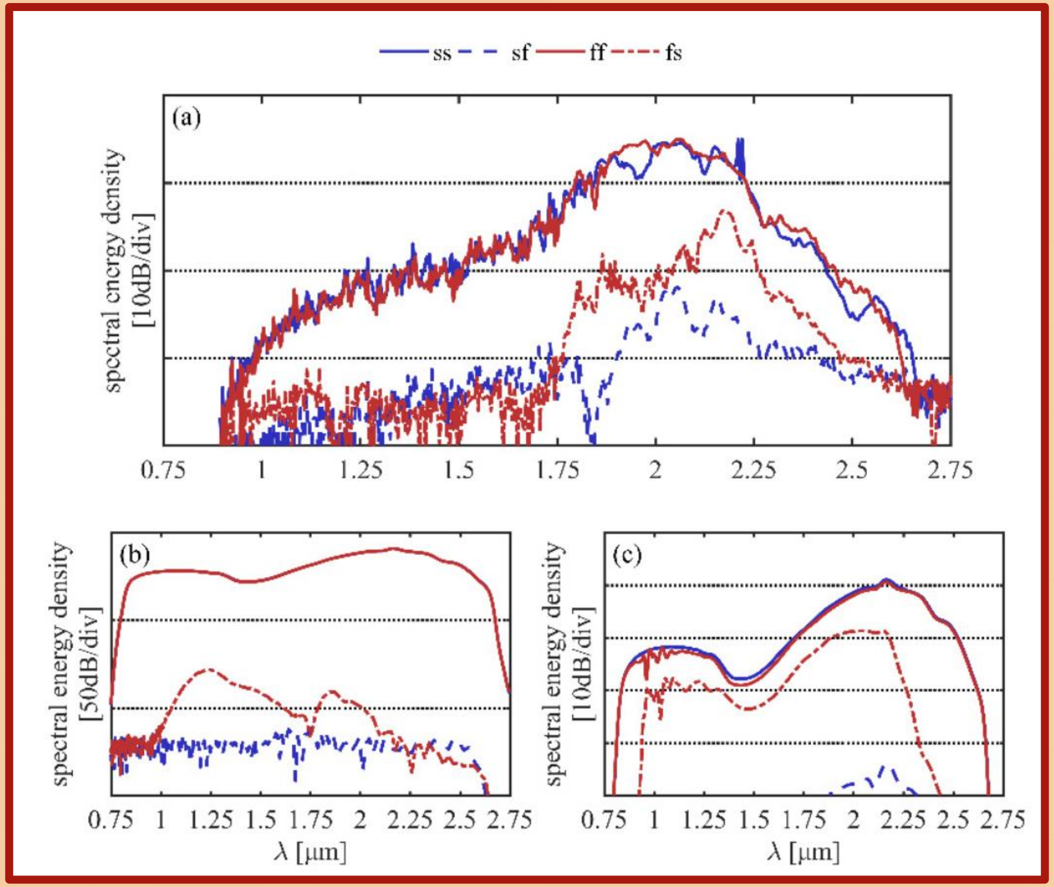


Optics Express 25(22): 27452-27463 (2017)

Polarized all-normal SC

Supercontinnum generation

- normal dispersion regime
- polarized
- coherent



Optics Express 25(22): 27452-27463 (2017)

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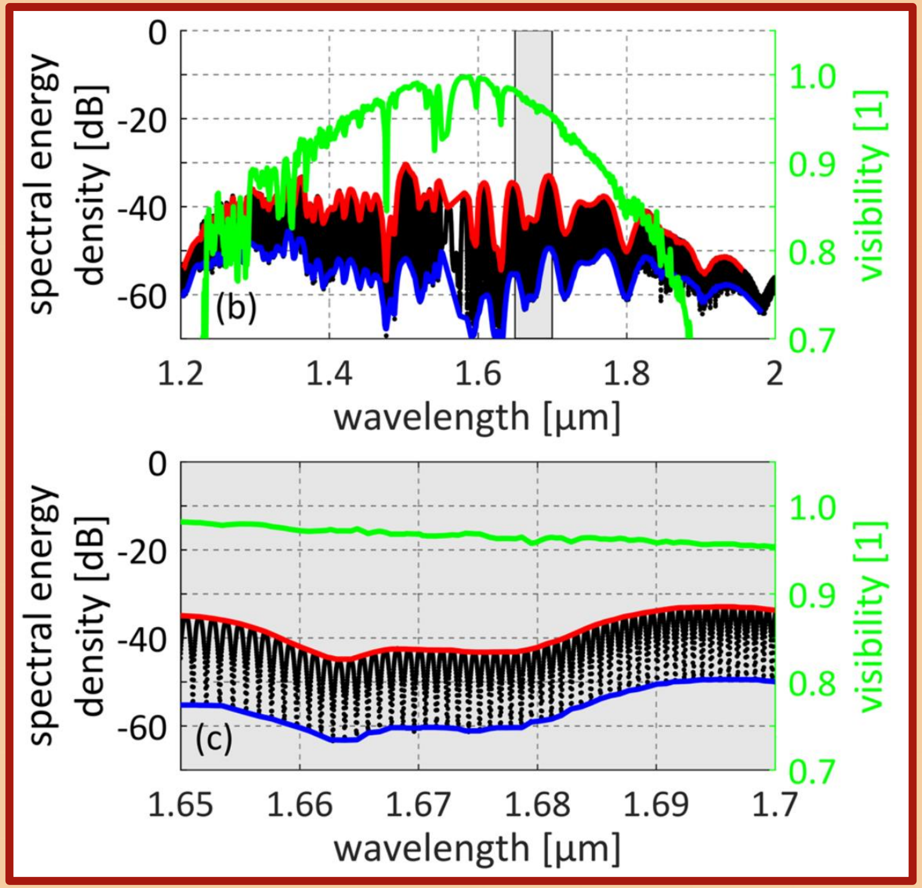
Polarized all-normal SC

Supercontinnum generation

- normal dispersion regime
- polarized
- coherent



Scientific Reports 9: 12313 (2019)

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Few mode fibers

System of coupled nonlinear Schrodinger equations

$$\frac{\partial A_p}{\partial z} = -\frac{\alpha_p}{2} A_p + i\left(\beta_0^{(p)} - \beta_0^{(0)}\right) A_p +$$

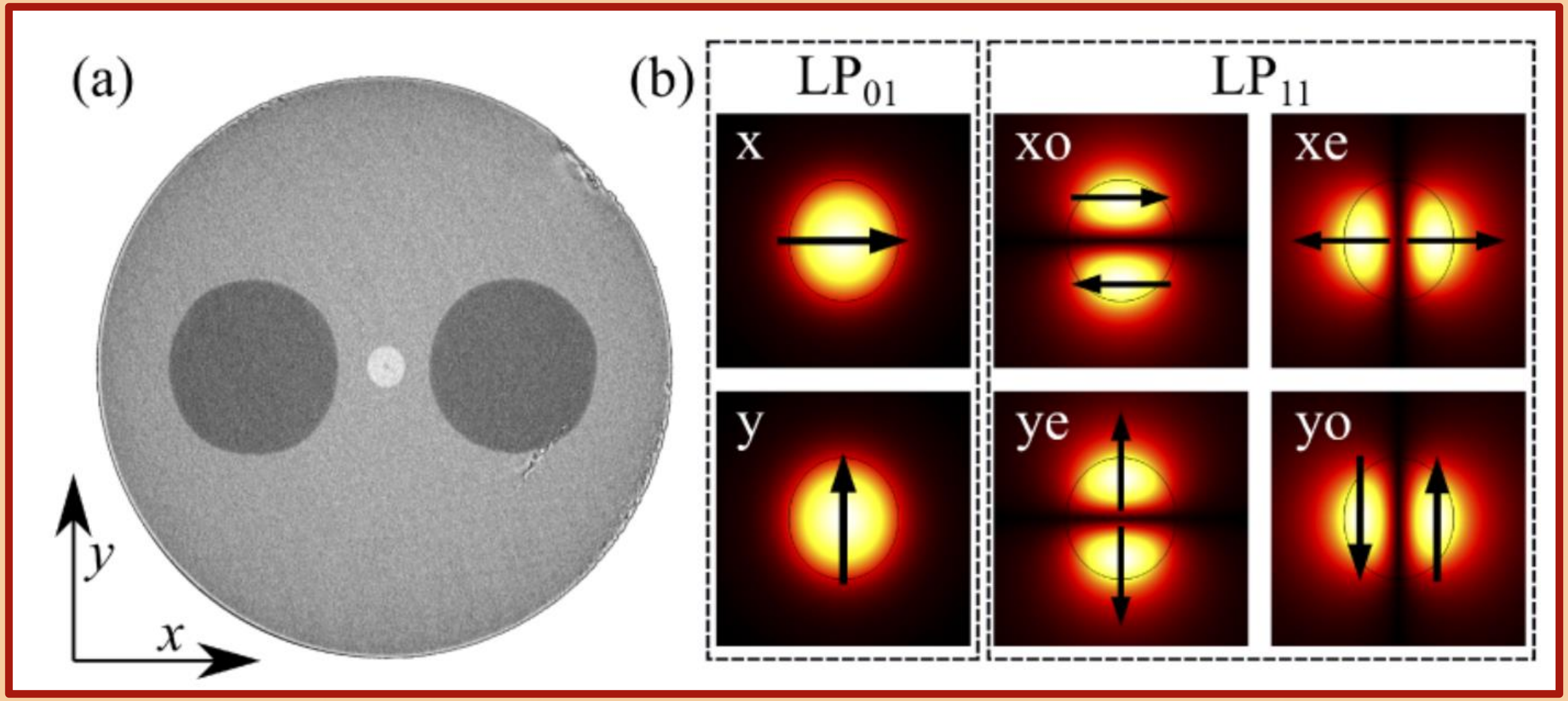
$$-\left(\beta_1^{(p)} - \beta_1^{(0)}\right)\frac{\partial A_p}{\partial t} + i\sum_{n\geq 2}^{\infty} \frac{i^n \beta_n^{(p)}}{n!} \frac{\partial^n A_p}{\partial t^n} +$$

$$+i\frac{n_2 \omega_0}{c}\left(1 + \frac{i}{\omega_0}\frac{\partial}{\partial t}\right) \times$$

$$\times \sum_{l,m,n}^{N-1} \left\{ \left(1 - f_R\right) S_K^{(plmn)} A^{(l)} A^{(m)} A^{(n)*} + f_R S_R^{(plmn)} A^{(l)} \left[h \otimes \left(A^{(m)} A^{(n)*} \right) \right] \right\}$$

Intermodal-vectorial FWM

Fiber modes

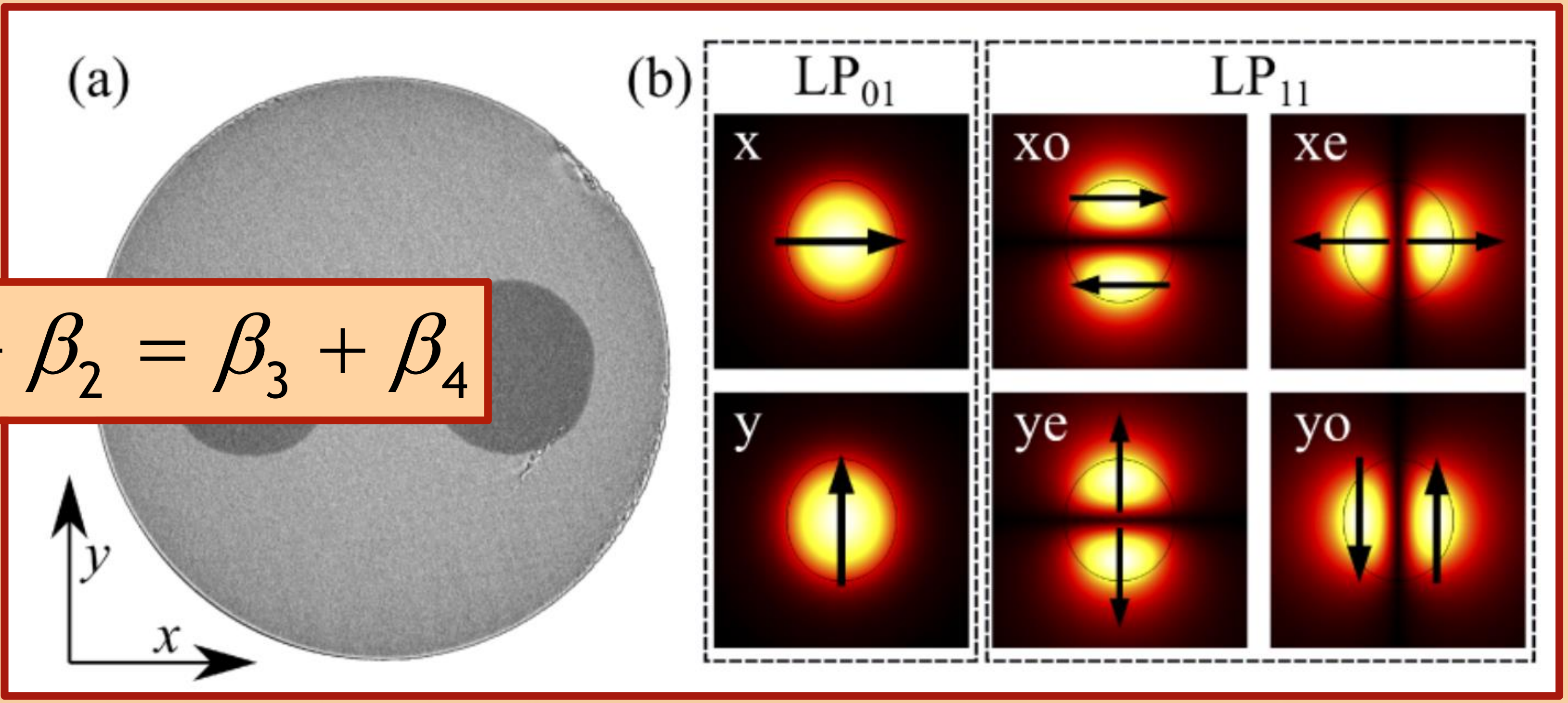


S. Majchrowska, K. Żołnacz et al., Optics Letters 47(10): 2522 (2022)

Intermodal-vectorial FWM

Phase matching condition

$$\beta_1 + \beta_2 = \beta_3 + \beta_4$$



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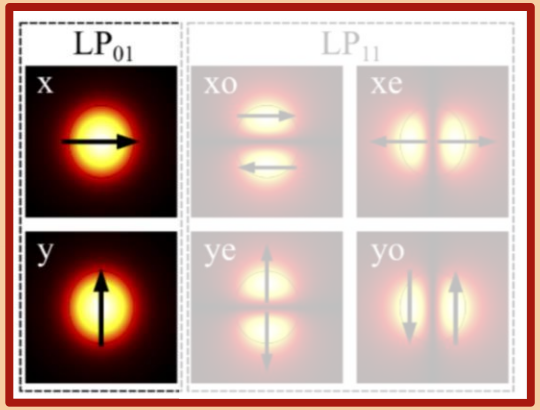
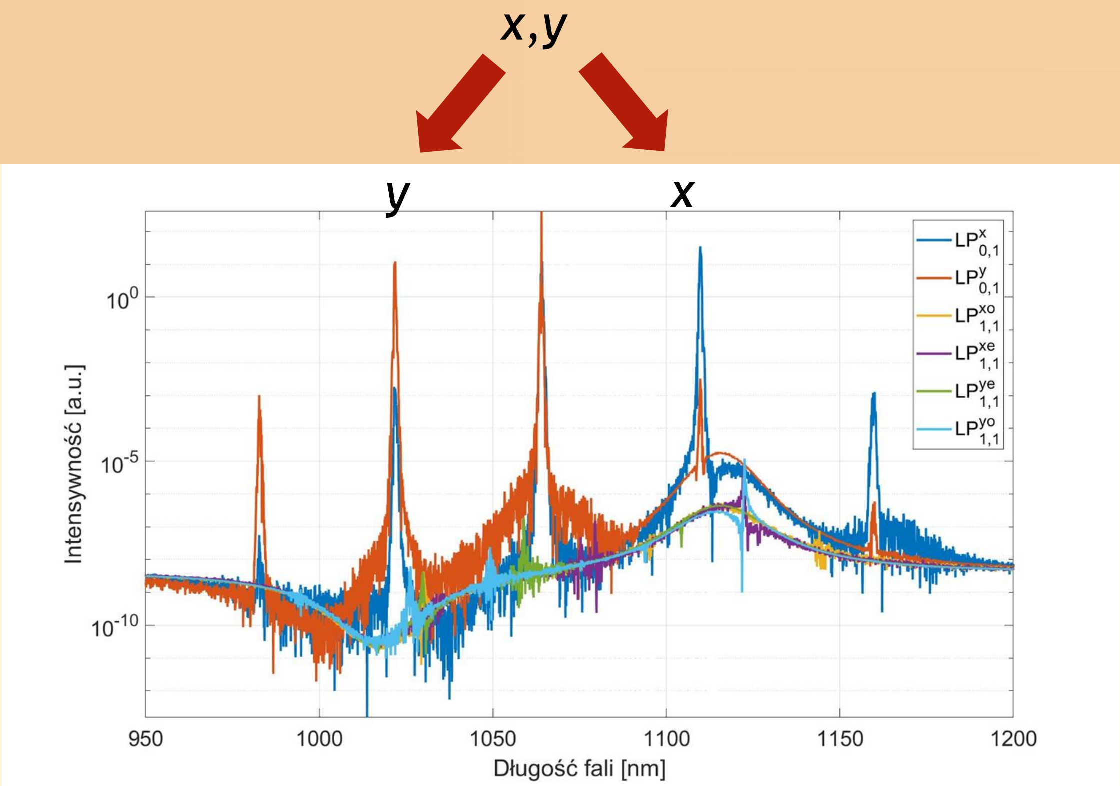
Intermodal-vectorial FWM

Vectorial FWM



$$\beta_0^x + \beta_0^y = \beta_0^x + \beta_1^x\Omega + \frac{1}{2}\beta_2^x\Omega^2 + \beta_0^y - \beta_1^y\Omega + \frac{1}{2}\beta_2^y\Omega^2$$

$$-\Delta\beta_1\Omega = \beta_2\Omega^2$$



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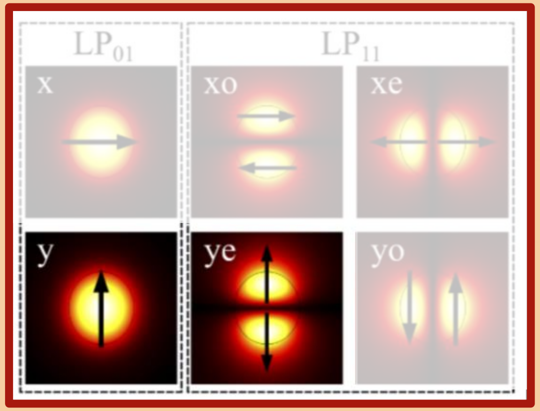
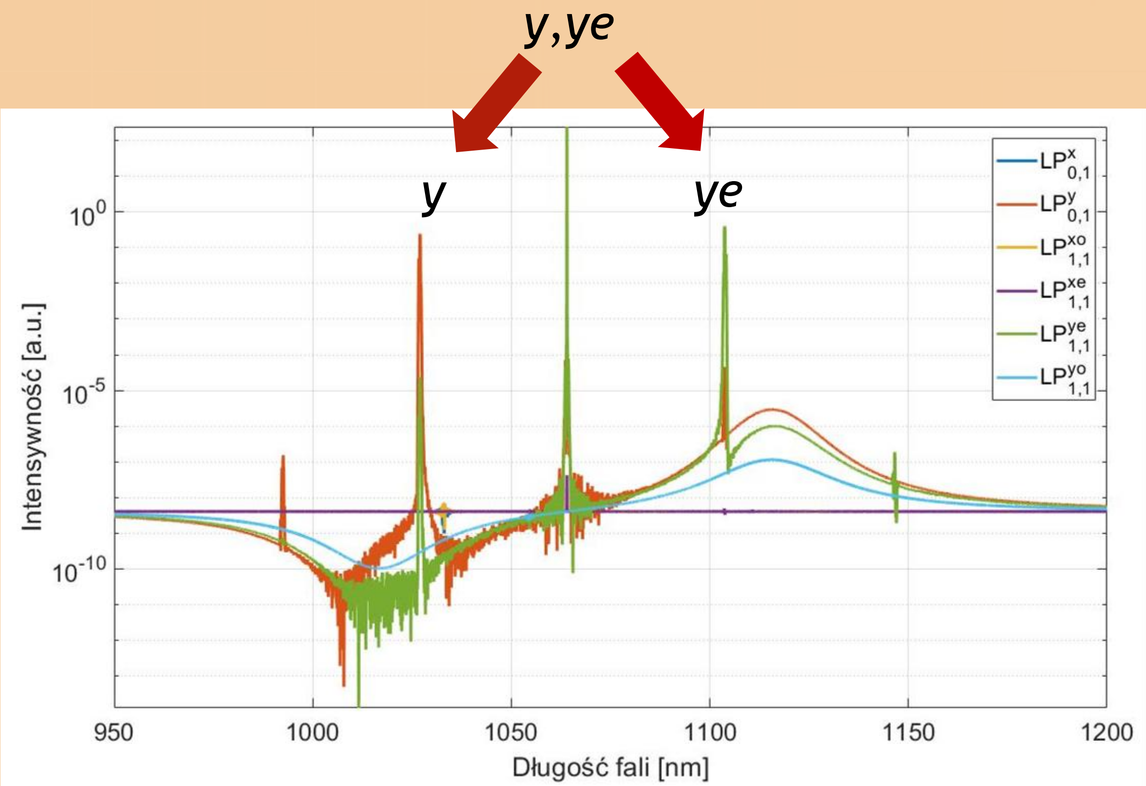
Intermodal-vectorial FWM

Intermodal FWM



$$\beta_0^{y} + \beta_0^{ye} = \beta_0^{y} + \beta_1^{y}\Omega + \frac{1}{2}\beta_2^{y}\Omega^2 + \beta_0^{ye} - \beta_1^{ye}\Omega + \frac{1}{2}\beta_2^{ye}\Omega^2$$

$$-\Delta\beta_1\Omega = \beta_2\Omega^2$$



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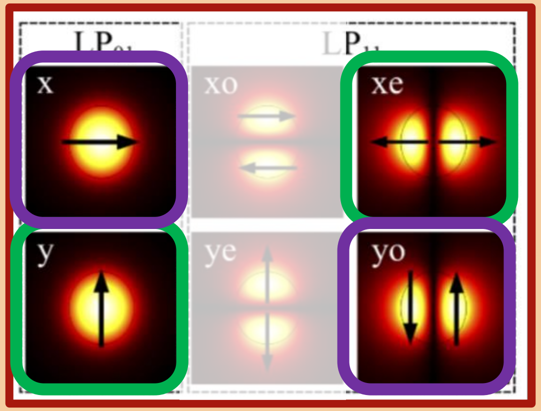
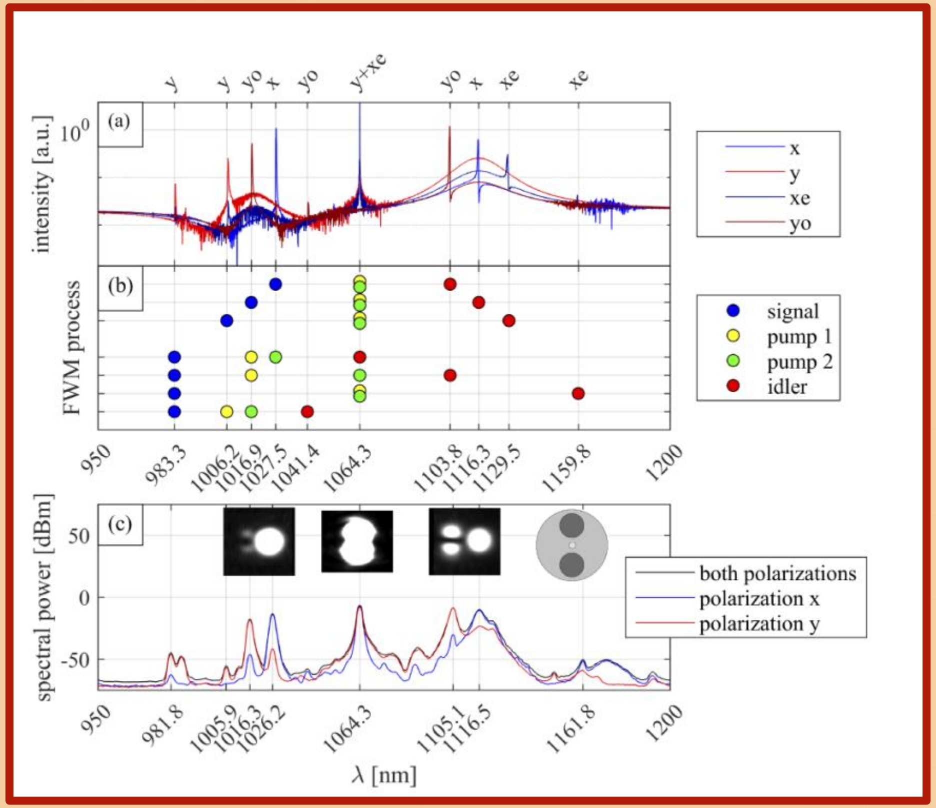
Intermodal-vectorial FWM

Proccesses enabled by selective excitation of modes





$$\beta_0^y + \beta_0^{xe} = \beta_0^x + \beta_1^x\Omega + \frac{1}{2}\beta_2^x\Omega^2 + \beta_0^{ye} - \beta_1^{ye}\Omega + \frac{1}{2}\beta_2^{ye}\Omega^2$$

$$\frac{1}{2}\left(\beta_2^x + \beta_2^{ye}\right)\Omega^2 + \left(\beta_1^x - \beta_1^{ye}\right)\Omega + \Delta\beta_0^{x,y} - \Delta\beta_0^{xe,ye} = 0$$

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Summary

- Optical fibers are interesting media for investigating nonlinear processes
- Properties of optical fibers can be tailored
- Numerical simulations allow to get insight into dynamics of nonlinear conversion processes

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Acknowledgments

Fiber Optics Group
www.fog.pwr.edu.pl

- Prof. Wacław Urbańczyk
- Tadeusz Martynkien
- Kinga Żołnacz
- Sylwia Majchrowska
- Andrzej Gawilk
- Karolina Stefańska
- Rafał Cichowski

Laboratory of Optical Fiber Technology, Lublin

- Paweł Mergo
- Krzysztof Poturaj

Laser & Fiber Electronics Group, Wrocław

- Jarosław Sotor
- Grzegorz Soboń

Laboratoire Interdisciplinaire Carnot de Bourgogne, Dijon

- Bertrand Kibler
- Karolina Stefańska
- Pierre Béjot

Acknowledgments

Narodowe Centrum Nauki

- 2014/13/D/ST7/02090, Sonata 7 Program
- 2018/30/E/ST7/00862, Sonata Bis 8
- 2016/22/A/ST7/00089, Maestro 8

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Narodowa Agencja Wymiany Akademickiej

- Polonium 2019-2021
- Polonium 2023-2024

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Acknowledgments

Thank you for your attention