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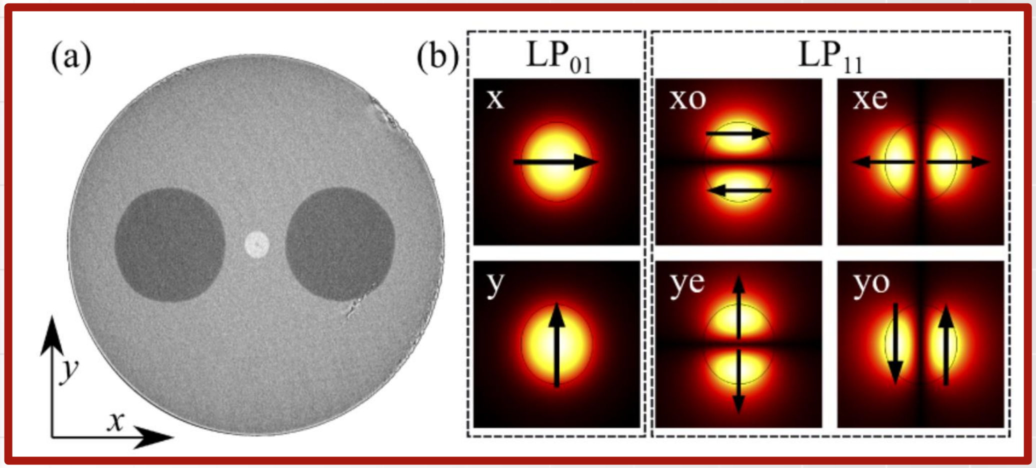
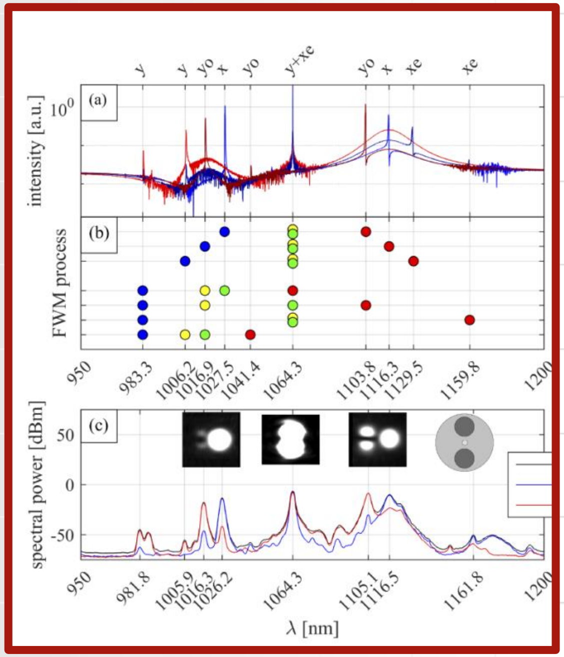
Selected frequency conversion processes in optical fibers





Karol Tarnowski

Faculty of Fundamental Problems of Technology
Department of Optics and Photonics
Fiber Optics Group
30.01.2023

HR EXCELLENCE IN RESEARCH

Outline

Introduction	• Description of frequency conversion processes in optical fibers
Single mode propagation	• All-normal dispersion supercontinuum • Soliton self-frequency shift
Birefringent fibers	• Polarized all-normal dispersion SC • Solitons - orthogonal Raman scattering • Vector modulation instability
Few mode fibers	• Intermodal-vectorial four wave mixing
Multimode fibers	• Discretized conical emission

Outline

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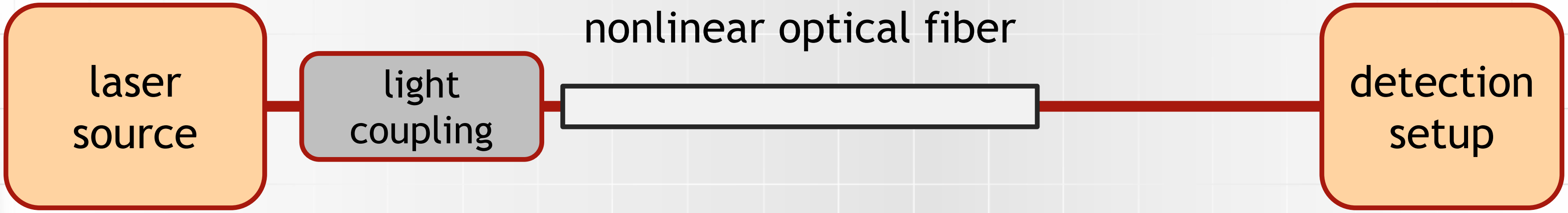
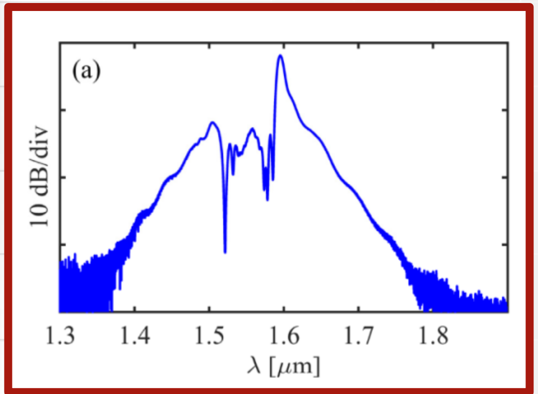
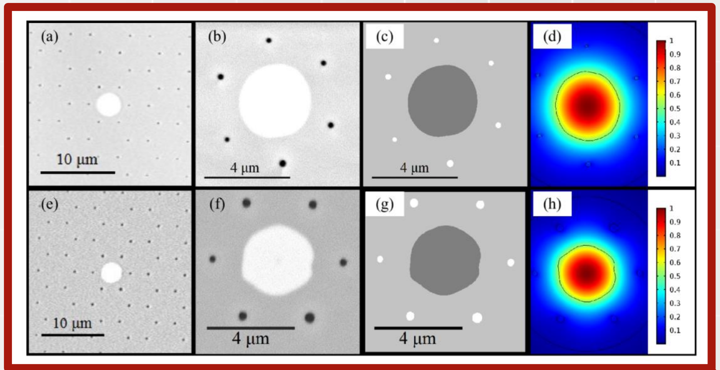
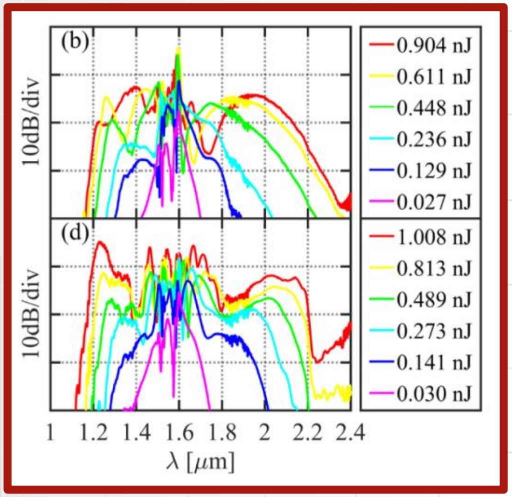
Few mode fibers	• Intermodal-vectorial four wave mixing
Multimode fibers	• Conical emission

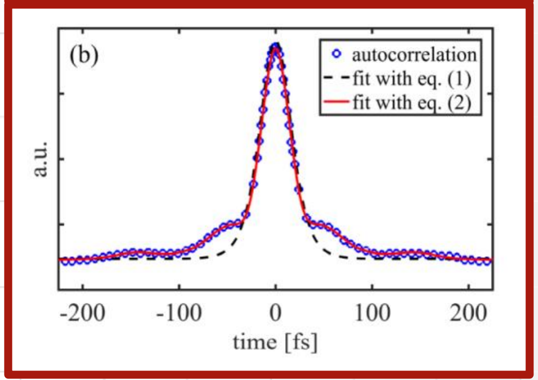
Typical experimental setup

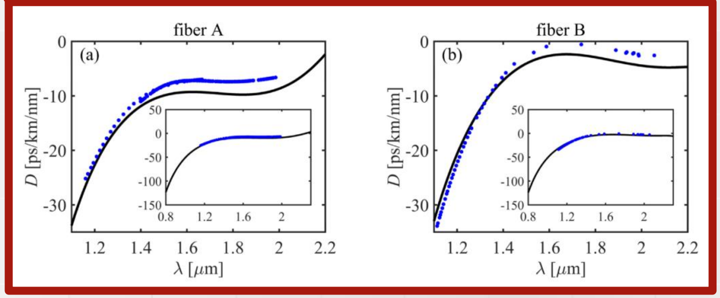




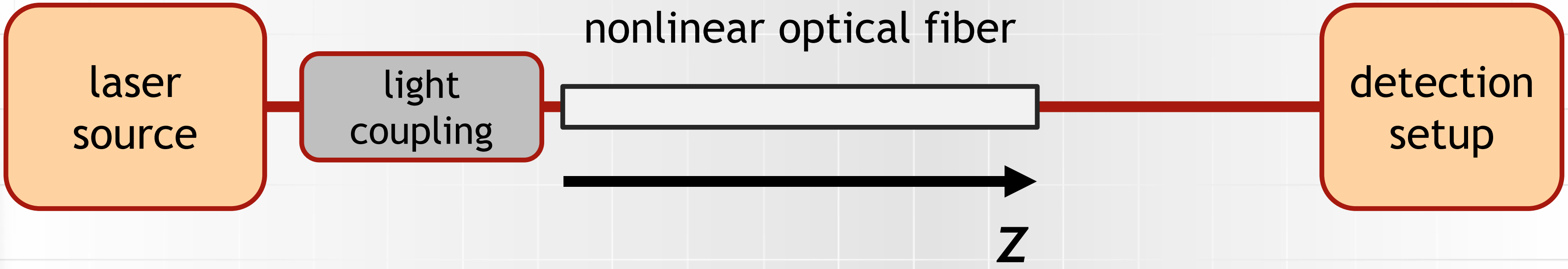








Numerical experiment



laser source

light coupling

nonlinear optical fiber

detection setup

z

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

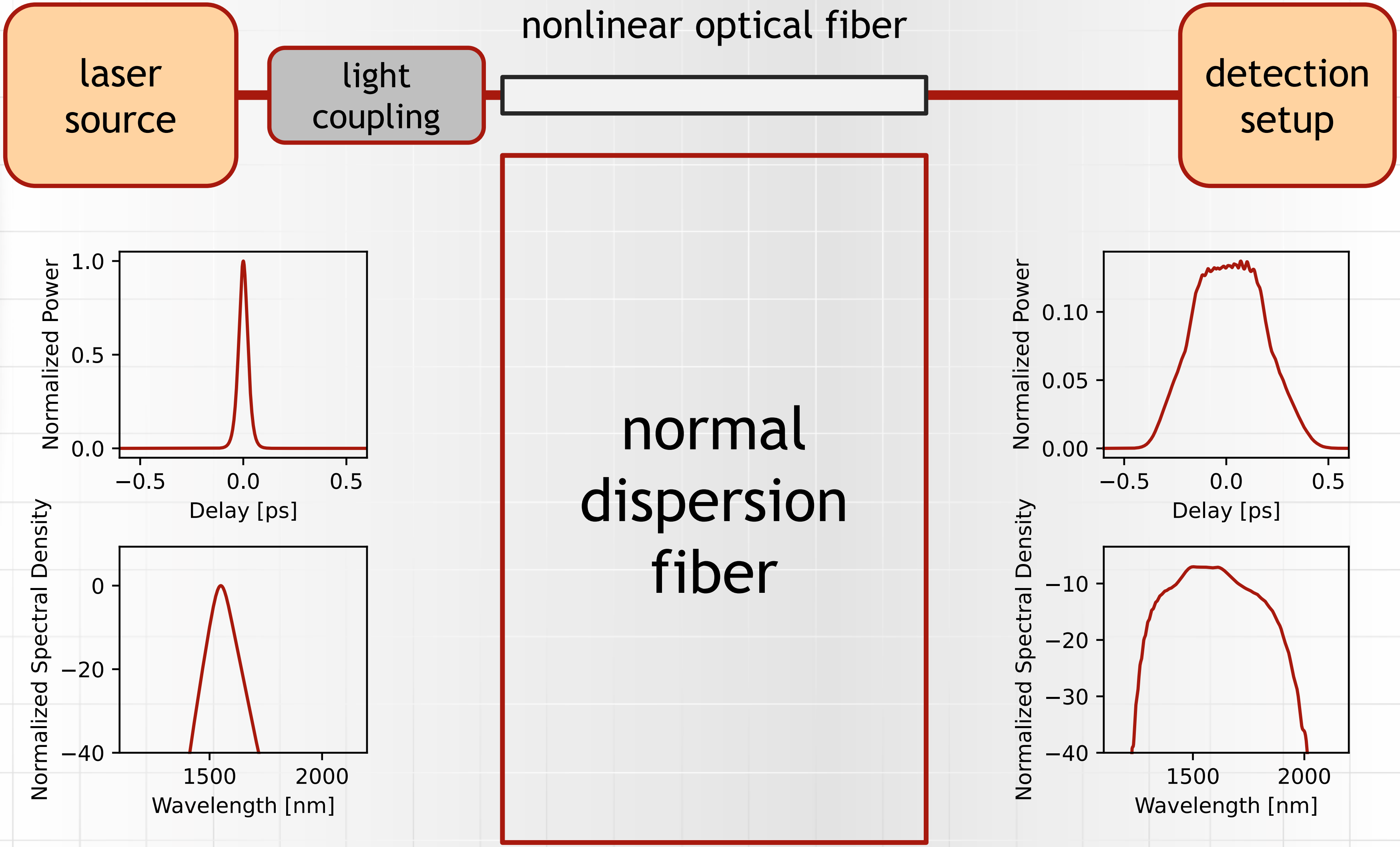
$$\tilde{A}(0,\Omega) = \mathcal{F}\left\{A(0,T)\right\}$$

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

$$I_\Omega = \left|A(z,\Omega)\right|^2$$

$$I_T = \left|A(z,T)\right|^2$$

Numerical experiment



laser source

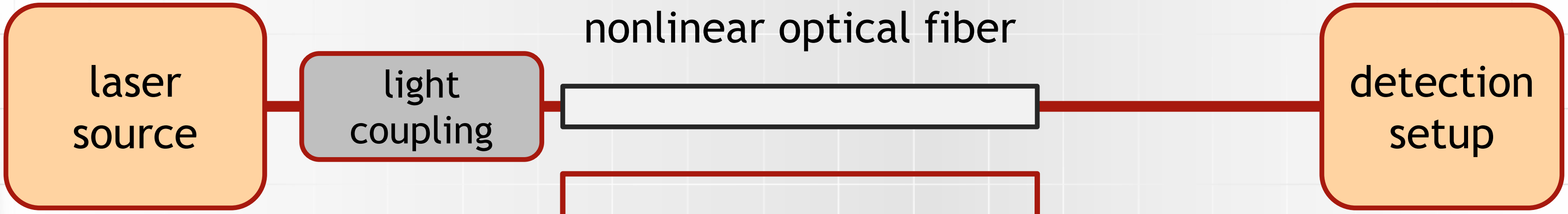
light coupling

nonlinear optical fiber

detection setup

normal dispersion fiber

Numerical experiment

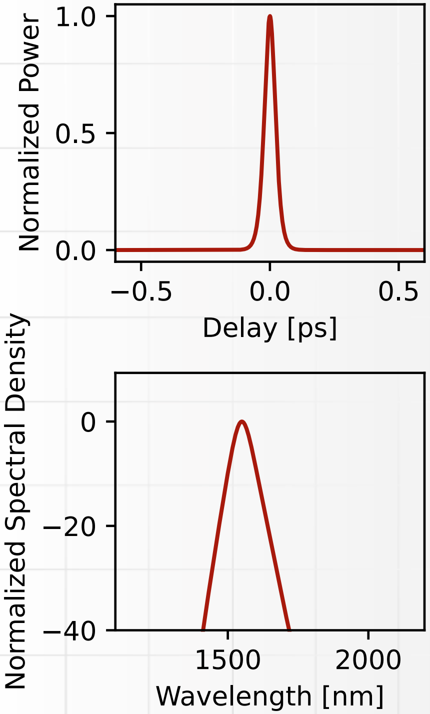


laser source

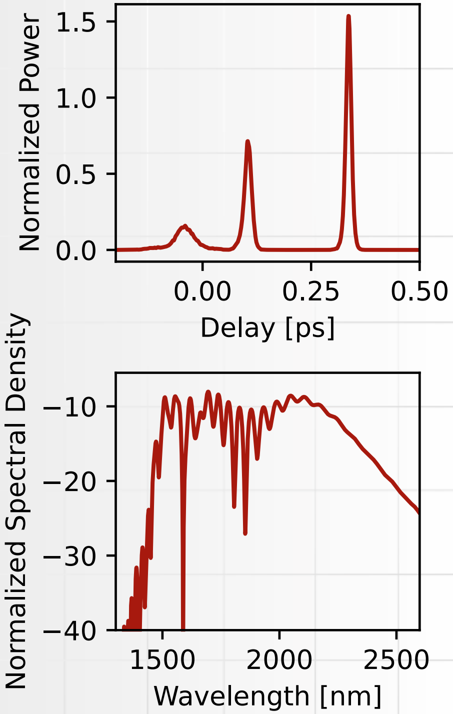
light coupling

nonlinear optical fiber

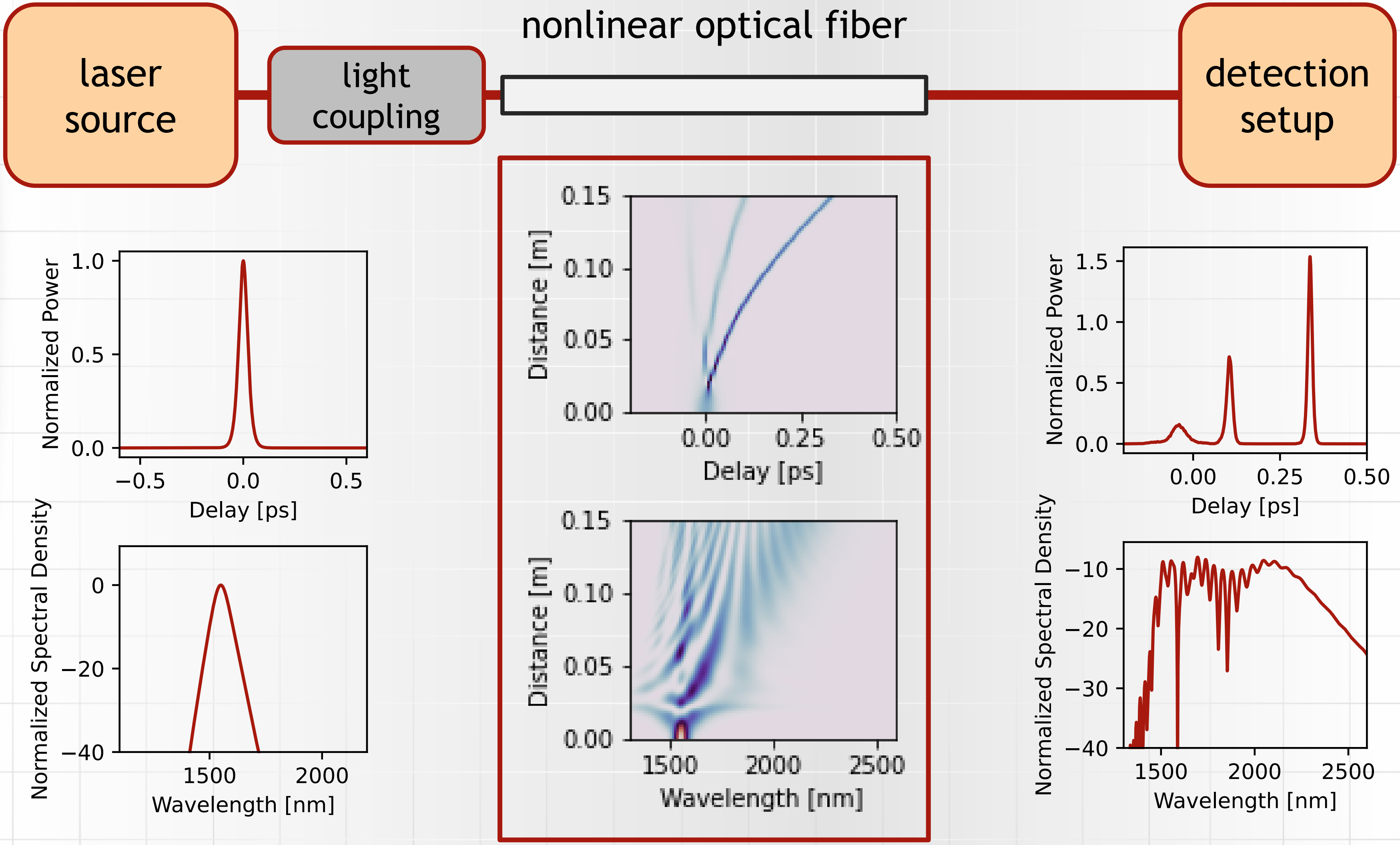
detection setup



anomalous dispersion fiber



Numerical experiment



laser source

light coupling

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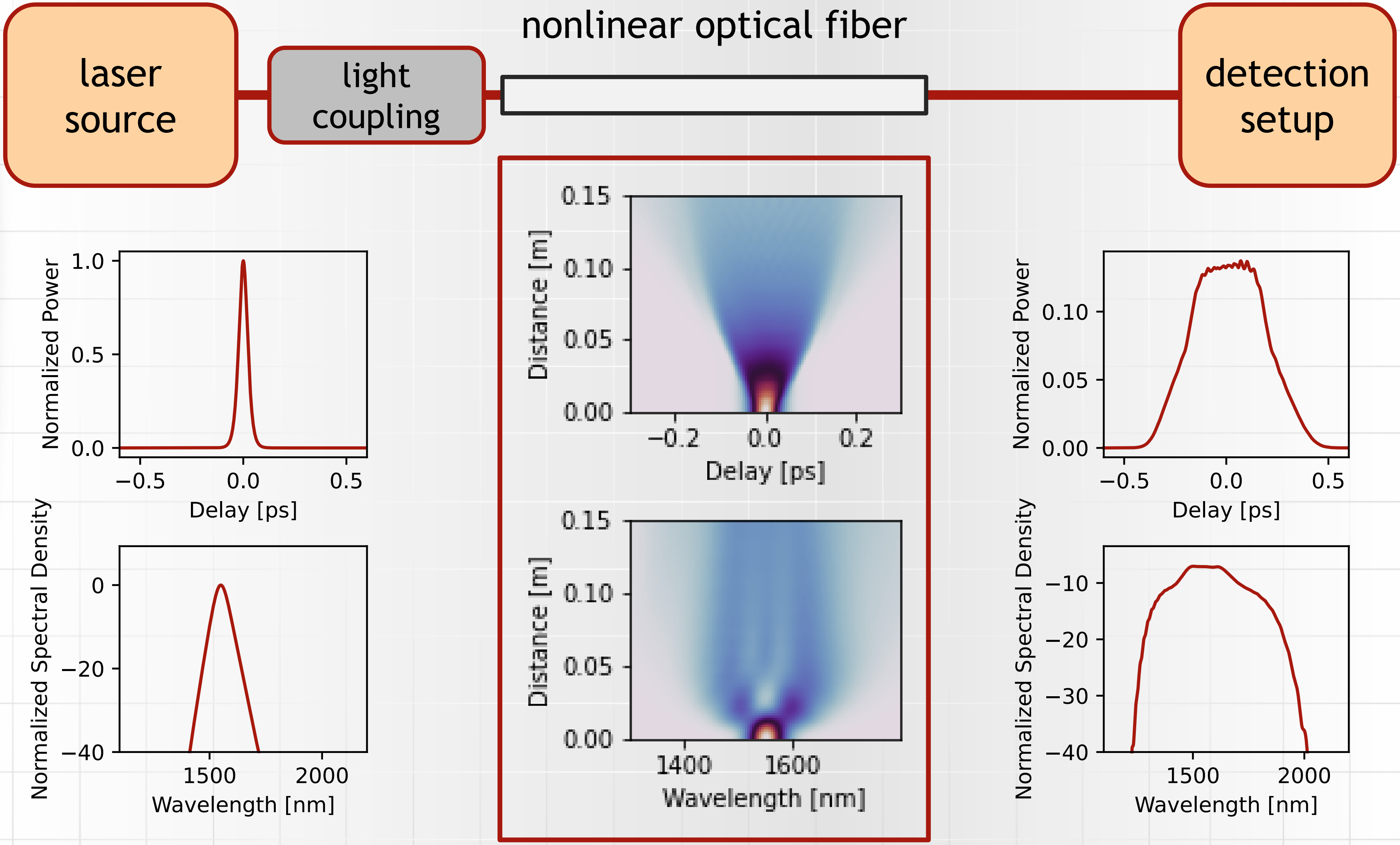
detection setup

Numerical experiment



laser source

light coupling

nonlinear optical fiber

detection setup

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

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

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

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)

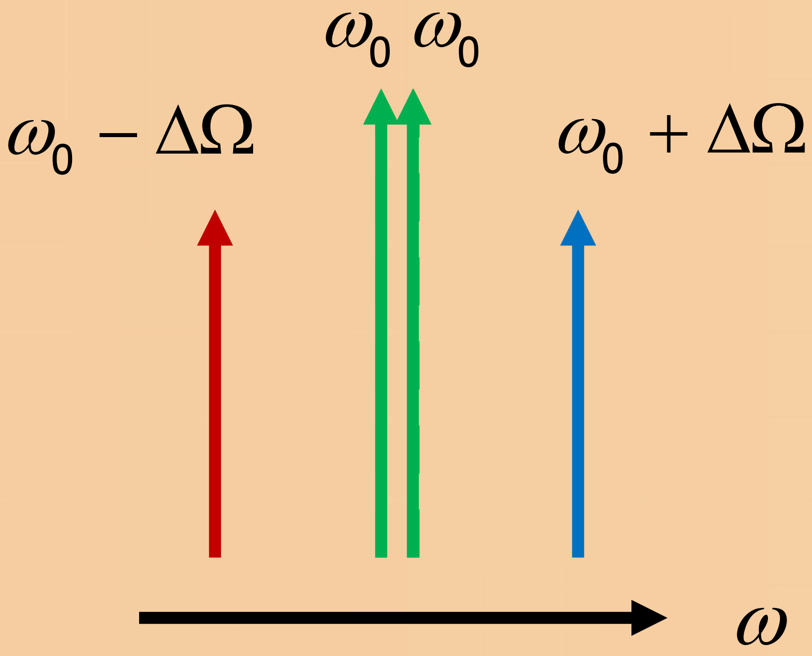
Inelastic scattering

- stimulated Raman scattering (SRS)

Frequency conversion

Optically induced change in the refracitve index

- SPM
- XPM
- MI
- degenerated FWM



Frequency conversion

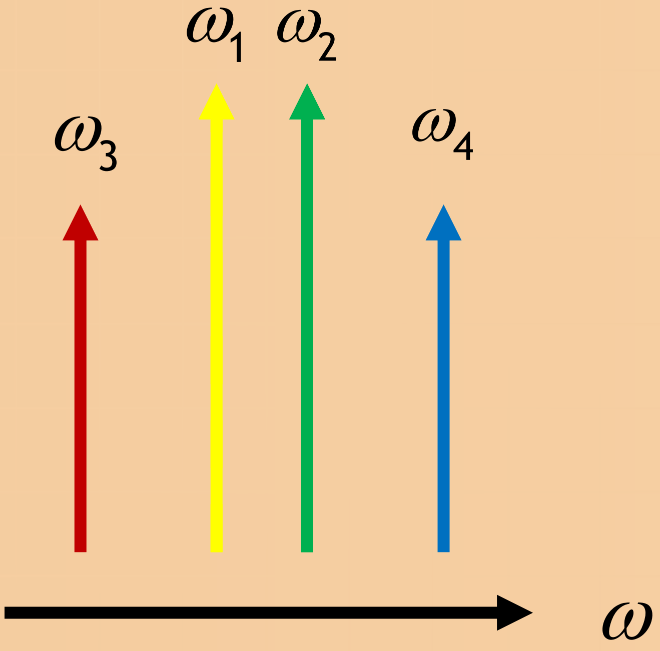
Optically induced change in the refracitve index

- four-wave mixing

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

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

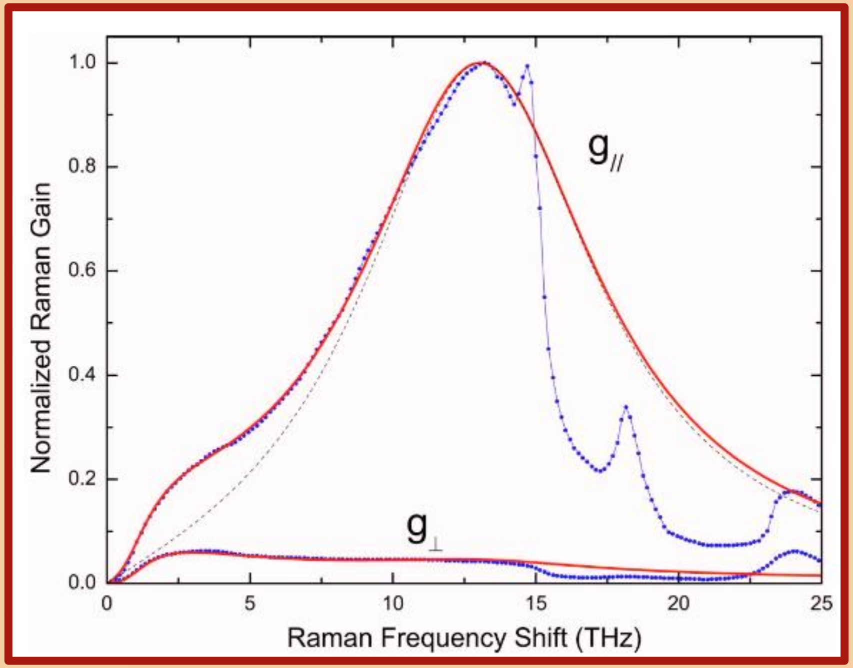
$$\beta_1 + \beta_2 = \beta_3 + \beta_4 + \Delta k_{NL}$$

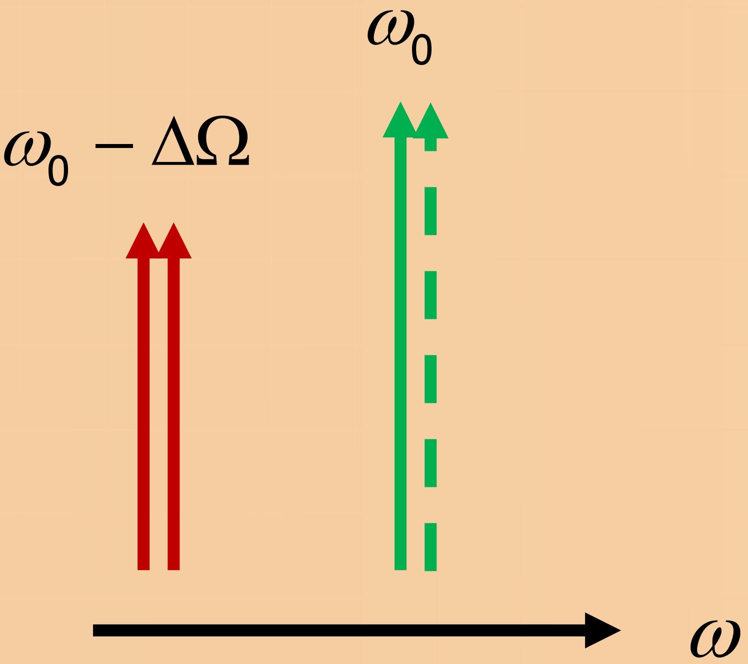


Frequency conversion

Inelastic scattering

- stimulated Raman scattering (SRS)



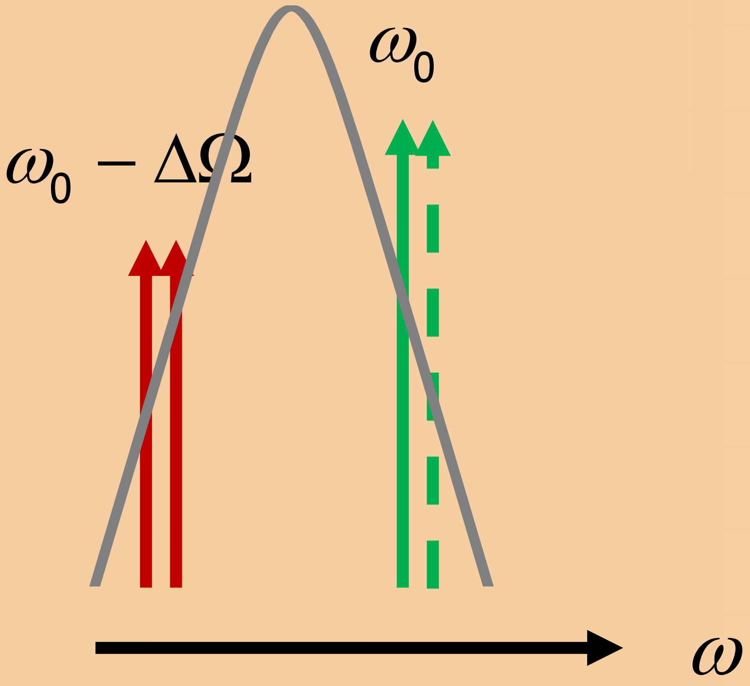


Q. Lin, G. P. Agrawal, Optics Letters, 31(21): 3086 (2006)

Frequency conversion

Inelastic scattering

- Intrapulse Raman scattering (SRS)



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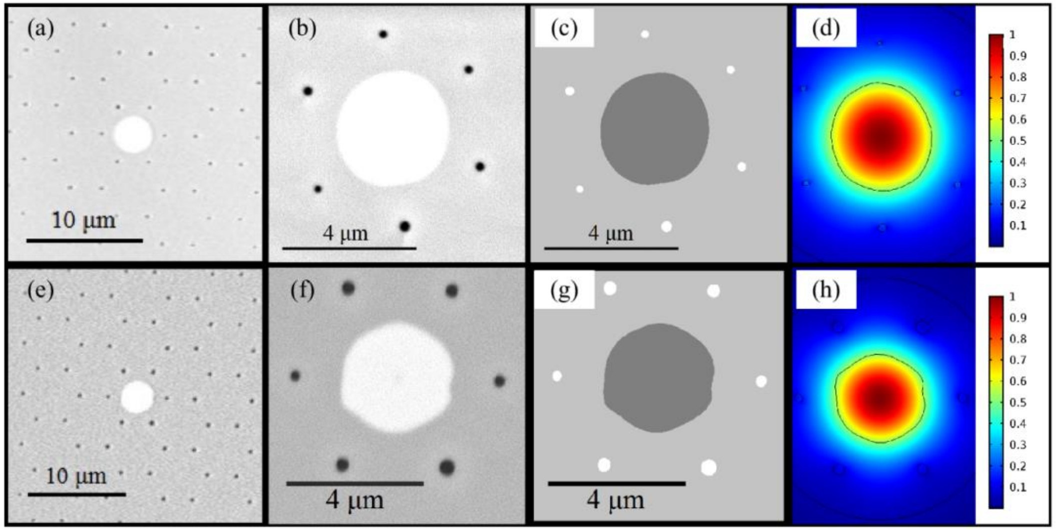
Single mode propagation

All-normal dispersion SC

- Design and fabrication of microstructured optical fibers for efficient generation of coherent SC in normal dispersion regime



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

All-normal dispersion SC

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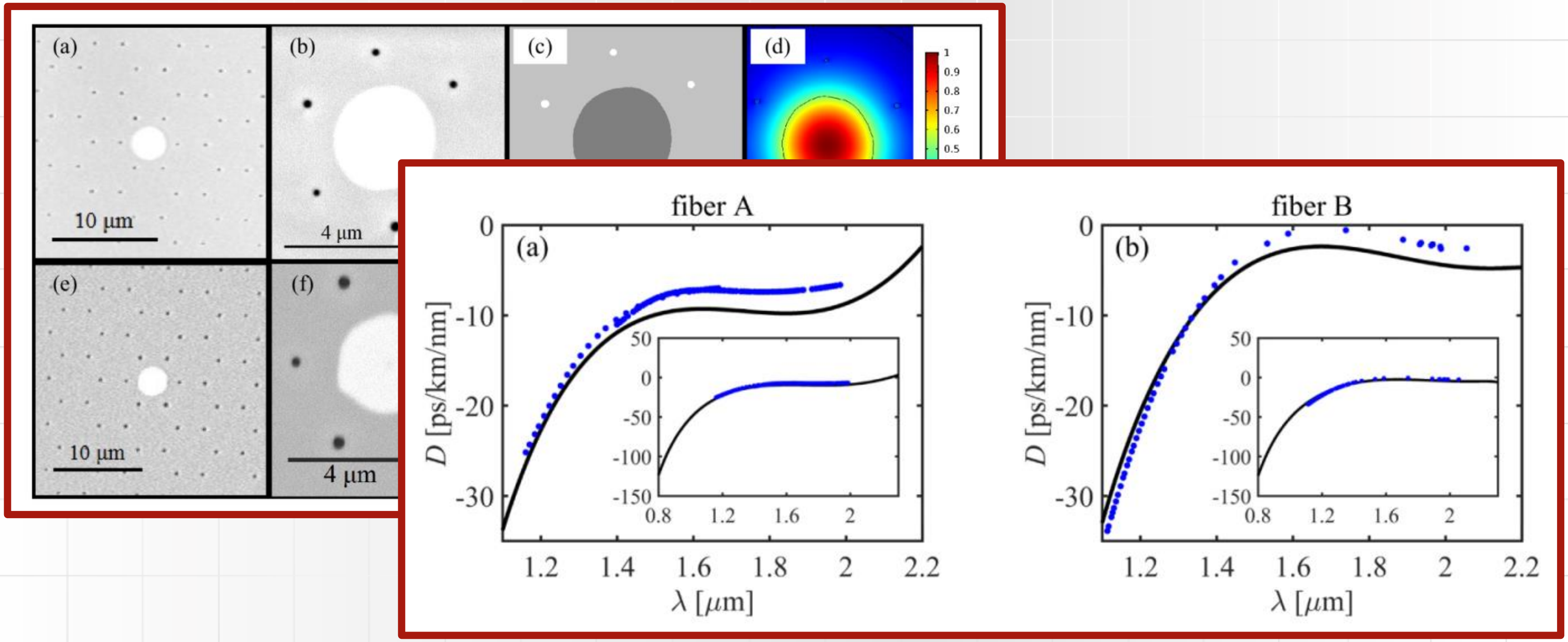
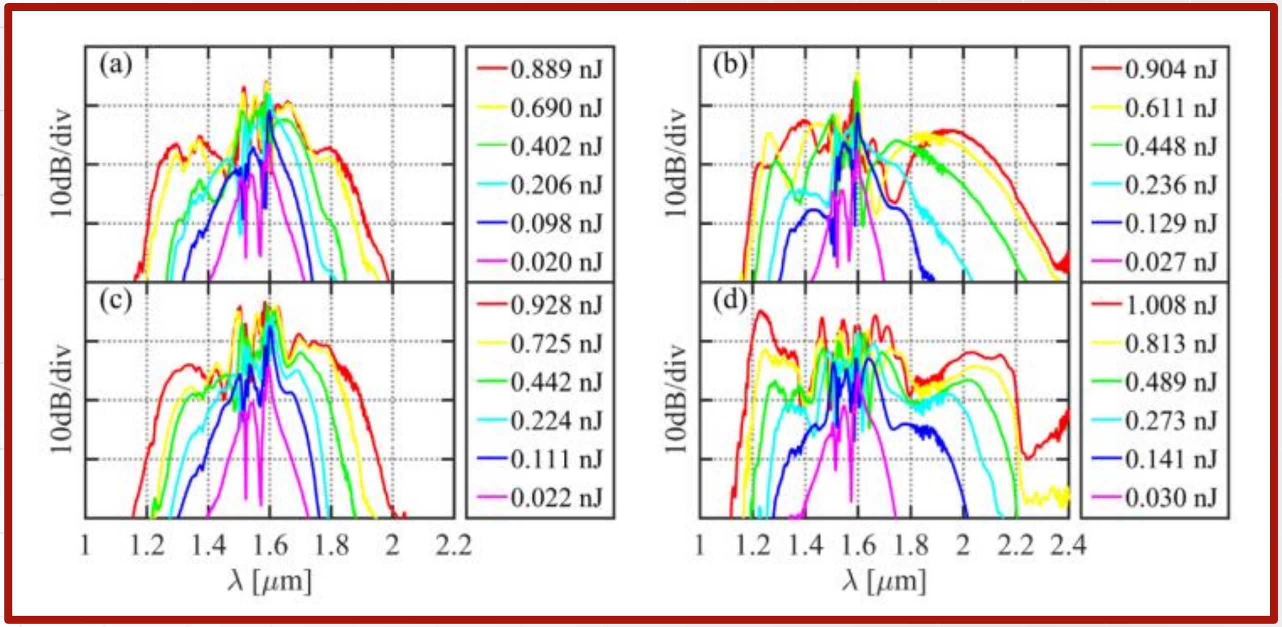


Optics Express, 24(26): 30523 (2016)

All-normal dispersion SC

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

23-fs pumping



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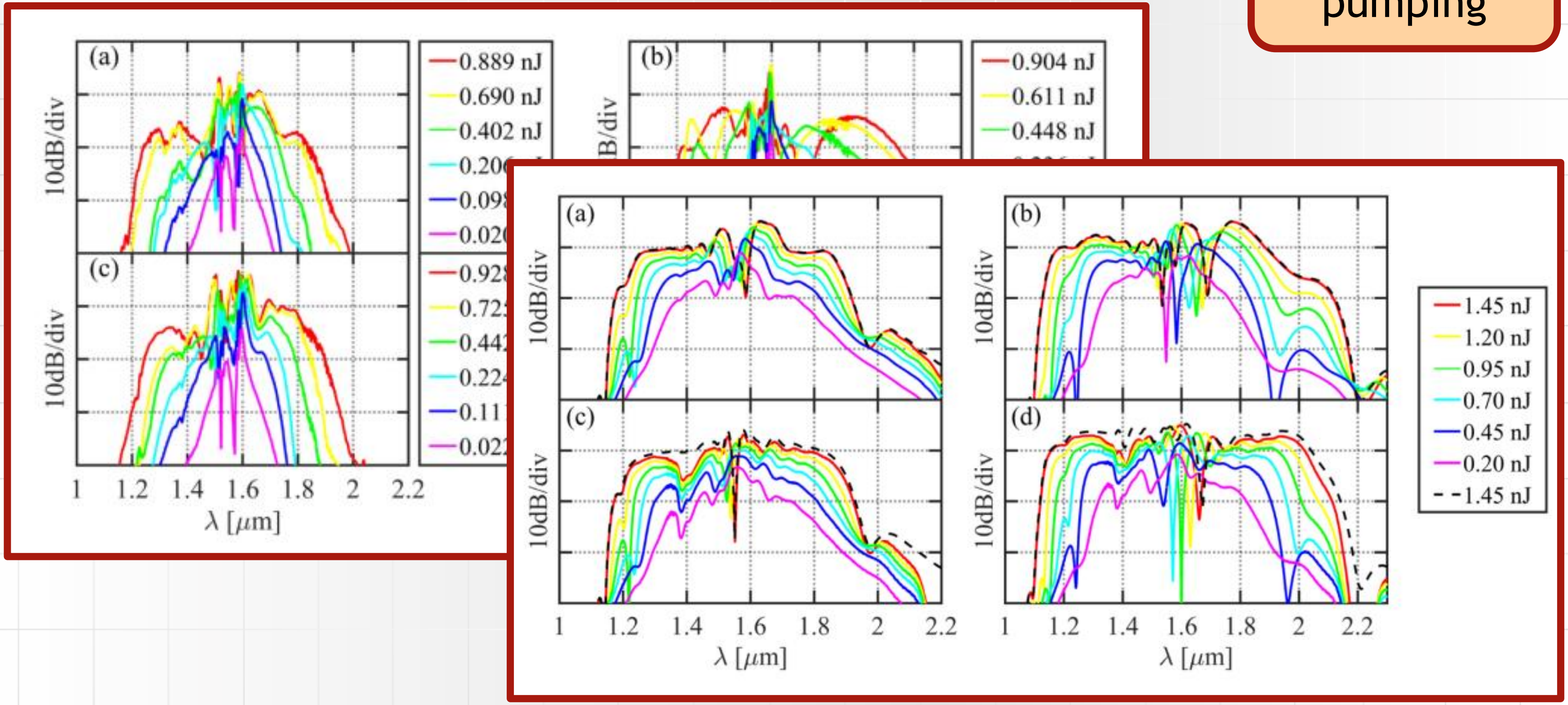


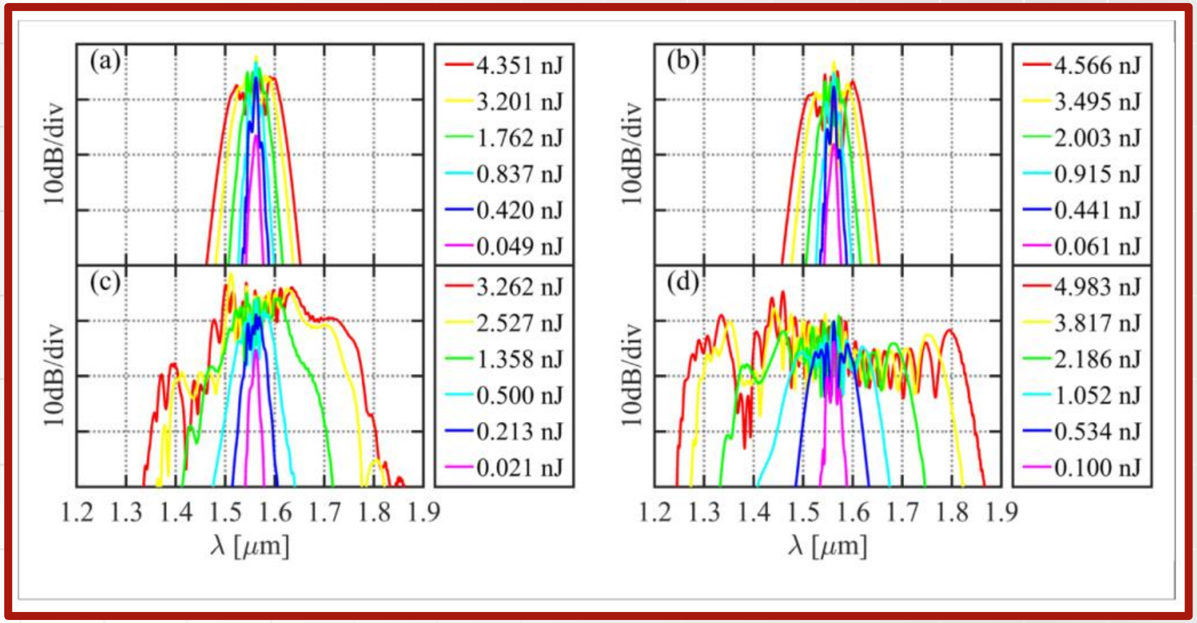
Optics Express, 24(26): 30523 (2016)

Single mode propagation

All-normal dispersion SC

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

460-fs pumping

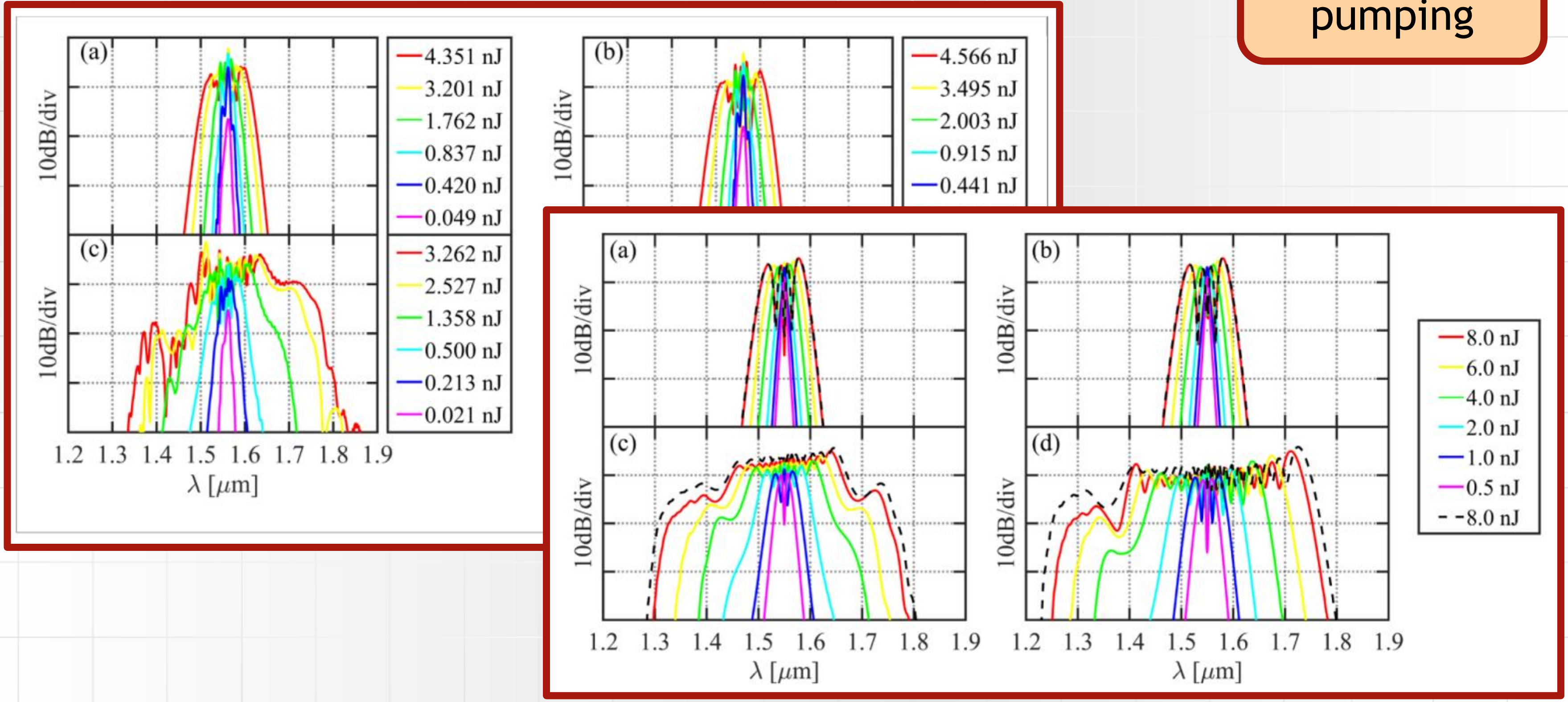


Optics Express, 24(26): 30523 (2016)

All-normal dispersion SC

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

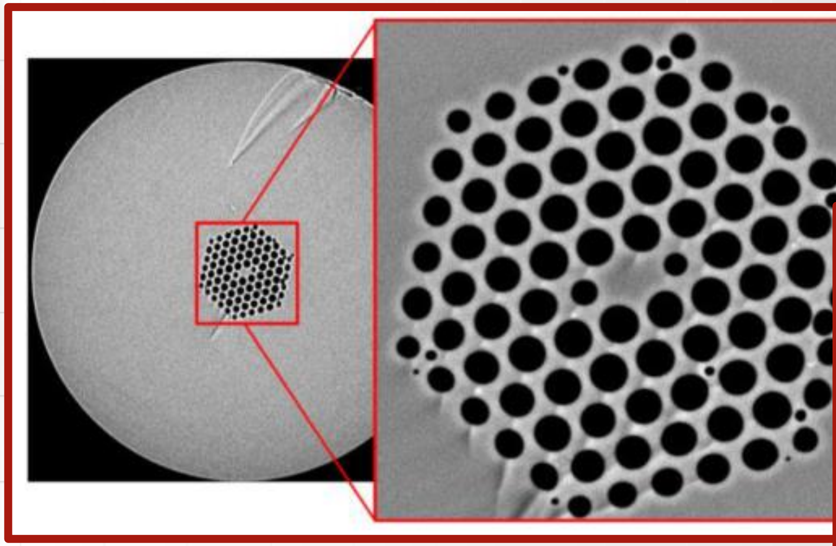
460-fs pumping

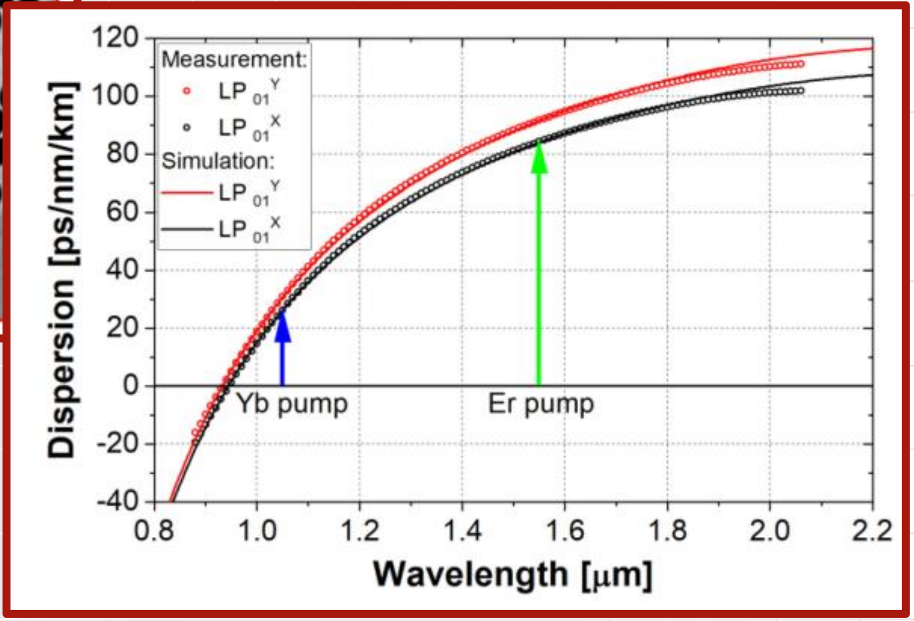


Optics Express, 24(26): 30523 (2016)

Soliton self-frequency shift

- Microstructured optical fiber for efficient soliton tuning

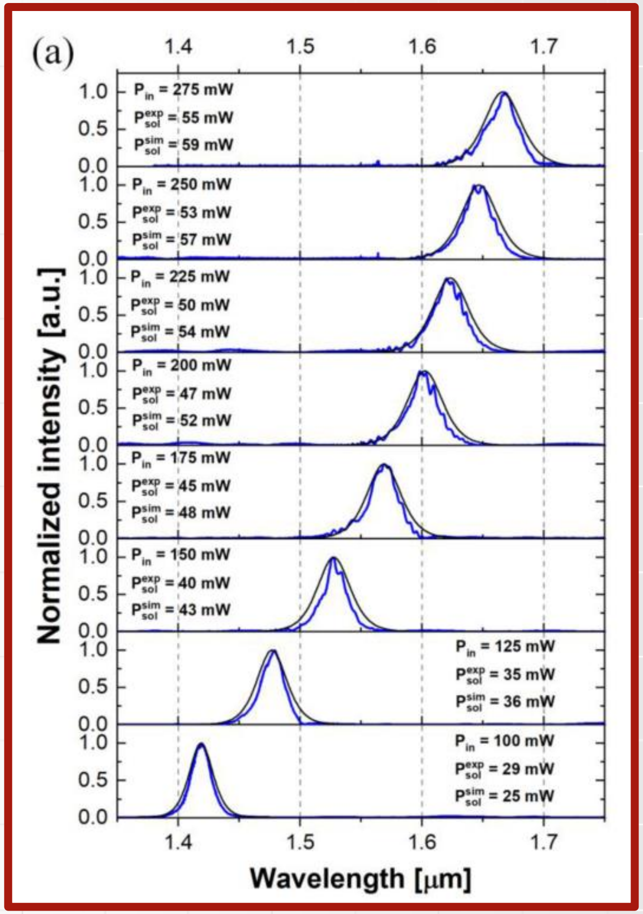


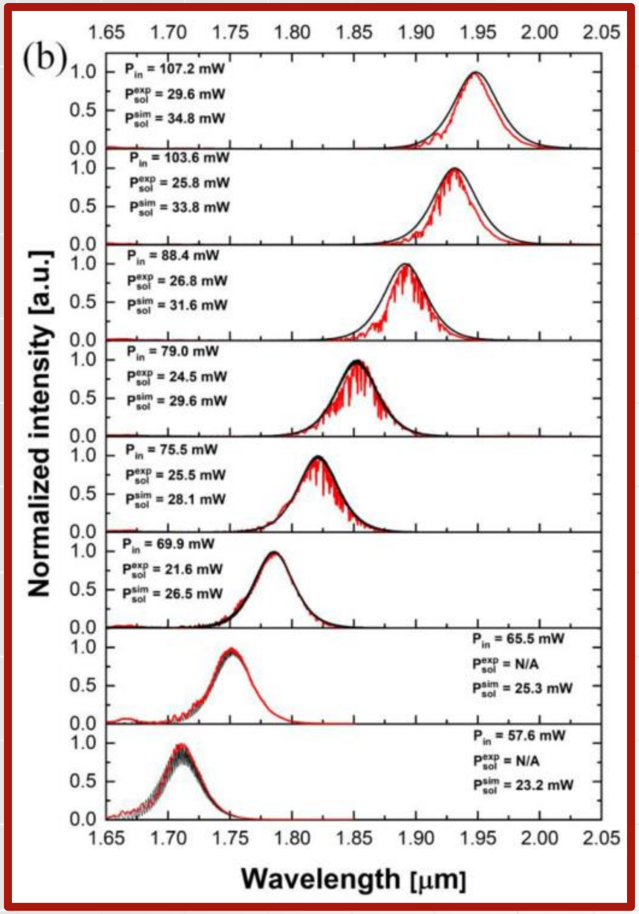


O. Szewczyk et al., IEEE Journal of Lightwave Technology 39(10): 3260 (2021)

Soliton self-frequency shift

- Broadband tuning of soliton pulses





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Polarized all-normal SC

Coupled nonlinear Schrödinger equations

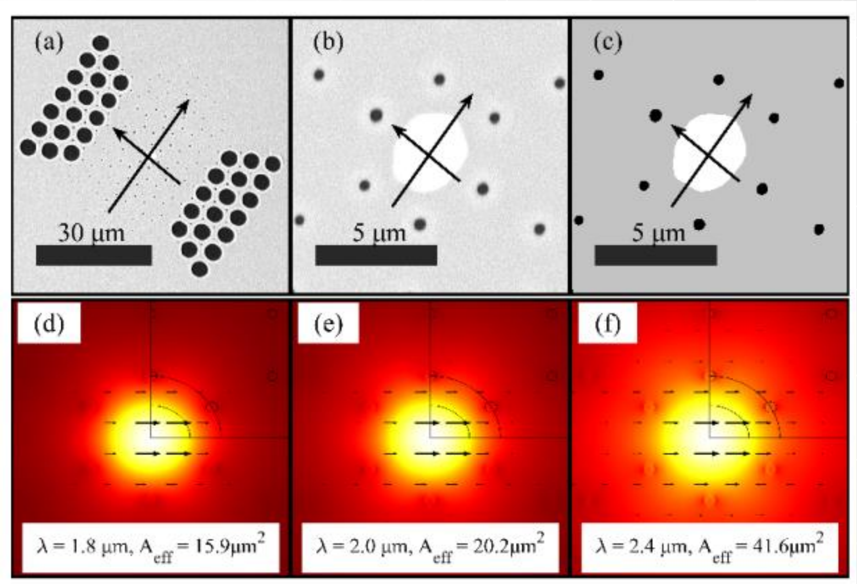
$$\tilde{C}_x = \sqrt[4]{\frac{A_{\text{eff}}(\omega)}{A_{\text{eff}}(\omega_0)}}\,\tilde{A}_x, \quad \tilde{C}_y = \sqrt[4]{\frac{A_{\text{eff}}(\omega)}{A_{\text{eff}}(\omega_0)}}\,\tilde{A}_y$$

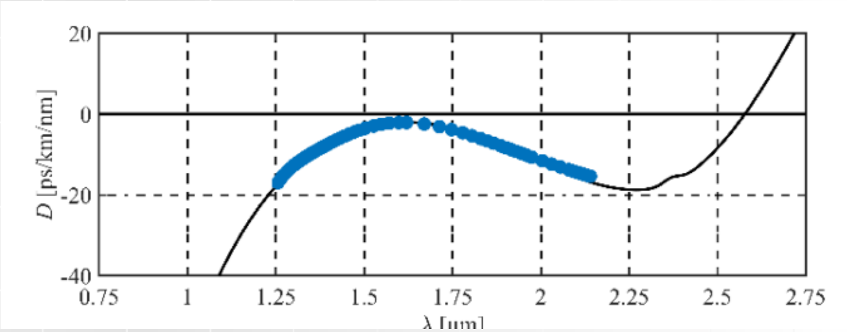
$$\begin{aligned}\frac{\partial \tilde{C}_x}{\partial z} &= D_x\left(\tilde{C}_x\right) + \\ &+i\frac{n_2 n_0 \omega}{c n_{\text{eff}}\sqrt{A_{\text{eff}}(\omega)A_{\text{eff}}(\omega_0)}}\cdot\mathcal{F}\Bigg\{\Bigg(\Big(|C_x|^2 + \boxed{\frac{2}{3}}|C_y|^2\Big)C_x + \boxed{\frac{1}{3}}C_y^2 C_x^* \exp(-2i\Delta\beta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

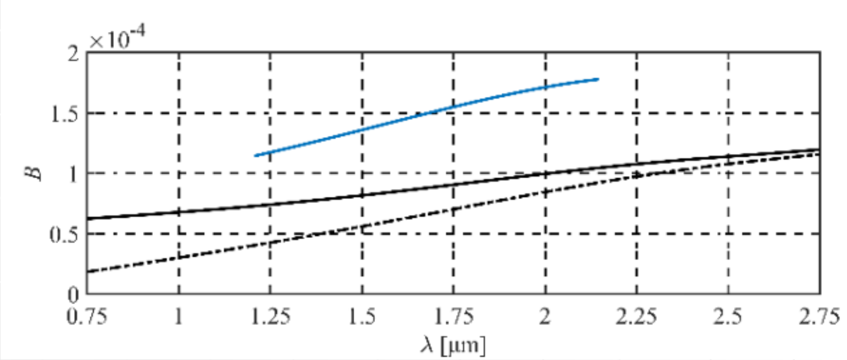
$$\begin{aligned}\frac{\partial \tilde{C}_y}{\partial z} &= D_y\left(\tilde{C}_y\right) + \\ &+i\frac{n_2 n_0 \omega}{c n_{\text{eff}}\sqrt{A_{\text{eff}}(\omega)A_{\text{eff}}(\omega_0)}}\cdot\mathcal{F}\Bigg\{\Bigg(\Big(|C_y|^2 + \boxed{\frac{2}{3}}|C_x|^2\Big)C_y + \boxed{\frac{1}{3}}C_x^2 C_y^* \exp(+2i\Delta\beta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

Polarized all-normal SC

- Design, fabrication and characterization of a birefringent all-normal microstructured fiber for PolAND-SC generation



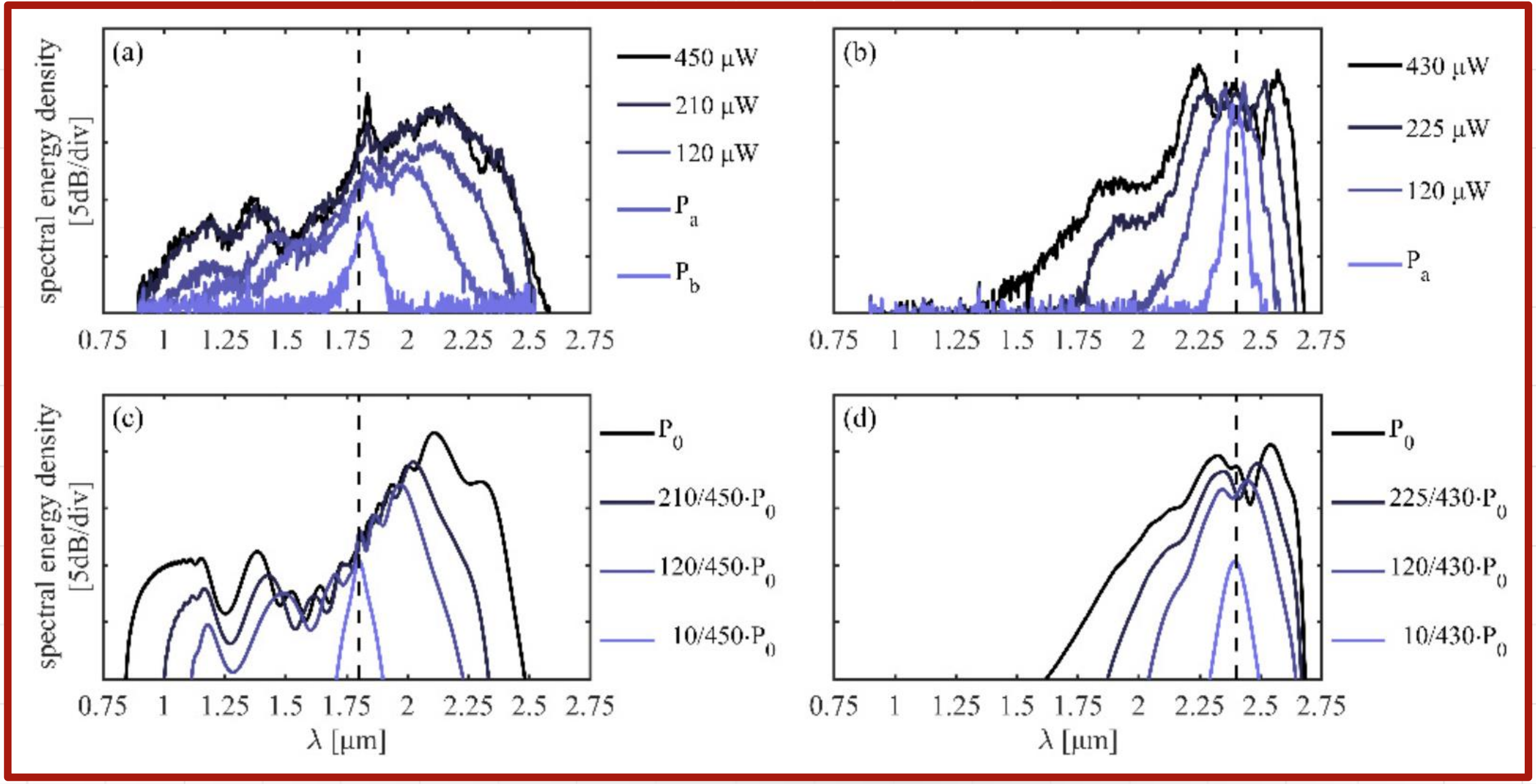




Optics Express 25(22): 27452-27463 (2017)

Polarized all-normal SC

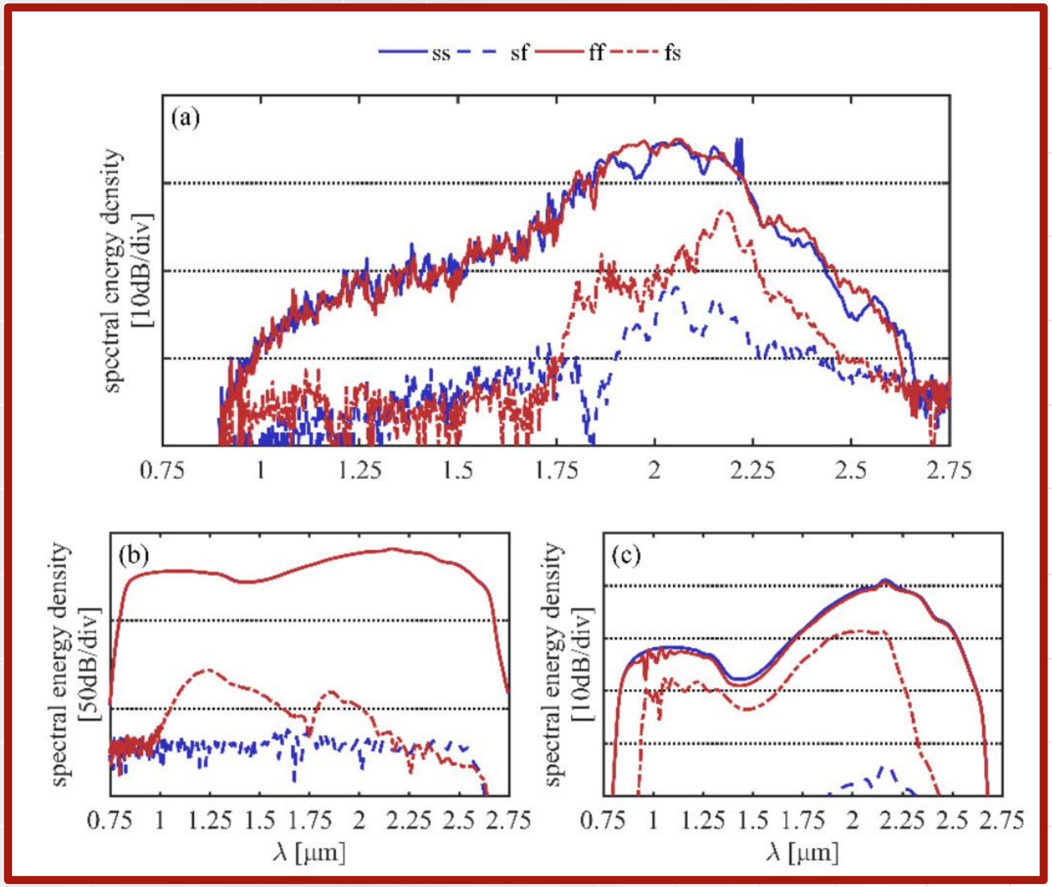
- SC generation in birefringent all-normal dispersion fiber



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

Polarized all-normal SC

- SC generation in birefringent all-normal dispersion fiber
  - broad
  - polarized
  - coherent



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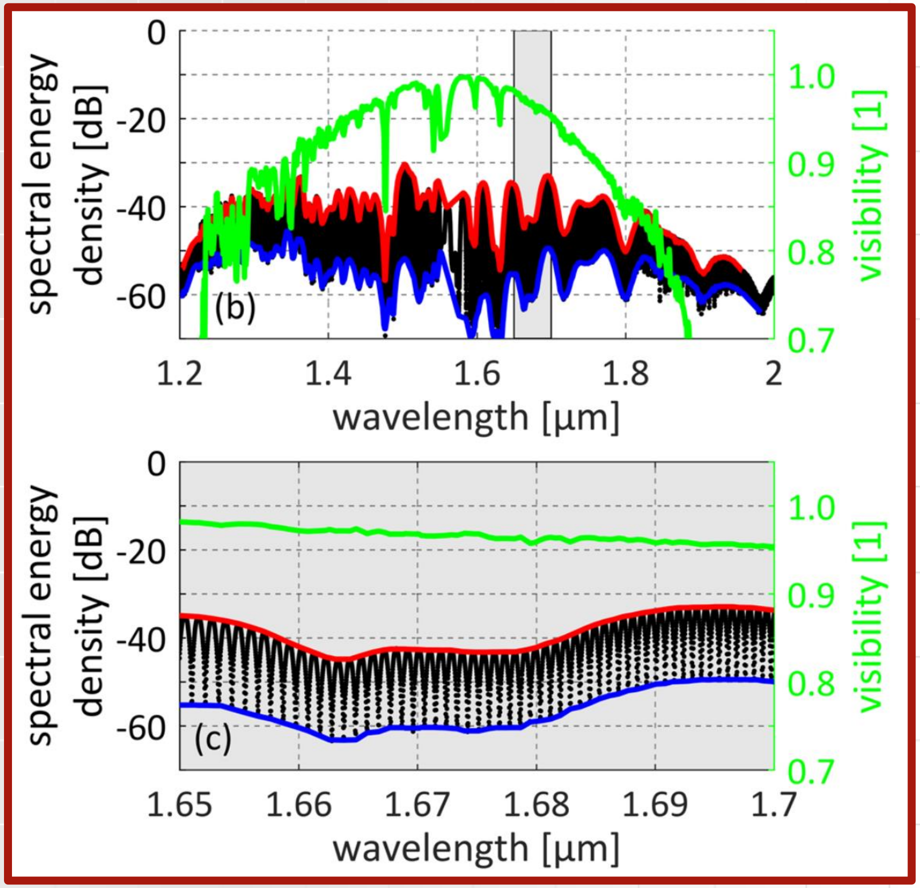
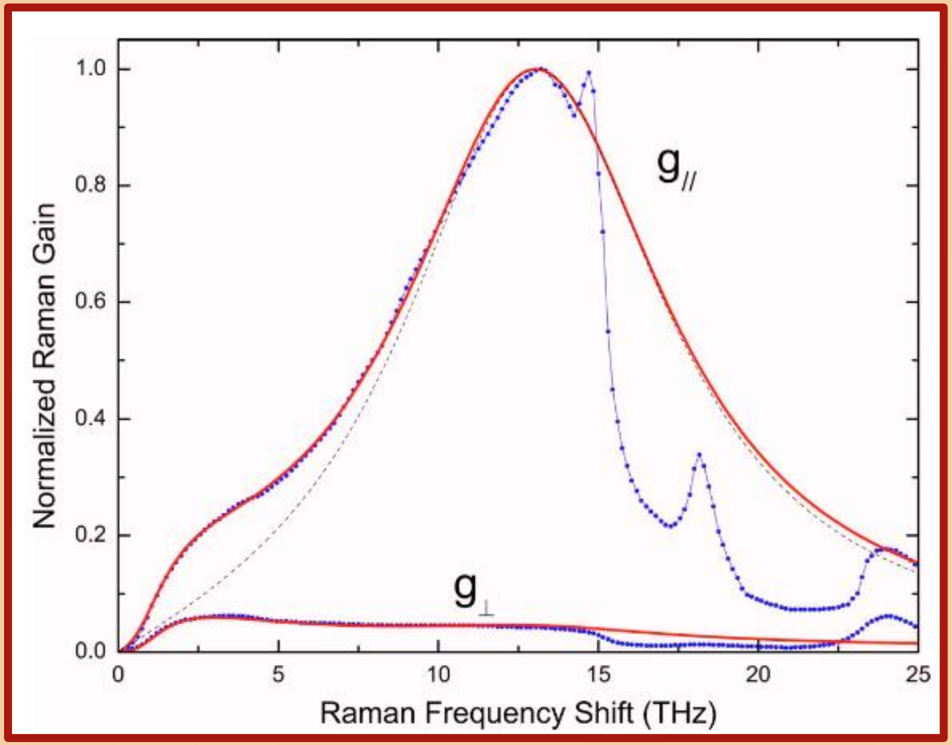


Scientific Reports 9: 12313 (2019)

Orthogonal Raman scattering

Raman response function



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

Orthogonal Raman scattering

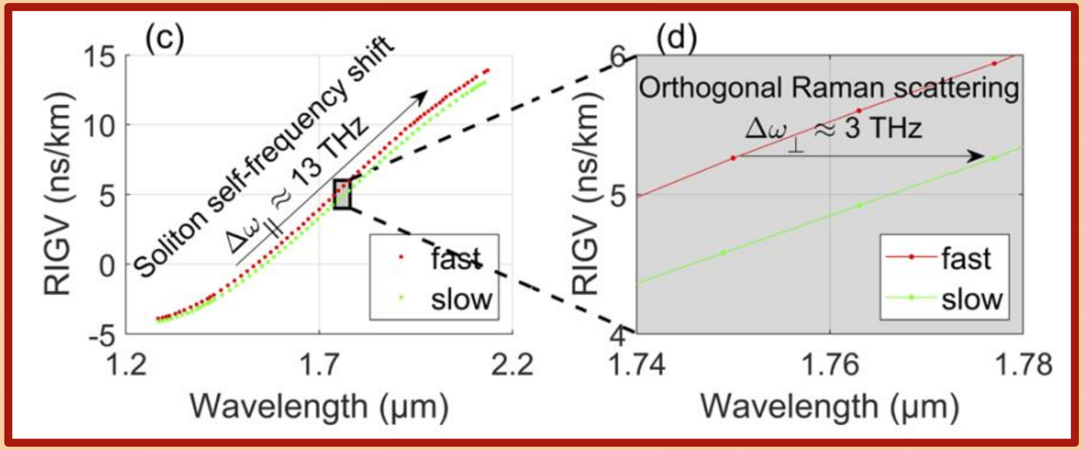
Coupled nonlinear Schrödinger equations with vector Raman response

$$N_x\left(\tilde{C}_x,\tilde{C}_y\right)=\bar{\gamma}_x\mathcal{F}\left\{\begin{aligned}&\left(1-f_R\right)\times\left(\left(\left|C_x\right|^2+\frac{2}{3}\left|C_y\right|^2\right)C_x+\frac{1}{3}C_y^2C_x^*\exp\left(-2i\Delta\beta z\right)\right)+\\&+f_R\times\left[\begin{aligned}&\left(h_1\otimes\left|C_x\right|^2+h_2\otimes\left|C_y\right|^2\right)C_x+\\&+h_3\otimes\left(C_xC_y^*+C_yC_x^*\exp\left(-2i\Delta\beta z\right)\right)C_y\end{aligned}\right]\end{aligned}\right\}$$

$$N_y\left(\tilde{C}_y,\tilde{C}_x\right)=\bar{\gamma}_y\mathcal{F}\left\{\begin{aligned}&\left(1-f_R\right)\times\left(\left(\left|C_y\right|^2+\frac{2}{3}\left|C_x\right|^2\right)C_y+\frac{1}{3}C_x^2C_y^*\exp\left(+2i\Delta\beta z\right)\right)+\\&+f_R\times\left[\begin{aligned}&\left(h_1\otimes\left|C_y\right|^2+h_2\otimes\left|C_x\right|^2\right)C_y+\\&+h_3\otimes\left(C_yC_x^*+C_xC_y^*\exp\left(+2i\Delta\beta z\right)\right)C_x\end{aligned}\right]\end{aligned}\right\}$$

Orthogonal Raman scattering

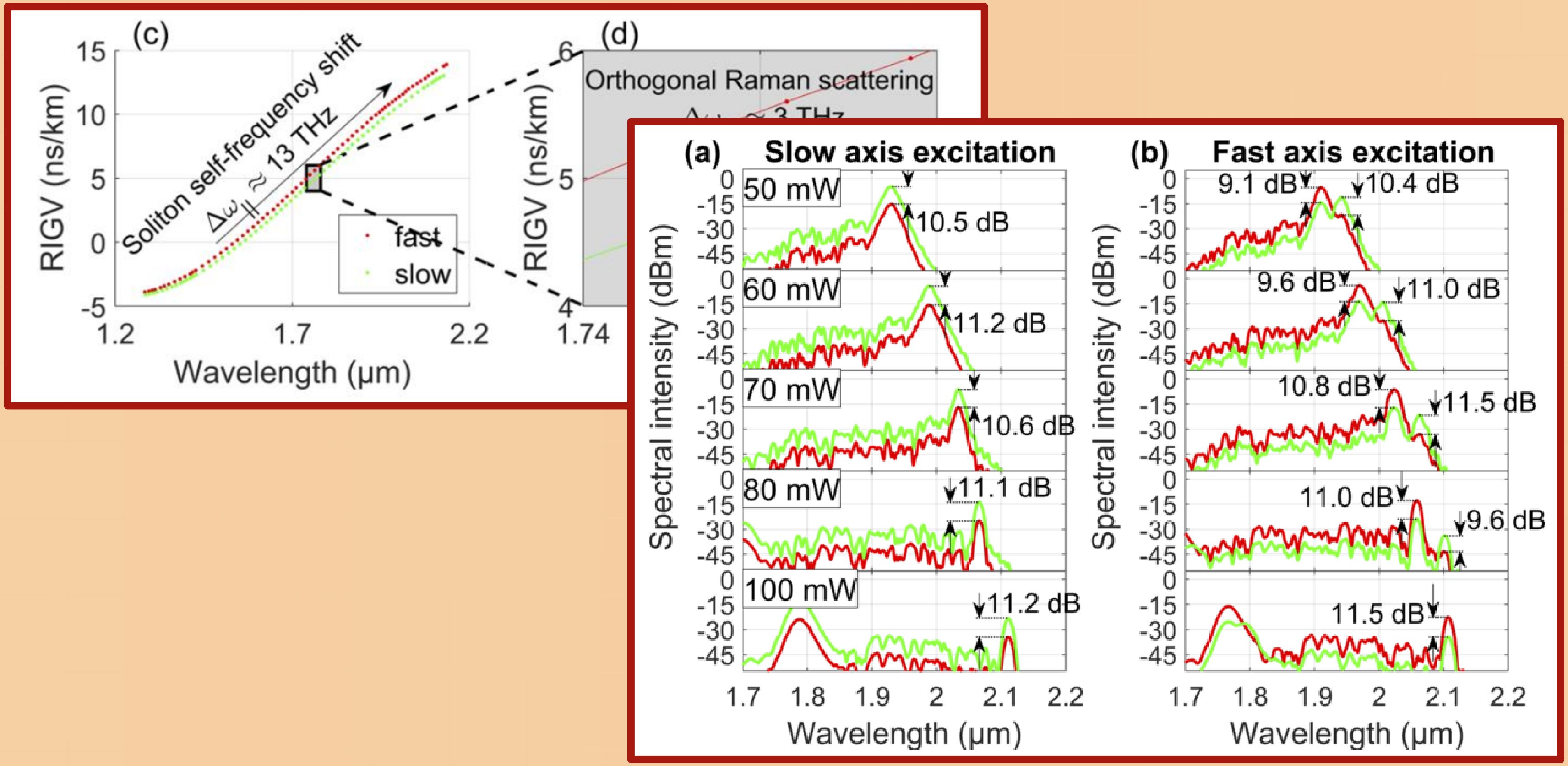
Polarization conversion by Raman scattering



K. Stefańska et al., Optics Letters 47(16): 4183 (2022)

Orthogonal Raman scattering

Polarization conversion by Raman scattering



K. Stefańska et al., Optics Letters 47(16): 4183 (2022)

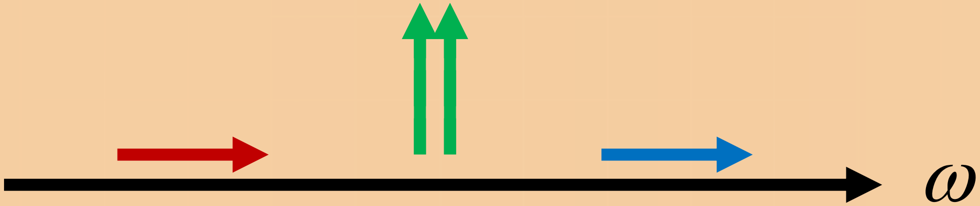
Orthogonal Raman scattering

Polarization conversion by Raman scattering

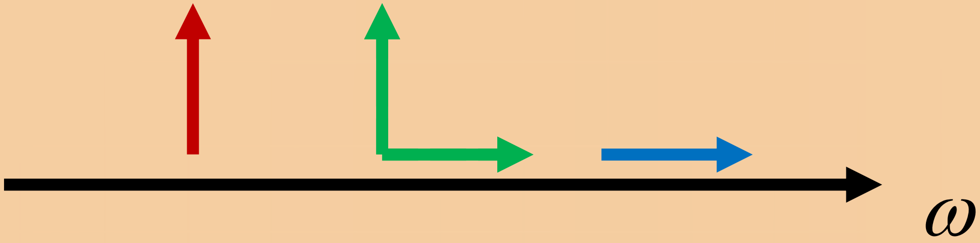
- Oposite signs of phase and group birefringnences allow to indicate the preferable polarization axis for Raman soliton tunig in terms of polarization purity

Vector modulation instability in linearly birefringent fibers

Low birefringent fibers



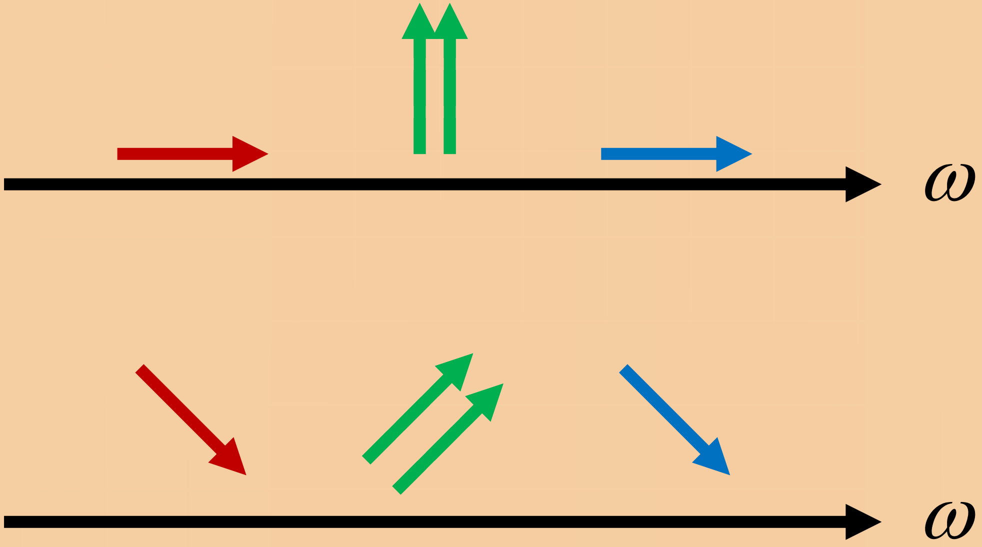
High birefringent fibers



Vector modulation instability in linearly birefringent fibers

Isotropic fibers

- Linearly polarized light generate bands polarized linearly and orthogonally to the pump



Vector modulation instability in circularly birefringent fibers

Coupled nonlinear Schrödinger equations for circular eigenmodes

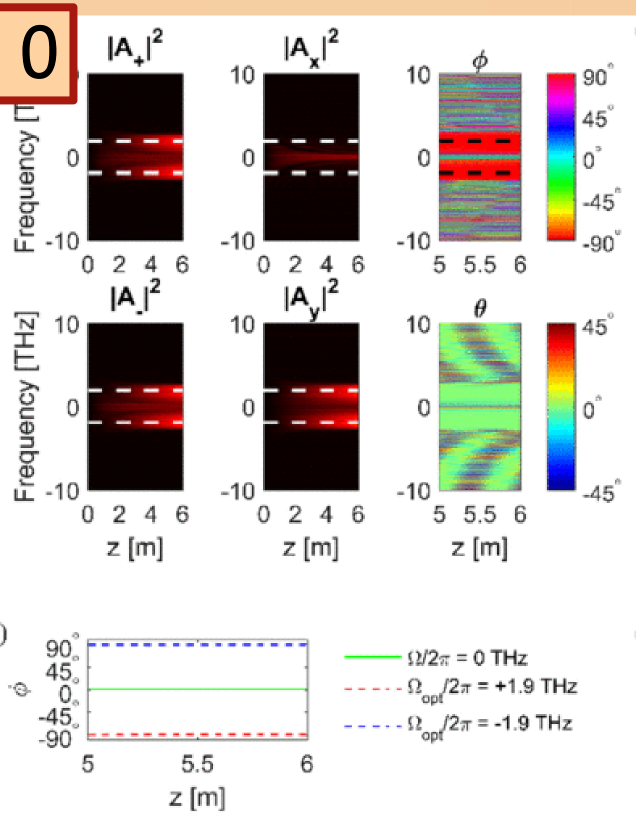
$$\frac{\partial A_+}{\partial z} + \frac{\Delta\beta_1}{2}\frac{\partial A_+}{\partial t} + i\frac{\beta_{2+}}{2}\frac{\partial^2 A_+}{\partial t^2} = i\gamma'\left(\left|A_+\right|^2 \boxed{+2}\left|A_-\right|^2\right)A_+$$

$$\frac{\partial A_-}{\partial z} - \frac{\Delta\beta_1}{2}\frac{\partial A_-}{\partial t} + i\frac{\beta_{2-}}{2}\frac{\partial^2 A_-}{\partial t^2} = i\gamma'\left(\left|A_-\right|^2 \boxed{+2}\left|A_+\right|^2\right)A_-$$

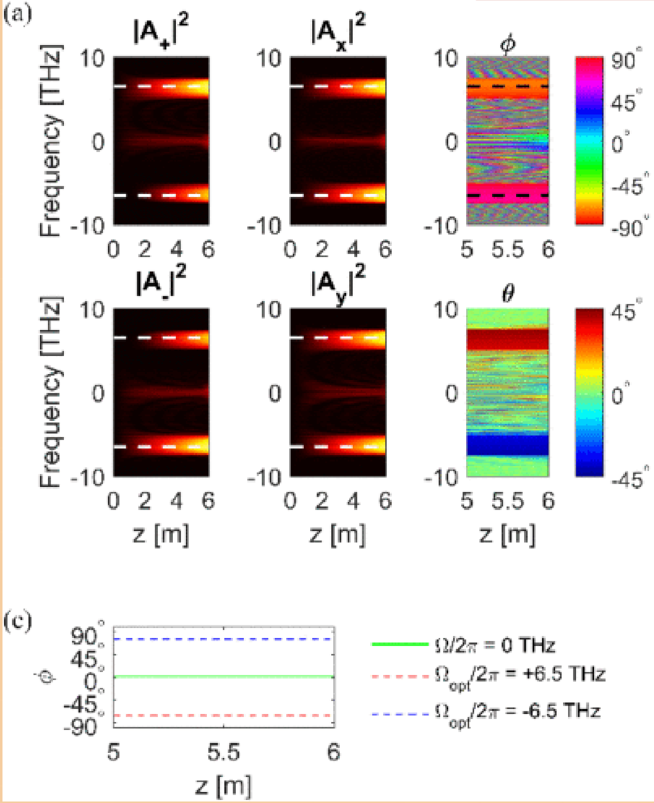
Vector modulation instability in circularly birefringent fibers

Coupled nonlinear Schrödinger equations for circular eigenmodes

$\Delta N = 0$



$\Delta N = 2 \times 10^{-4}$

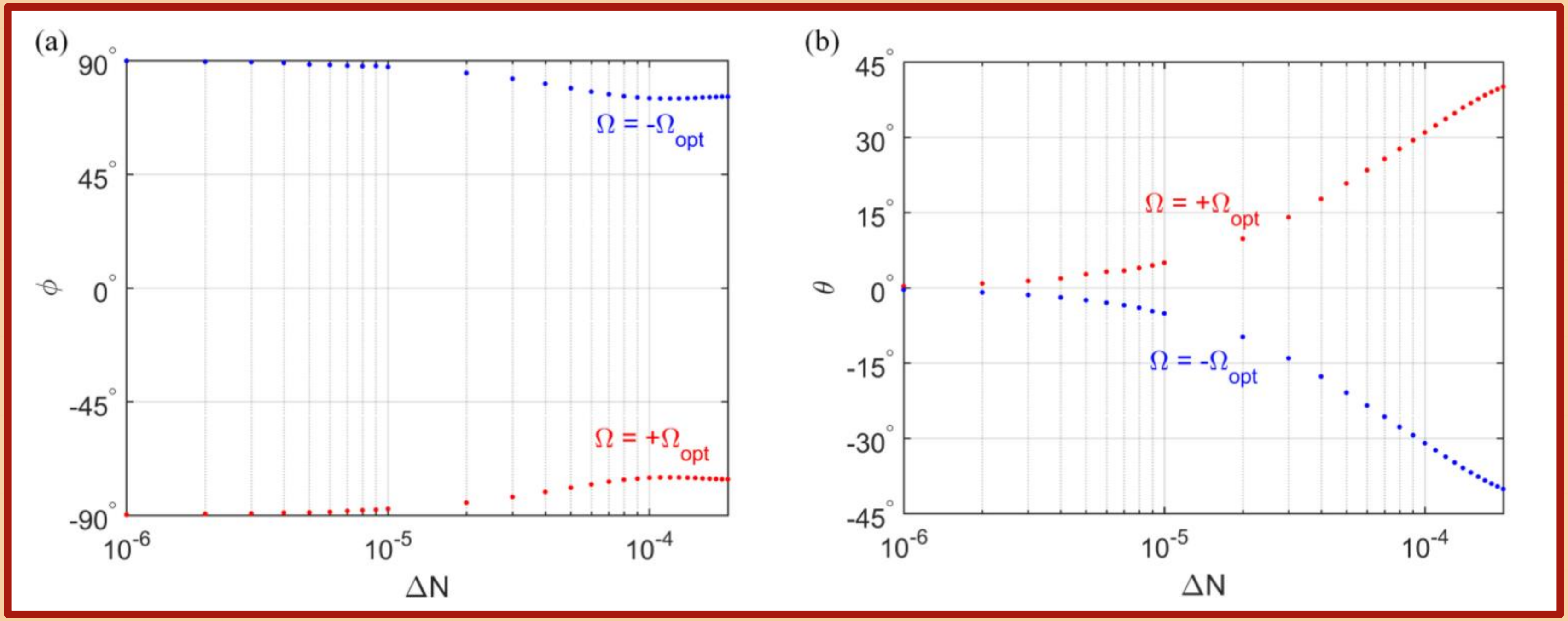


K. Żołnacz et al., IEEE Photonics Journal 13(1): 7100616 (2021)

Birefringnet fibers

Vector modulation instability in circularly birefringent fibers

Coupled nonlinear Schrödinger equations for circular eigenmodes

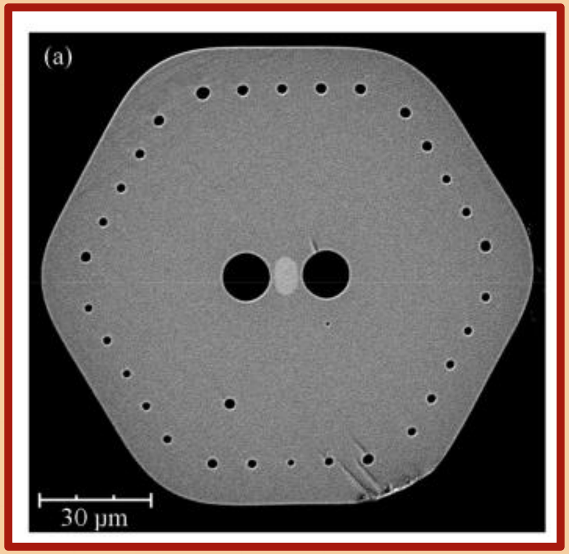


K. Żołnacz et al., IEEE Photonics Journal 13(1): 7100616 (2021)

Vector modulation instability in circularly birefringent fibers

Experimental results

- VMI in a nearly circularly birefringent spun fiber shows behaviour typical for isotropic fiber even for significant birefringence $\Delta N = -2.2\times10^{-6}$

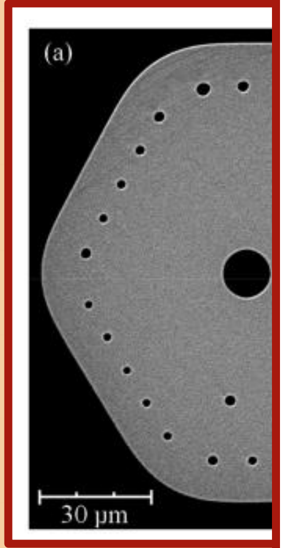


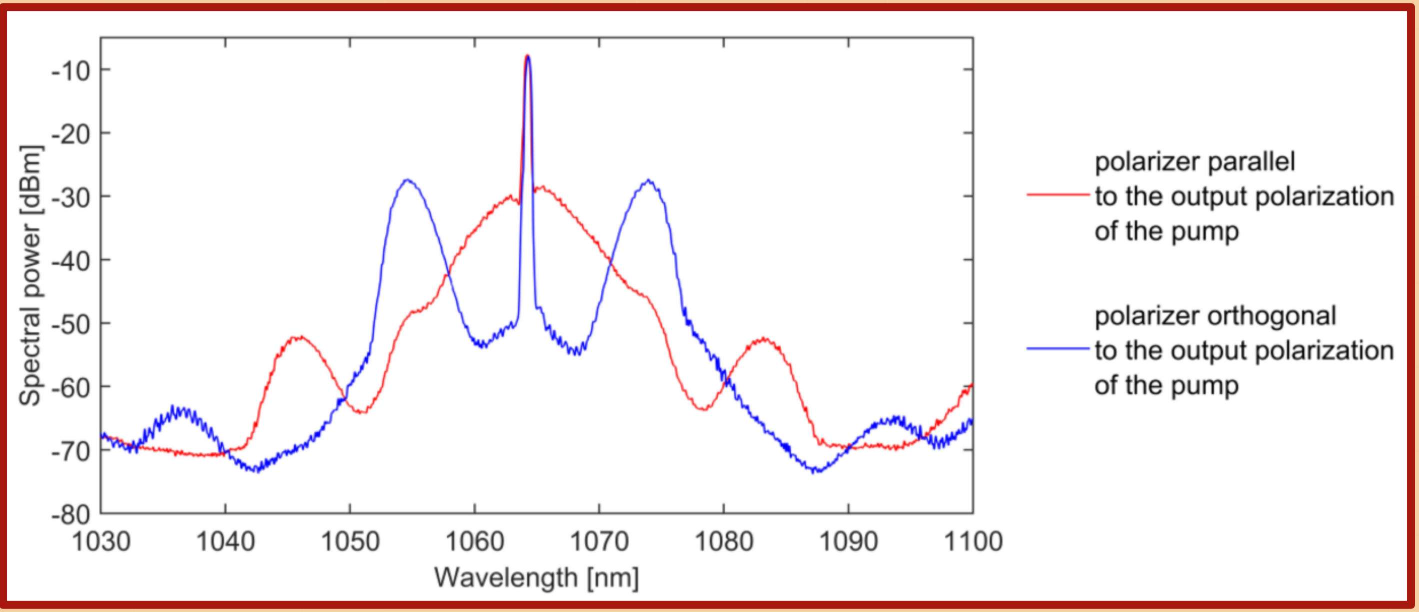
K. Żołnacz et al., IEEE Photonics Journal 13(1): 7100616 (2021)

Vector modulation instability in circularly birefringent fibers

Experimental results

- VMI in a nearly circularly birefringent spun fiber shows behaviour typical for isotropic fiber even for significant birefringence Δ$N = -2.2\times10^{-6}$





K. Żołnacz et al., IEEE Photonics Journal 13(1): 7100616 (2021)

Outline

Introduction

- Description of frequency conversion processes in optical fibers

Single mode propagation

- All-normal dispersion supercontinuum
- Soliton self-frequency shift

Birefringent fibers

- Polarized all-normal dispersion SC
- Solitons - orthogonal Raman scattering
- Vector modulation instability

Few mode fibers

- Intermodal-vectorial four wave mixing

Multimode fibers

- Conical emission

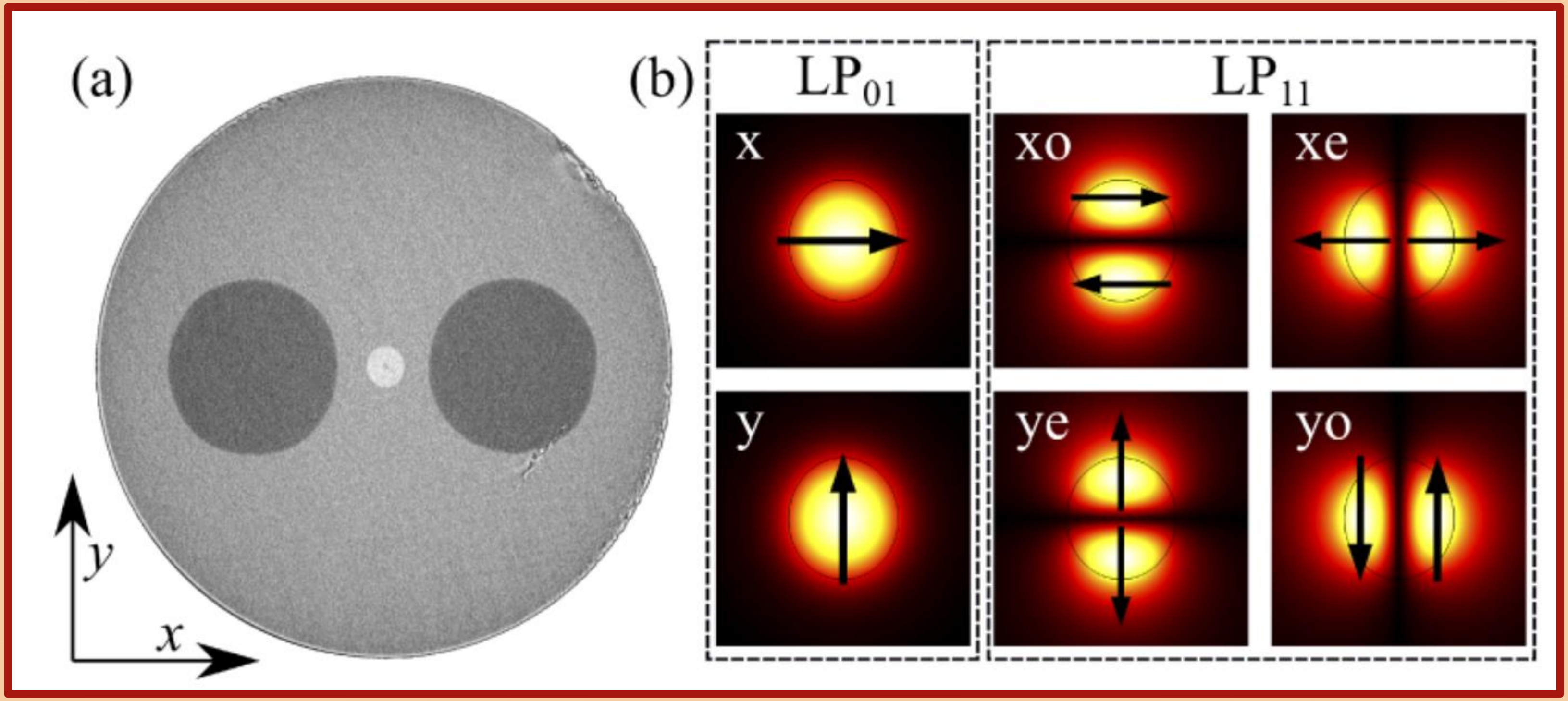
Intermodal-vectorial FWM

System of coupled nonlinear Schrodinger equations

$$
\begin{aligned}
\frac{\partial A_p}{\partial z} &= -\frac{\alpha_p}{2} A_p + i\left(\beta_0^{(p)} - \beta_0^{(0)}\right) A_p + \\
&-\left(\beta_1^{(p)} - \beta_1^{(0)}\right)\frac{\partial A_p}{\partial t} + i\sum_{n\geq 2}^{\infty} \frac{i^n \beta_n^{(p)}}{n!} \frac{\partial^n A_p}{\partial t^n} + \\
&+i\frac{n_2\omega_0}{c}\left(1 + \frac{i}{\omega_0}\frac{\partial}{\partial t}\right) \times \\
&\times \sum_{l,m,n}^{N-1} \left\{ \left(1 - f_R\right) \boxed{S_K^{(plmn)} A^{(l)}} A^{(m)} A^{(n)^*} + f_R \boxed{S_R^{(plmn)} A^{(l)}} \left[h \otimes \left(A^{(m)} A^{(n)^*} \right) \right] \right\}
\end{aligned}
$$

Intermodal-vectorial FWM

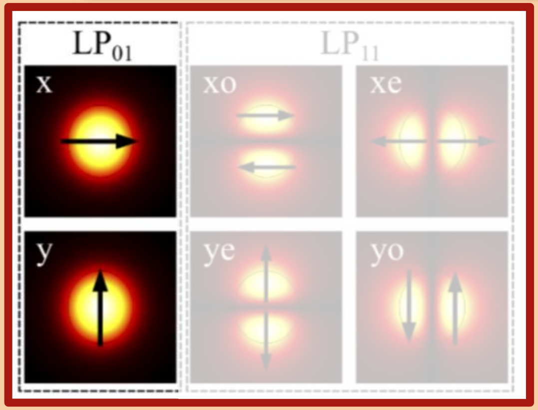
Fiber modes

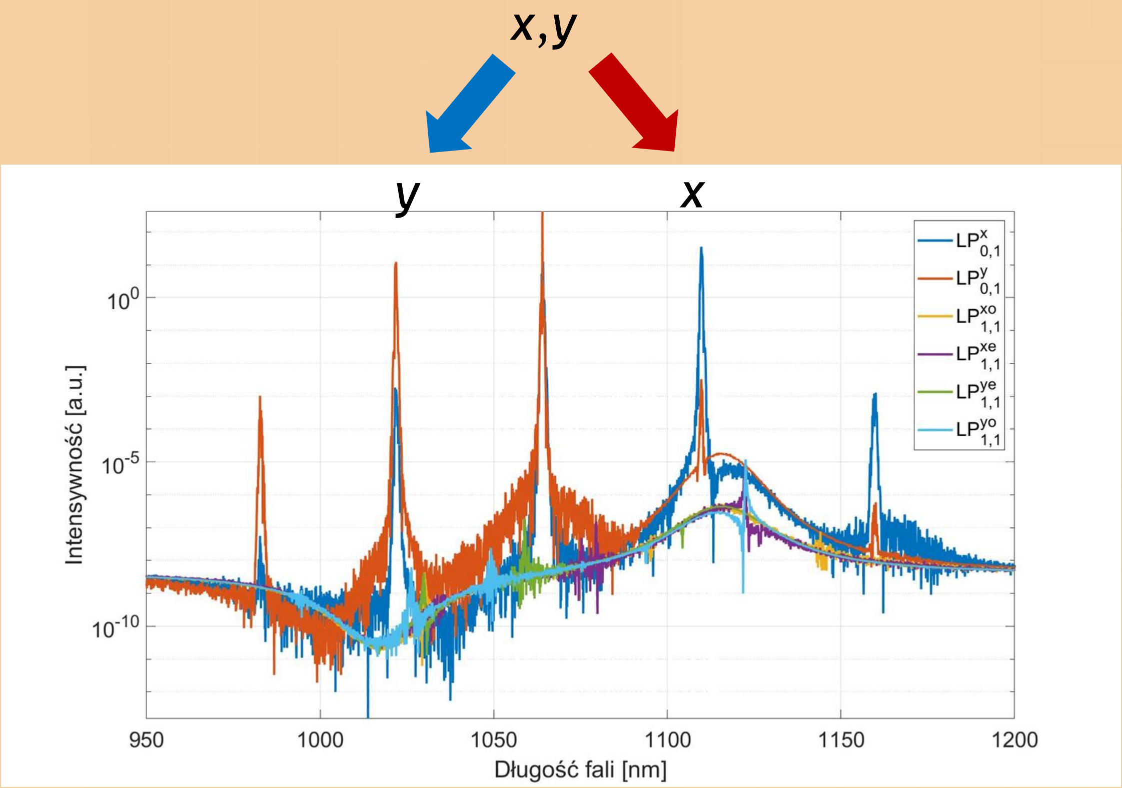


S. Majchrowska, K. Żołnacz et al., Optics Letters 47(10): 2522 (2022)

Intermodal-vectorial FWM

Vectorial FWM





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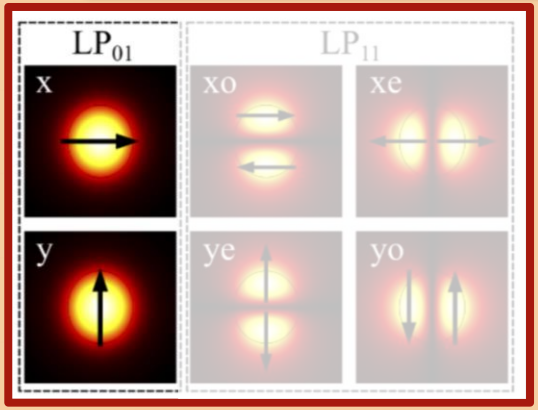
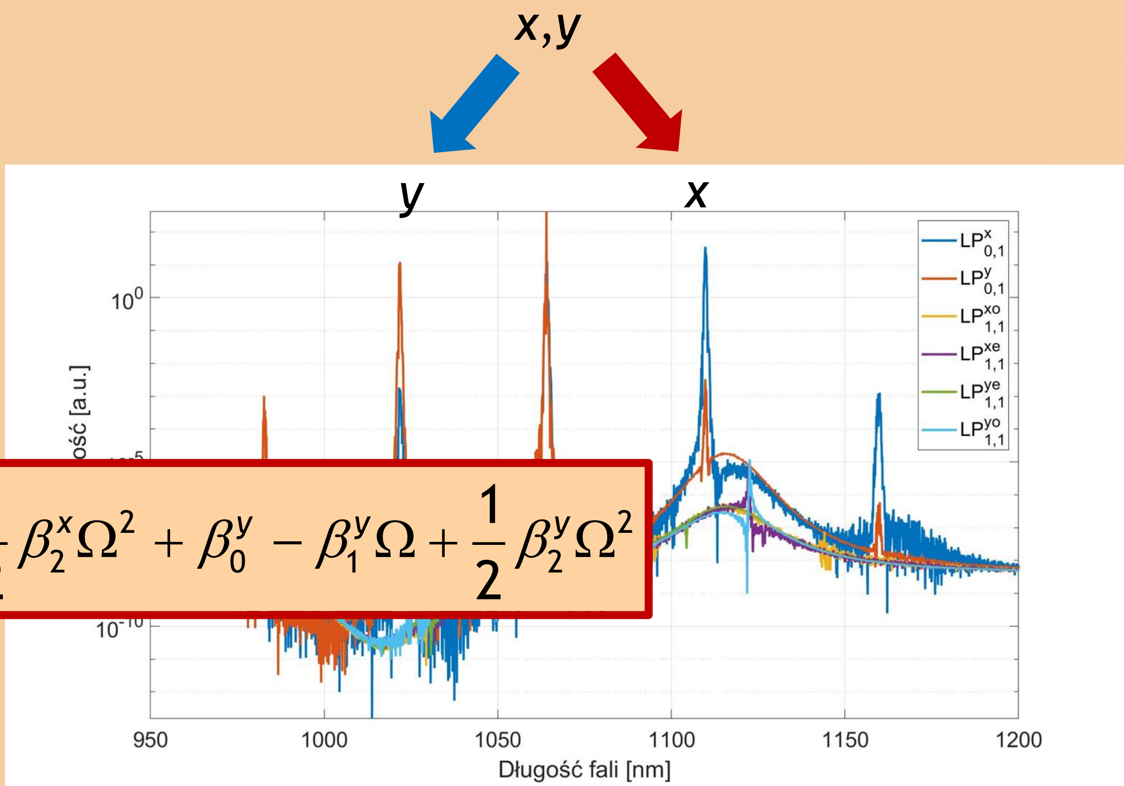
Intermodal-vectorial FWM

Vectorial FWM





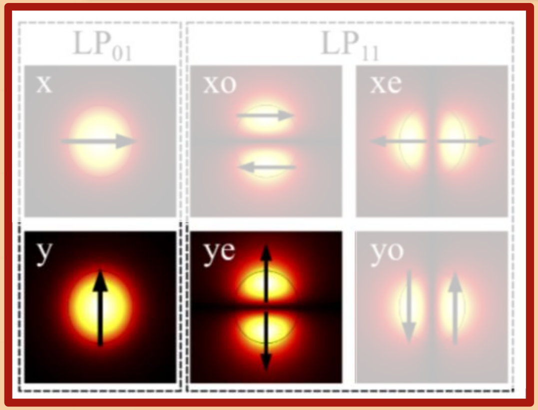
$$\beta_0^x + \beta_0^y = \beta_0^x + \beta_1^x\Omega + \frac{1}{2}\beta_2^x\Omega^2 + \beta_0^y - \beta_1^y\Omega + \frac{1}{2}\beta_2^y\Omega^2$$

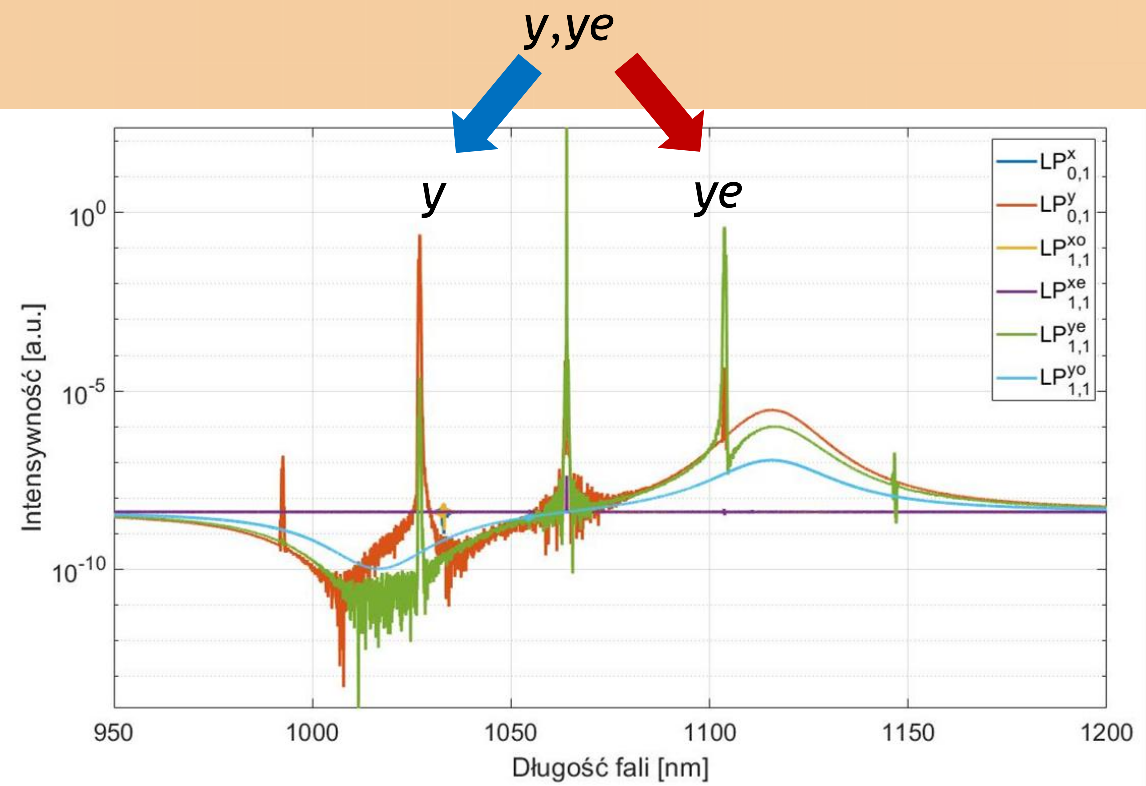
$$-\Delta\beta_1\Omega = \beta_2\Omega^2$$

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

Intermodal-vectorial FWM

Intermodal FWM





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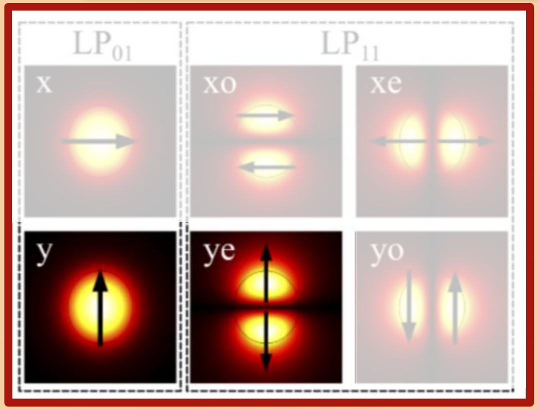
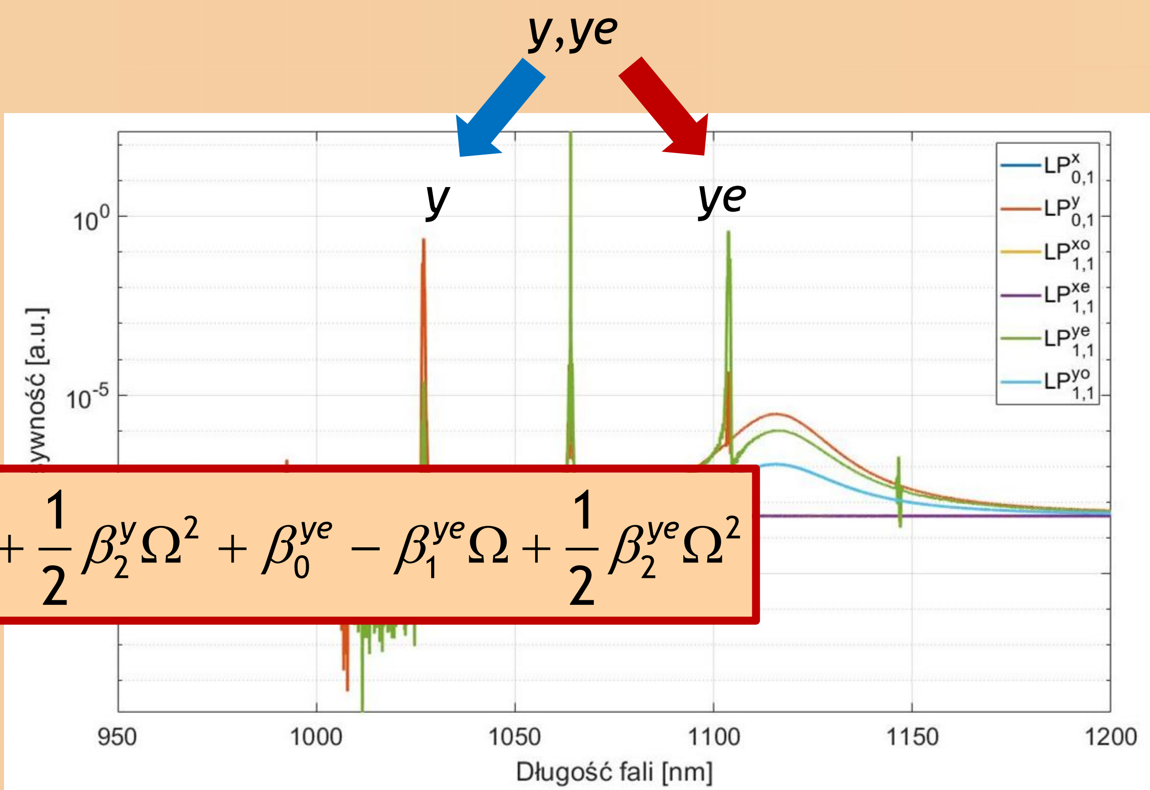
Intermodal-vectorial FWM

Intermodal FWM





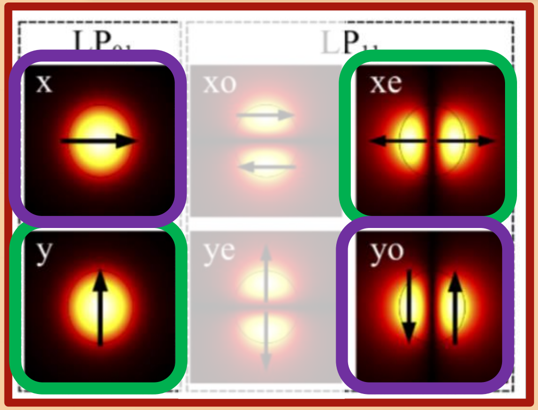
$$\beta_0^y + \beta_0^{ye} = \beta_0^y + \beta_1^y\Omega + \frac{1}{2}\beta_2^y\Omega^2 + \beta_0^{ye} - \beta_1^{ye}\Omega + \frac{1}{2}\beta_2^{ye}\Omega^2$$

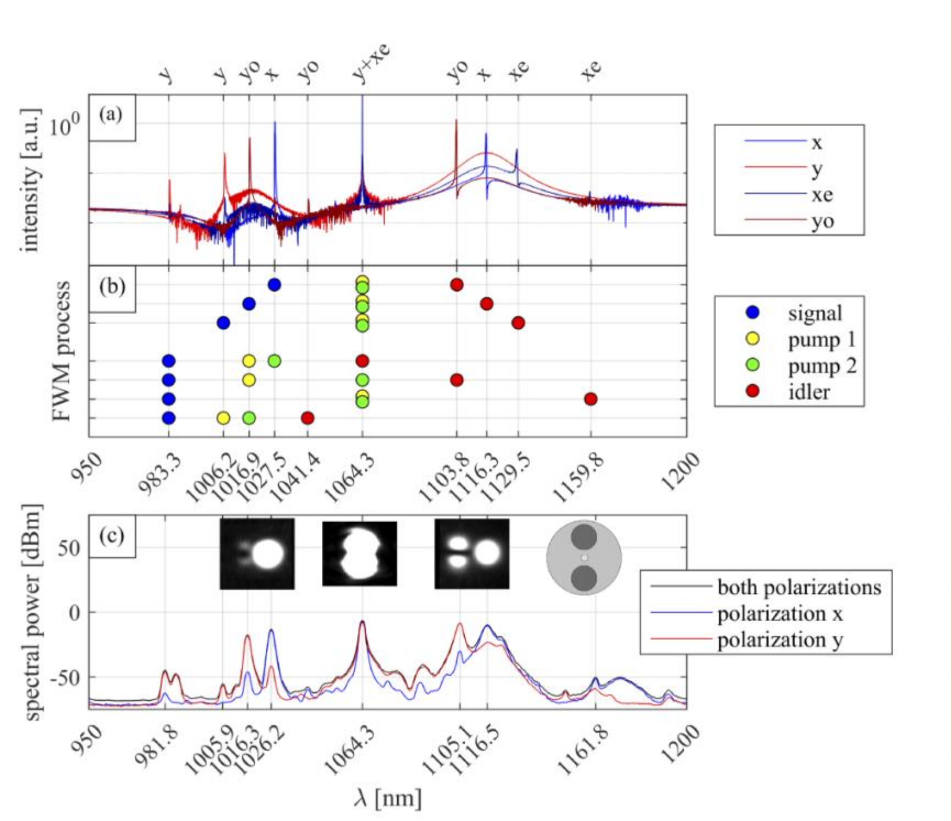
$$-\Delta\beta_1\Omega = \beta_2\Omega^2$$

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

Intermodal-vectorial FWM

Proccesses enabled by selective excitation of modes





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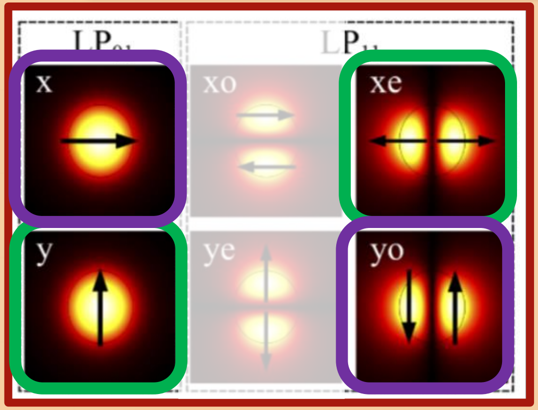
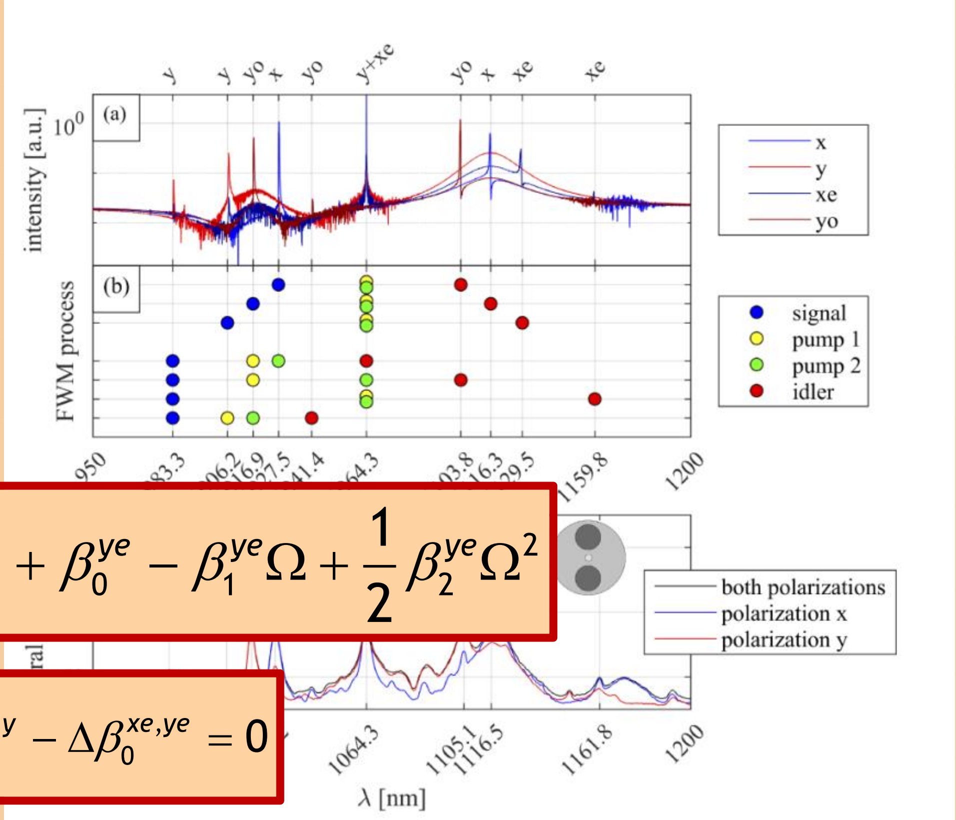
Intermodal-vectorial FWM

Proccesses enabled by selective excitation of modes





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

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

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

Outline

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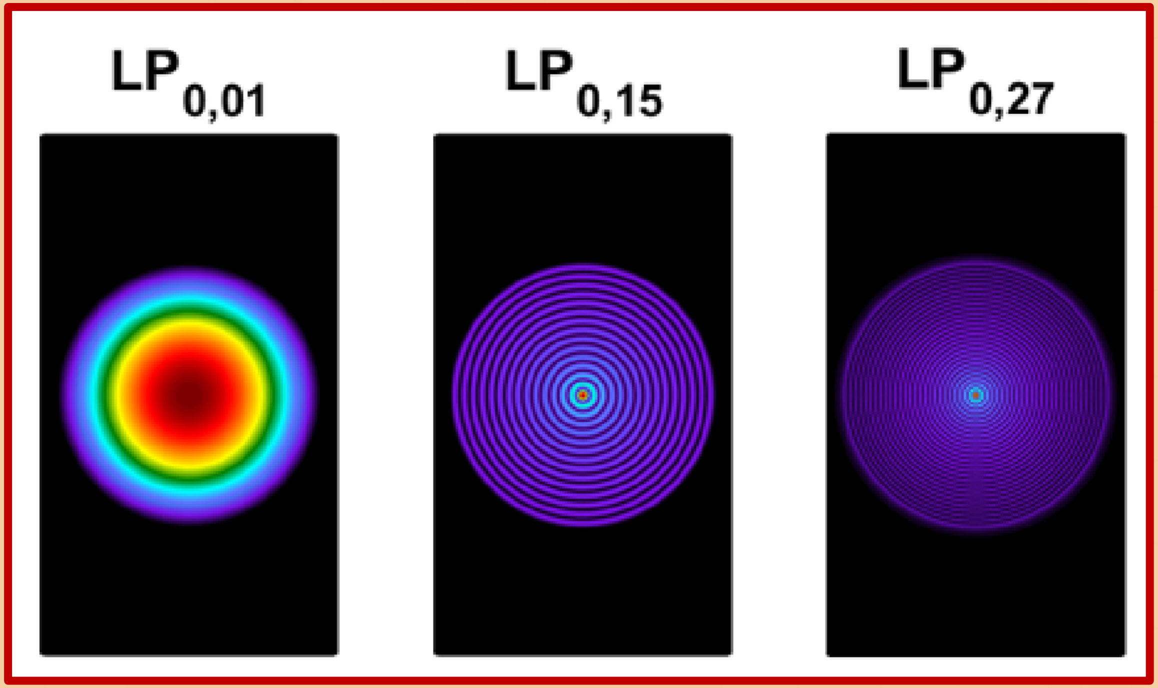
Multimode fibers	• Discretized conical emission

Discretized conical emission

Multimode optical fiber

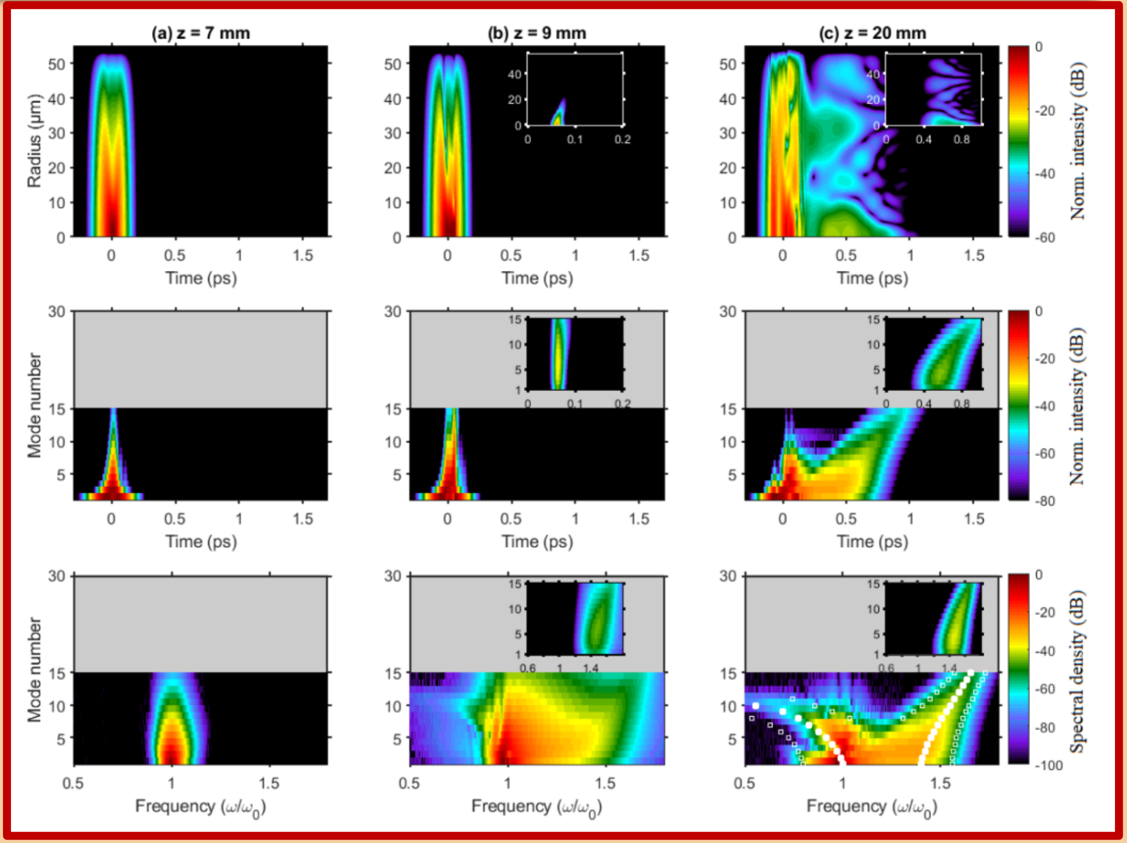
- Core diameter 105 µm
- NA = 0.22



Journal of the Optical Society of America B 38(3): 732-742 (2021)

Discretized conical emission

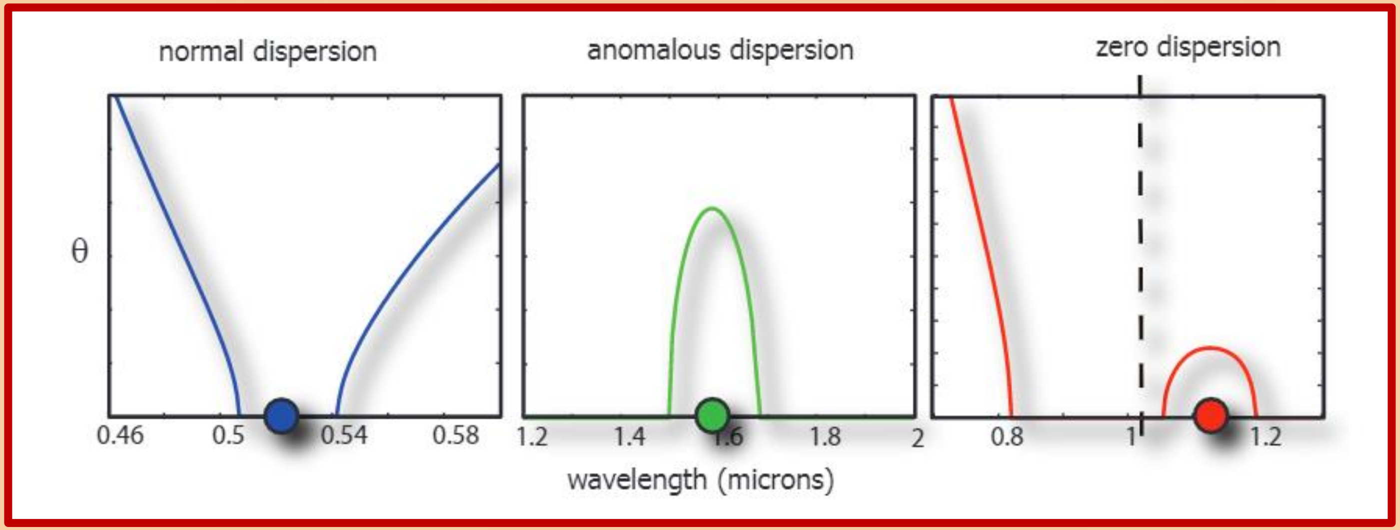
Results of modeling with MM-GNLSE



Journal of the Optical Society of America B 38(3): 732-742 (2021)

Discretized conical emission

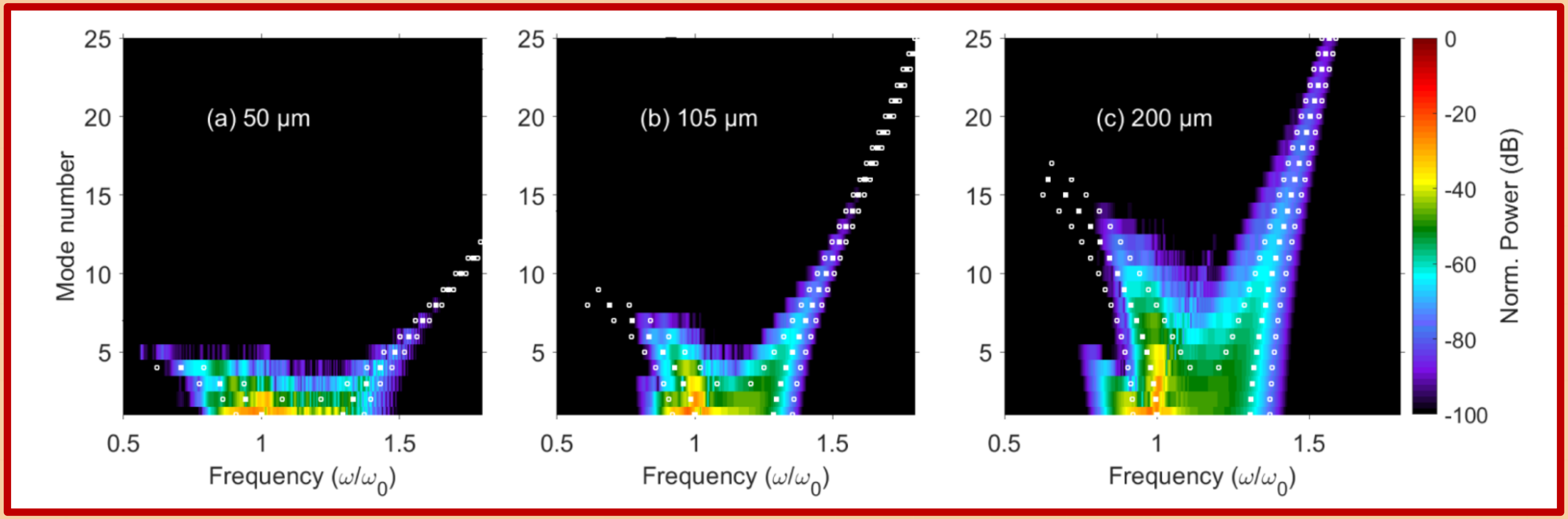
Conical waves



D. Faccio, P. Di Trapani, Nonlinear Filamentation Dynamics (2007)

Discretized conical emission

Results of modeling with MM-UPPE

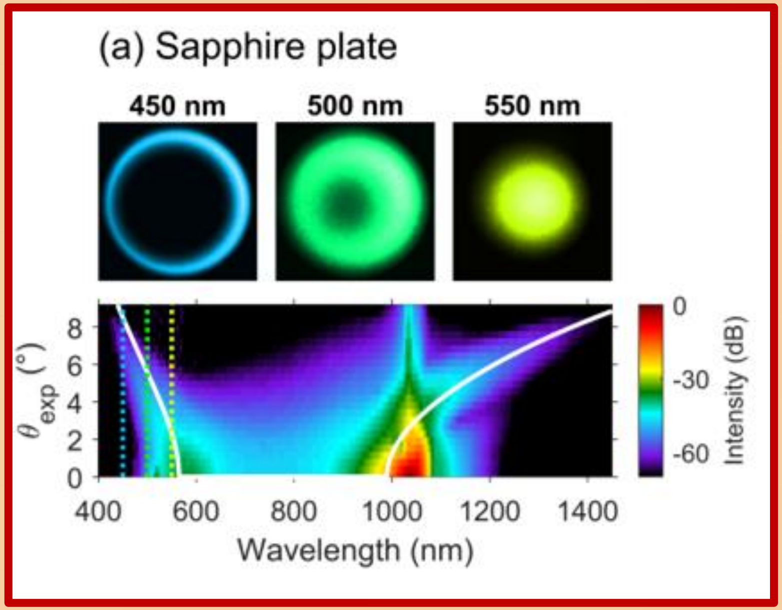


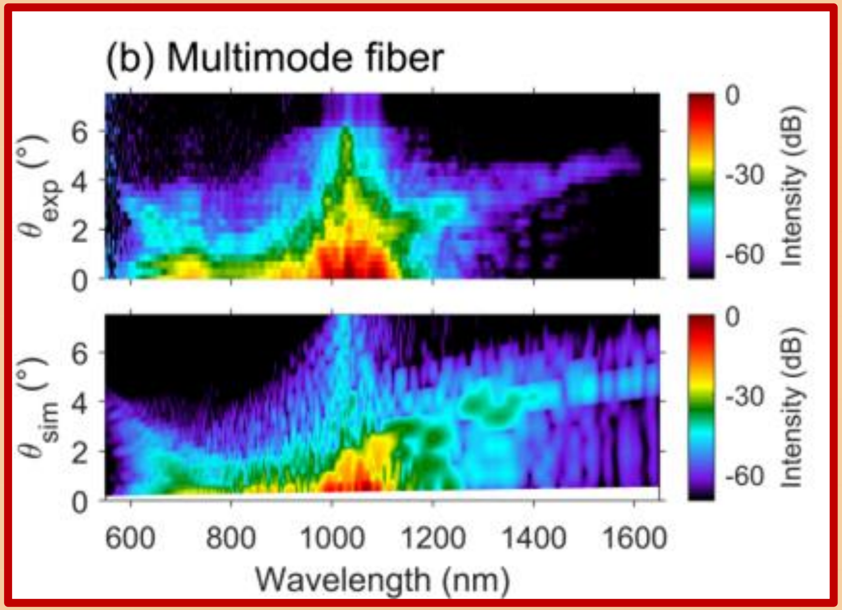
$$\boxed{\left|\beta_{\omega}^{p}-\beta_{0}^{0}-\left(\beta_{1}^{0}+\delta\beta_{1}\right)\left(\omega-\omega_{0}\right)\right|\leq\frac{2\pi}{d_{z}}}$$

Journal of the Optical Society of America B 38(3): 732-742 (2021)

Discretized conical emission

Experimental results





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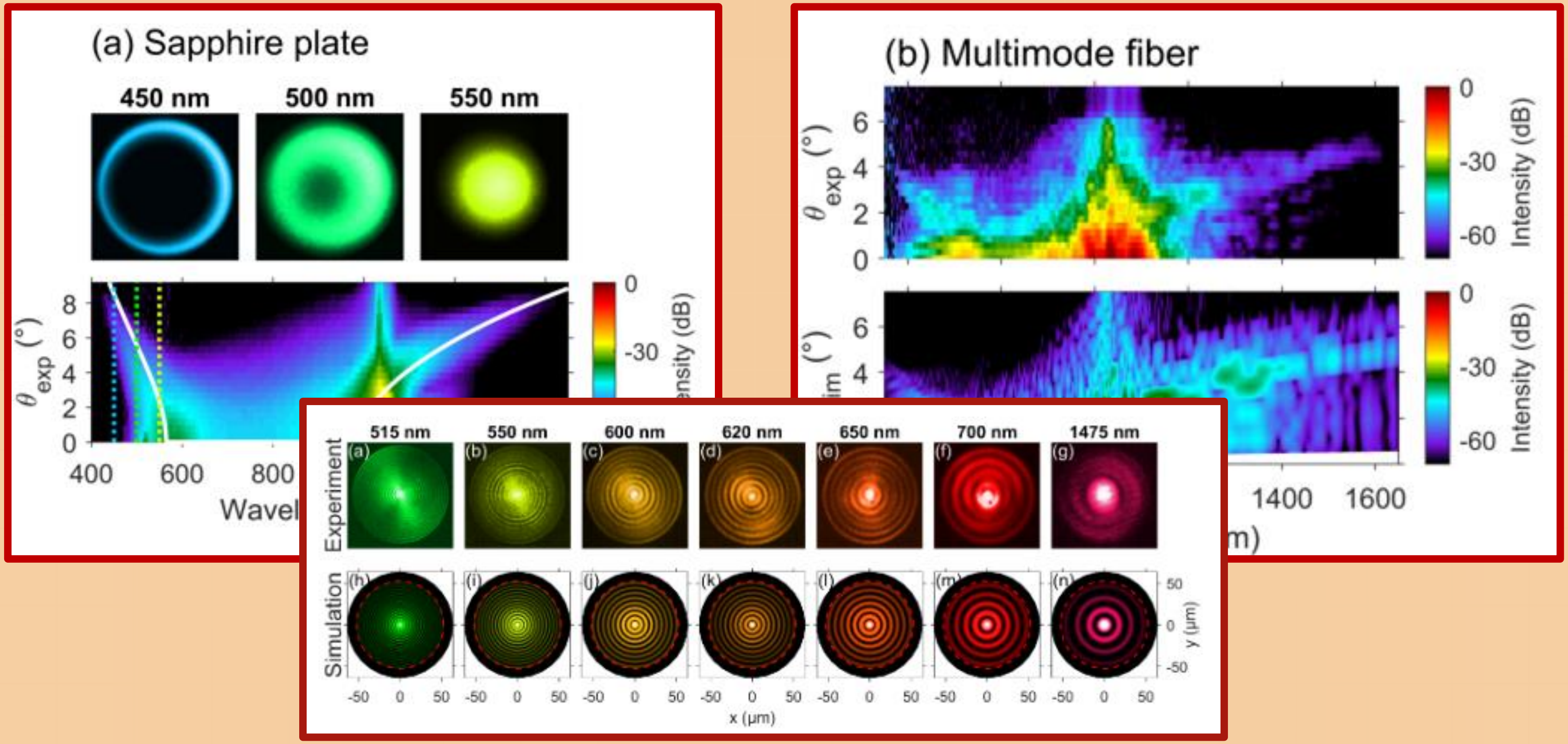
Discretized conical emission

Experimental results



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Discretized conical emission

Spatio-temporal wave packets

- Spontaneous emission of a discretized conical wave in a step-index multimode fiber during propagation of an intense ultrashort pulse
- The resulting 2D+1 ST wavepacket propagates with a deterministic group-velocity and it results from a linear superposition of fiber modes with an engineered spatiotemporal spectrum.

K. Stefańska, ACS Photonics in review

Conclusions

- Optical fibers allow to observe and investigate the broad spectrum of frequency conversion processe
- The numerical experiments allow to get insight into the complex dynamics of nonlinear phenomena

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Thank you for your attention