# Zjawiska nieliniowe w światłowodach

## W11OPA-SM0050W (FTP003030W)

rok akademicki 2024/25

semestr zimowy

## Wykład 7

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L-1 p. 221

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23rd Slovak-Czech-Polish Optical Conference, Štrbské Pleso, September 02-06, 2024

# Looking into the landscape of frequency conversion processes in optical fibers: from single mode to multimode


*Karol Tarnowski*
Wrocław University of Science and Technology, Faculty of Fundamental Problems of Technology
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05.09.2024

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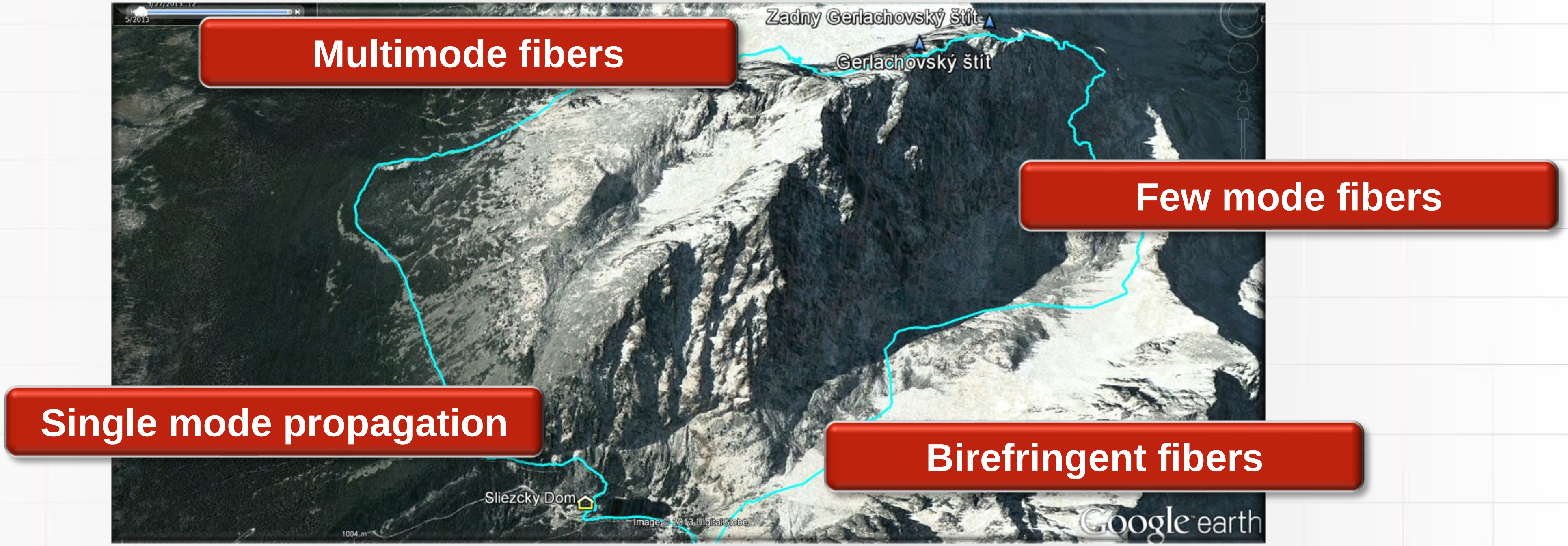
# Looking into the landscape of frequency conversion processes in optical fibers: from single mode to multimode

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# Outline

| | | |
|---|---|---|
| **Introduction** | • Description of frequency conversion processes in optical fibers | |
| **Single mode propagation** | • All-normal dispersion supercontinuum<br>• Soliton self-frequency shift | **1** |
| **Birefringent fibers** | • Polarized all-normal dispersion SC<br>• Solitons - orthogonal Raman scattering | **2** |
| **Few mode fibers** | • Intermodal-vectorial four-wave mixing<br>• Far-detuned four-wave mixing | **few** |
| **Multimode fibers** | • Discretized conical emission | **many** |

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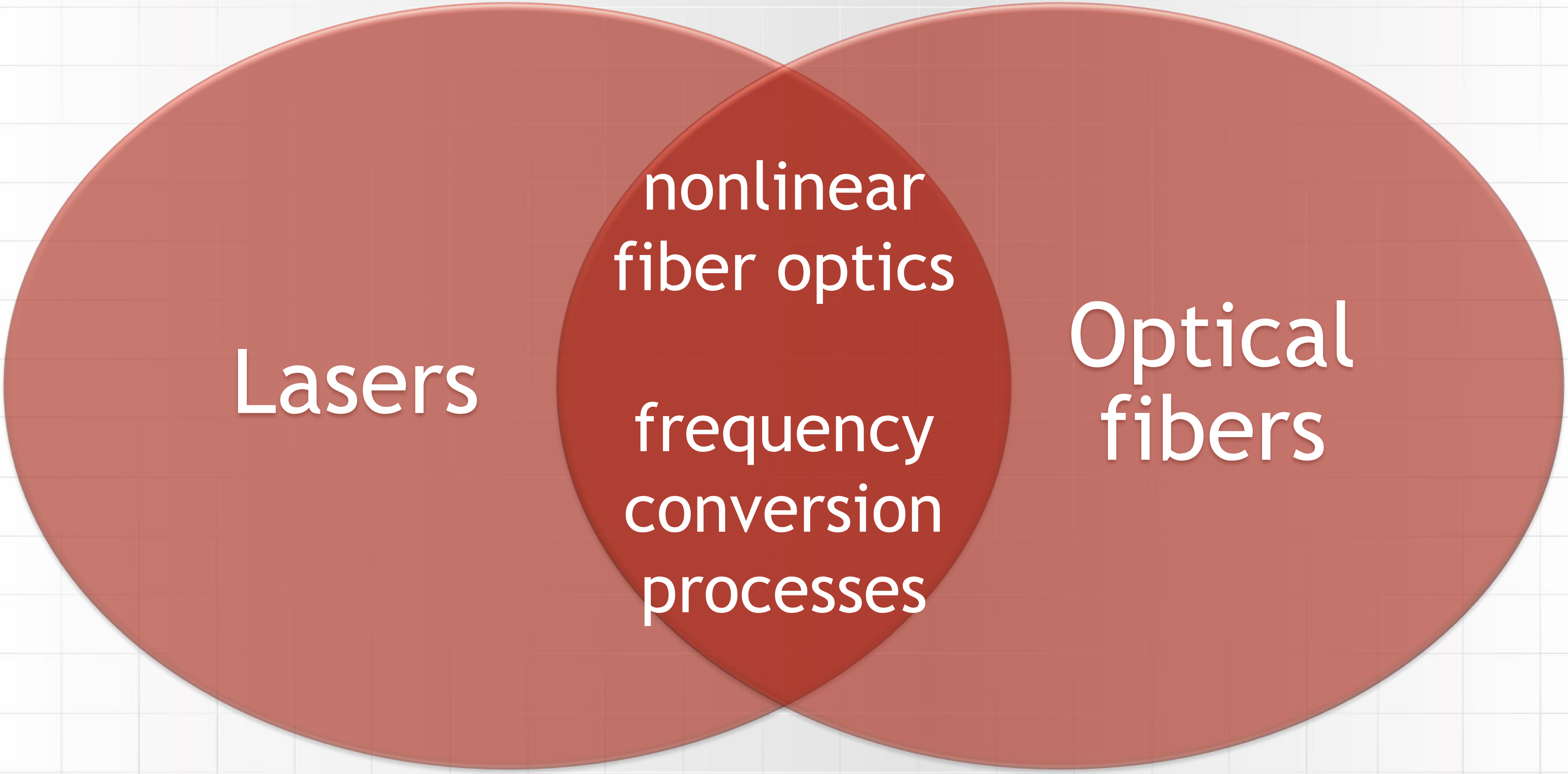
# Introduction



# Introduction

| Experiment | Theory/simulations |
| --- | --- |
| • Laser source | • Input field |

wavelength, pulse/CW, duration, energy/power

| | |
| --- | --- |
| • Nonlinear fiber | • Fiber properties |

chromatic dispersion, effective mode area, overlap coefficients

| | |
| --- | --- |
| • Detection setup | • Output field |

spectrometer, optical spectrum analyzer, autocorrelator, FROG system

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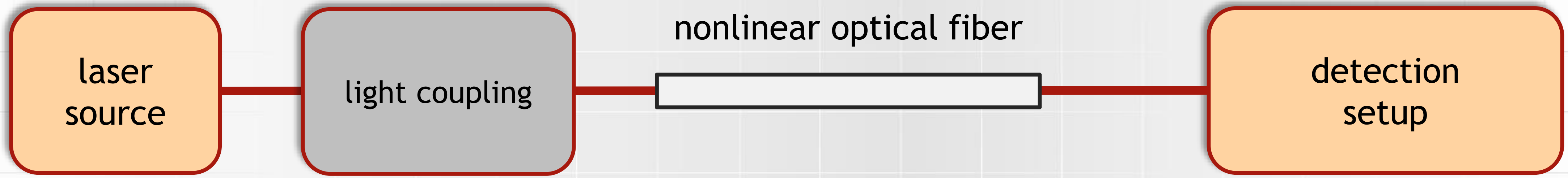
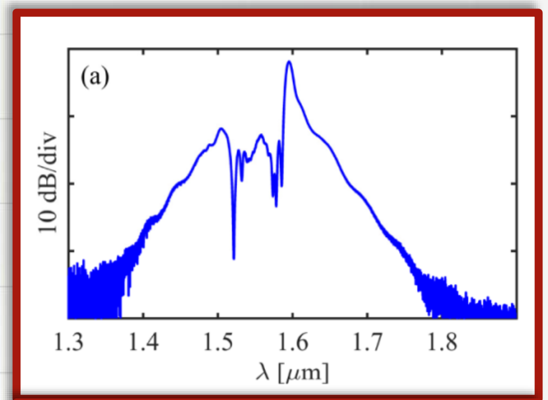
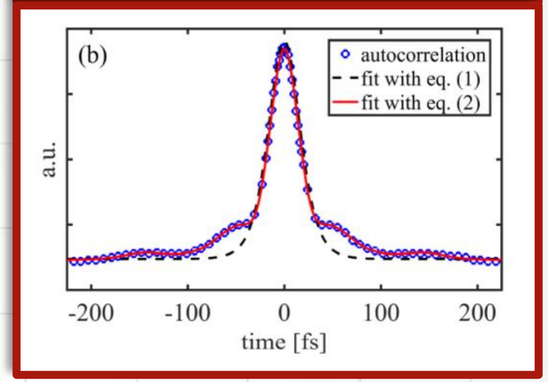
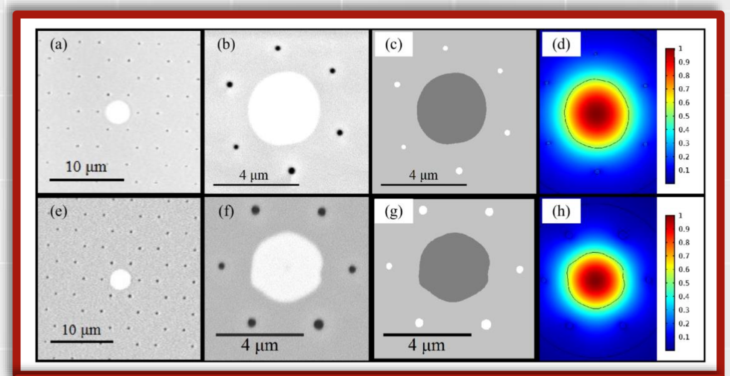
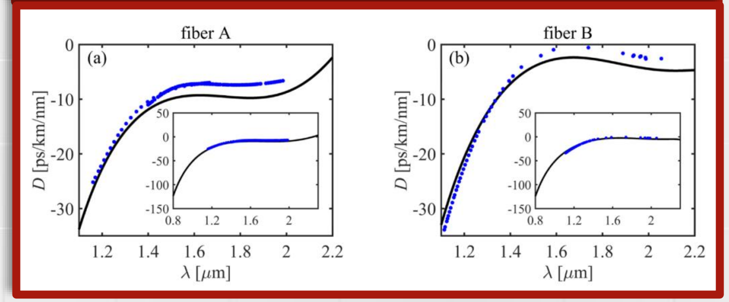
# Typical experimental setup

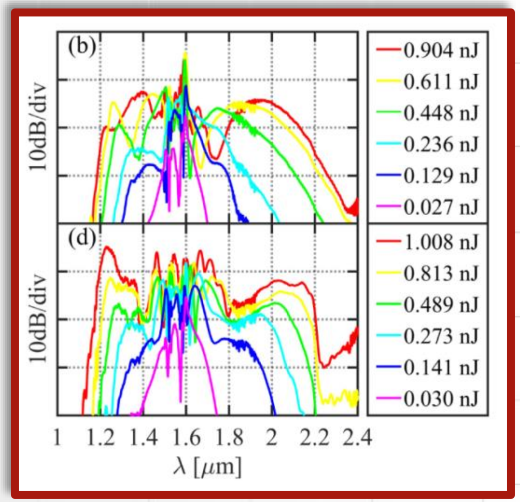


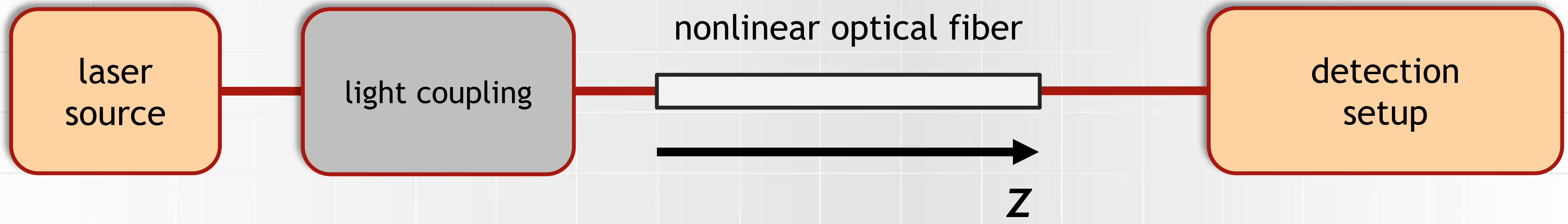



# Numerical experiment

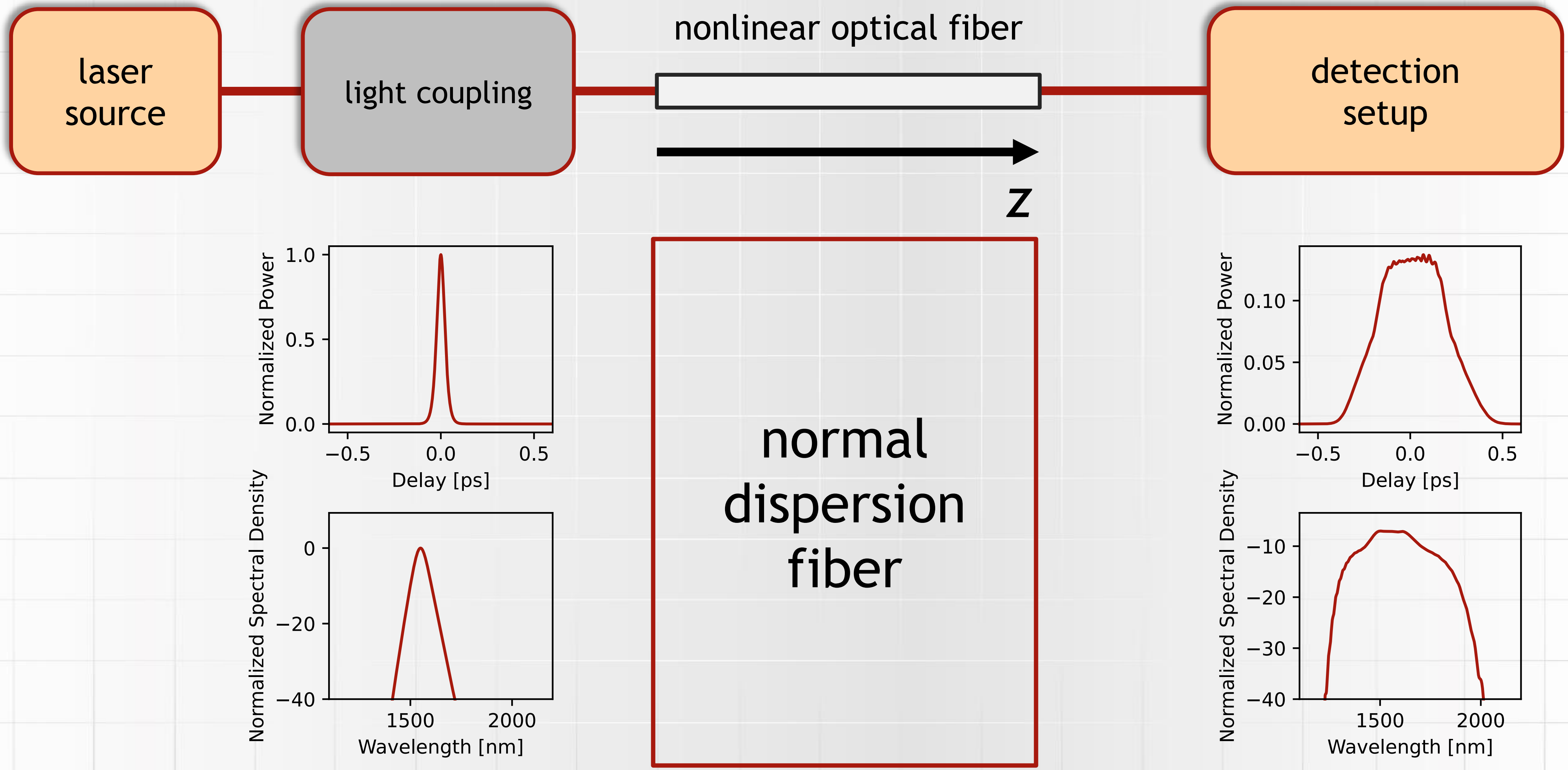



$$A(0,T) = \mathcal{F}^{-1}\left\{\tilde{A}(0,\Omega)\right\}$$
$$\tilde{A}(0,\Omega) = \mathcal{F}\left\{A(0,T)\right\}$$

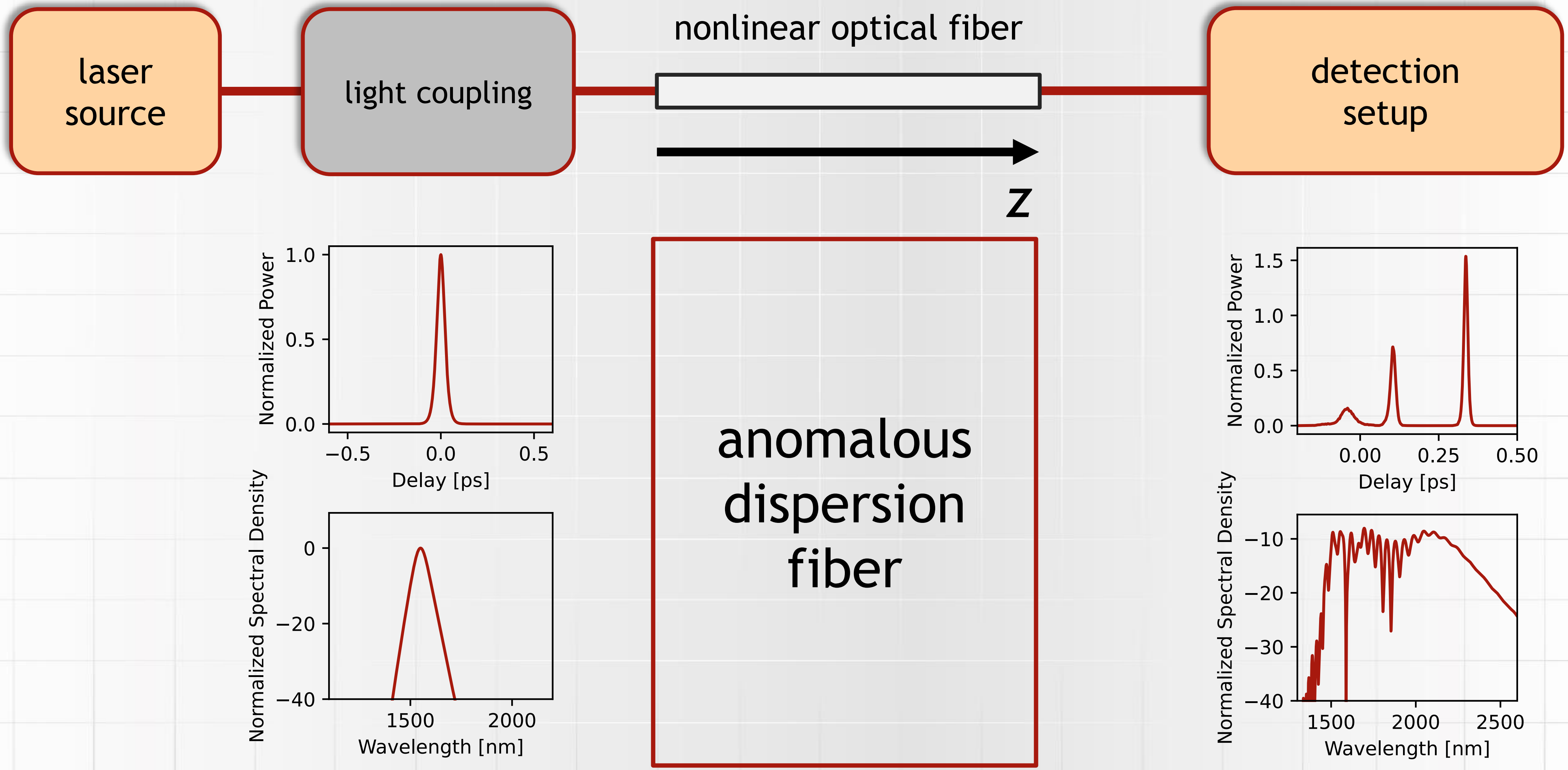
$$\frac{\partial A}{\partial z} = D(A) + N(A)$$

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

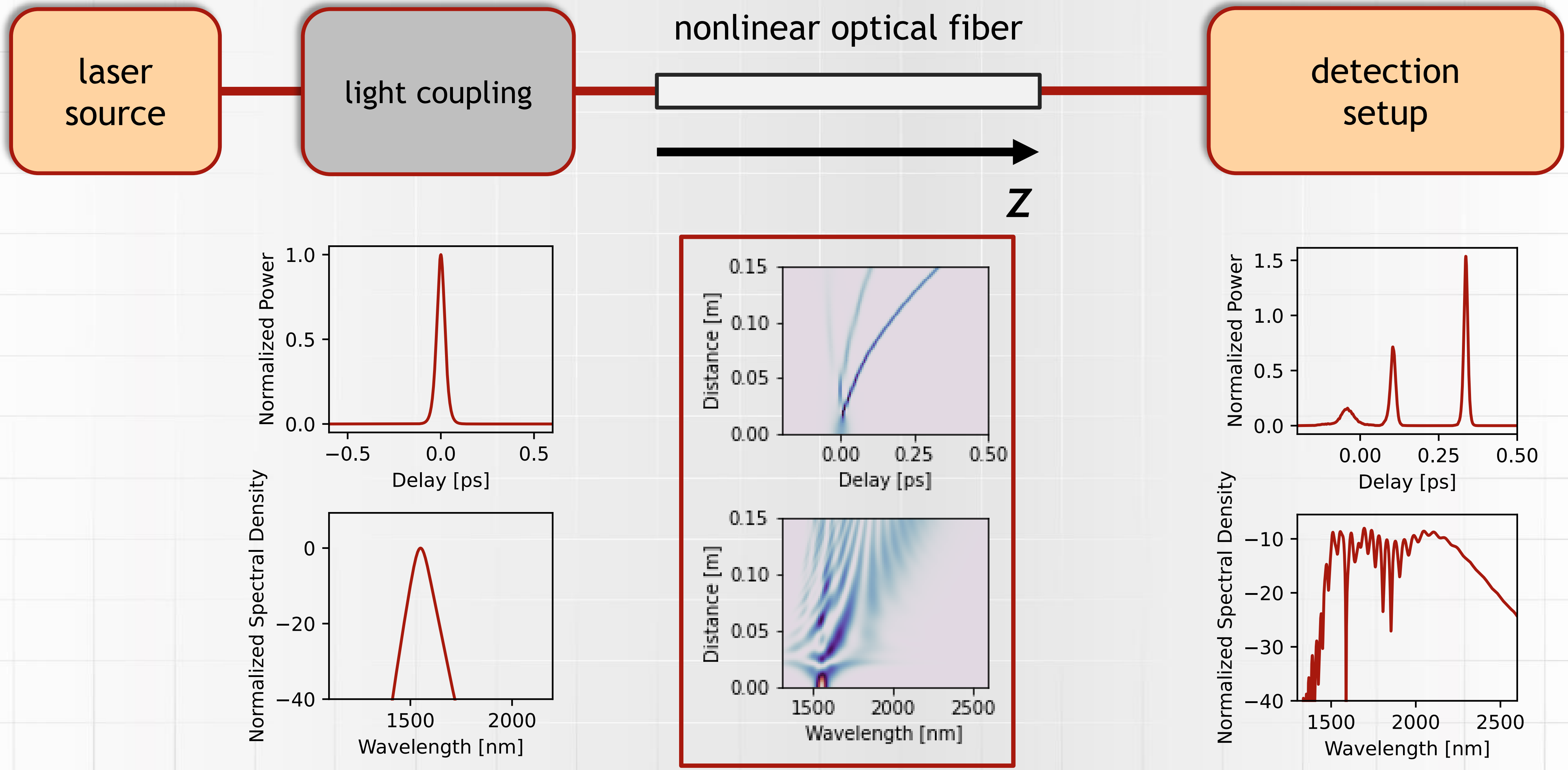
# Numerical experiment



# Numerical experiment



# Numerical experiment



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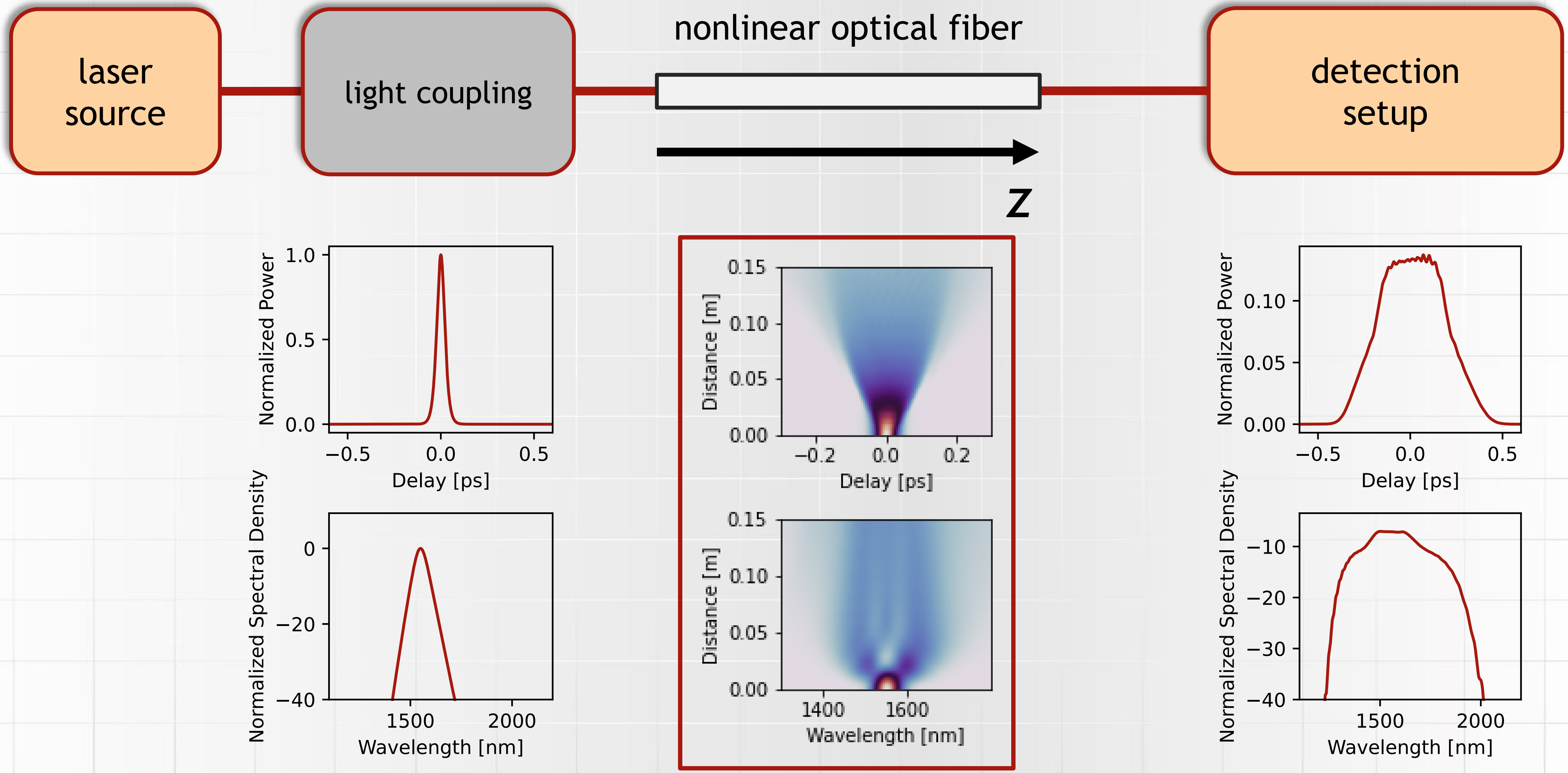
# Numerical experiment



# 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 processes

## Optically induced change in the refractive index

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

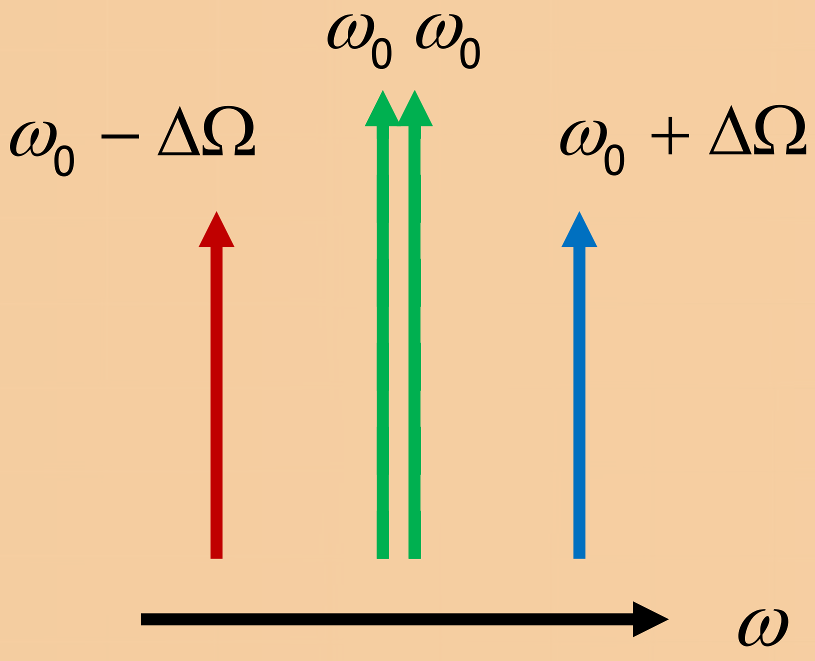
## Inelastic scattering

- stimulated Raman scattering (SRS)

# Frequency conversion processes

## Optically induced change in the refractive index

- SPM
- XPM
- MI
- degenerated FWM



# Frequency conversion processes

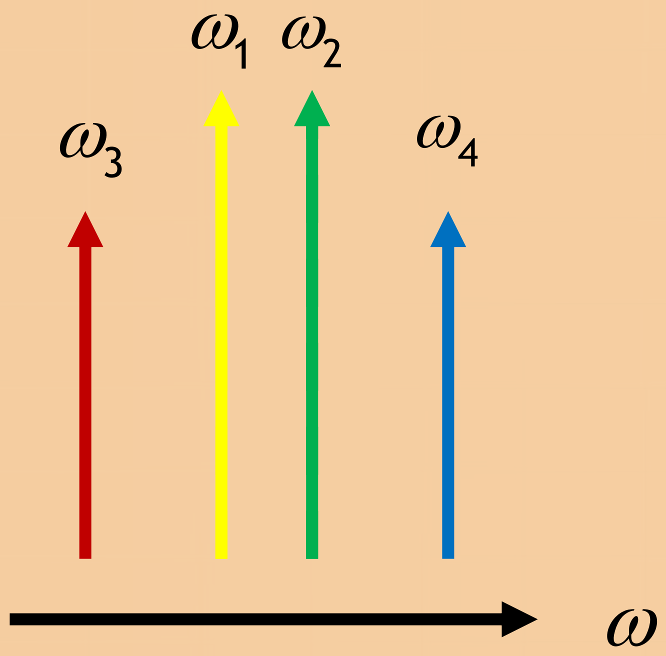
## Optically induced change in the refractive index

- four-wave mixing

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

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

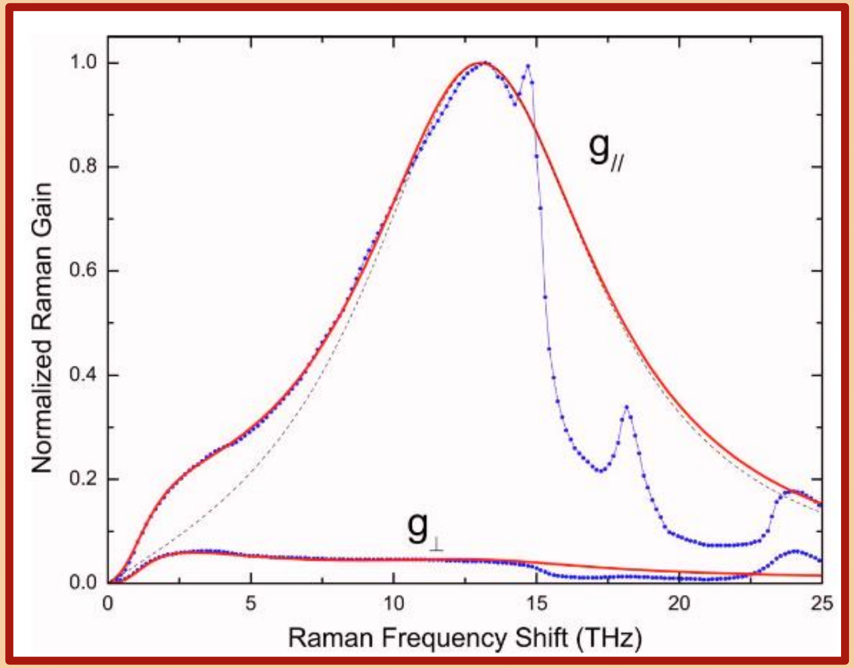
$$\beta_1 + \beta_2 = \beta_3 + \beta_4 + \Delta k_{NL}$$



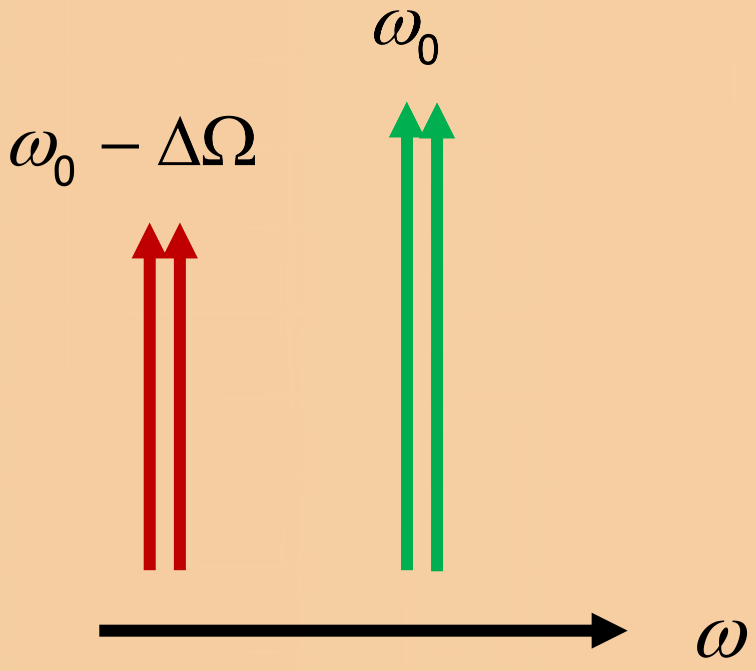
# Frequency conversion processes

## Inelastic scattering

- stimulated Raman scattering (SRS)



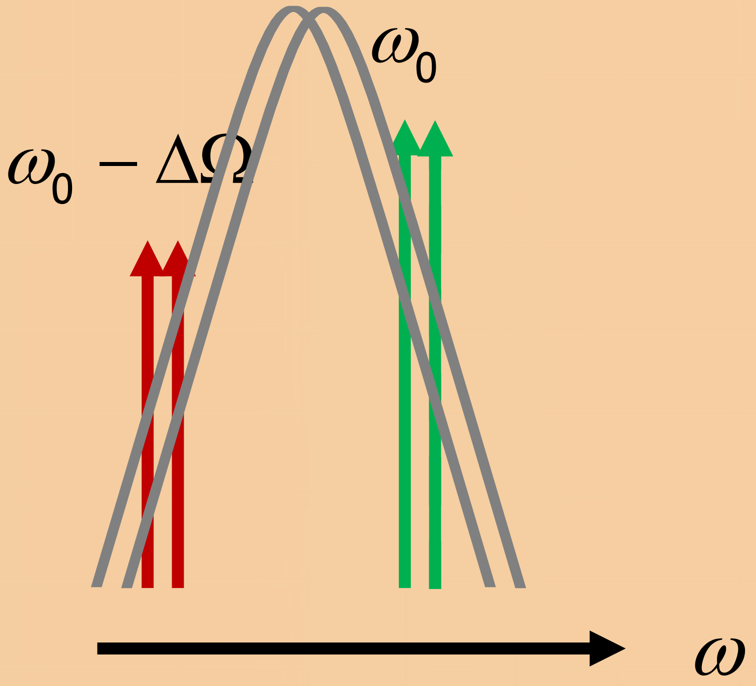

Q. Lin, G. P. Agrawal, Optics Letters, 31(21): 3086 (2006)



# Frequency conversion processes

## Inelastic scattering

- Intrapulse Raman scattering (SRS)



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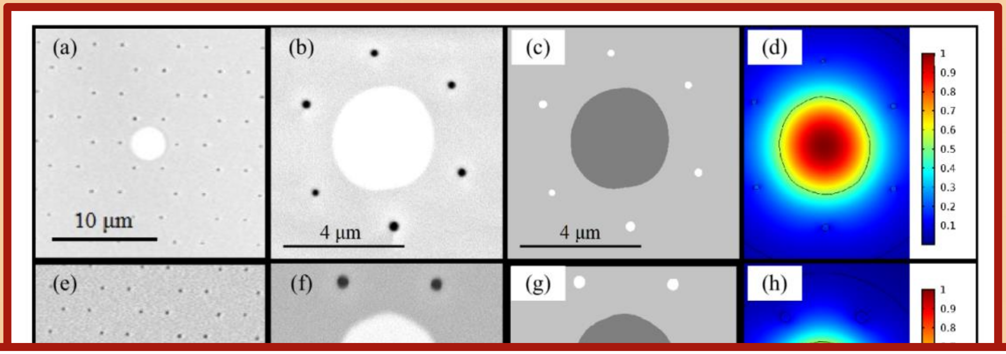
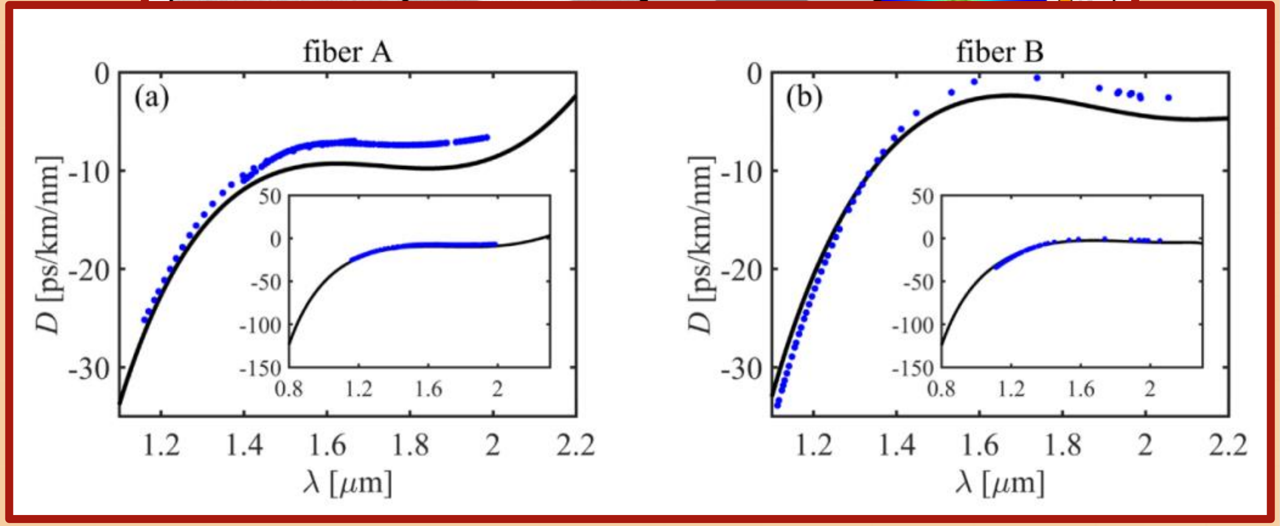
# All-normal dispersion supercontinuum

## Nonlinear microstructured fiber with normal dispersion

- design
- fabrication
- characterization
- supercontinuum generation



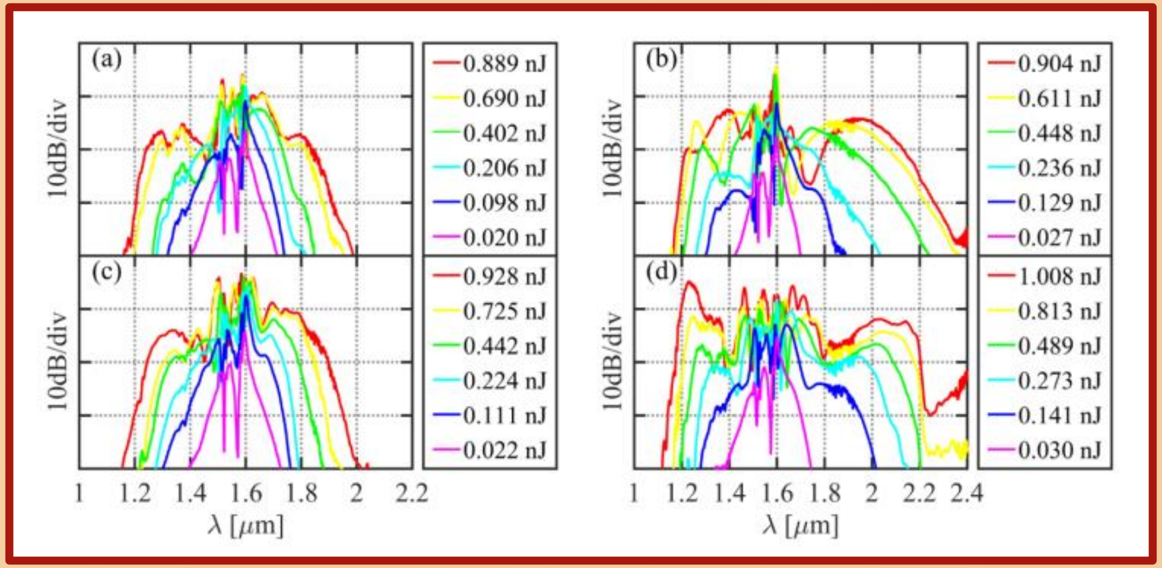

Optics Express, 24(26): 30523 (2016)

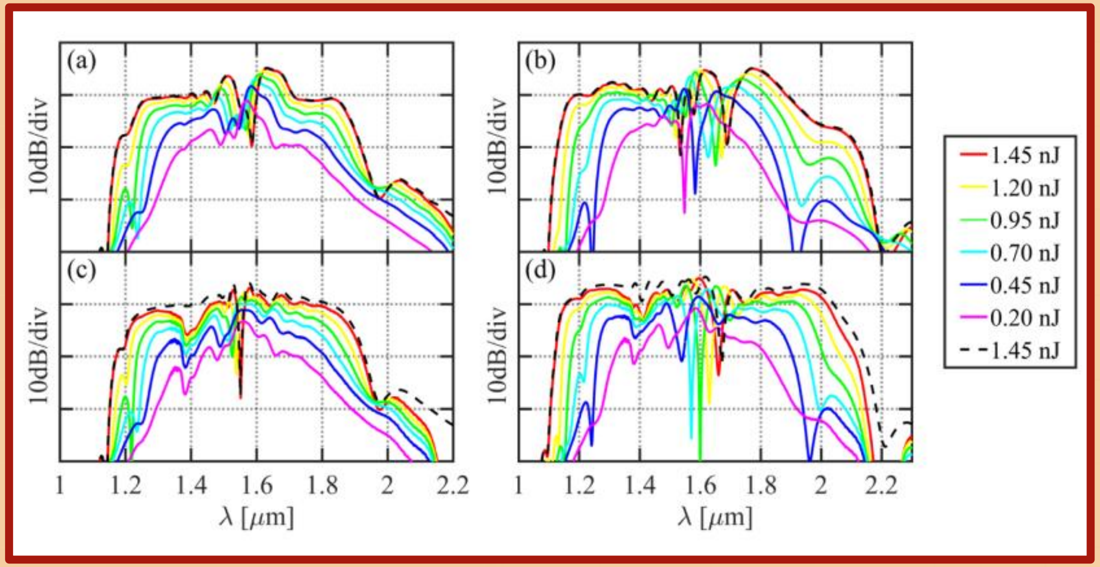
# All-normal dispersion supercontinuum

## Nonlinear microstructured fiber with normal dispersion

- broad and coherent supercontinuum spectrum

23-fs pumping



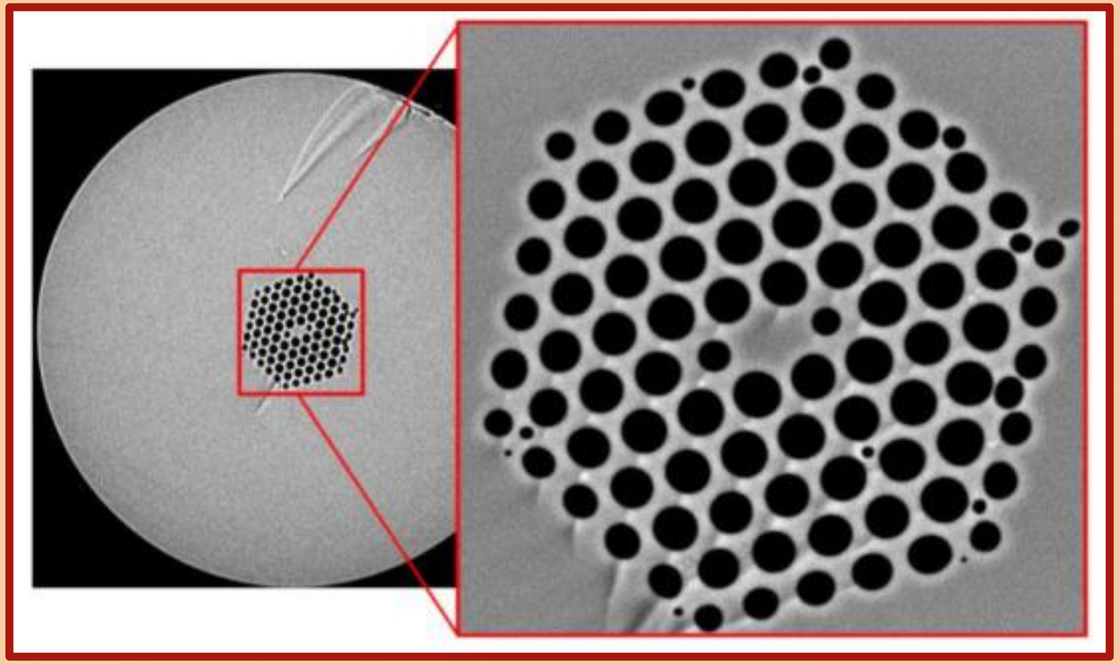



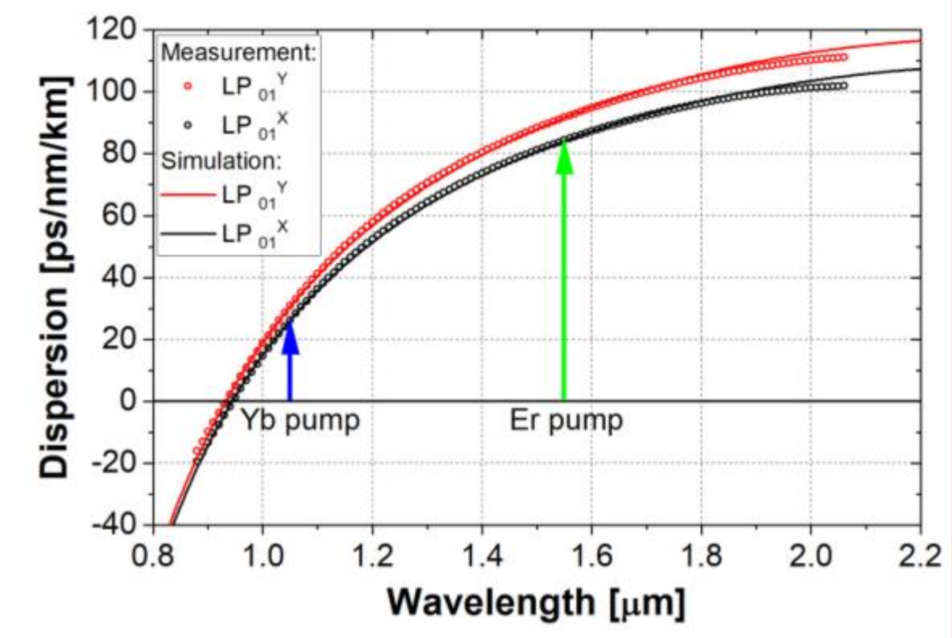

Optics Express, 24(26): 30523 (2016)

# Soliton self-frequency shift

## Nonlinear microstructured fiber with anomalous dispersion

- broad spectral tuning






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

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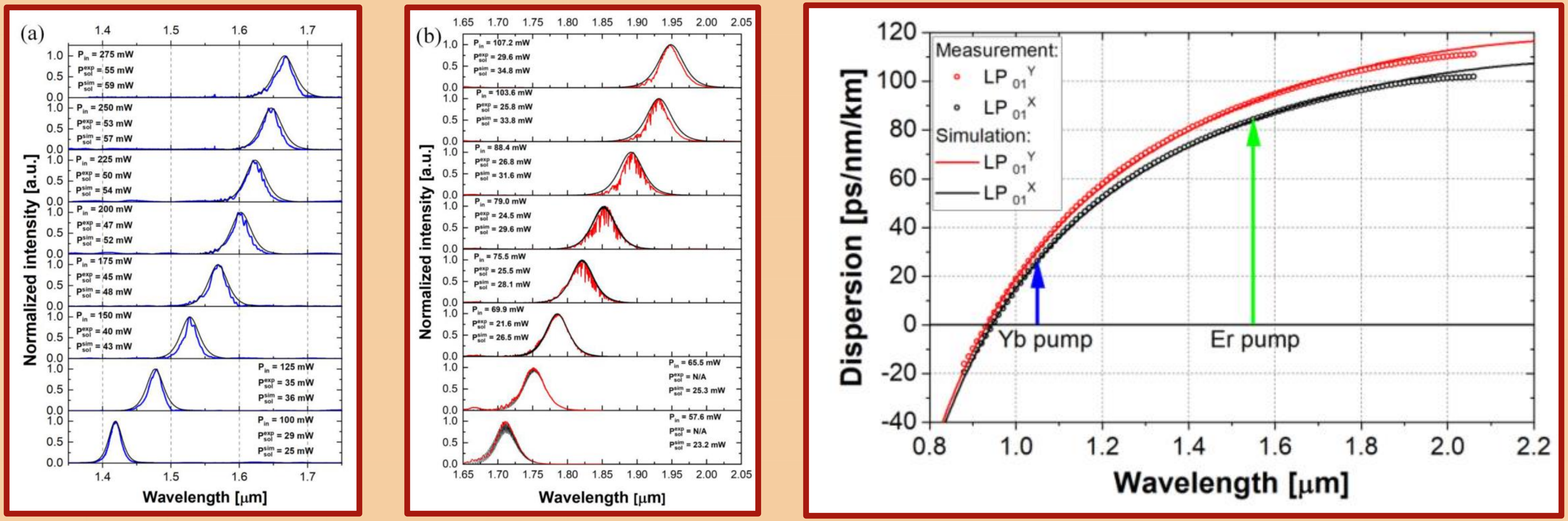


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# Polarized all-normal supercontinuum (Pol-AND SC)

## Coupled nonlinear Schrödinger equations

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

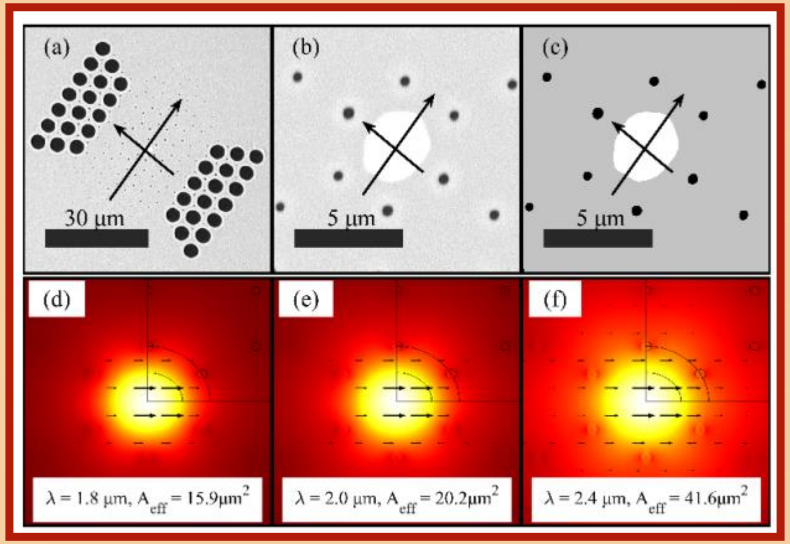
$$\frac{\partial \tilde{C}_x}{\partial z} = D_x\left(\tilde{C}_x\right) + \\ +i\frac{n_2 n_0 \omega}{c n_{\text{eff}}\sqrt{A_{\text{eff}}(\omega) A_{\text{eff}}(\omega_0)}} \cdot \mathcal{F}\left\{\left(\left|C_x\right|^2 + \frac{2}{3}\left|C_y\right|^2\right)C_x + \frac{1}{3}C_y^2 C_x^* \exp\left(-2i\Delta\beta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

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

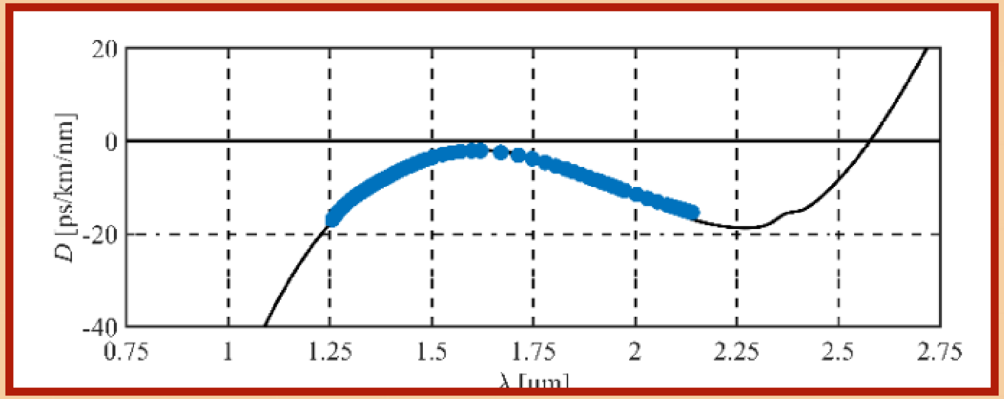
# Polarized all-normal supercontinuum (Pol-AND SC)

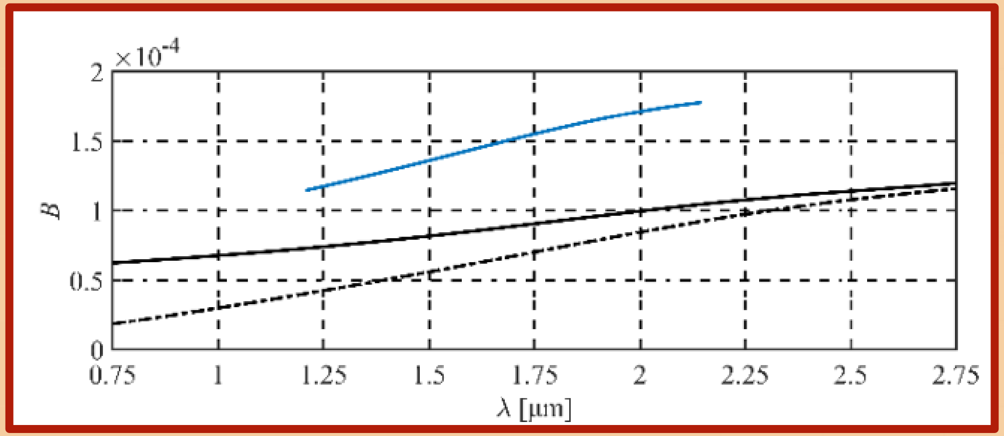
## Nonlinear birefringent microstructured fiber with normal dispersion

- design
- fabrication
- characterization
- supercontinuum generation




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

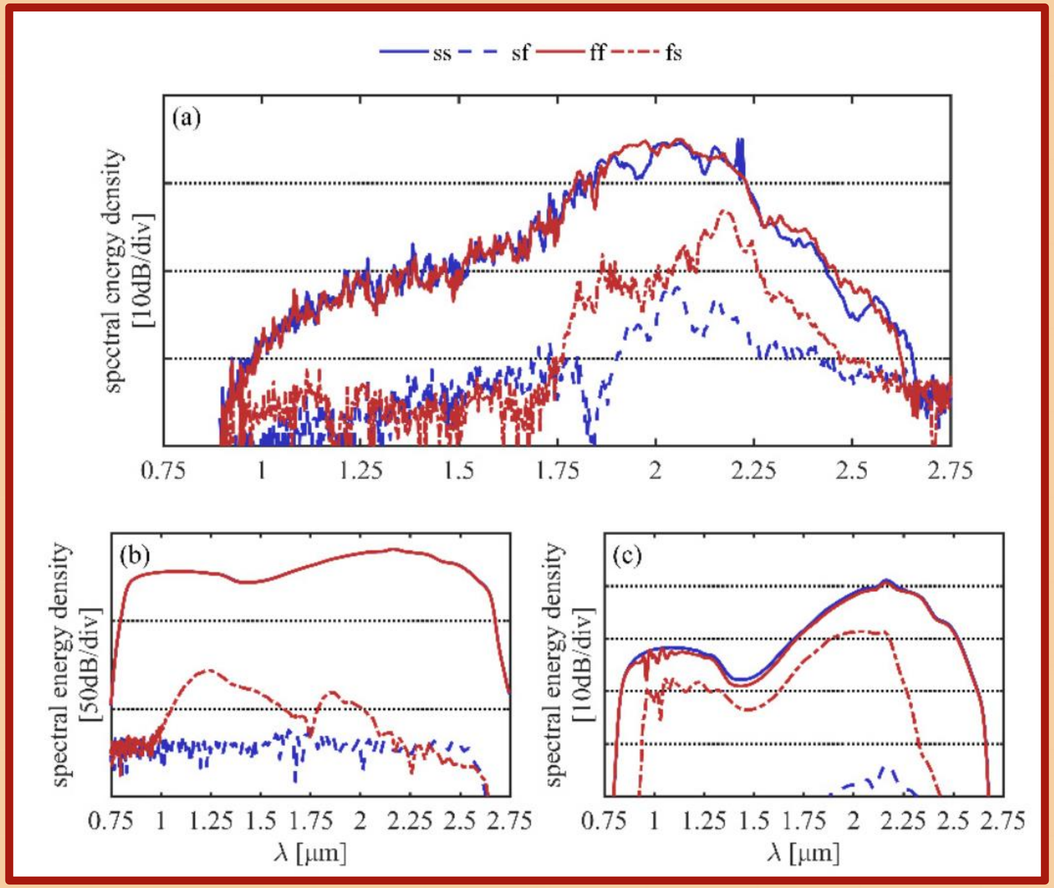


# Polarized all-normal supercontinuum (Pol-AND SC)

## Supercontinuum generation

- normal dispersion
- linearly polarized
- coherent

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## Supercontinuum generation

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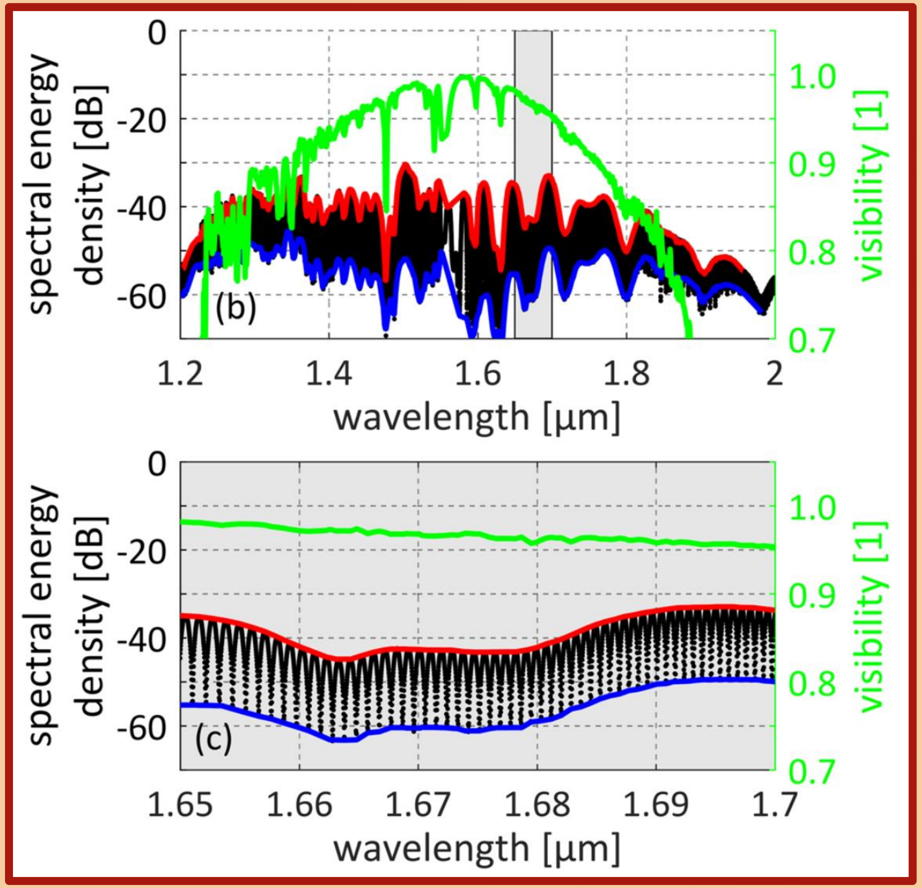
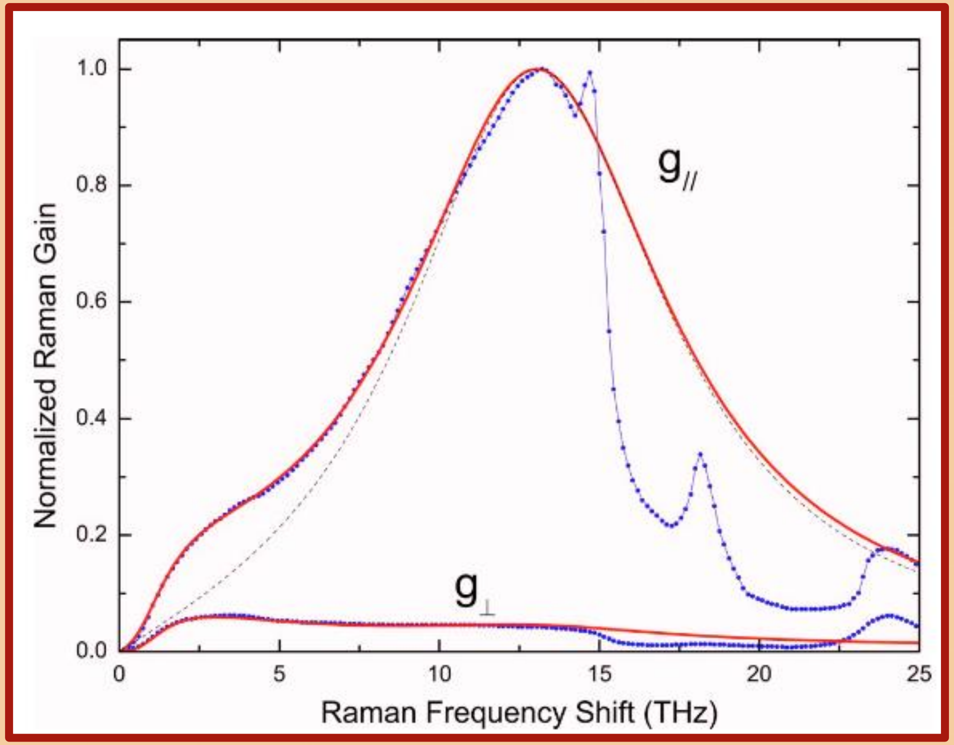



Scientific Reports 9: 12313 (2019)

# Orthogonal Raman scattering

## Raman response function




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

# Orthogonal Raman scattering

## Coupled nonlinear Schrödinger equations

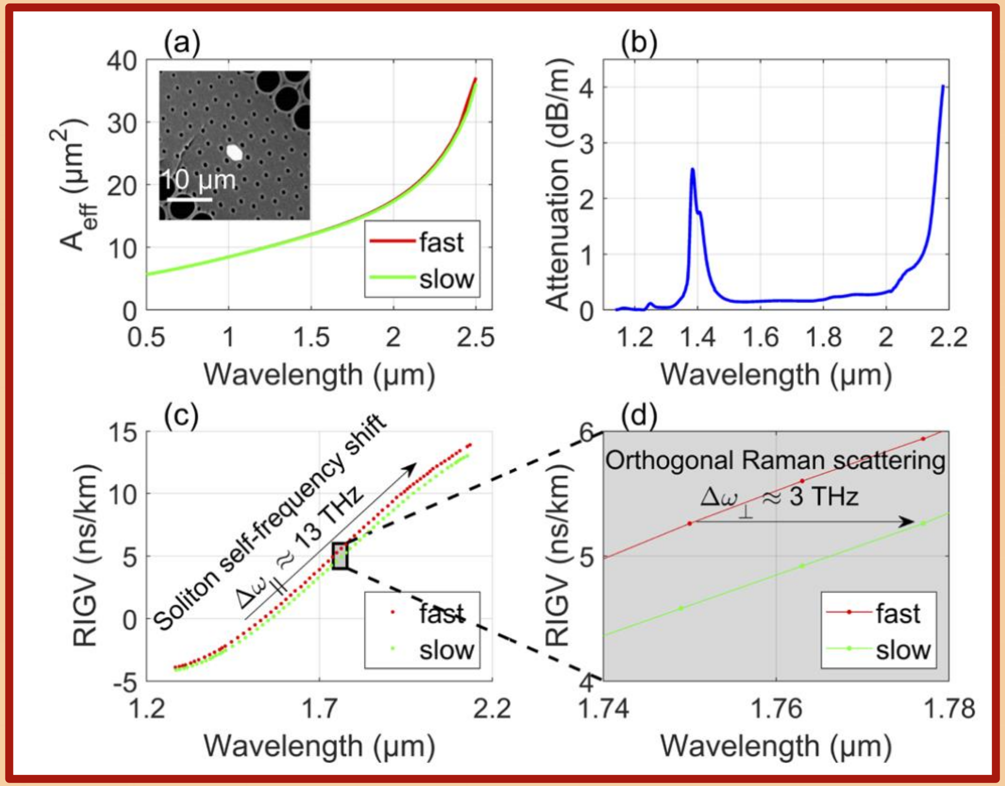
- with vector Raman response

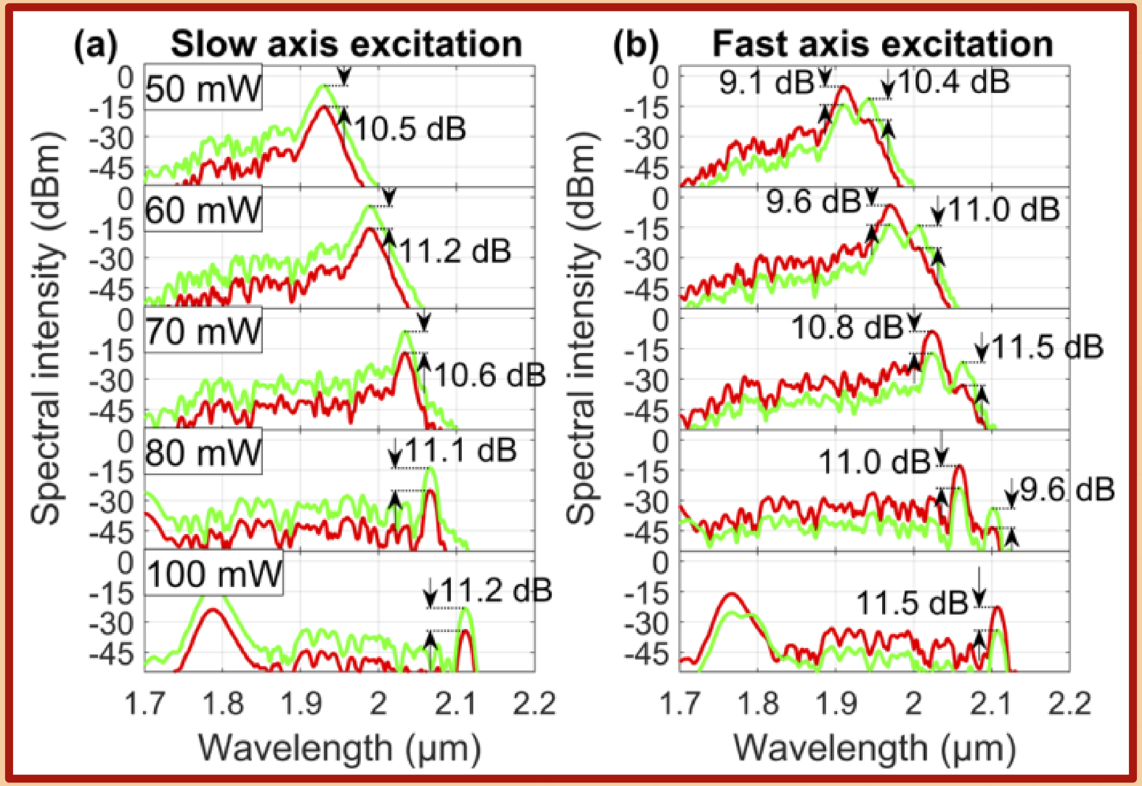
$$N_x\left(\tilde{C}_x,\tilde{C}_y\right)=\bar{\gamma}_x\mathcal{F}\left\{\begin{array}{l}(1-f_R)\times\left(\left(|C_x|^2+\frac{2}{3}|C_y|^2\right)C_x+\frac{1}{3}C_y^2C_x^*\exp(-2i\Delta\beta z)\right)+\\ +f_R\times\left[\begin{array}{l}\left(h_1\otimes|C_x|^2+h_2\otimes|C_y|^2\right)C_x+\\ +h_3\otimes\left(C_xC_y^*+C_yC_x^*\exp(-2i\Delta\beta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

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

# Orthogonal Raman scattering

## Polarization conversion




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

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# Few mode fibers

## System of nonlinear Schrödinger equations

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

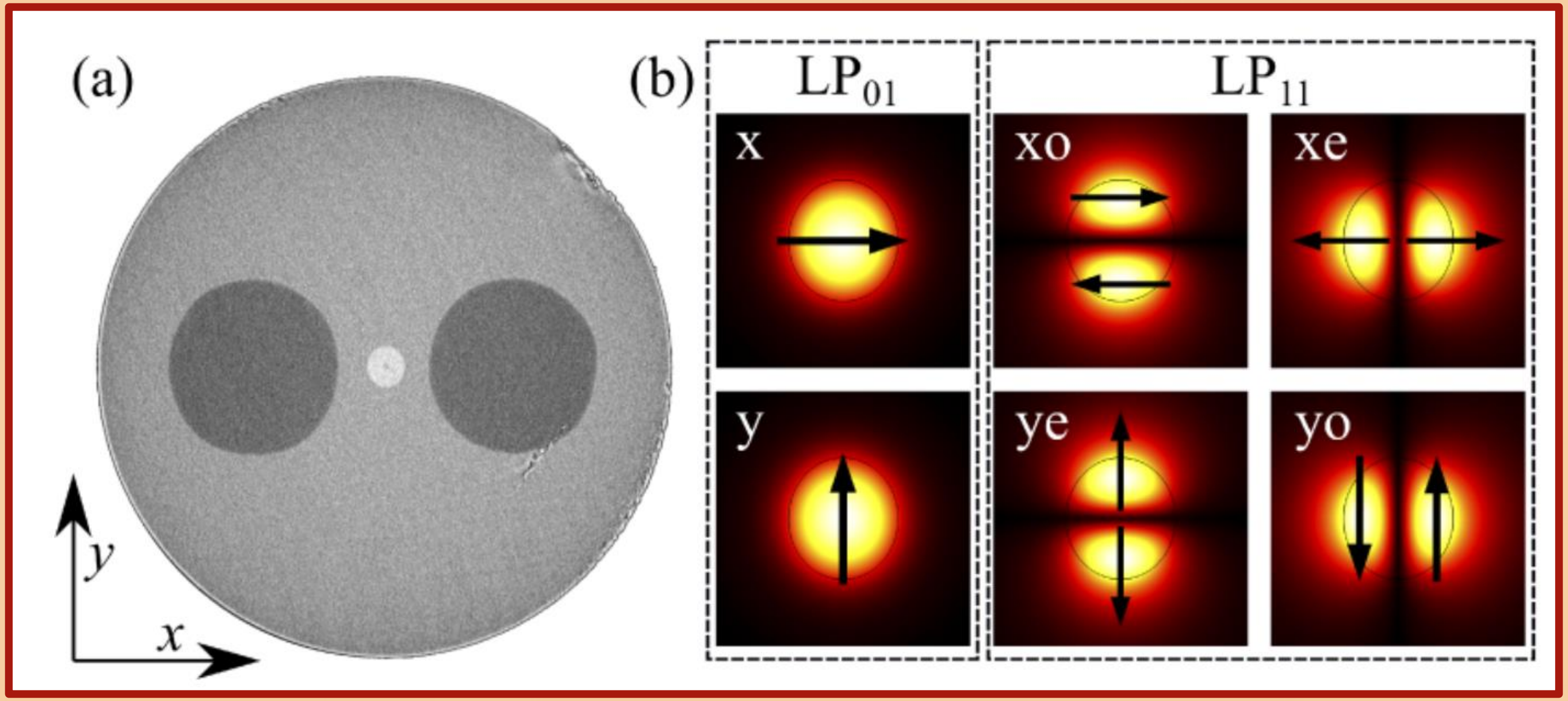
$$-\left(\beta_1^{(p)} - \beta_1^{(0)}\right)\frac{\partial A_p}{\partial t} + i\sum_{n\geq 2}^{\infty} \frac{i^n \beta_n^{(p)}}{n!} \frac{\partial^n A_p}{\partial t^n} +$$

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

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

# Intermodal-vectorial FWM

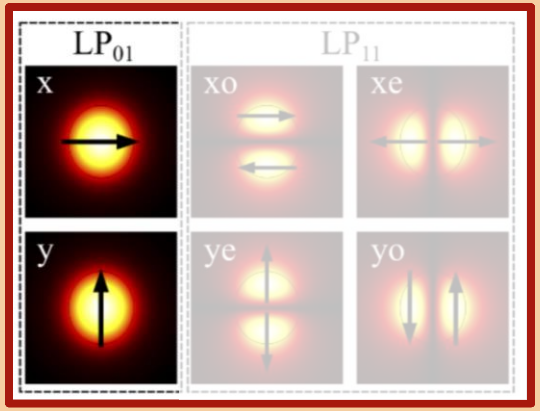
## Fiber modes




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

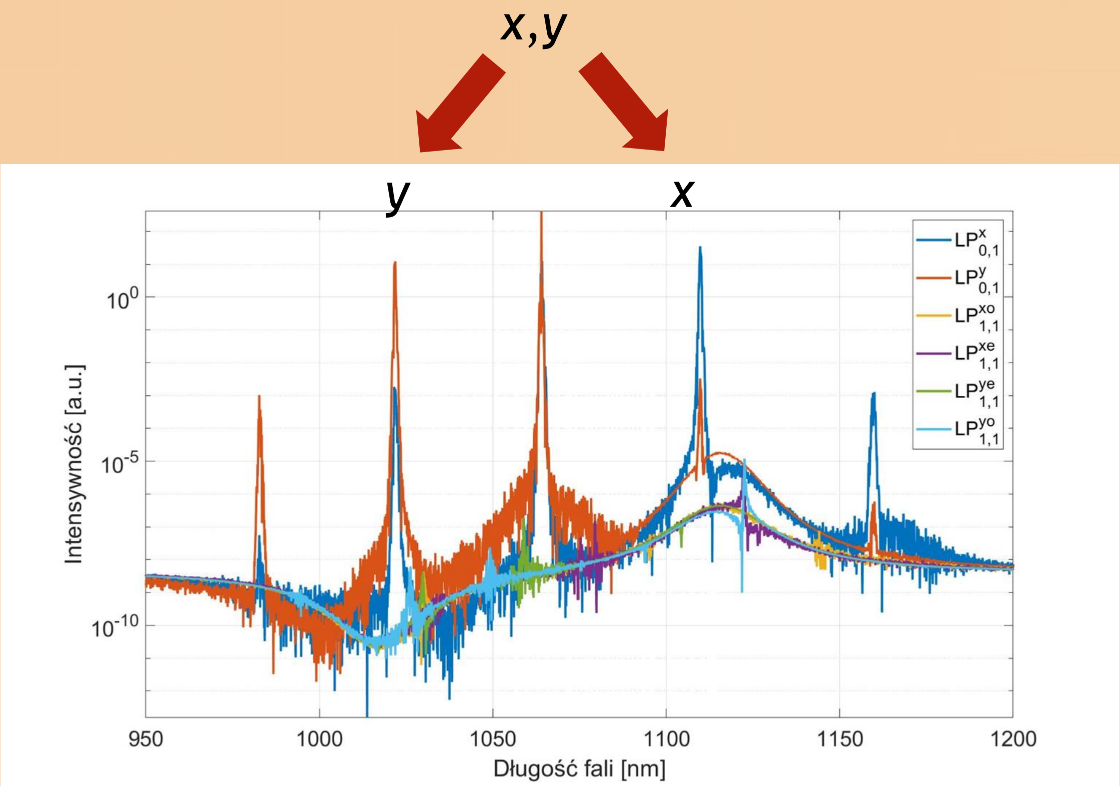
# Intermodal-vectorial FWM

## Vectorial four-wave mixing




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

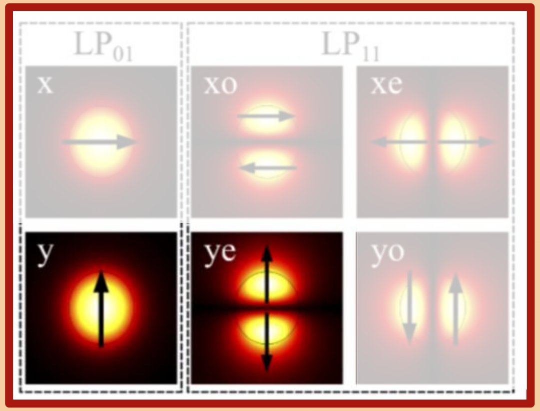
$$-\Delta\beta_1\Omega = \beta_2\Omega^2$$




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

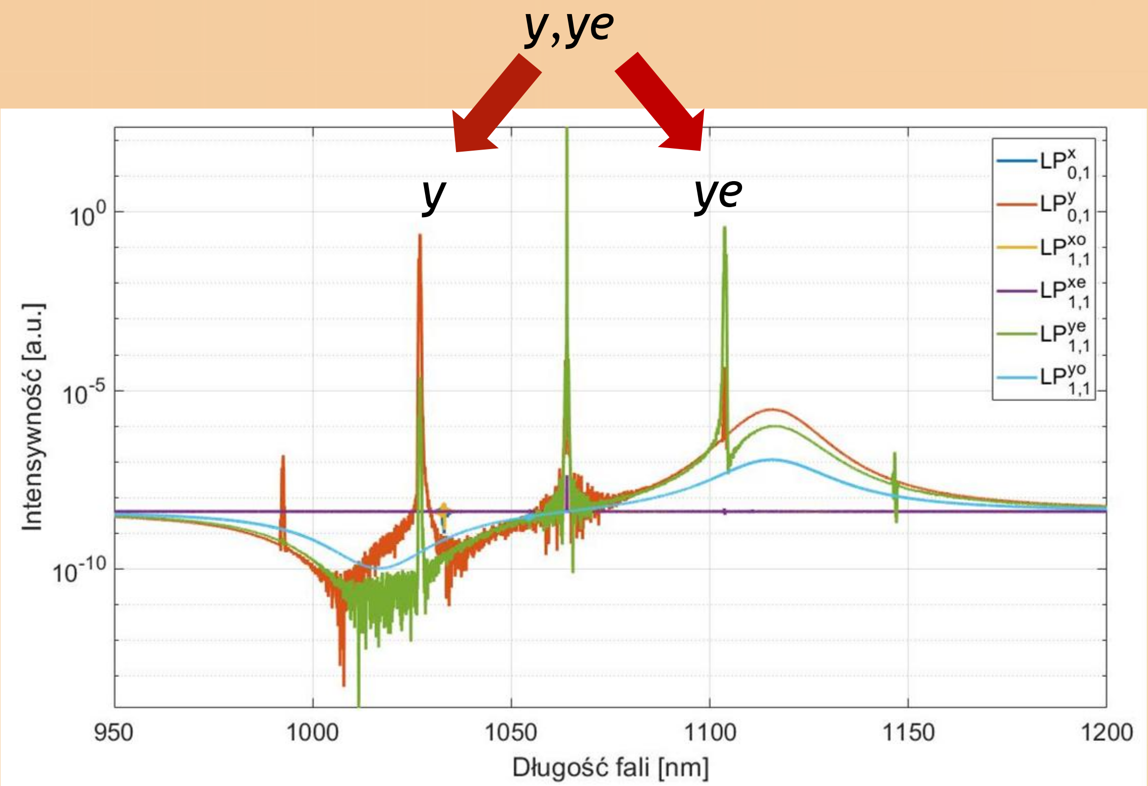
# Intermodal-vectorial FWM

## Intermodal four-wave mixing




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

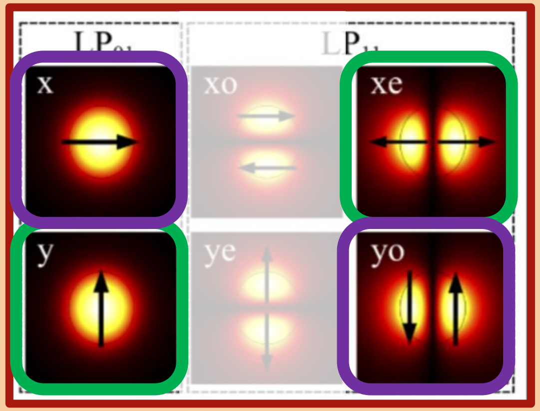
$$-\Delta\beta_1\Omega = \beta_2\Omega^2$$

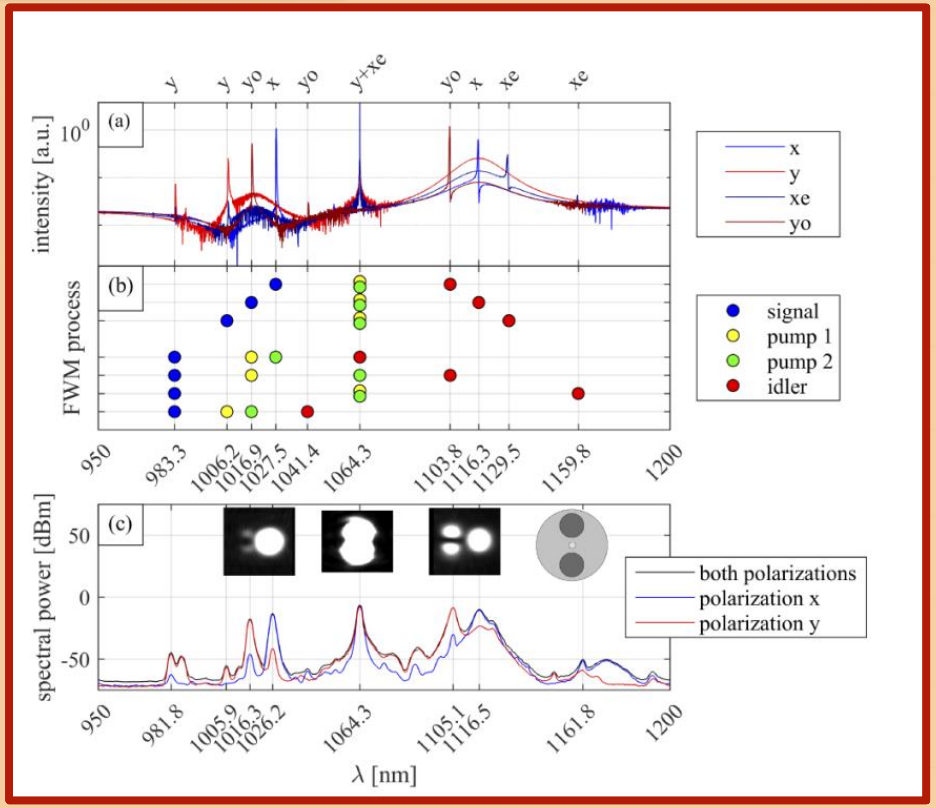



S. Majchrowska, K. Żołnacz et al., Optics Letters 47(10): 2522 (2022)

# Intermodal-vectorial FWM

## Proccesses enabled by selective excitation of modes



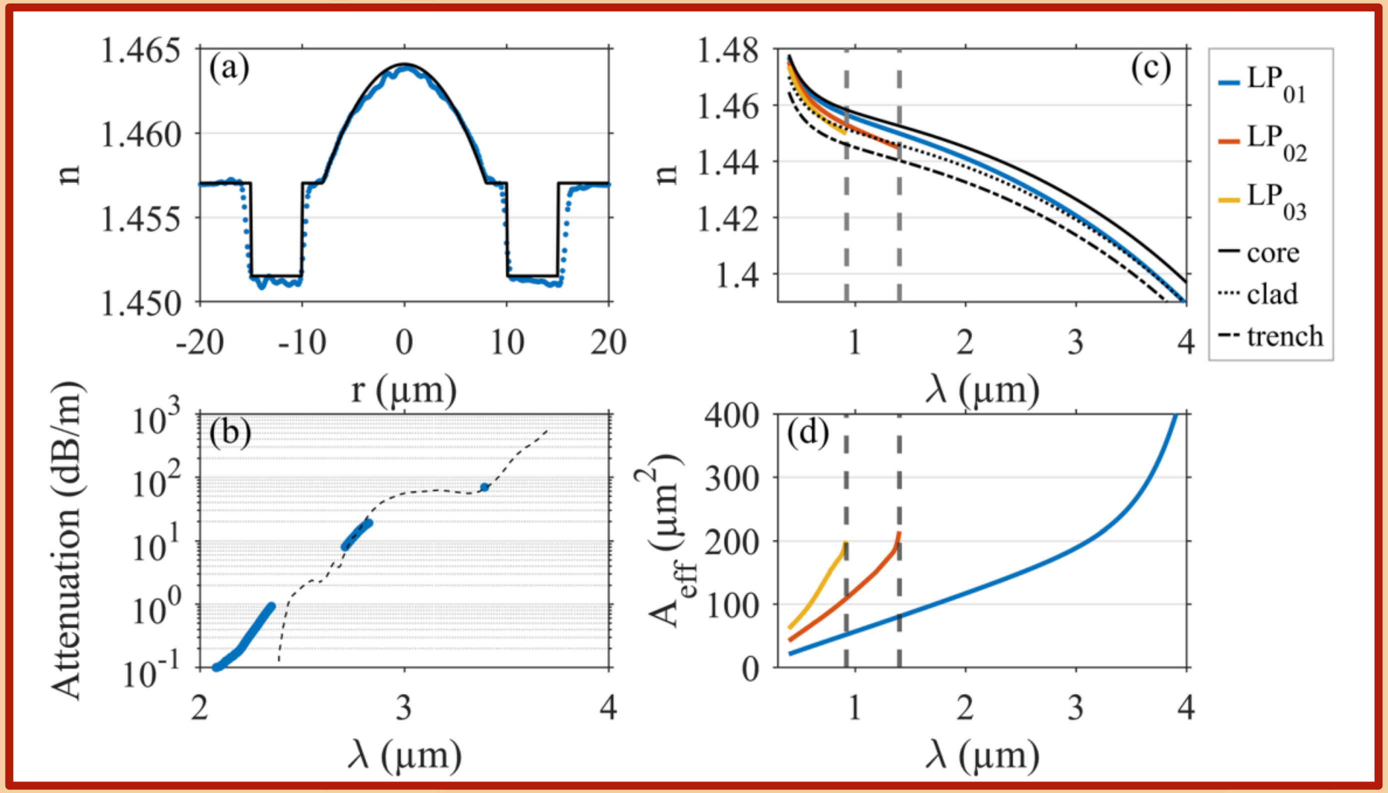

$$\beta_0^y + \beta_0^{xe} = \beta_0^x + \beta_1^x\Omega + \frac{1}{2}\beta_2^x\Omega^2 + \beta_0^{ye} - \beta_1^{ye}\Omega + \frac{1}{2}\beta_2^{ye}\Omega^2$$

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

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

# Far-detuned FWM

## Graded-index fiber

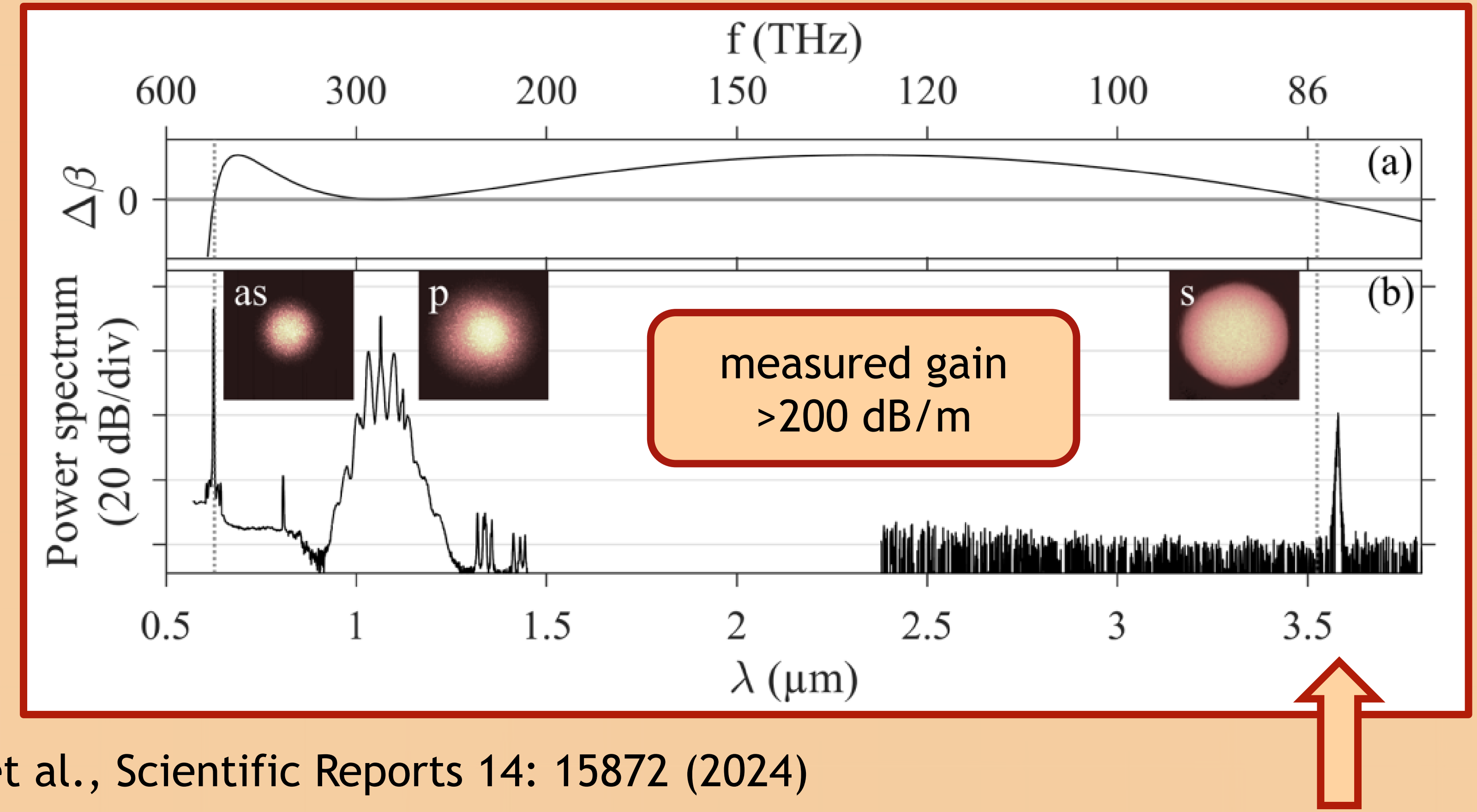



K. Stefańska et al., Scientific Reports 14: 15872 (2024)

23rd Slovak-Czech-Polish Optical Conference, Štrbské Pleso, September 02-06, 2024

# Far-detuned FWM

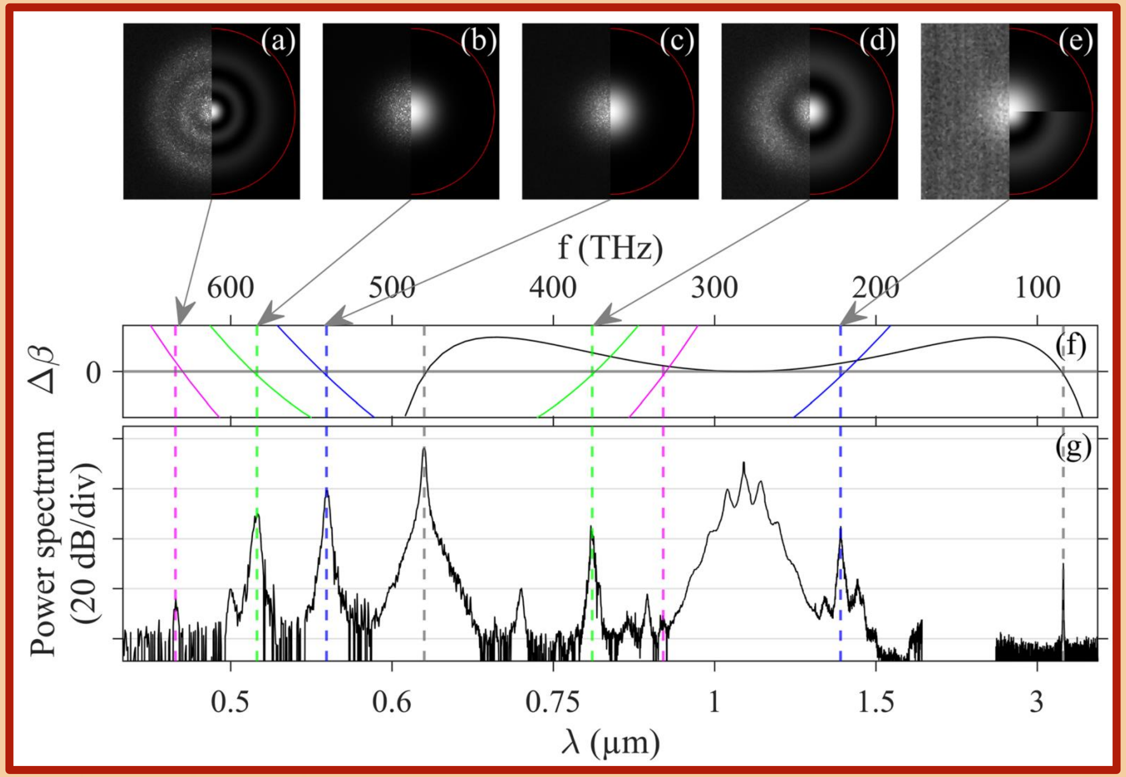
## Graded-index fiber




K. Stefańska et al., Scientific Reports 14: 15872 (2024)

# Far-detuned FWM

## Graded-index fiber



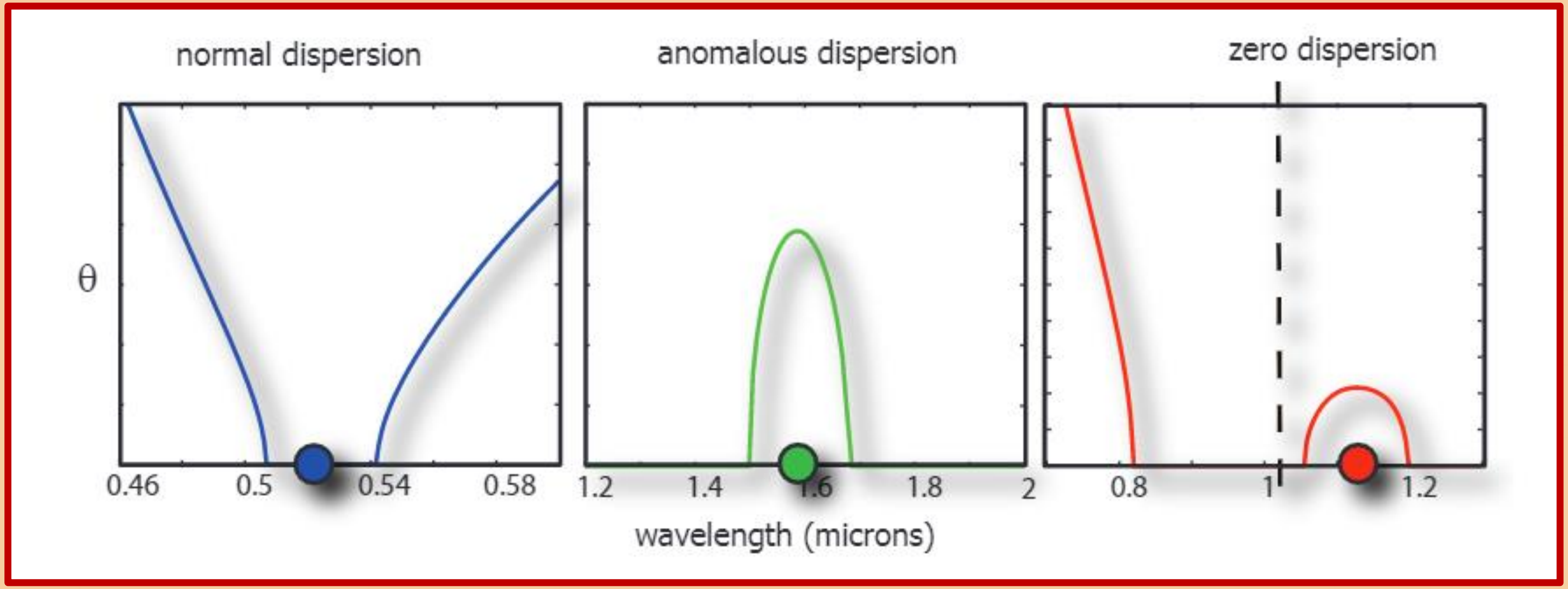

K. Stefańska et al., Scientific Reports 14: 15872 (2024)

# Outline

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

# Discretized conical emission

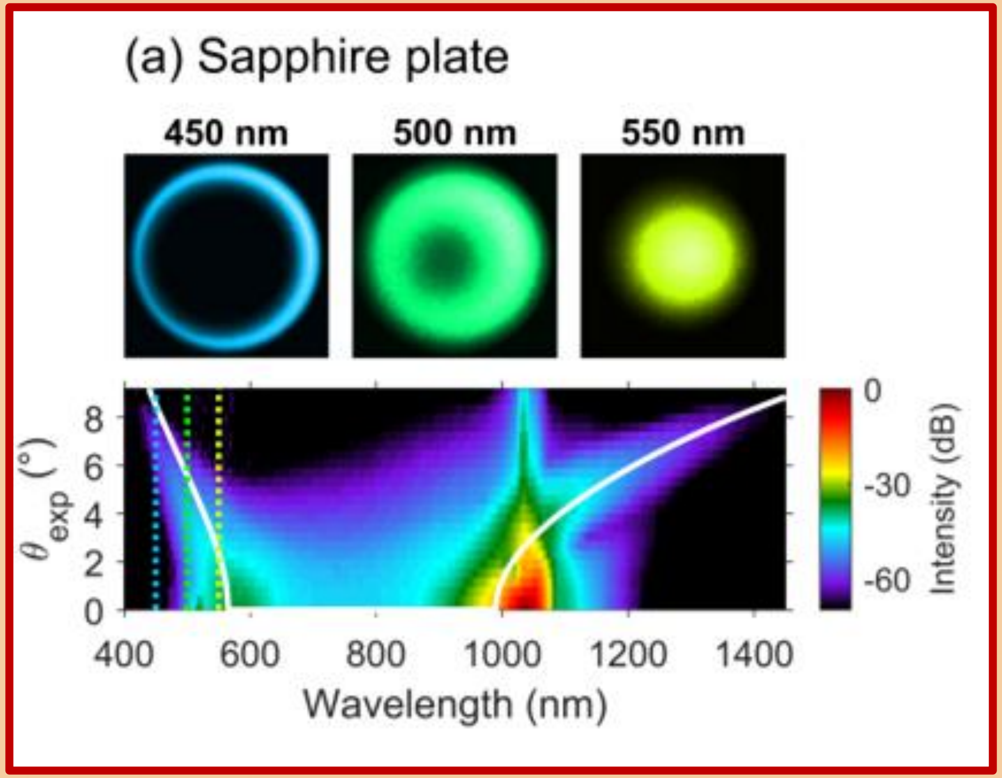
## Conical waves




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

# Discretized conical emission

## Conical emission in bulk

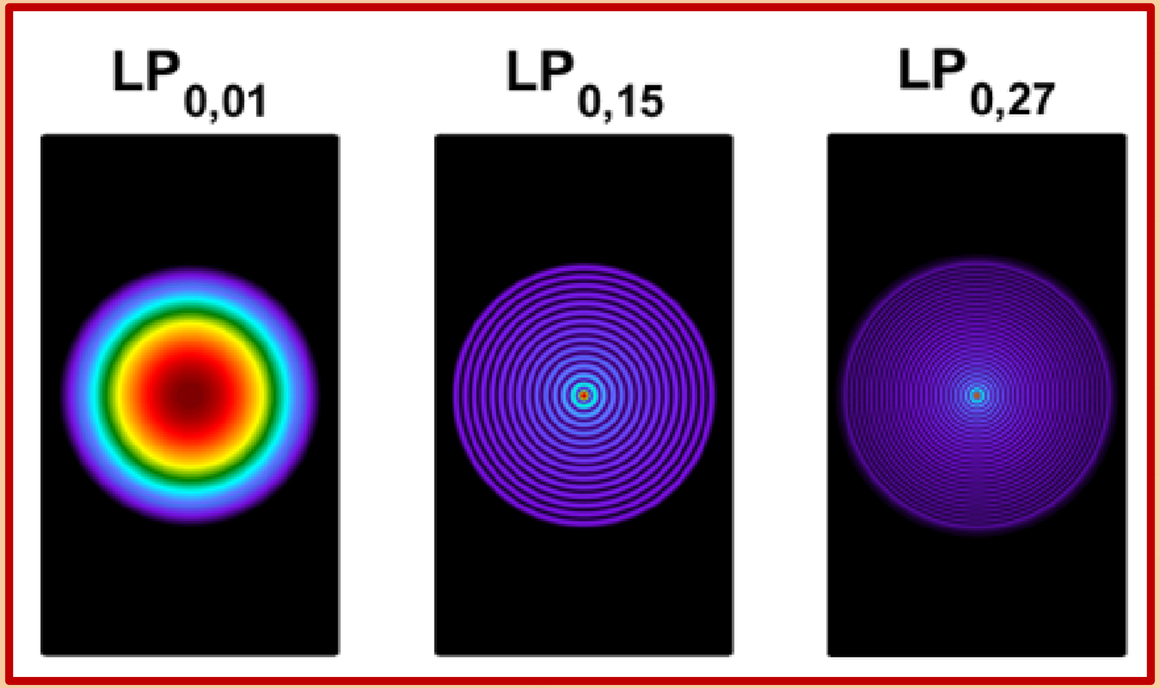



K. Stefańska et al., ACS Photonics, vol. 10(3), pp. 727-732, 2023

# Discretized conical emission

## Multimode optical fiber

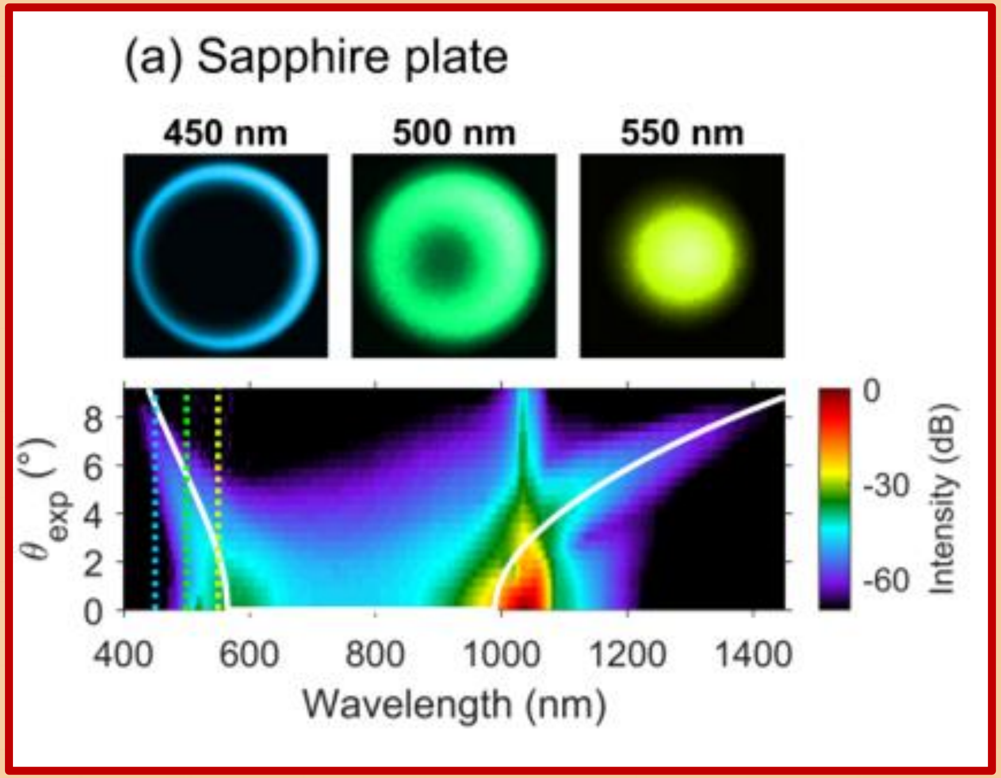
- Core diameter 105 μm
- NA = 0.22

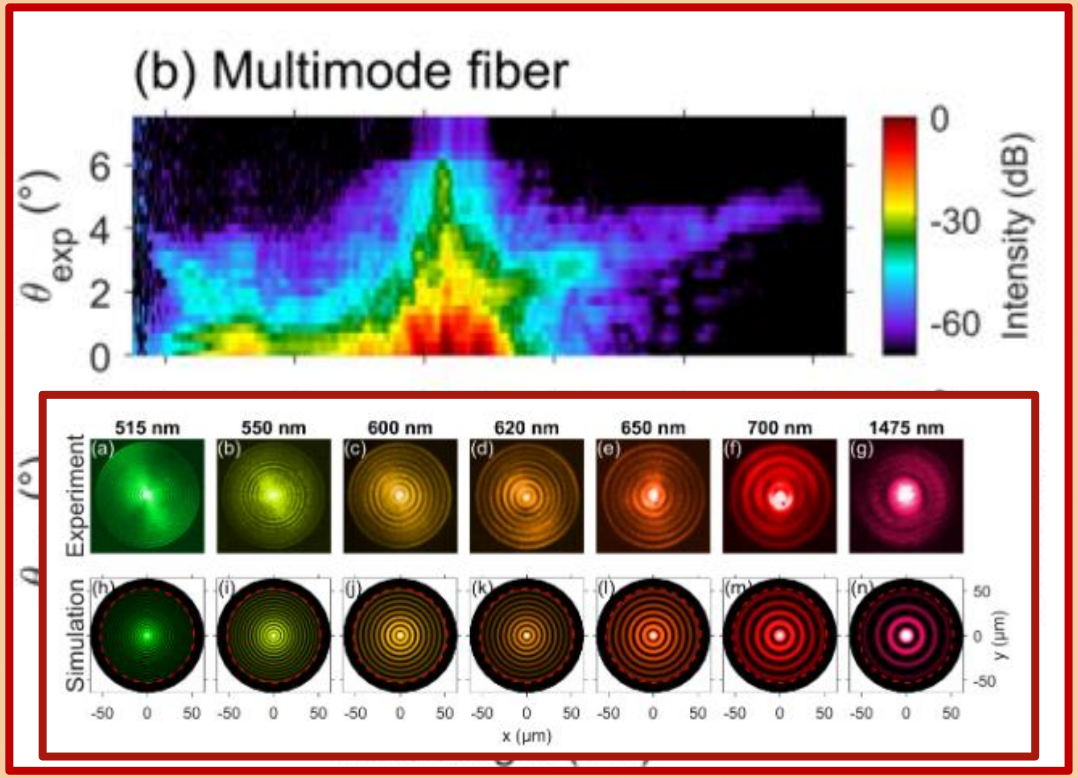



Journal of the Optical Society of America B 38(3): 732-742 (2021)

# Discretized conical emission

## Experimental results




K. Stefańska et al., ACS Photonics, vol. 10(3), pp. 727-732, 2023

# Conclusions

Optical fibers allow to observe and investigate the broad spectrum of frequency conversion processes

The numerical experiments allow to get insight into the complex dynamics of nonlinear phenomena

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www.fog.pwr.edu.pl

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Thank you for your attention