Modulation Instability and Tunable Raman Gain in Mid-IR Waveguides

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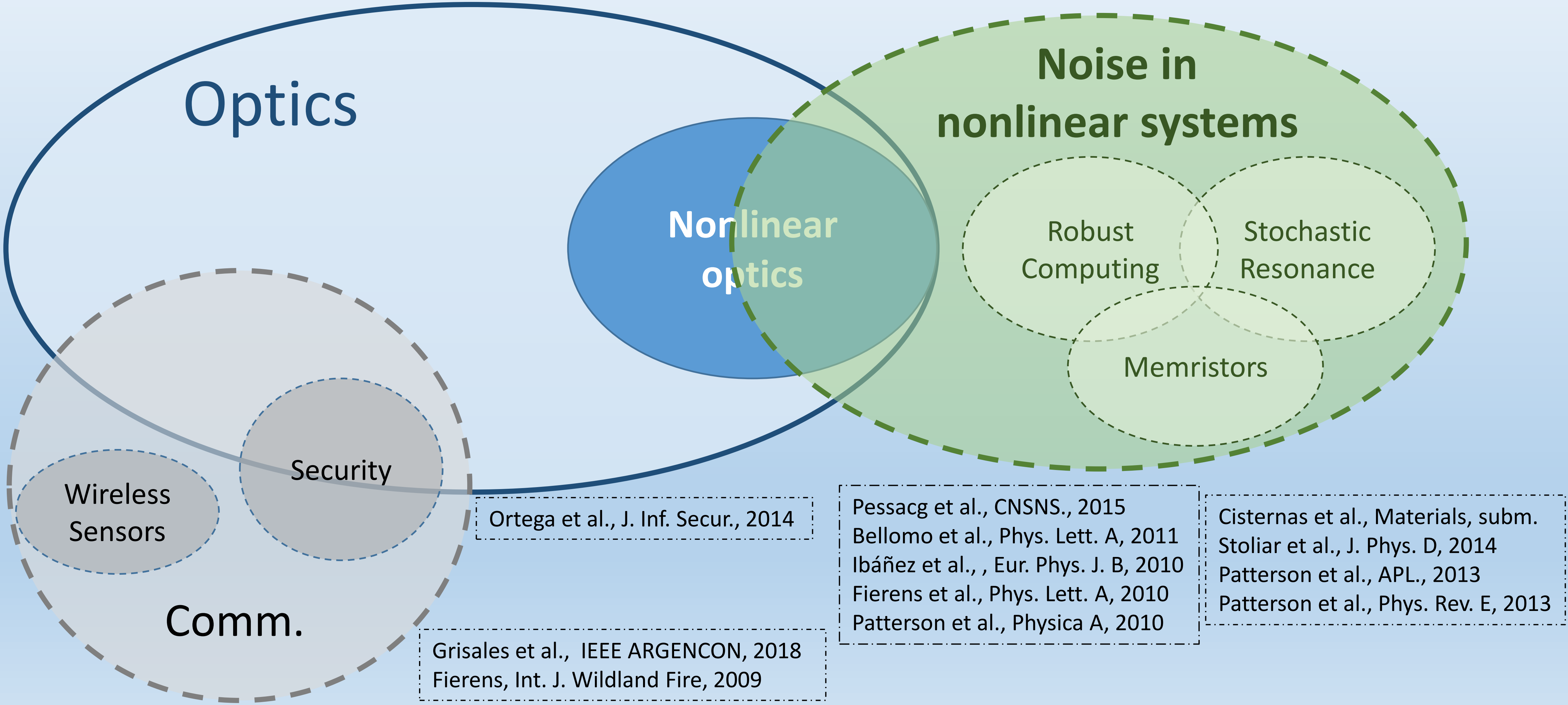
Our group

- Instituto Tecnológico de Buenos Aires
  - Private university
  - ~ 3500 students
  - Focus on engineering
  - 3 PhD programs
  - Several graduate programs
  - 10 undergrad degrees

Our group


Optics
Nonlinear optics
Noise in nonlinear systems
Robust Computing
Stochastic Resonance
Memristors
Wireless Sensors
Security
Comm.
Ortega et al., J. Inf. Secur., 2014
Pessacg et al., CNSNS., 2015
Bellomo et al., Phys. Lett. A, 2011
Ibáñez et al., , Eur. Phys. J. B, 2010
Fierens et al., Phys. Lett. A, 2010
Patterson et al., Physica A, 2010
Cisternas et al., Materials, subm.
Stoliar et al., J. Phys. D, 2014
Patterson et al., APL., 2013
Patterson et al., Phys. Rev. E, 2013
Grisales et al., IEEE ARGENCON, 2018
Fierens, Int. J. Wildland Fire, 2009

Light sources in the mid-IR

- Molecular fingerprint region
- Need for broadband and intense light sources
  - A common approach: supercontinuum generation (SC)
    - ✓ CO_2 laser as pump (10 µm, 5 µm from SHG) on a chalcogenide waveguide?

SC

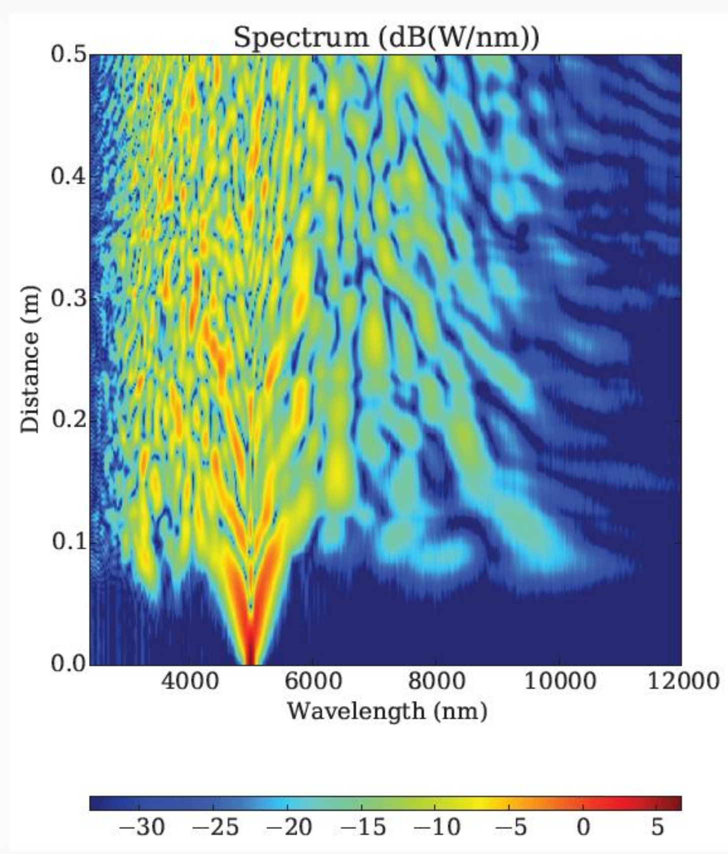
MI

This talk

- Correlated photon pairs in the atmospheric windows (3-4 and 8-12 µm) for quantum information transmission
    - ✓ Parametric processes of sum/difference of frequencies in crystals (GaSe, $AgGaSe_2$) with second order nonlinear susceptivility χ_2?

Nonlinear optics

- What are we interested in?
  - Supercontinuum generation in the mid IR (Dudley, Genty & Coen, Rev. Mod. Phys, 2006)

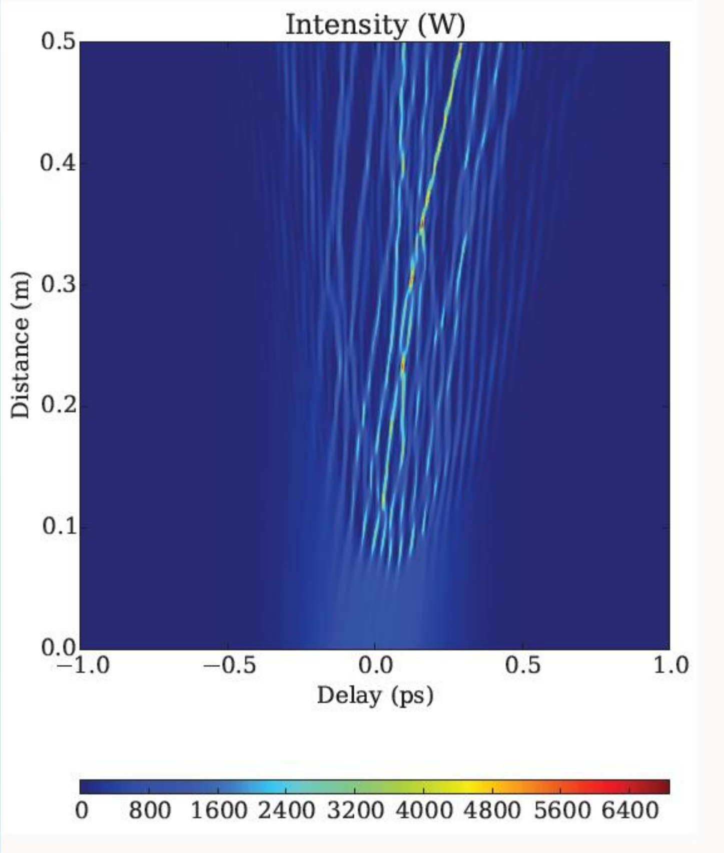


- ✓ Simulation: 200 fs pump pulse + noise
- ✓ Chalcogenide glass fiber
- ✓ $P_0 = 1$ kW, $\lambda_0 = 5$ μm

Grosz et al., EECOS 2015

Nonlinear optics

- What are we interested in?
  - Intense pulses - rogue waves (Solli et al., Nature, 2007)



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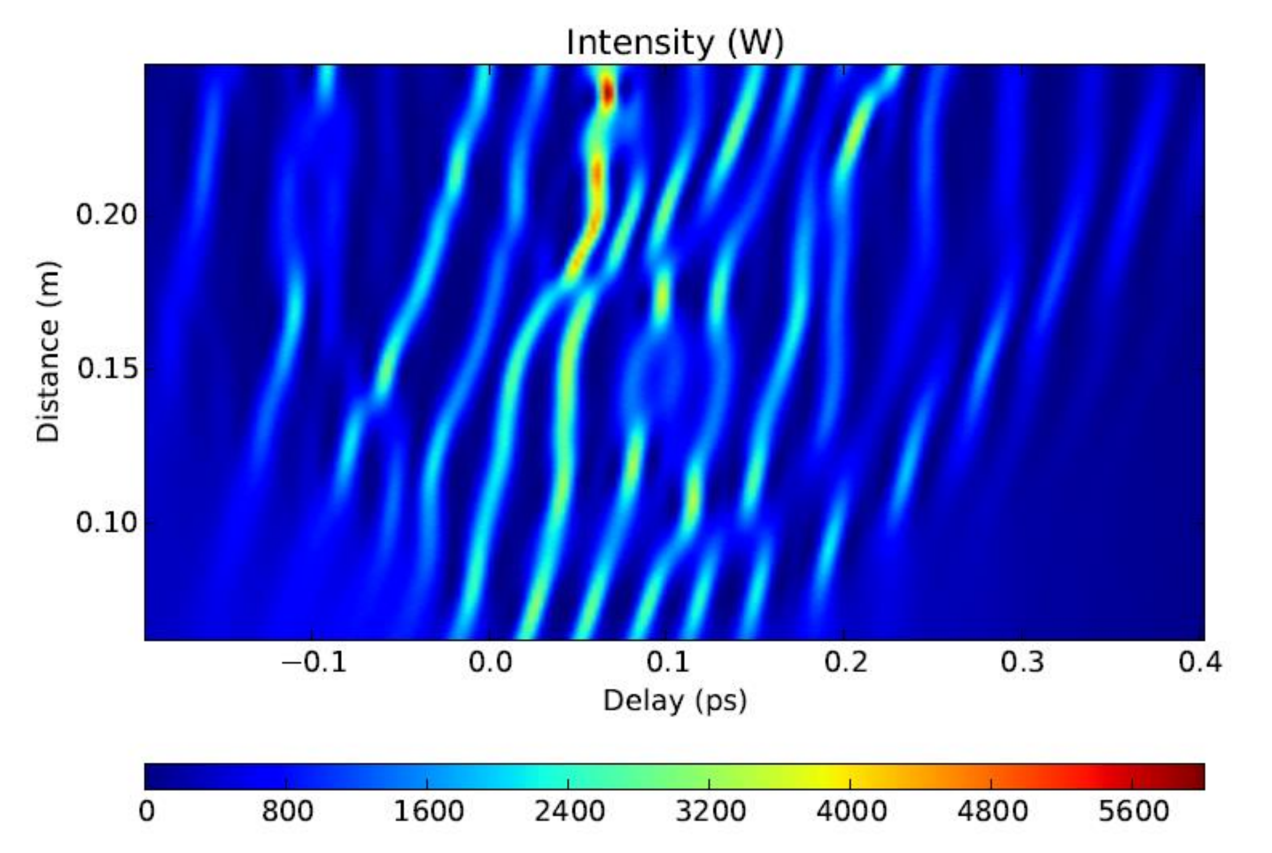


Grosz et al., EECOS 2015

Nonlinear optics

- What are we interested in?
  - Supercontinuum generation in the mid IR
  - Intense pulses - rogue waves
  - Parametric amplification (Stolen & Bjorkholm, IEEE J. Quantum Electron., 1982)

Nonlinear optics

- What are we interested in?
  - Supercontinuum generation in the mid IR
  - Intense pulses - rogue waves
  - Parametric amplification

Modulation instability

breaks up into pulses ← propagation of a CW in an optical fiber is unstable

Benjamin & Feir, J. Fluid Mech., 1967
Shabat & Zakharov, JETP, 1972
Akhmediev & Korneev, Theor. Math. Phys, 1986
Tai, Hasegawa & Tomita, PRL, 1986
Potasek, Optics Lett., 1987

Modulation instability

- 40 years of research! Should I end my talk now?
  - Most of the analyses of MI do not include all details relevant to optical fibers.
    - ✓ One exception: Béjot et al., Phys. Rev. A, 2011
  - Not a lot of work on (quasi-)analytical approaches to the interaction of noise and nonlinearity in MI
- Coming next…
  - A complete analysis of the spectral evolution of a perturbation to a CW
  - Analytical results on input noise + MI

Propagation in optical fibers

- Generalized Nonlinear Schrödinger Equation (GNLSE)

$$\frac{\partial A}{\partial z} - i\hat{\beta}A = i\hat{\gamma}A(z,T)\int_{-\infty}^{+\infty} R(T')|A(z,T-T')|^2 dT'$$

- Dispersion $$\hat{\beta} = \sum_{m\geq 2} \frac{i^m}{m!}\beta_m \frac{\partial^m}{\partial T^m}$$

- Nonlinearity $$\hat{\gamma} = \sum_{n\geq 0} \frac{i^n}{n!}\gamma_n \frac{\partial^n}{\partial T^n}$$

- Raman scattering $$R(T) = (1 - f_R)\delta(T) + f_R h(T)$$

Perturbation to the stationary solution

$$A(z,T) = \left(\sqrt{P_0} + a\right)e^{i\gamma_0 P_0 z} = A_s + a e^{i\gamma_0 P_0 z}$$

- Input power: P_0
- Perturbation: $a(z;\ T)$

- Linear terms in the frequency domain

$$\frac{\partial \tilde{a}(z,\Omega)}{\partial z} + \tilde{N}(\Omega)\tilde{a}(z,\Omega) = \tilde{M}(\Omega)\widetilde{a^*}(z,-\Omega)$$

- Frequency: $\Omega = \omega - \omega_0$
- $\tilde{N}(\Omega) = -i\left[\tilde{\beta}(\Omega) + P_0\tilde{\gamma}(\Omega)\left(1 + \tilde{R}(\Omega)\right) - P_0\gamma_0\right]$
- $\tilde{M}(\Omega) = iP_0\tilde{\gamma}(\Omega)\tilde{R}(\Omega)$

Perturbation to the stationary solution

$$\frac{\partial \tilde{a}(z,\Omega)}{\partial z} + \tilde{N}(\Omega)\tilde{a}(z,\Omega) = \tilde{M}(\Omega)\widetilde{a^*}(z,-\Omega)$$

- Ansatz: $a(z,\Omega) = D\exp(iK(\Omega)z)$

$$\Downarrow$$

$$K(\Omega) = -\tilde{B}(\Omega) \pm K_D(\Omega) = -\tilde{B}(\Omega) \pm \sqrt{\widetilde{B^2}(\Omega) - \tilde{C}(\Omega)}$$

- $\tilde{B}(\Omega)$ and $\tilde{C}(\Omega)$ are complex functions of the parameters
- Agrees with Béjot et al., Phys. Rev. A, 2011

Fierens et al., ICAND 2016
Bonetti et al., Phys. Rev. A, 2016

Modulation instability gain

- Only self-steepening: $\gamma_1 = \gamma_0 \tau_{sh}$, $\gamma_n = 0$ for $n \geq 2$

$$K(\Omega) = \widetilde{\beta_o} + P_0\gamma_0\tau_{sh}\Omega\left(1+\tilde{R}\right) \pm \sqrt{\left(\widetilde{\beta_e} + 2\gamma_0 P_0\tilde{R}\right)\widetilde{\beta_e} + P_0^2\gamma_0^2\tau_{sh}^2\Omega^2\widetilde{R^2}}$$

- Well-known facts about MI gain $= 2\mathrm{Im}\{K(\Omega)\}$:
  - It does not depend on odd terms of the dispersion relation
  - Self-steepening enables a gain even in a zero-dispersion fiber
  - In the large power limit, it is independent of the dispersion and it is dominated by Raman:

$$|g(\Omega)| \approx 2P_0\gamma_0\tau_{sh}|\Omega| \cdot \left|\mathrm{Im}\{\tilde{R}(\Omega)\}\right|$$

Spectral evolution

$$\tilde{a}(z,\Omega) = \frac{e^{-i\tilde{B}(\Omega)z}}{K_D(\Omega)} \cdot \tilde{M}(\Omega)\sin(K_D(\Omega)z)\,\widetilde{a^*}(0,-\Omega) + \frac{e^{-i\tilde{B}(\Omega)z}}{K_D(\Omega)} \cdot \left[K_D(\Omega)\cos(K_D(\Omega)z) - \left(\tilde{N}(\Omega) - i\tilde{B}(\Omega)\right)\sin(K_D(\Omega)z)\right]\tilde{a}(0,\Omega)$$

- Interaction between $\tilde{a}(z,\Omega)$ and $\tilde{a}(z,-\Omega)$ due to the nonlinearity
- $a(0,T) \in \mathbb{R} \Longrightarrow \tilde{a}(z,\Omega) = \tilde{H}(\Omega,z)\Lambda(\Omega)$

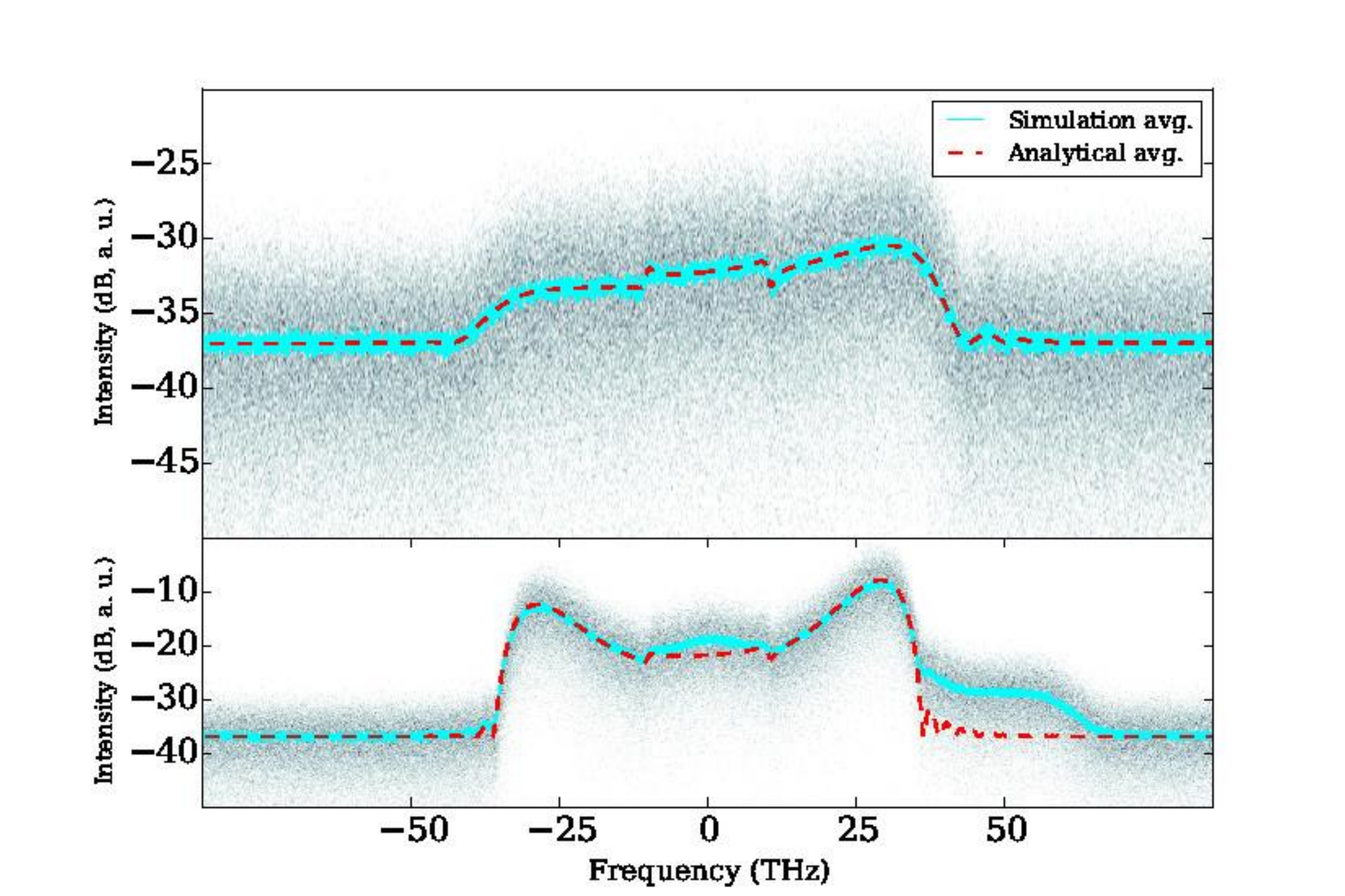
Noise-only

$$\tilde{a}(0,\Omega) \sim \mathcal{CN}(0,\sigma^2) \longrightarrow \tilde{a}(z,\Omega) \sim \mathcal{CN}\left(0,\sigma_{\tilde{a}}^2\right)$$

$$\longrightarrow |\tilde{a}(z,\Omega)| \sim \mathit{Rayleigh}(\sigma_{\tilde{a}}) \longrightarrow |\tilde{a}(z,\Omega)|^2/\sigma_{\tilde{a}}^2 \sim \chi_2^2$$

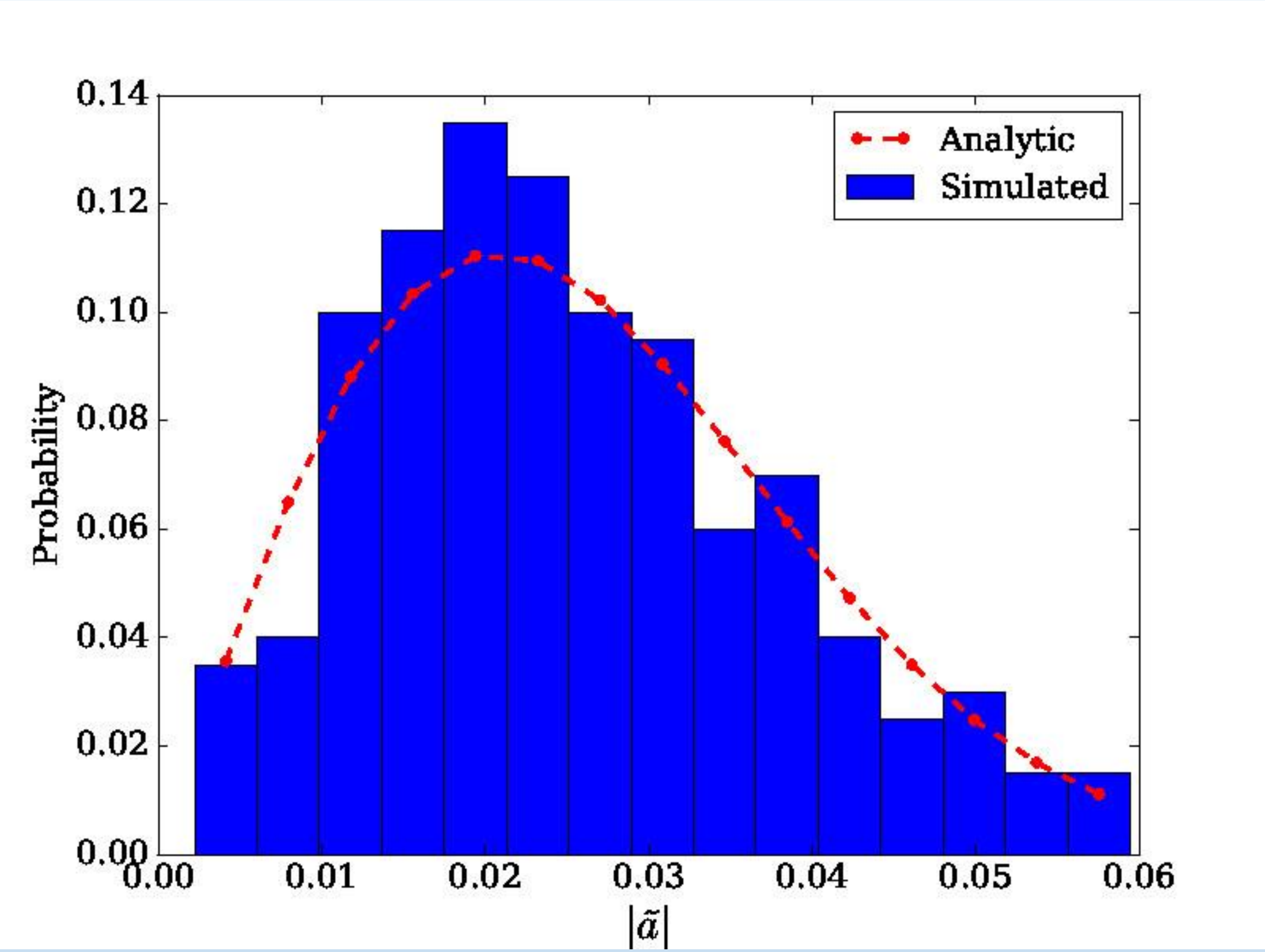
- $\sigma_{\tilde{a}}^2(z,\Omega)$ can be easily computed from previous equations

Noise-only



Fierens et al., ICAND 2016

Noise-only



Fierens et al., ICAND 2016

Noisy input

- A more interesting case: additive white Gaussian noise

$$a(0,\Omega) = \tilde{s}(\Omega) + \eta(\Omega), \qquad \eta(\Omega) \sim \mathcal{CN}(0, \sigma_a^2)$$

- Relevant for controlling the generation of rogue waves
  - Solli, Ropers & Jalali, PRL, 2008
  - Dudley, Genty & Eggleton, Opt. Express, 2008
  - Sørensen et al., JOSA B, 2012
- We developed analytical expressions for some relevant metrics of the resulting spectrum

Noisy input

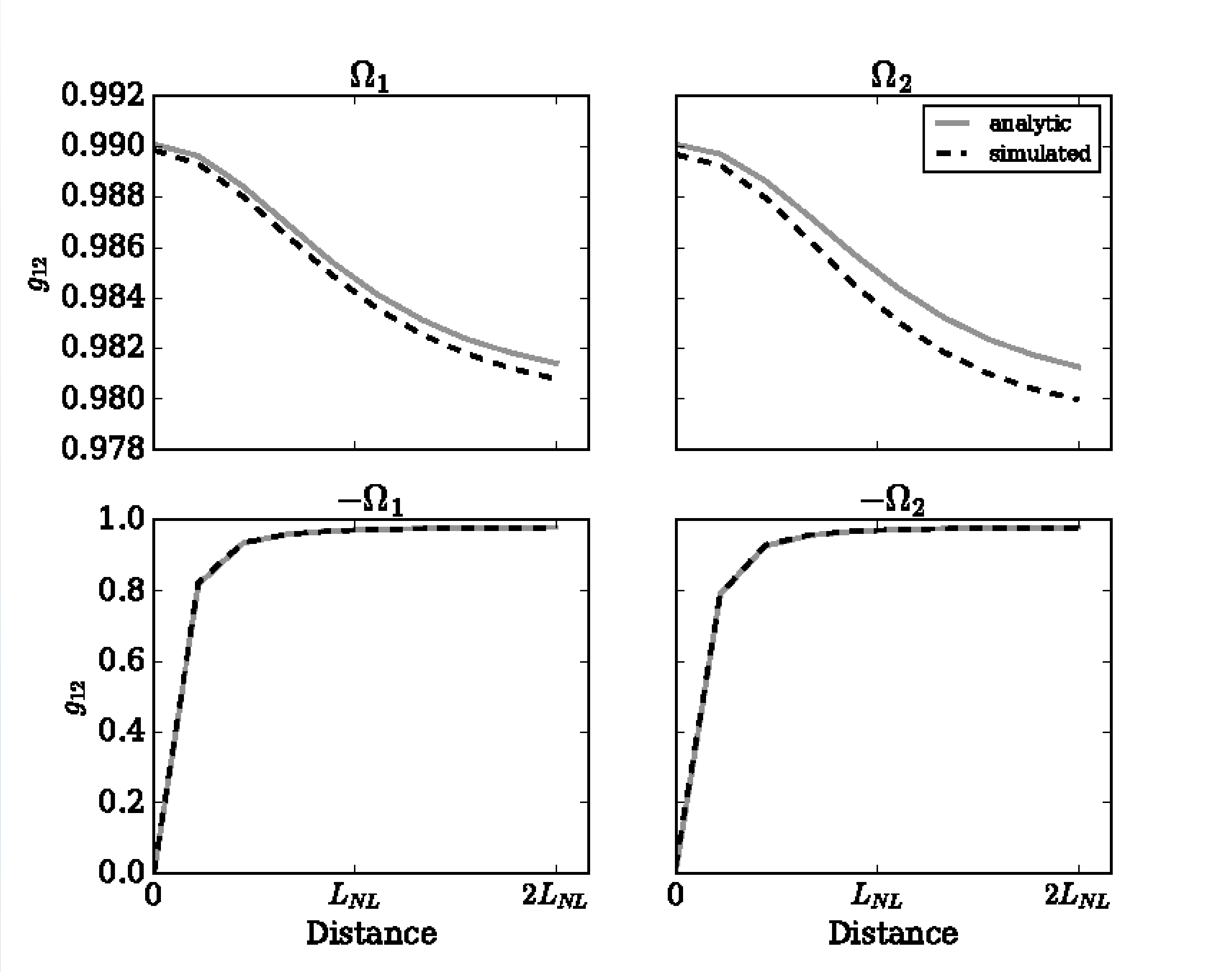
- Coherence (Dudley, Genty & Coen, Phys. Rev. Mod., 2006)

$$g_{12}(z,\Omega) = \frac{< \widetilde{a_k^*}(z,\Omega)\tilde{a}_l(z,\Omega) >_{k\neq l}}{\sqrt{< |\widetilde{a_k}(z,\Omega)|^2 > < |\tilde{a}_l(z,\Omega)|^2 >}}$$

- Characterizes shot-to-shot fluctuations in the phase of supercontinuum spectra

Noisy input

- Coherence
  - ✓ Standard Single Mode Fiber (SSMF)
  - ✓ 1 W pump at 1550 nm
  - ✓ 1 mW power seeds at 31 and 46 GHz



Bonetti et al., Phys. Rev. A., 2016

Noisy input

- A simple case:
  - One-sided seed, $\tilde{s}(\Omega) = 0$ for $\Omega < 0$
  - No self-steepening and no Raman
- Small z

$$g_{12}(z,\Omega) \approx 1 - \left(1 + \left(\frac{z}{L_{NL}}\right)^2\right) \frac{\sigma^2}{|\tilde{s}(|\Omega|)|^2} \qquad \Omega > 0$$

$$g_{12}(z,\Omega) \approx 1 - \left(2 + \left(\frac{L_{NL}}{z}\right)^2\right) \frac{\sigma^2}{|\tilde{s}(|\Omega|)|^2} \qquad \Omega < 0$$

- Large z

$$g_{12}(z,\Omega) \approx 1 - 2\frac{\sigma^2}{|\tilde{s}(|\Omega|)|^2}$$

Modulation instability

- Analytical expressions for the spectral evolution of a perturbation to a continuous pump propagating in an optical fiber, including all relevant details

- Analytical results for some metrics of supercontinuum generation, such as coherence, for noisy inputs

- Problems:
  - Undepleted pump $\Rightarrow$ valid for short distances
  - Disregards cascading four-wave mixing effect

Higher-order perturbation

- The analysis can be extended to higher-order perturbation

Bonetti et al., ICAND 2018
Bonetti et al., Comm. Nonlinear Sci. Numer. Simulat., 2019

- If $< |\tilde{a}(0,\Omega)|^2 >= s$, the first order solution can be written as

$$< |\widetilde{a_1}(z,\Omega)|^2 >\approx s + \left(e^{2g(\Omega)z} - 1\right)|A_1(\Omega)|^2 s$$

- This first order solution motivates the ansatz

$$\tilde{a}(z,\Omega) \approx \sqrt{s}e^{i\phi_0(z,\Omega)} + \sum_{n=1}^{\infty}\left(e^{G_n(\Omega)z} - 1\right)A_n(\Omega)\sqrt{s^n}\, e^{i\phi_n(z,\Omega)}$$

Higher-order perturbation

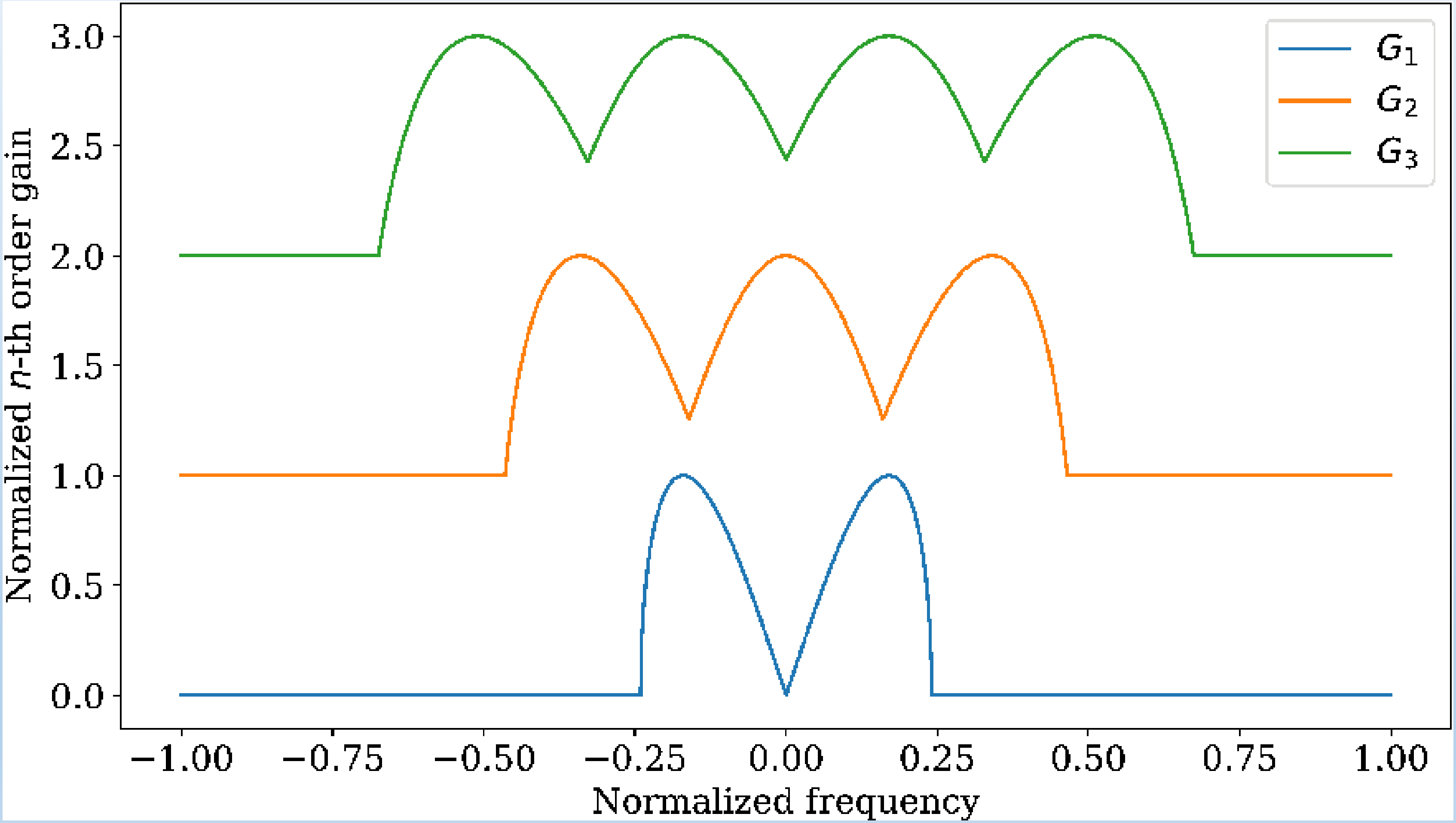
- After some lengthy manipulations, we arrive at the following expressions:

$$G_n(\Omega) = \max_u G_1(u) + G_{n-1}(u - \Omega)$$

$$< |A_n(\Omega)|^2 >= \frac{\alpha^{n-1}\widetilde{\gamma^2}(\Omega)\left[\left|\tilde{B}(-\Omega) - iG_n(\Omega)\right|^2 + \widetilde{\gamma^2}(-\Omega)\right]}{\left|\left(\tilde{B}(\Omega) + iG_n(\Omega)\right)\left(\tilde{B}(\Omega) - iG_n(\Omega)\right) - \tilde{\gamma}(\Omega)\tilde{\gamma}(-\Omega)\right|^2}$$

- The first equation describes the cascading effect of four-wave mixing

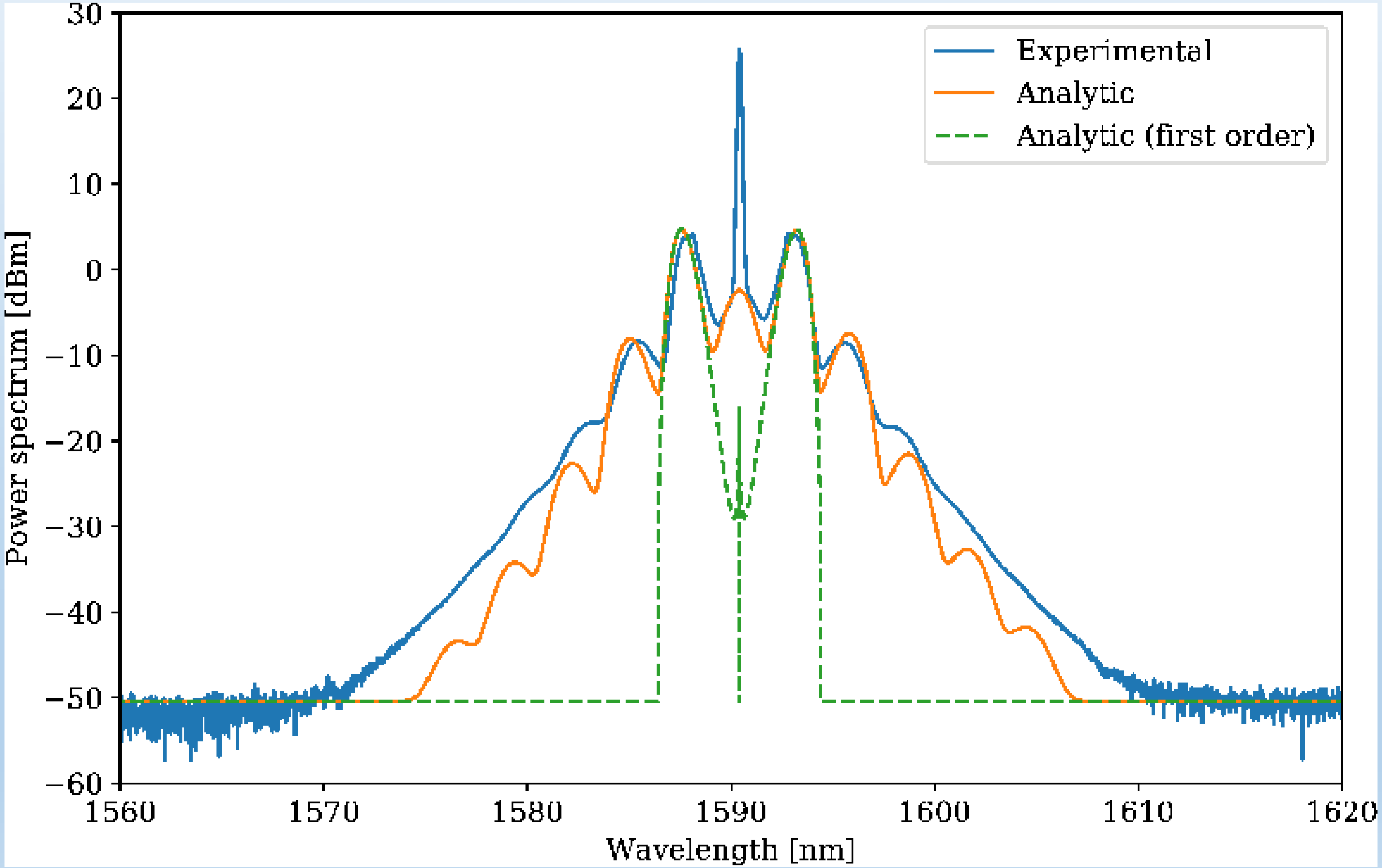
Higher-order perturbation



Bonetti et al., CNSNS, 2019

Higher-order perturbation

- ✓ 770 m-long, dispersion-stabilized Highly-Nonlinear Fiber (HNLF)
- ✓ CW 30-dBm pump laser at 1590.4 nm



Bonetti et al., CNSNS, 2019

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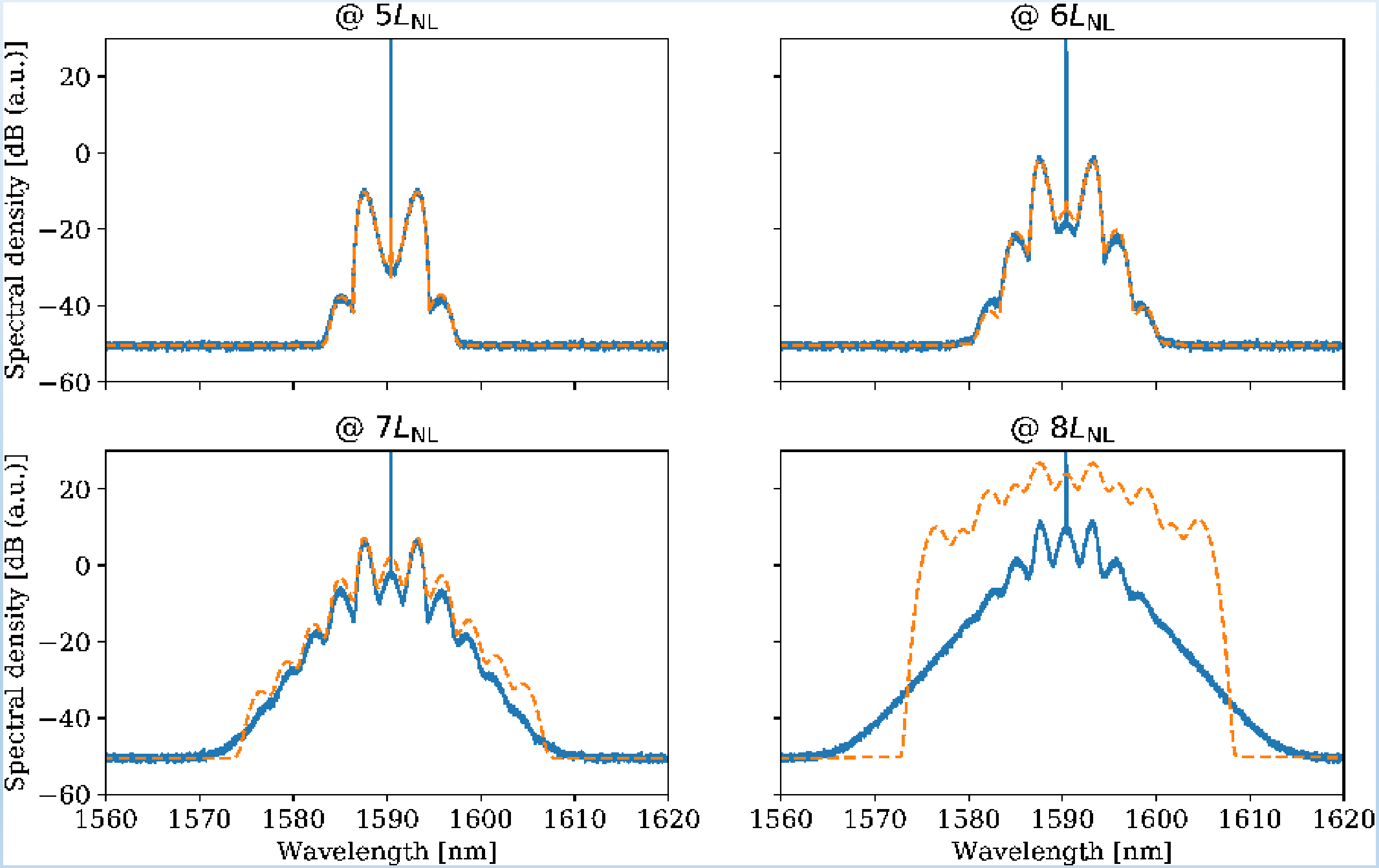

Bonetti et al., CNSNS, 2019

Modulation instability: Power cutoff

- In the absence of Raman scattering, there is a limit in the MI gain due to self-steepening (Shukla & Rasmussen, Opt. Lett., 1986, De Angelis et al., JOSA B, 1996)
- In general, the MI gain vanishes whenever the power is equal to

$$P_{\pm} = \hat{P}(\Omega) \times \left(1 \pm \sqrt{1 - \tau_{sh}^{2}\Omega^{2}}\right)$$

$$\hat{P}(\Omega) = -\frac{\widetilde{\beta_{e}}(\Omega)}{\gamma_{0}\tau_{sh}^{2}\Omega^{2}}$$

Hernandez et al., IEEE Photonics J., 2017

Modulation instability: Power cutoff

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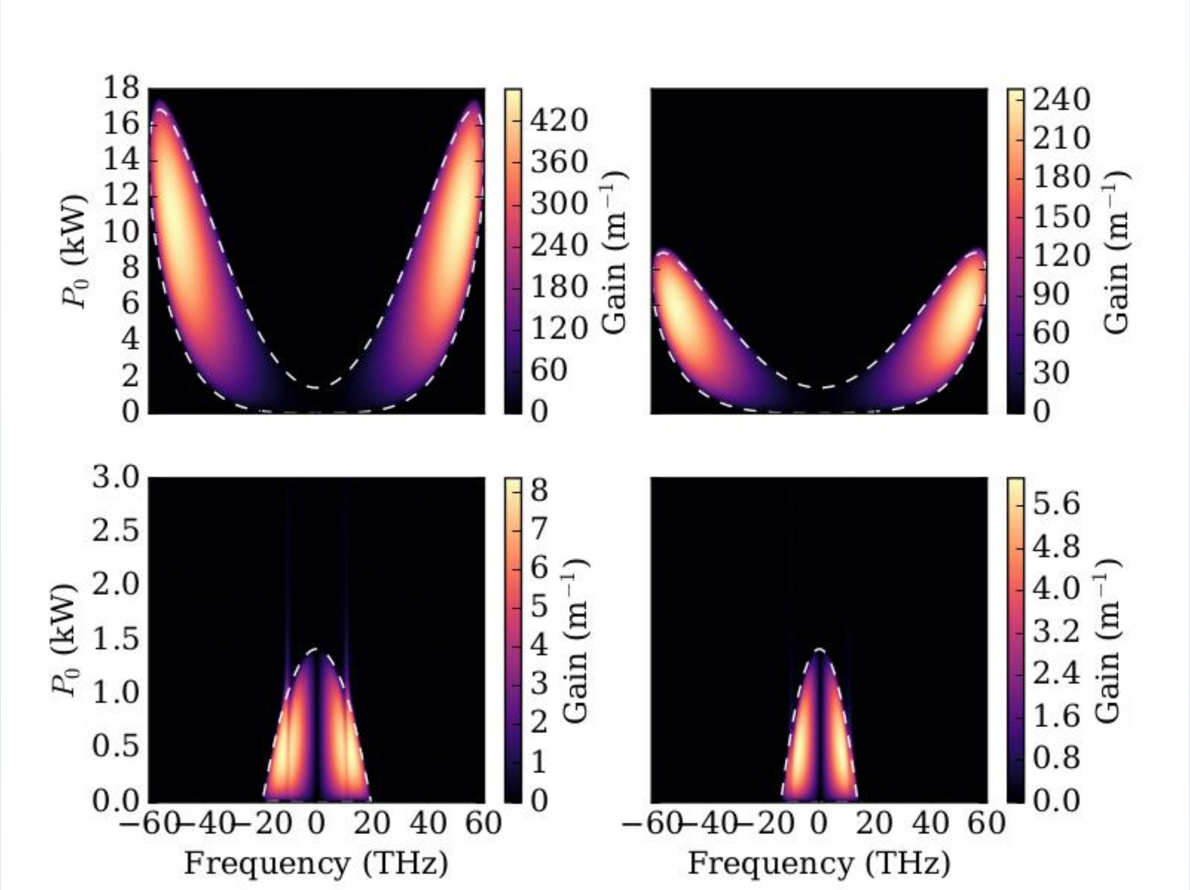


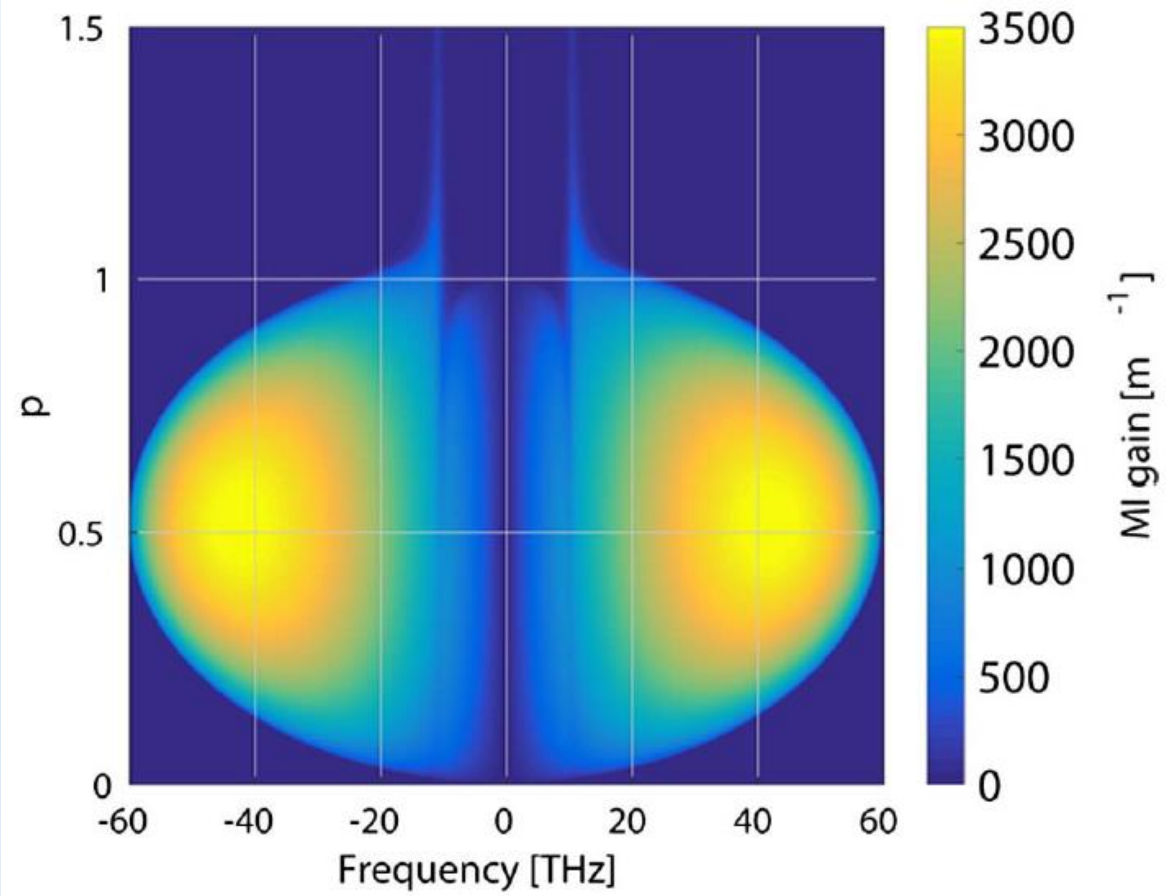
- ✓ MI gain versus pump power
- ✓ $\beta_2 = -1\ \mathrm{ps}^2/\mathrm{km}$
- ✓ $\beta_4 = -16, -8, +8, +16\ \times 10^{-4}\mathrm{ps}^4/\mathrm{km}$
- ✓ $\gamma_0 = 100\ 1/(\mathrm{W\ km})$
- ✓ $\lambda_0 = 5\ \mu\mathrm{m}$

- Gain region
- Location of the maximum MI gain

Hernandez et al., IEEE Photonics J., 2017

Modulation instability: Power cutoff

- In the presence of Raman scattering, there is still gain after the power cutoff



- ✓ MI gain versus normalized pump power
- ✓ $\beta_2 = -50\ \mathrm{ps}^2/\mathrm{km}$
- ✓ $\gamma_0 = 100\ 1/(\mathrm{W\ km})$
- ✓ $\lambda_0 = 5\ \mu\mathrm{m}$

Sánchez et al., JOSA B, 2018

Tunable Raman gain

- Gain beyond the cutoff power can be tuned using the pump power
- Possible applications
  - Mid-IR fiber Raman lasers
  - Mid-IR supercontinuum generation
- Why mid-IR?
  - Cuttoff power $\propto \tau_{sh}^{-2}$ and $\tau_{sh} \approx \omega_0^{-1}$

Sánchez et al., JOSA B, 2018

Tunable Raman gain

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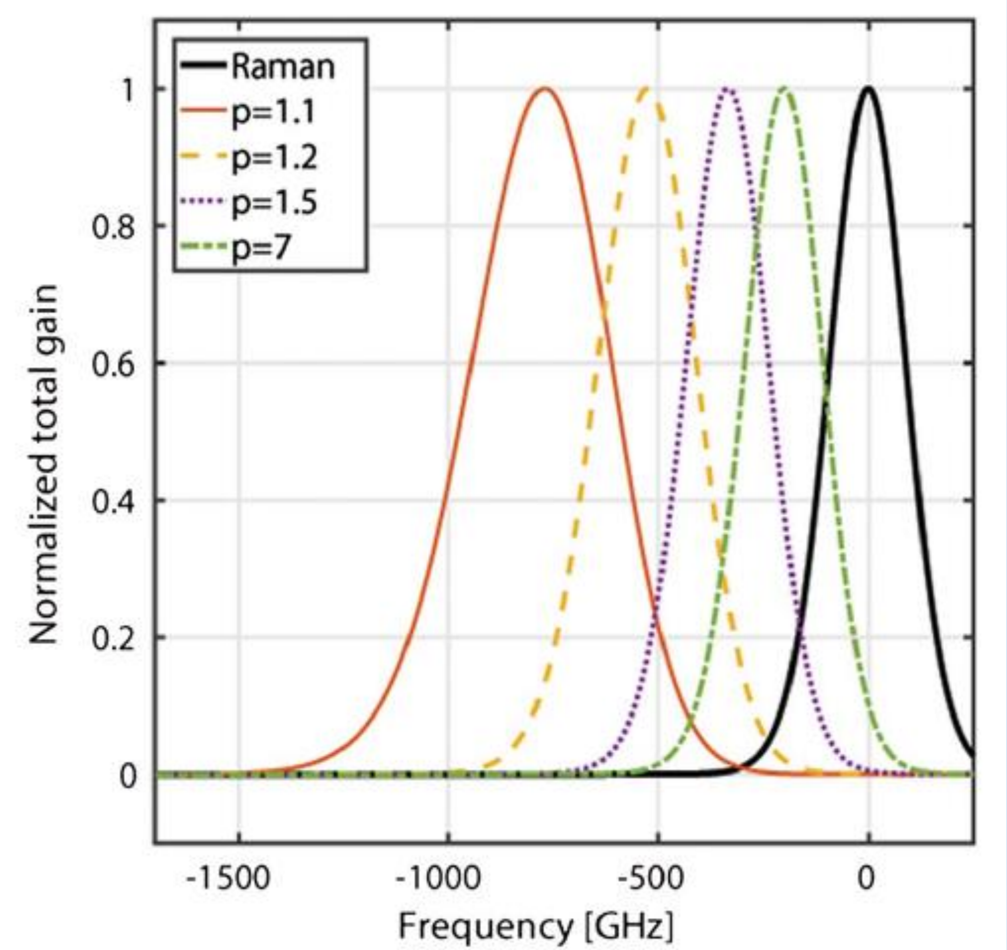

Sánchez et al., JOSA B, 2018

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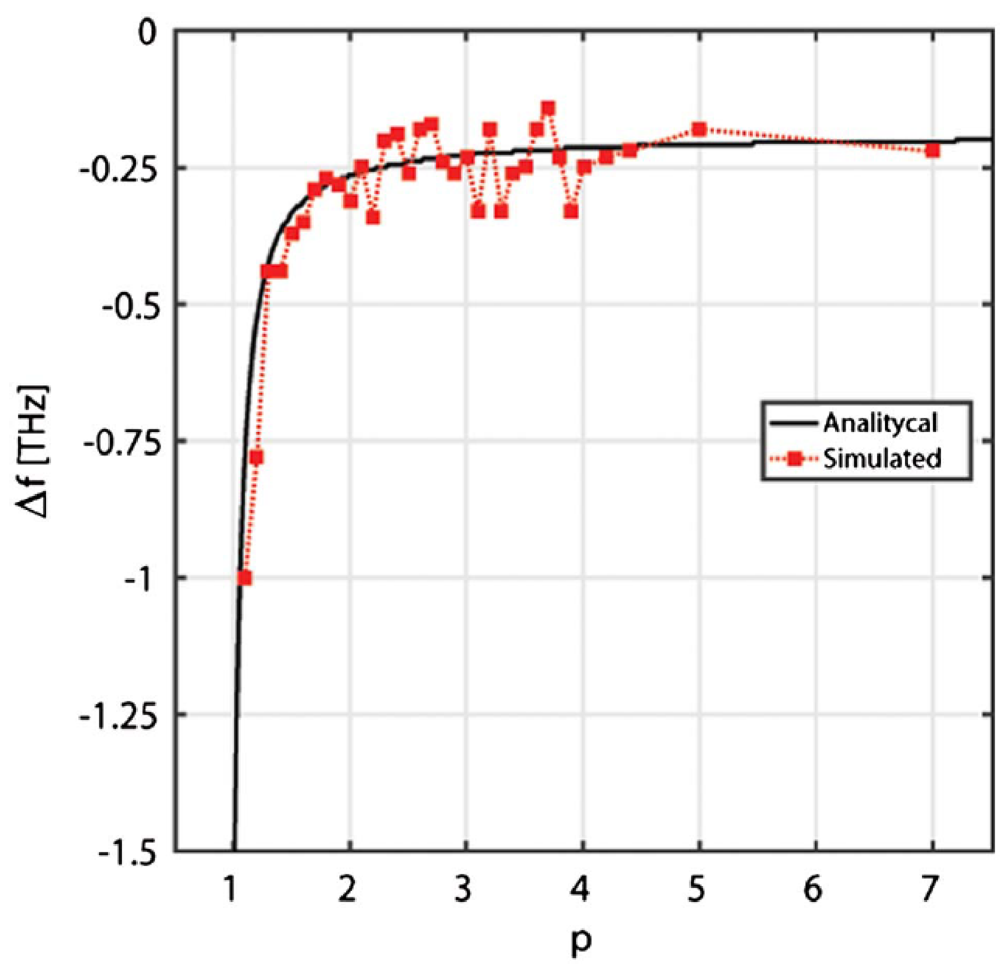
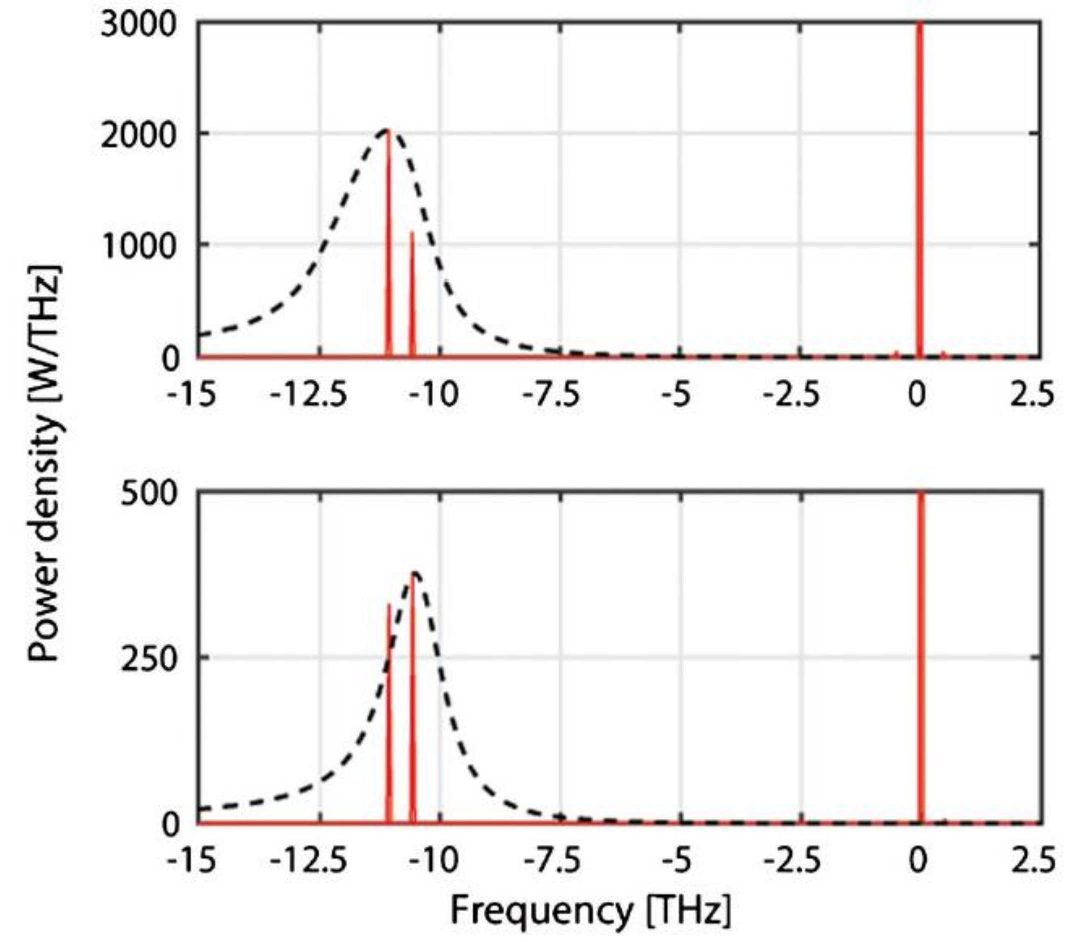


✓ Central frequency (deviation from Raman peak) as a function of the normalized power

Sánchez et al., JOSA B, 2018

Tunable Raman gain

- Tuning a filter central frequency

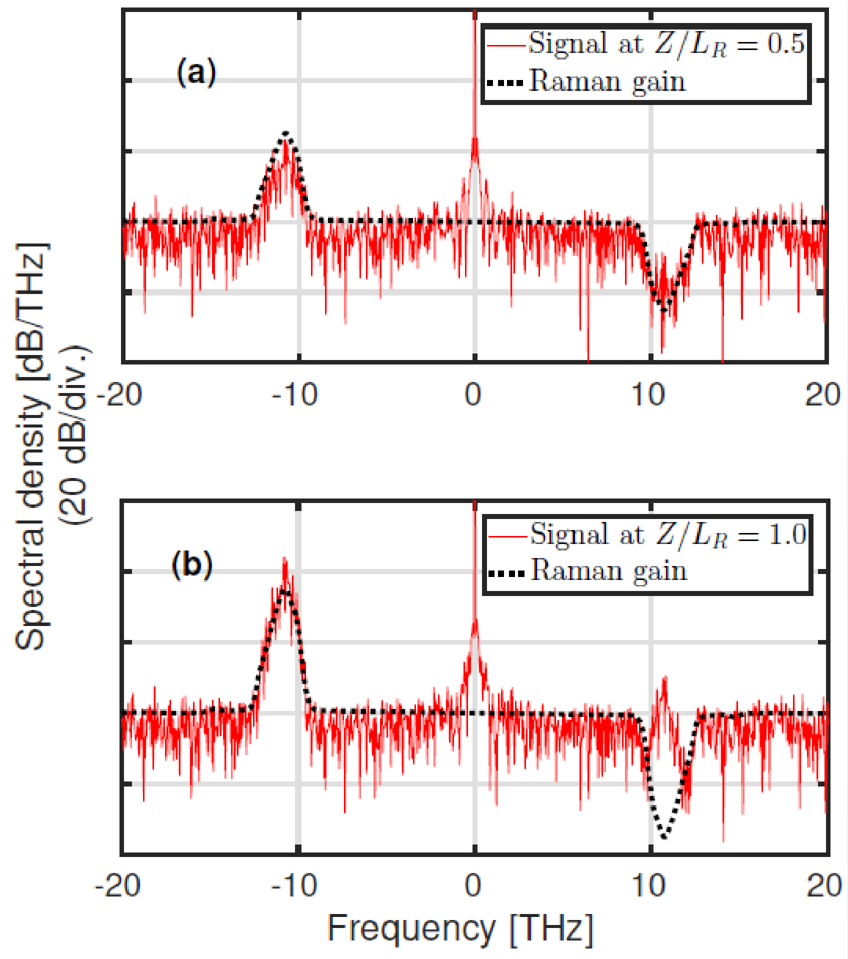


- ✓ Same pump and two seeds (simulations)
- ✓ $p = 1.1$ (top) and $p = 3.0$ (bottom)
- ✓ Output spectra after 3.6 mm

Sánchez et al., JOSA B, 2018

Anti-Stokes Raman gain

- Raman gain appears only in the Stokes side of the pump (lower frequencies)



- ✓ CW pump + noise (simulations)
- ✓ Normal regime: $\beta_2 = +50\ \mathrm{ps}^2/\mathrm{km}$
- ✓ $\gamma_0 = 100\ 1/(\mathrm{W\ km})$
- ✓ $\lambda_0 = 5\ \mu\mathrm{m}$

- Initially, there is no gain in the Stokes side
- Gain in the Stokes side appears as a consequence of four-wave mixing

Sánchez et al., JOSA B, 2018 B

Anti-Stokes Raman gain

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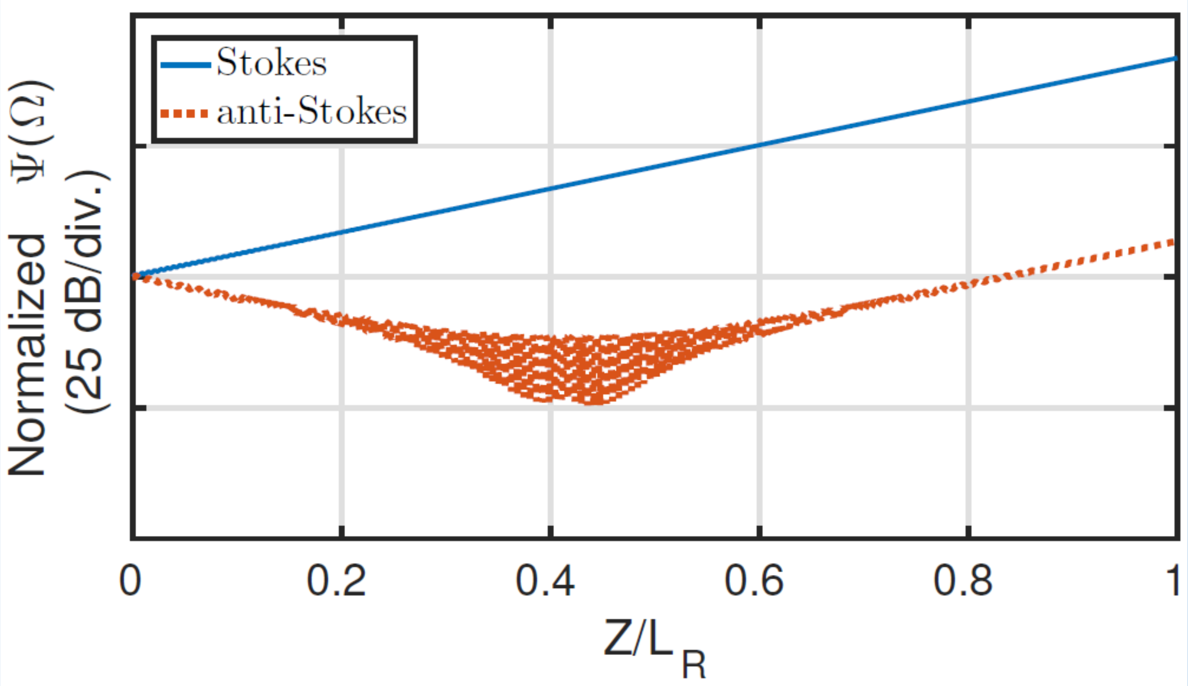


- ✓ CW pump + seeds (simulations)
- ✓ Normal regime: $\beta_2 = +50\ \mathrm{ps}^2/\mathrm{km}$
- ✓ $\gamma_0 = 100\ 1/(\mathrm{W\ km})$
- ✓ $\lambda_0 = 5\ \mu\mathrm{m}$

- Photon number is a conserved quantity

Sánchez et al., JOSA B, 2018 B

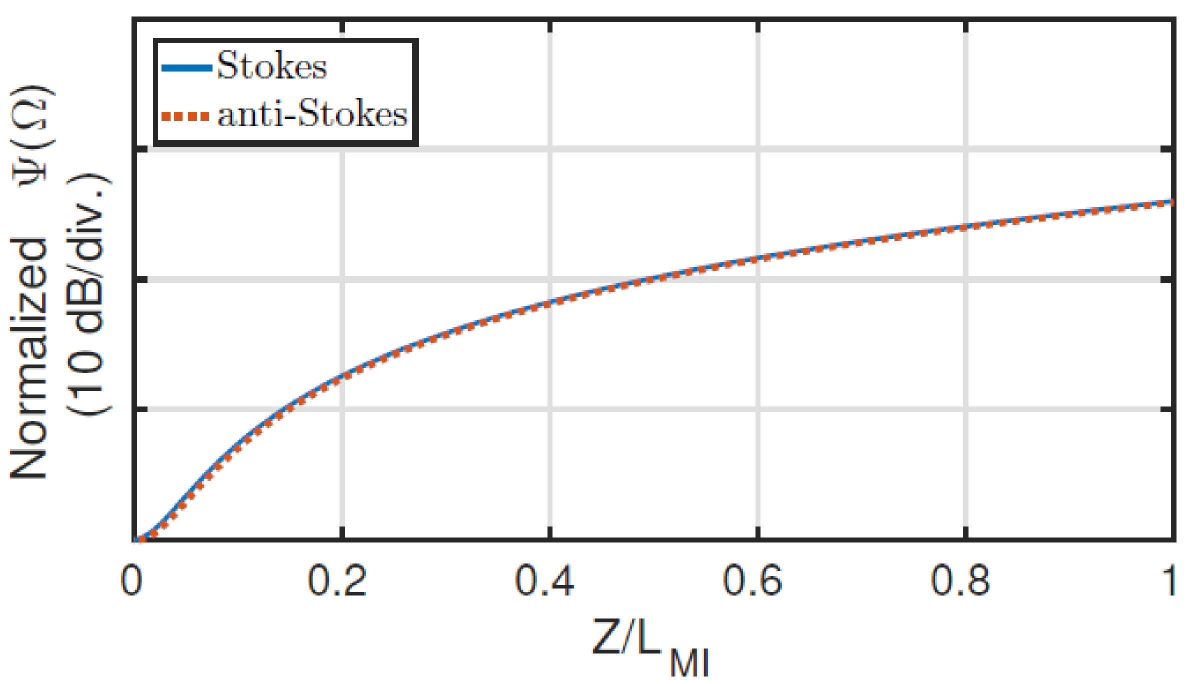
Anti-Stokes Raman gain

- Raman gain appears only in the Stokes side of the pump (lower frequencies)
- However, in the case of tunable Raman gain, it appears also in the anti-Stokes band (higher frequencies)
- Both gain sidelobes are Raman-shaped
- It is a pseudo-parametric gain

Sánchez et al., JOSA B, 2018 B

Anti-Stokes Raman gain

- Raman gain appears only in the Stokes side of the pump (lower frequencies)



- ✓ CW pump + seeds (simulations)
- ✓ Anomalous regime: $\beta_2 = -50\ \mathrm{ps}^2/\mathrm{km}$
- ✓ $\gamma_0 = 100\ 1/(\mathrm{W\ km})$
- ✓ $\lambda_0 = 5\ \mu\mathrm{m}$
- ✓ $p = 1.1$

- Both seeds grow simultaneously

Sánchez et al., JOSA B, 2018 B

Characterization of Raman

- Raman delayed response

$$\frac{\partial A}{\partial z} - i\hat{\beta}A = i\hat{\gamma}A(z,T)\int_{-\infty}^{+\infty} R(T')|A(z,T-T')|^2 dT'$$

$$R(T) = (1 - f_R)\delta(T) + f_R h(T)$$

- $h(t)$ can be estimated from the Raman gain ($\propto f_R n_2 \mathrm{Im}\{\tilde{h}(\Omega)\}$) and using the Kramer-Kronig relations
- f_R can be estimated given independent measurements of the Raman gain and n_2

Characterization of Raman

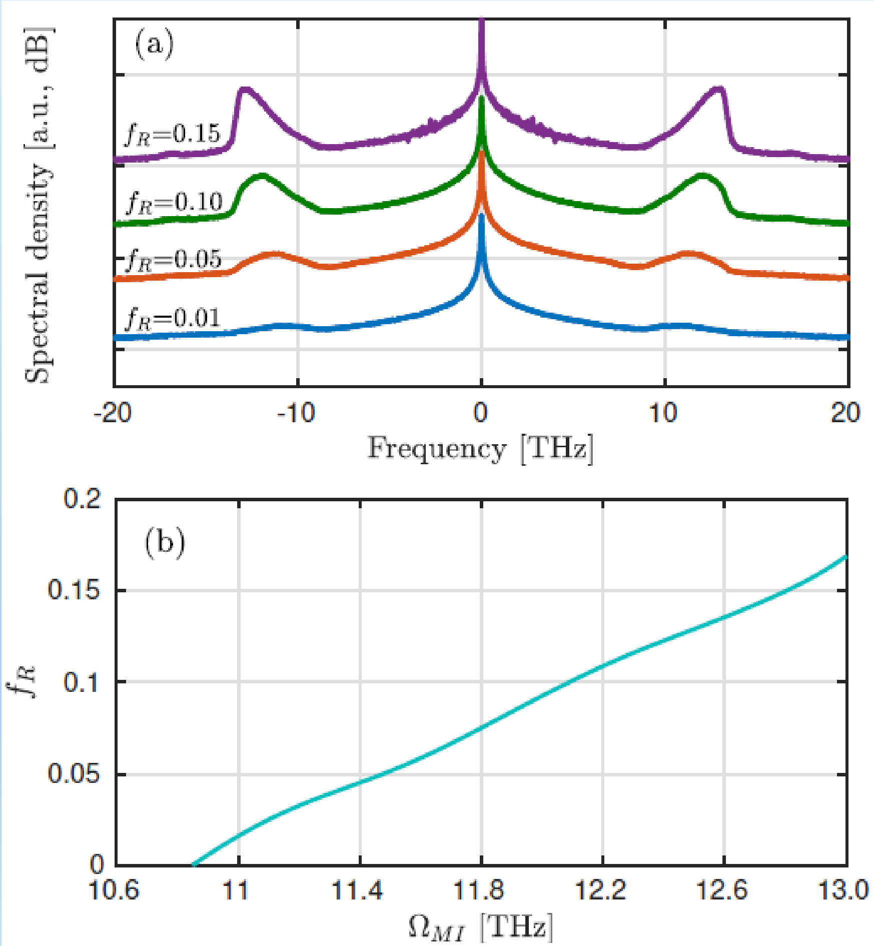
- Raman delayed response

$$R(T) = (1 - f_R)\delta(T) + f_R h(T)$$

- f_R can also estimated from independent measurements of the Raman gain and the differential scattering cross-section
  - This approach was used in Stolen et al., JOSAB, 1989, to fix the value $f_R = 0.18$ used for silica fibers
- Time-resolved Z-scan can be used to measure both f_R and $h(t)$
  - Error > 25% for f_R (Smolorz et al., J. Non-Crystalline Solids, 1999)

Characterization of Raman

- Raman gain beyond the cuttoff power enables another path to estimate f_R



- The position of the peak of the Raman gain depends f_R $(p = 10)$

- Equations relating the position of the peak with f_R

Sánchez et al., Opt. Lett, 2019

Extension of the GNLSE

- The Generalized Nonlinear Schrödinger Equation (GNLSE) does not preserve the photon number when a general nonlinear coefficient $\tilde{\gamma}(\Omega)$ is used
- Waveguides based on new metamaterials require the use strongly frequency-dependent $\tilde{\gamma}(\Omega)$: some waveguides present a zero-nonlinearity wavelength
- We developed a new extension to the GNLSE that is physically meaningful and can model the propagation in new materials

Bonetti et al., JOSA B, submitted
Bonetti et al., arXiV, 2019.

Extension of the GNLSE

- Following a quantum mechanical approach, the equation can be derived (dispersionless case) from the mean evolution of the Schrödinger equation (Lai & Haus, Phys. Rev. A, 1989)

$$\frac{\partial}{\partial z}|\psi >= i\hat{H}|\psi >$$

$$\hat{H} = \iiint \frac{\kappa}{2} \hat{a}^{\dagger}_{\omega_1}\hat{a}^{\dagger}_{\omega_2}\, \hat{a}_{\omega_1-\mu}\hat{a}_{\omega_2-\mu} d\omega_1 d\omega_2 d\mu$$

- $\hat{A}_{\omega} \propto \hat{a}_{\omega}\sqrt{\omega_0 + \omega}$
- κ is related to the third order susceptibility
- Restriction on frequency dependence: hermiticity requires $\kappa_{\omega_1,\omega_2,\omega_3,\omega_4} = \kappa^{*}_{\omega_4,\omega_3,\omega_2,\omega_1}$

Extension of the GNLSE

- Hard-to-conduct measurements of the four-frequency dependence

- Idea: use generalized Miller's rule

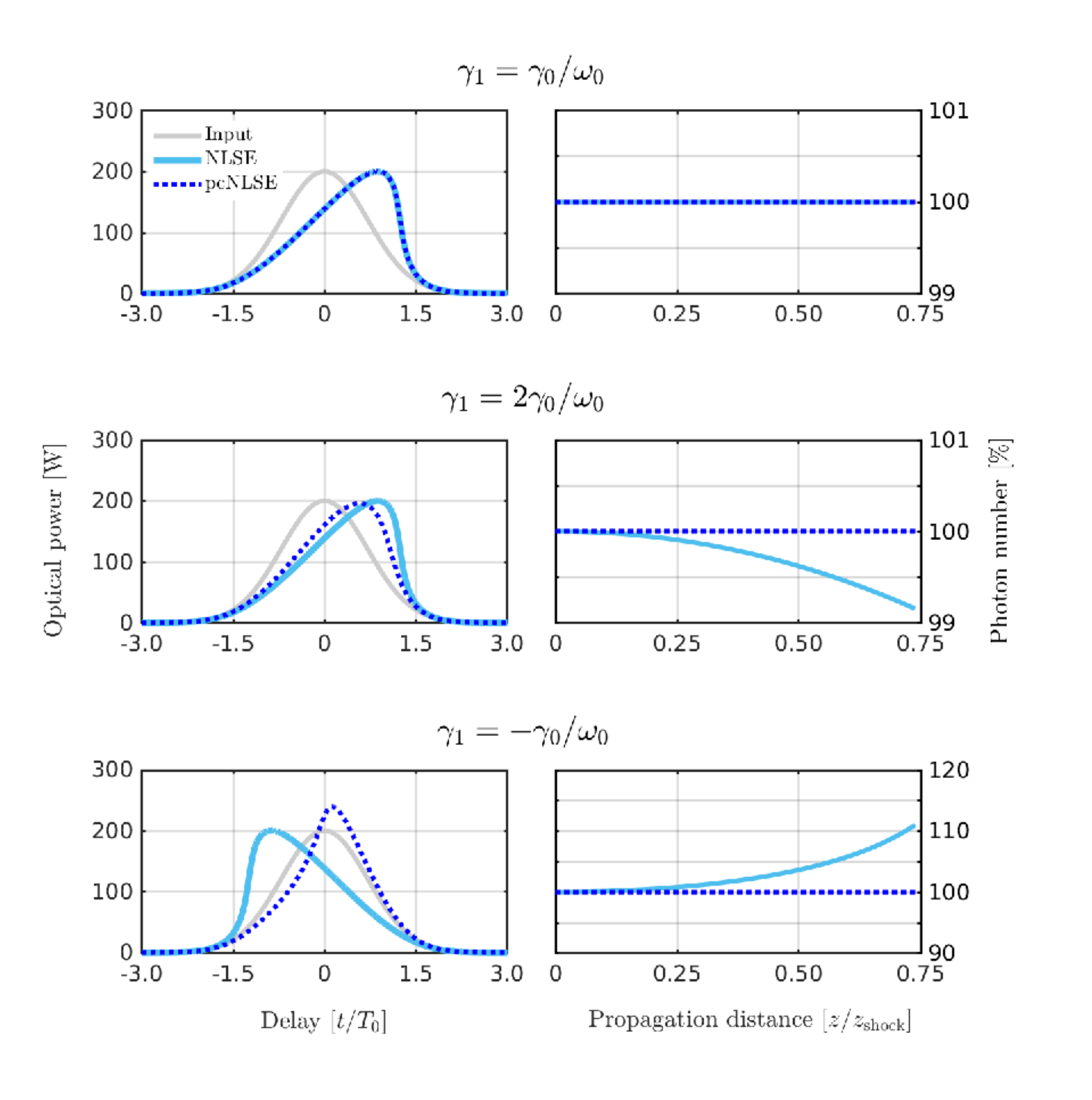
$$\chi^{(3)}_{\omega_1,\omega_2,\omega_3,\omega_4} \propto \chi^{(1)}_{\omega_1}\chi^{(1)}_{\omega_2}\chi^{(1)}_{\omega_3}\chi^{(1)}_{\omega_4}$$

- Motivated by this idea:

$$r_\omega \propto \sqrt[4]{\gamma(\omega) \times (\omega_0 + \omega)}$$

$$\kappa_{\omega_1,\omega_2,\omega_3,\omega_4} = \mathrm{Re}\left(r_{\omega_1} r_{\omega_2} r_{\omega_3} r_{\omega_4}\right)$$

Extension of the GNLSE



- ✓ 100 ns pulse
- ✓ Dispersionless
- ✓ $\gamma_0 = 1.2 \times 10^{-3}$ 1/(W km)
- ✓ $\lambda_0 = 1550$ nm
- ✓ $P_0 = 200$ W

Bonetti et al., JOSA B, submitted

Summary

- Analytical expressions for the initial stage of MI in the pump+noise case
- Higher-order perturbation solution beyond the first-order linear solution
- Study of the pump power limits of the MI gain
- Tunable Raman (both Stokes and anti-Stokes bands) beyond the pump cuttoff power
- A method to measure the fractional Raman gain f_R
- Extension to the GNLSE that allows to model propagation in new materials

Ongoing work

- Extension of the GNLSE, valid for new materials, that includes Raman
- Parametric processes in bulk nonlinear crystals, such as GaSe and $AgGaSe_2$, with a second order nonlinear susceptibility χ^2
  - Generation of pairs of correlated photons for quantum information transmission

Thank you!

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