Communication using the discrete Nonlinear Fourier Spectrum: Counter-propagating Raman and EDFA

Workshop ITG-Fachgruppe 5.3.1

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Outline

- Motivation
- Introduction to the Nonlinear Fourier Transform
- Modulation of discrete spectrum
- Transmission in EDFA / counter-propagating Raman amplifier links
- Conclusion / prospect

Motivation

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- Modern optical transmission are using advanced modulation formats and coherent detection
- Current transmission formats are designed for linear channels

$\Rightarrow$ Fiber is a nonlinear medium due to Kerr nonlinearity

- Novel transmission formats to consider fiber nonlinearity

$\Rightarrow$ Theoretical framework of Nonlinear Fourier Transformation / Inverse Scattering Theory assumes lossless transmission or ideal distributed amplification

- Theoretical assumptions are hard to meet with current commercially available equipment and installed fibers

Signal Propagation in an Optical Fiber

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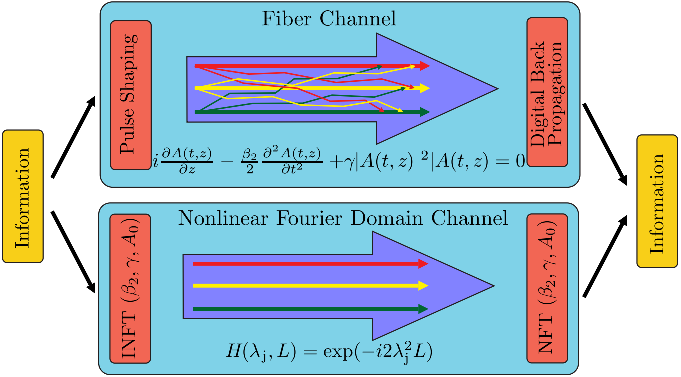
- Field propagation in an optical fiber: Nonlinear Schroedinger Equation
- "Linearization" of the nonlinear channel



Basic Idea

- We look for an invariant under evolution (noise and loss neglected)
- Normalization of NLSE $\Rightarrow$ transition to "soliton"-units

$$i\frac{\partial q(t,z)}{\partial z} + \frac{1}{2}\frac{\partial^2 q(t,z)}{\partial t^2} + |q(t,z)|^2 q(t,z) = 0$$

- Normalization constants

$$q = A\sqrt{\gamma Z_\mathrm{s}}, \quad z = \frac{Z}{Z_\mathrm{s}}, \quad t = \frac{T}{T_\mathrm{s}}, \quad Z_\mathrm{s} = \frac{T_\mathrm{s}^2}{|\beta_2|}$$

γ: nonlinear coefficient, β_2: group velocity dispersion coefficient, T_s: free time scale

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$$i\frac{\partial q(t,z)}{\partial z} + \frac{1}{2}\frac{\partial^2 q(t,z)}{\partial t^2} + |q(t,z)|^2 q(t,z) = 0$$

- Nonlinear Fourier spectrum

Continuous: $\hat{q}(\lambda) = \frac{b(\lambda)}{a(\lambda)}$ $(\lambda \in \mathbb{R})$

Discrete: λ_j $(a(\lambda_\mathrm{j}) = 0,\ \lambda \in \mathbb{C},\ \Im(\lambda_j) > 0,$

$\tilde{q}(\lambda_\mathrm{j}) = \frac{b(\lambda_\mathrm{j})}{\frac{da(\lambda)}{d\lambda}\Big|_{\lambda=\lambda_\mathrm{j}}}$ $j = 1, .., N)$

Modulation of discrete spectrum

- Fundamental soliton:

$$q(t) = 2\Im(\lambda_j)\,\mathrm{sech}\left(2\Im(\lambda_j)\cdot(t - t_0)\right)\cdot \mathrm{e}^{-i\Re(\lambda_j)t}\cdot \mathrm{e}^{-i\Phi_s}$$

- Degrees of freedom: $\Im(\lambda_j)$, $\Re(\lambda_j)$, t_0, Φ_s

[1] Gui et al. "High-order modulation on a single discrete eigenvalue for optical communications based on nonlinear Fourier transform". 2017.

[2] Aref. "Control and Detection of Discrete Spectral Amplitudes in Nonlinear Fourier Spectrum". 2016.

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- Degrees of freedom: $\Im(\lambda_j)$, $\Re(\lambda_j)$, t_0, Φ_s
- Evolution of the pulse center depending on eigenvalue and position[1]

$$t_0(z) = 4\Re(\lambda_j)\,z + \frac{1}{2\Im(\lambda_j)}\log\left(\frac{|\tilde{q}_j|}{2\Im(\lambda_j)}\right)$$

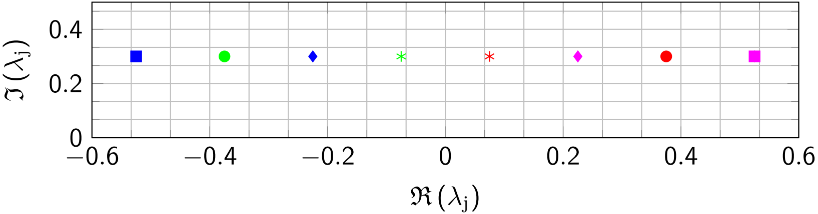
- Utilization of precise algorithm to control $\tilde{q}(\lambda_j)$[2]

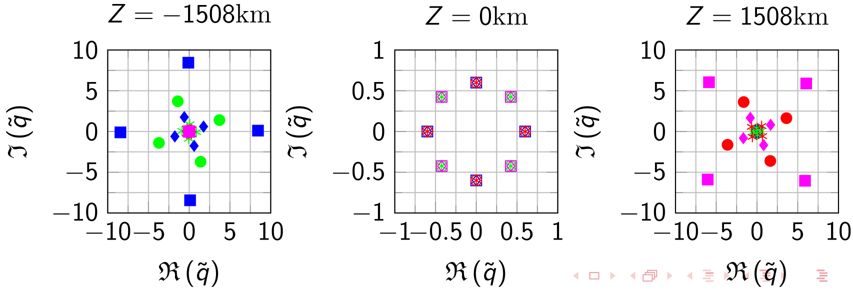
1 Gui et al. "High-order modulation on a single discrete eigenvalue for optical communications based on nonlinear Fourier transform". 2017.

2 Aref. "Control and Detection of Discrete Spectral Amplitudes in Nonlinear Fourier Spectrum". 2016.

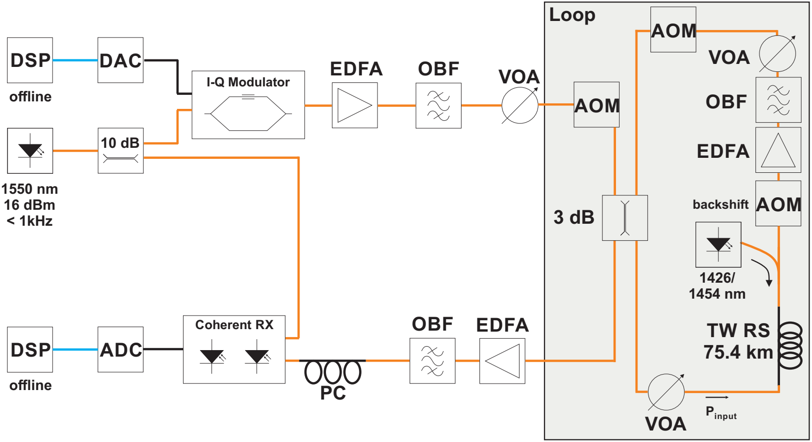
Modulation of discrete spectrum

Fiber: NZ-DSF, Symbolrate: 1GBd, $T_s = T_{Sym}/22$, $Z_s = 359.3$km





Loop Setup



$\alpha = 0.226 \frac{\text{dB}}{\text{km}}$ (span loss $> 17\text{dB}$) $\quad \beta_2 = -5.75 \frac{\text{ps}^2}{\text{km}} \quad \gamma = 1.6 \frac{1}{\text{Wkm}}$

Consideration of Fiber Losses

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- Theoretical assumption of lossless fiber for integrable differential equation collides with realistic link
- Periodic amplification by EDFA's after fiber span vs. distributed or ideal distributed Raman amplification
- Consideration of power variation by averaging over a virtual lossless link with reduced nonlinearity (LPA[3])

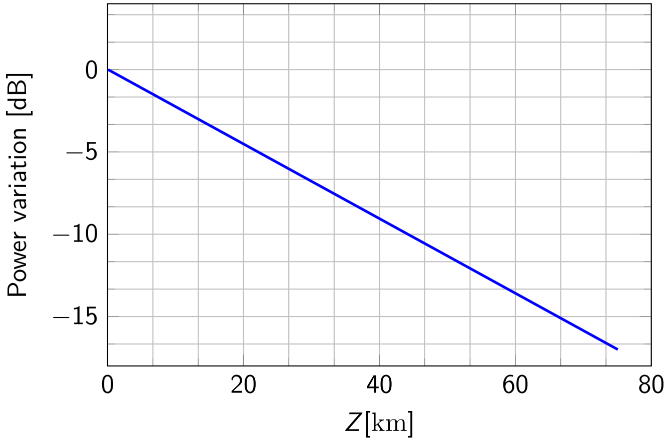
$$k = \frac{\int_0^{L_{\mathrm{Span}}} \exp\left(2\int_0^z g(y)dy\right)dz}{L_{\mathrm{Span}}}$$

$$\gamma_{\mathrm{eff}} = \gamma \cdot k, \quad \bar{P} = \frac{\int_{-T_{\mathrm{Sym}}/2}^{T_{\mathrm{Sym}}/2} \left|\frac{q(T)}{\sqrt{\gamma_{\mathrm{eff}} Z_s}}\right|^2 dT}{T_{\mathrm{Sym}}}$$

[3] Le et al. "Modified nonlinear inverse synthesis for optical links with distributed Raman amplification". 2015.

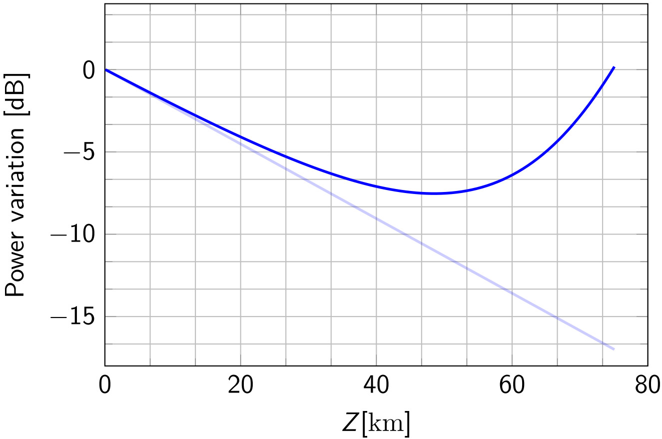
Counter-Raman & EDFA amplification

- Lumped amplification:
  $k = 0.237,\ \bar{P} = -3.97\mathrm{dBm}$



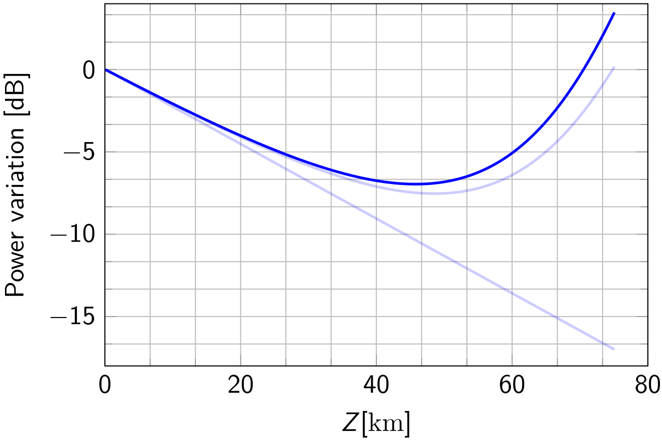
Counter-Raman & EDFA amplification

- Counter-propagating Raman - $P_1 = 320\mathrm{mW}$, $P_2 = 220\mathrm{mW}$:
  $k = 0.388$, $\bar{P} = -6.12\mathrm{dBm}$



Counter-Raman & EDFA amplification

- Counter-propagating Raman - $P_1 = 320\mathrm{mW}$, $P_2 = 280\mathrm{mW}$:
  $k = 0.474$, $\bar{P} = -7.00\mathrm{dBm}$



EDFA amplification

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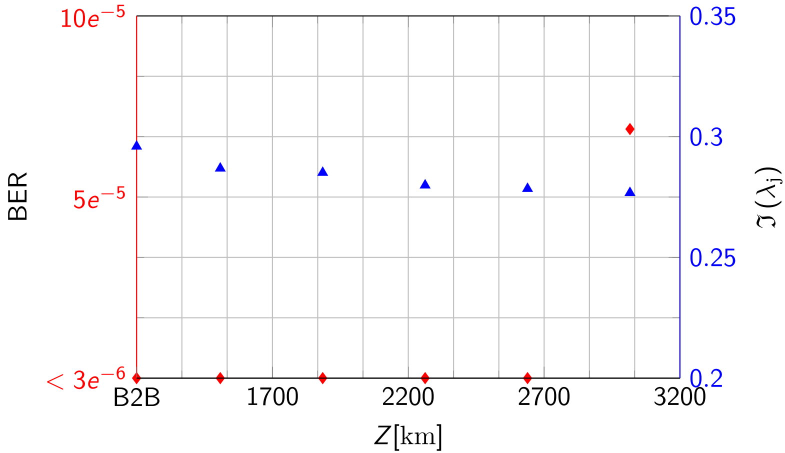

EDFA amplification

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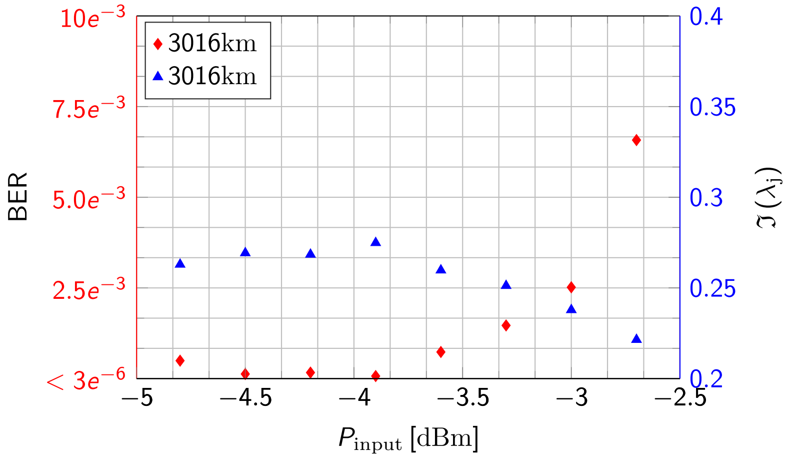

EDFA amplification

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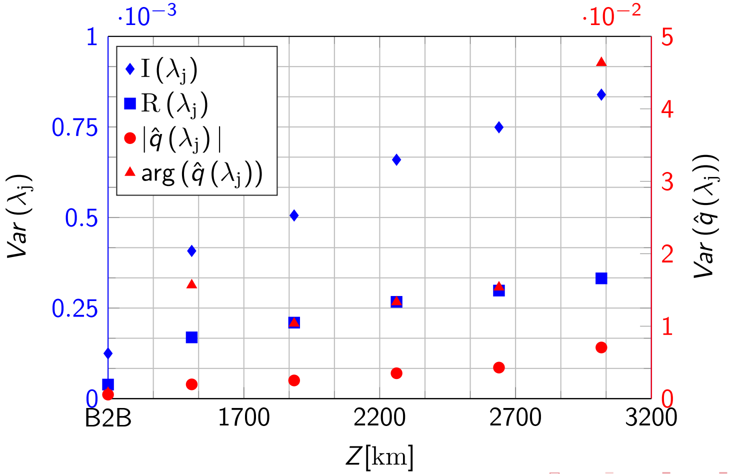
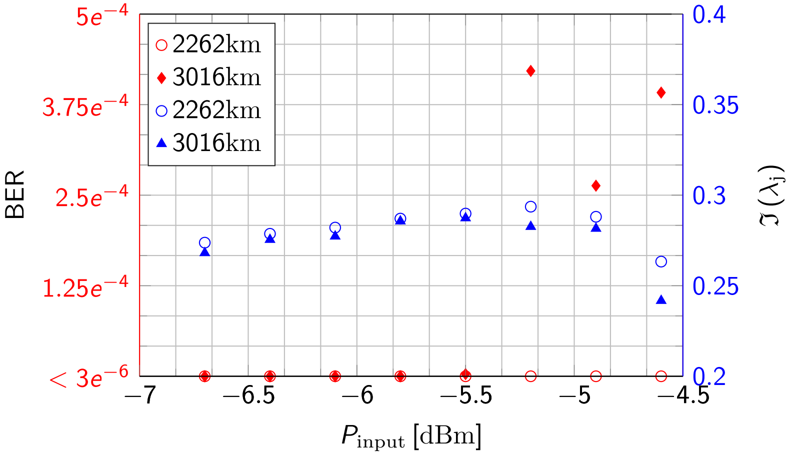


Counter-propagating Raman amplification

- Counter Raman: $k = 0.388$, $\bar{P} = -6.11\mathrm{dBm}$



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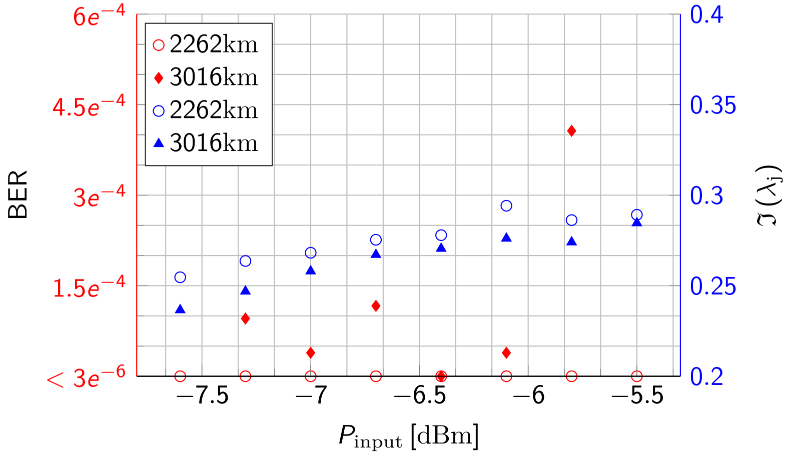

Counter-propagating Raman amplification

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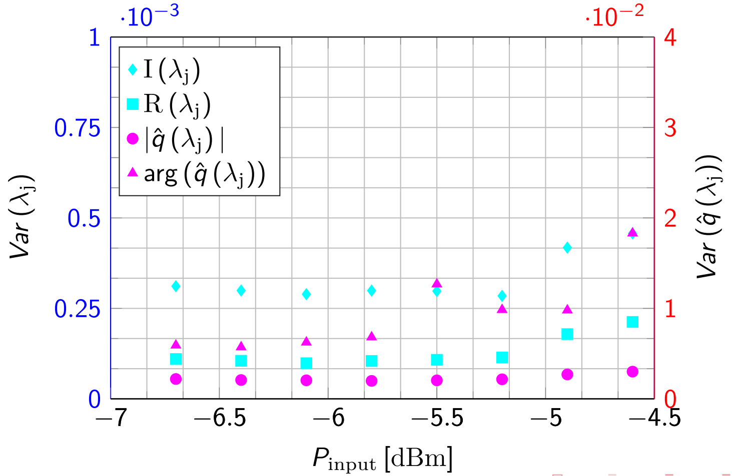
- Counter Raman: $k = 0.388$, $\bar{P} = -6.11\mathrm{dBm}$, $Z = 2262\mathrm{km}$



Transmission results

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- Slow / simple signal: reliable EDFA based transmission (BER: $6.8e^{-5}$ @ $3016\mathrm{km}$ with LMMSE equalization of $b(\lambda_{\mathrm{j}})$)
- Moderate Raman amplification (compensating span loss):

⇒ Reduction of eigenvalue and spectral amplitude variance by a factor 2..5 (BER: $<3e^{-6}$ @ $3016\mathrm{km}$)

- Intense Raman amplification (overcompensating span loss):

⇒ Reduction of eigenvalue variance by a factor 2, no effect on spectral amplitude (BER: $\approx 3e^{-6}$ @ $3016\mathrm{km}$)

(Within a propagation distance of $3450\,\mathrm{km}$ the fastest eigenvalue travels through one symbol $T_{\mathrm{Sym}} = 1\,\mathrm{ns}$ (99.9% energy))

Conclusion / prospect

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- First stokes order counter-propagating Raman amplification is suitable for NFT transmission
- First stokes order co-propagating Raman amplification can hardly be realized with commercial pump modules (FBG stabilized FP laser) due to high RIN penalty
- Second stokes order Raman amplification is not yet commercially available on a system level, implementing FBG in existing fibers would be challenging

⇒ Investigation of influence of amplification period for EDFA and Raman amplified signals

⇒ Investigation of interaction of multiple eigenvalues

References

R.-J. Essiambre, G. Kramer et al., "Capacity Limits of Optical Fiber Networks", J. Lightwave Technol., vol. 28, no. 4, pp. 662-701,02/2010

M.I. Yousefi, F.R. Kschischang, "Information Transmission Using the Nonlinear Fourier Transform, Part I-III", IEEE Trans. Inf. Theory, vol. 60, no. 1, pp. 4312-4369, 07/2014

S. Wahls, V. Poor, "Fast Numerical Fourier Transforms", arXiv:1402.1605v2, 10/2014

H. Buelow, V. Aref, W. Idler, "Transmission of Waveforms Determined by 7 Eigenvalues with PSK-Modulated Spectral Amplitudes", ECOC 2016, 09/2016

V. Aref, "Control and Detection of Discrete Spectral Amplitudes in Nonlinear Fourier Transform", Arxiv.org pre-print, 2016

V. Aref, S.T. Le, H. Buelow, "Demonstration of Fully Nonlinear Spectrum Modulated System in the Highly Nonlinear Optical Transmission Regime", ECOC 2016, 09/2016

T. Gui, C. Lu et al., "High-order modulation on a single discrete eigenvalue for optical communications based on nonlinear Fourier transform", Opt Express, vol. 25, no. 17, pp.20286-20297, 08/2017

S.T. Le, V. Aref, H. Buelow, "Nonlinear signal multiplexing for communication beyond the Kerr nonlinearity limit", Nat Photonics, vol. 11, no. 9, pp. 570-576, 09/2017

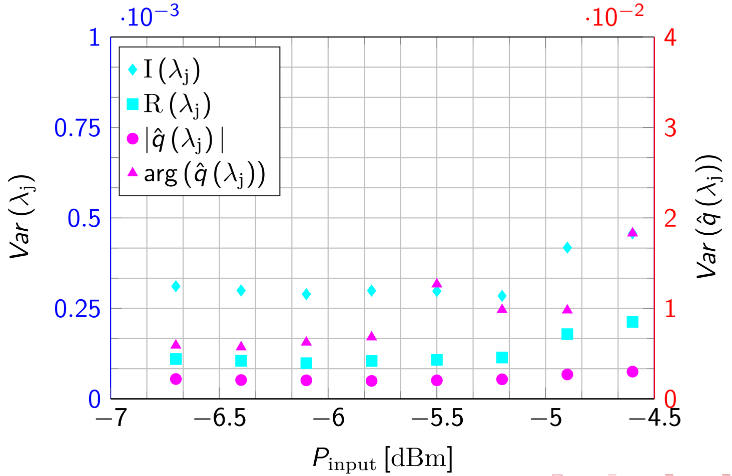
V. Aref, S.T. Le, H. Buelow, "Modulation over Nonlinear Fourier Spectrum: Continuous and Discrete Spectrum", J. Lightwave Technol., 2018, early access

Thank you for your attention!

http://www.lpi.usra.edu/publications/slidesets/oceans/images/tifs/ocean13.tif

Counter-propagating Raman amplification

- Counter Raman: $k = 0.388$, $\bar{P} = -6.11\mathrm{dBm}$, $Z = 2262\mathrm{km}$



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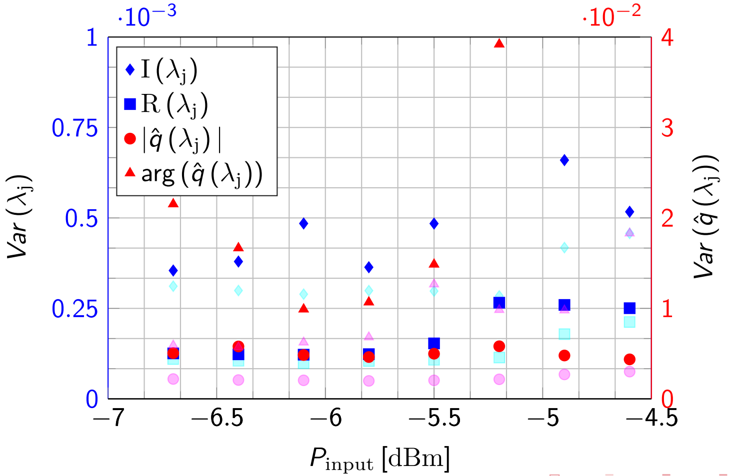

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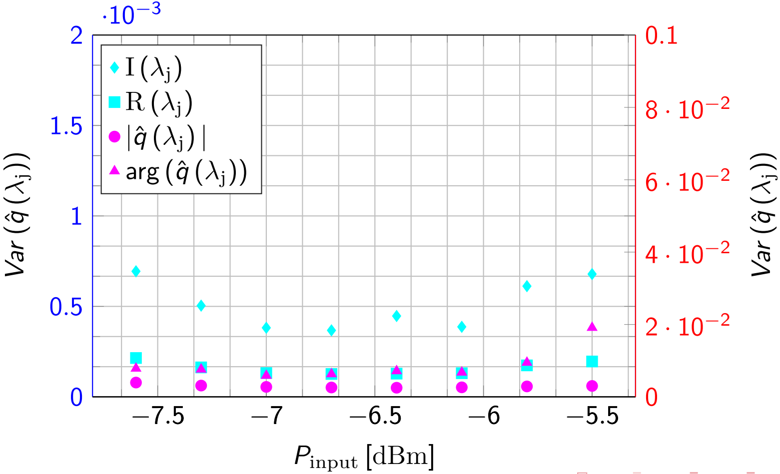

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