System Impact Of Fiber Parametric Gain in long-Haul Optical links

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Outline

- Introduction.
- The Transfer Matrix formalism developed to analyze the Parametric Gain (PG).
- Effects of Parametric Gain on ASE noise.
- Sideband Instability, a Parametric Gain related effect in periodical links.
- Effects of dispersion management on Parametric Gain.
- Optimization of dispersion map to reduce the Parametric Gain system impact.
- Conclusions.

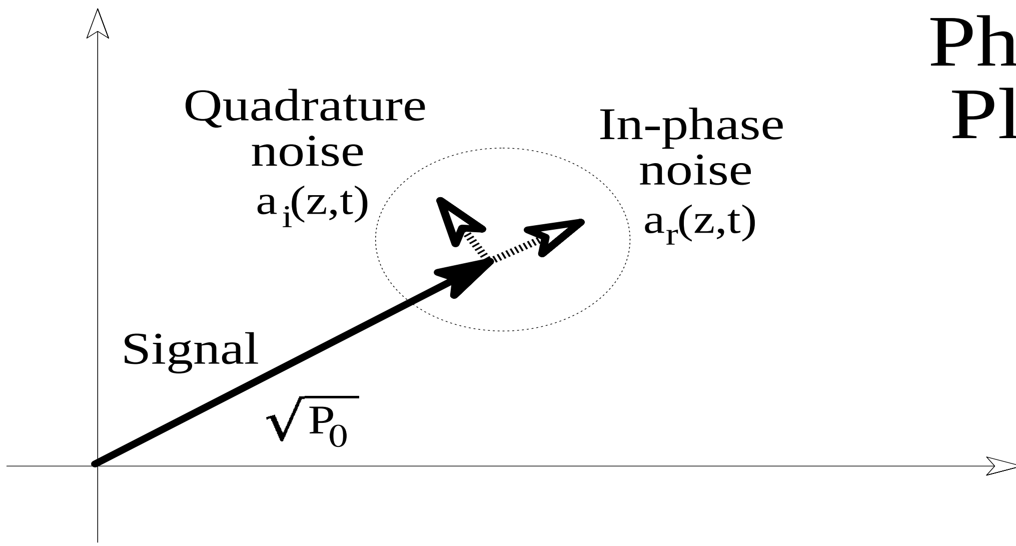
Introduction

- PG is caused by the interaction of fiber nonlinearities with dispersion.
- PG induces a transfer of optical power from the signal to the ASE noise, in both dispersion regions.
- PG effects

  Anomalous dispersion region $\Rightarrow$ Noise Enhancement, Modulation Instability

  Normal dispersion region $\Rightarrow$ Noise Enhancement
- Periodical structures are affected by Sideband Instability.
- Dispersion map influences PG characteristics.

Analytical Formalism (I)



Phasor Plane

Analyzed signal

$$U\left(z,T\right)=\left[\sqrt{P_0}+a(z,T)\right]\mathrm{e}^{\left[-\alpha z+\jmath\left(\omega_0 T-\Phi_{NL}\right)\right]}$$

PG linearized equation

$$\frac{\partial a}{\partial z}=\jmath\frac{1}{2}\beta_2\frac{\partial^2 a}{\partial T^2}-\jmath\gamma P_0\mathrm{e}^{\left(-2\alpha z\right)}\left(a+a^*\right)$$

Noise components

$$a_r(z,t)=\mathcal{R}e\left\{a(z,T)\right\}$$

$$a_i(z,t)=\mathcal{I}m\left\{a(z,T)\right\}$$

Analytical Formalism (II)

The solution has the following Transfer Matrix form:

$$\begin{bmatrix} A_r(z,\Omega) \\ A_i(z,\Omega) \end{bmatrix} = \begin{bmatrix} T_{11}(z,\Omega) & T_{12}(z,\Omega) \\ T_{21}(z,\Omega) & T_{22}(z,\Omega) \end{bmatrix} = \begin{bmatrix} A_r(0,\Omega) \\ A_i(0,\Omega) \end{bmatrix}$$

where the T_{ij}'s are expressed using Hankel's functions.

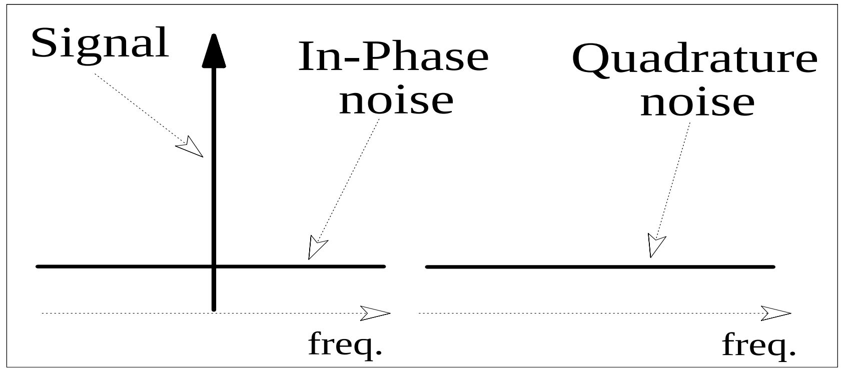
Using the spectral theory for multi-dimensional noise [a], we obtain the Noise Gain Matrix after the action of PG.

$$\underline{\underline{G}}(z,\Omega) = \begin{bmatrix} |T_{11}|^2 + |T_{12}|^2 & T_{11}T_{21} + T_{12}T_{22} \\ T_{11}T_{21} + T_{12}T_{22} & |T_{21}|^2 + |T_{22}|^2 \end{bmatrix} = \begin{bmatrix} G_{rr}(z,\Omega) & G_{ri}(z,\Omega) \\ G_{ri}(z,\Omega) & G_{ii}(z,\Omega) \end{bmatrix}$$

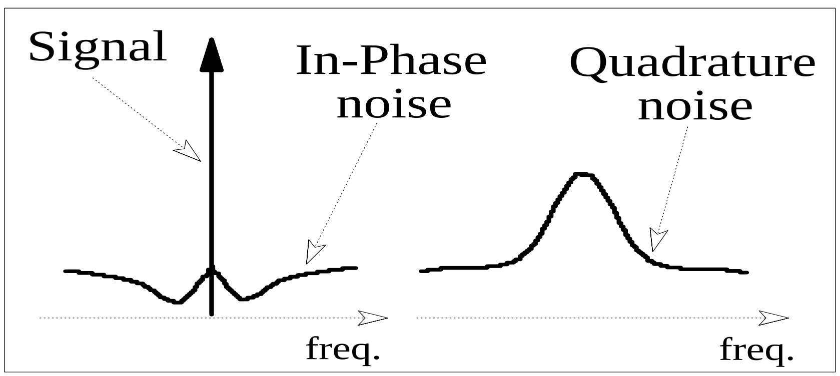
[a] A. Papoulis, *Probability, Random Variables, and Stochastic Processes*, p. 329, 3rd edition, McGraw-Hill International Editions, New York, 1991.

Effects of Parametric Gain on ASE noise

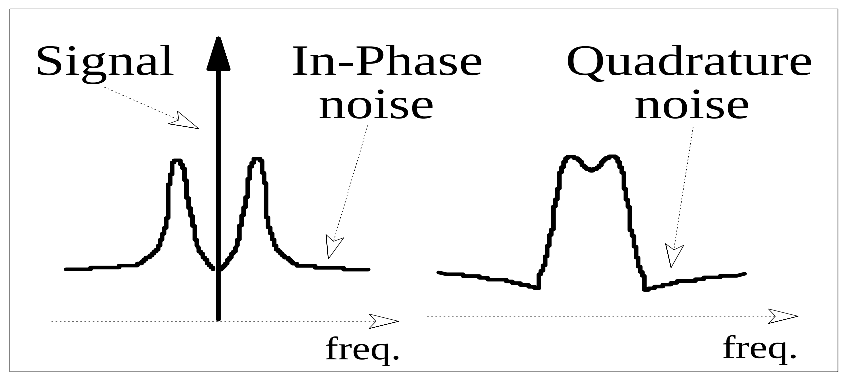
Input noise components



Output - Normal Dispersion

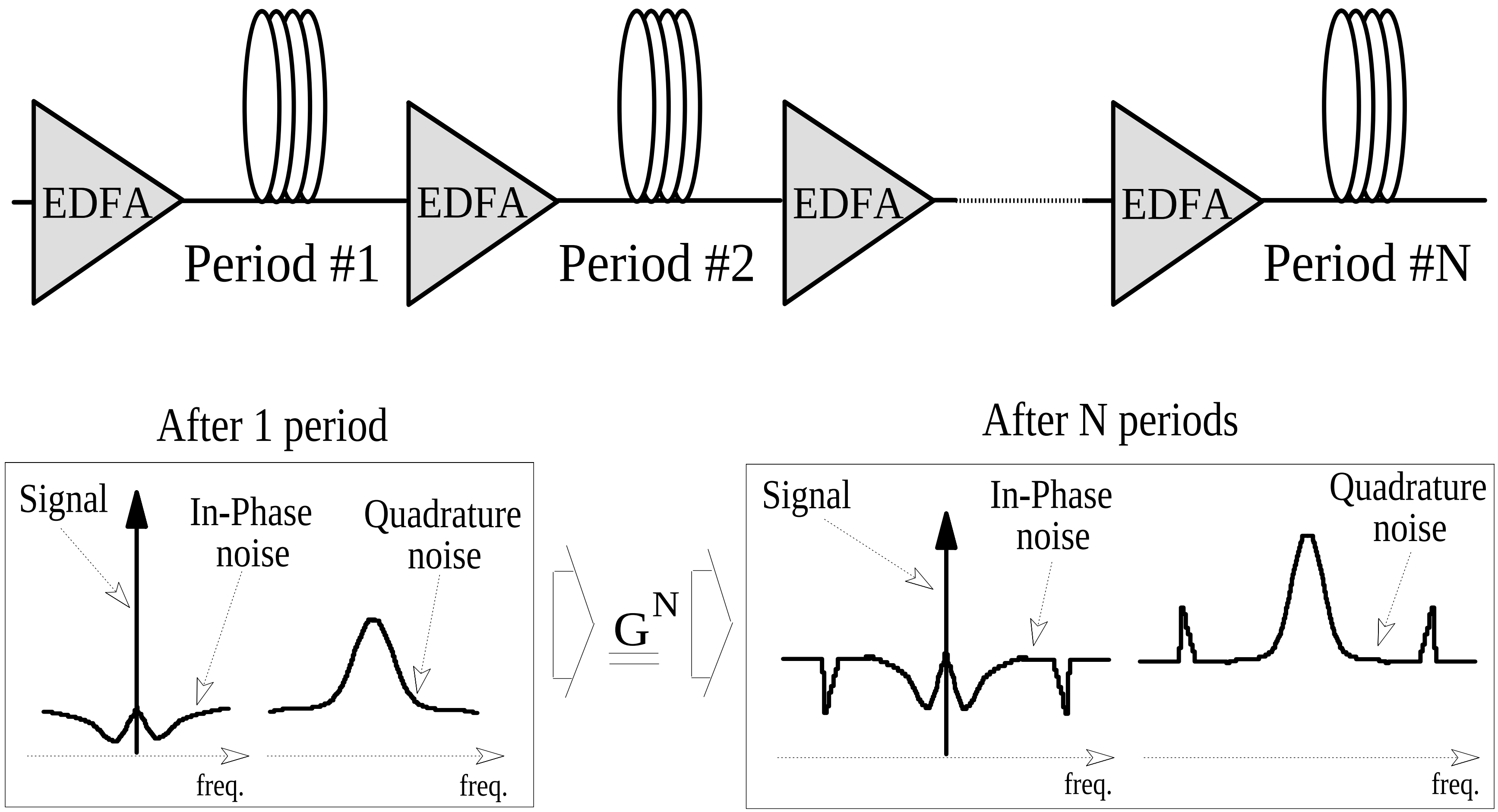


Output - Anomalous Dispersion



Reference: A. Carena,V. Curri, R. Gaudino, P. Poggiolini *New theoretical results on fiber Parametric Gain and its effects on ASE noise*, IEEE Photonics Technology Letters, vol. 9, n. 4, pp. 535-537, Apr. 1997.

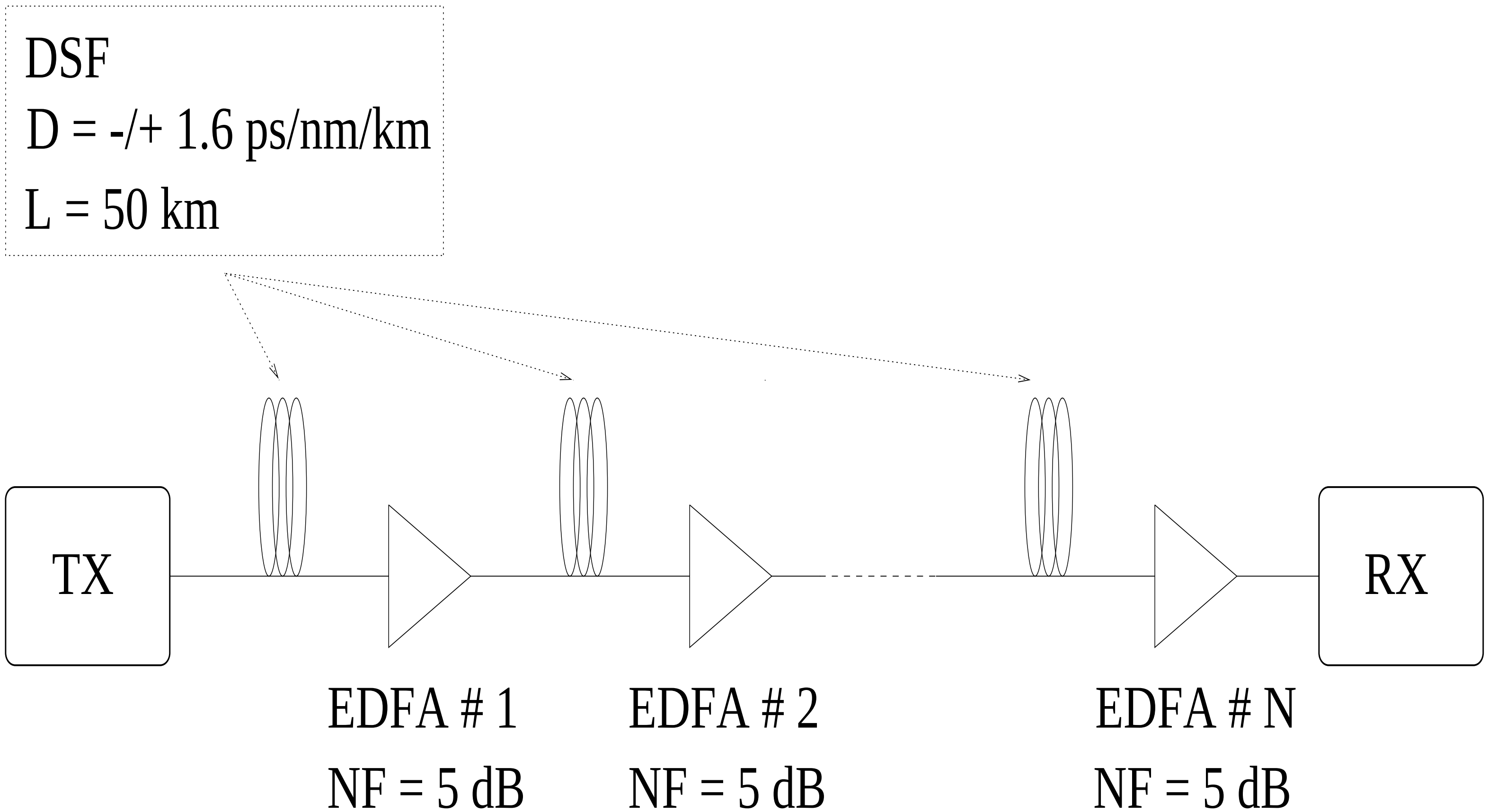
Sideband Instability



OPTSIM - Optical System Simulator

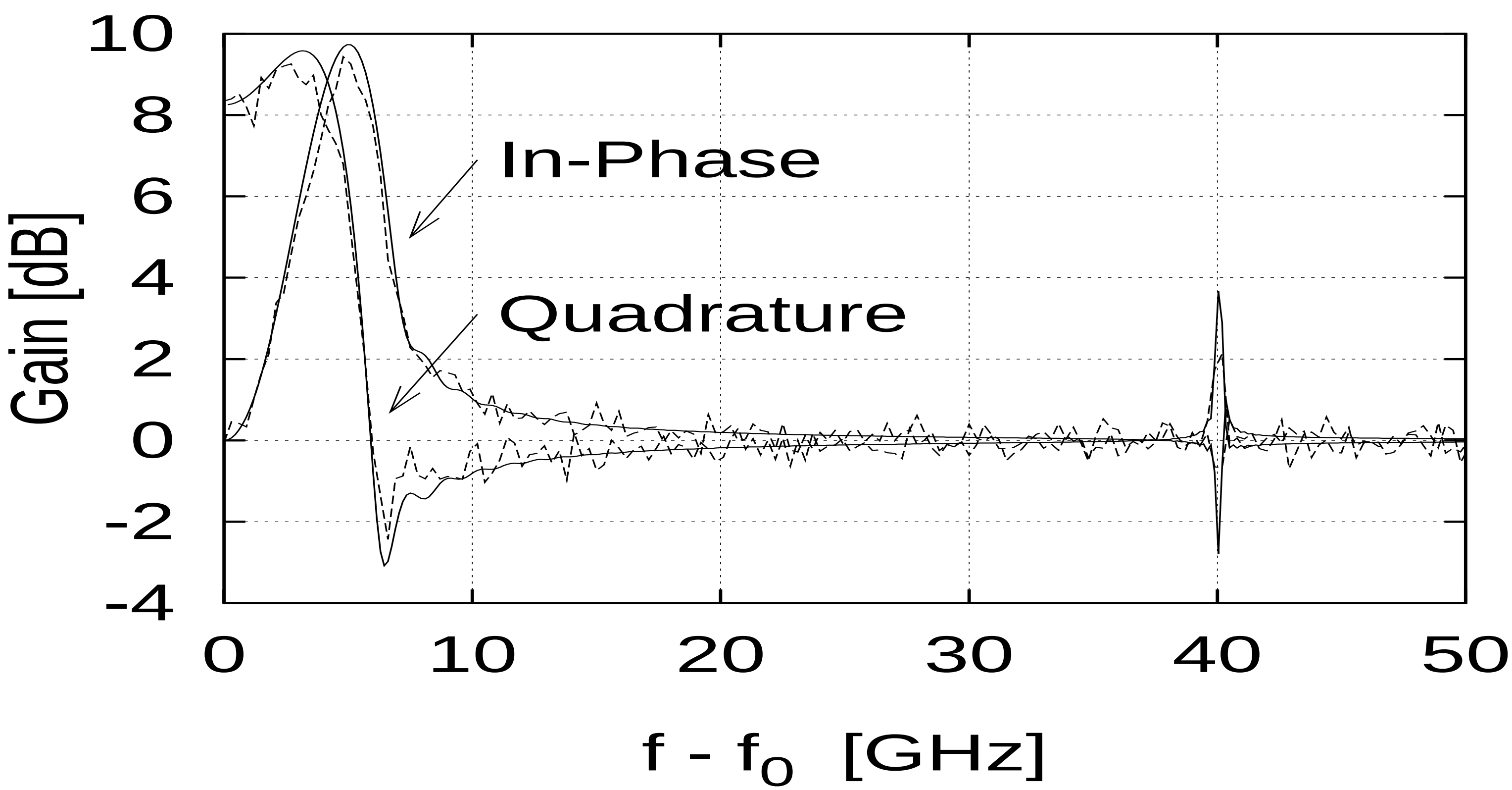
- Time-domain simulator.
- It is based on a split-step algorithm.
- A dual polarization fiber model is considered to include all polarization related phenomena.
- It takes into account attenuation, dispersion, birefringence and PMD.
- Non-linear Kerr effect is considered, too.
- Joint linear-nonlinear effects are accurately evaluated.

Amplified Link, DS Fiber, L=3,000 km



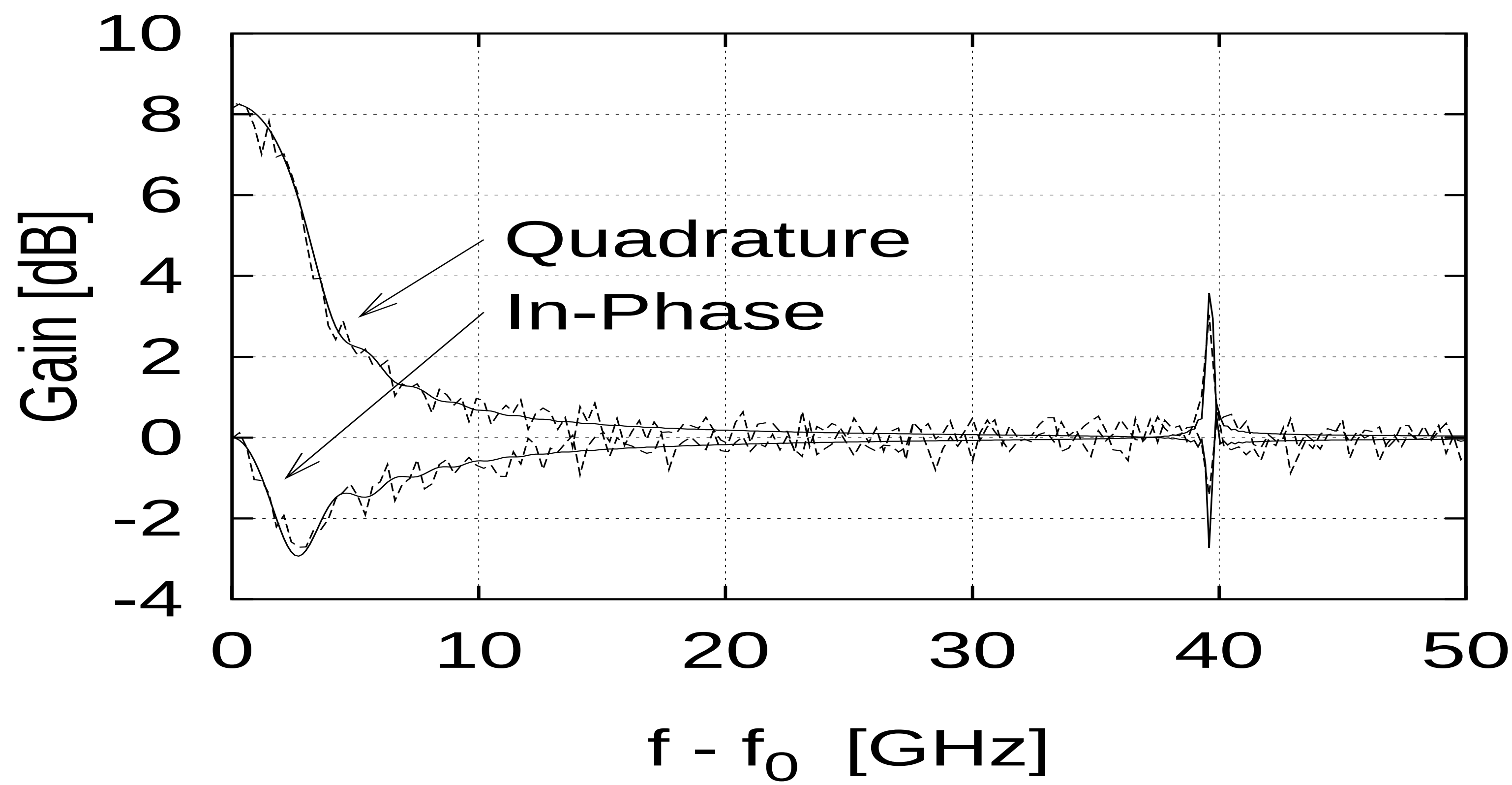
Parameters: CW power: 0 dBm, Fiber loss: $\alpha = 0.22$ dB/km, Fiber nonlinearity: $\gamma = 2\ \mathrm{W}^{-1}\mathrm{km}^{-1}$.

Noise gain L=3,000 km D=+1.6 ps/nm/km



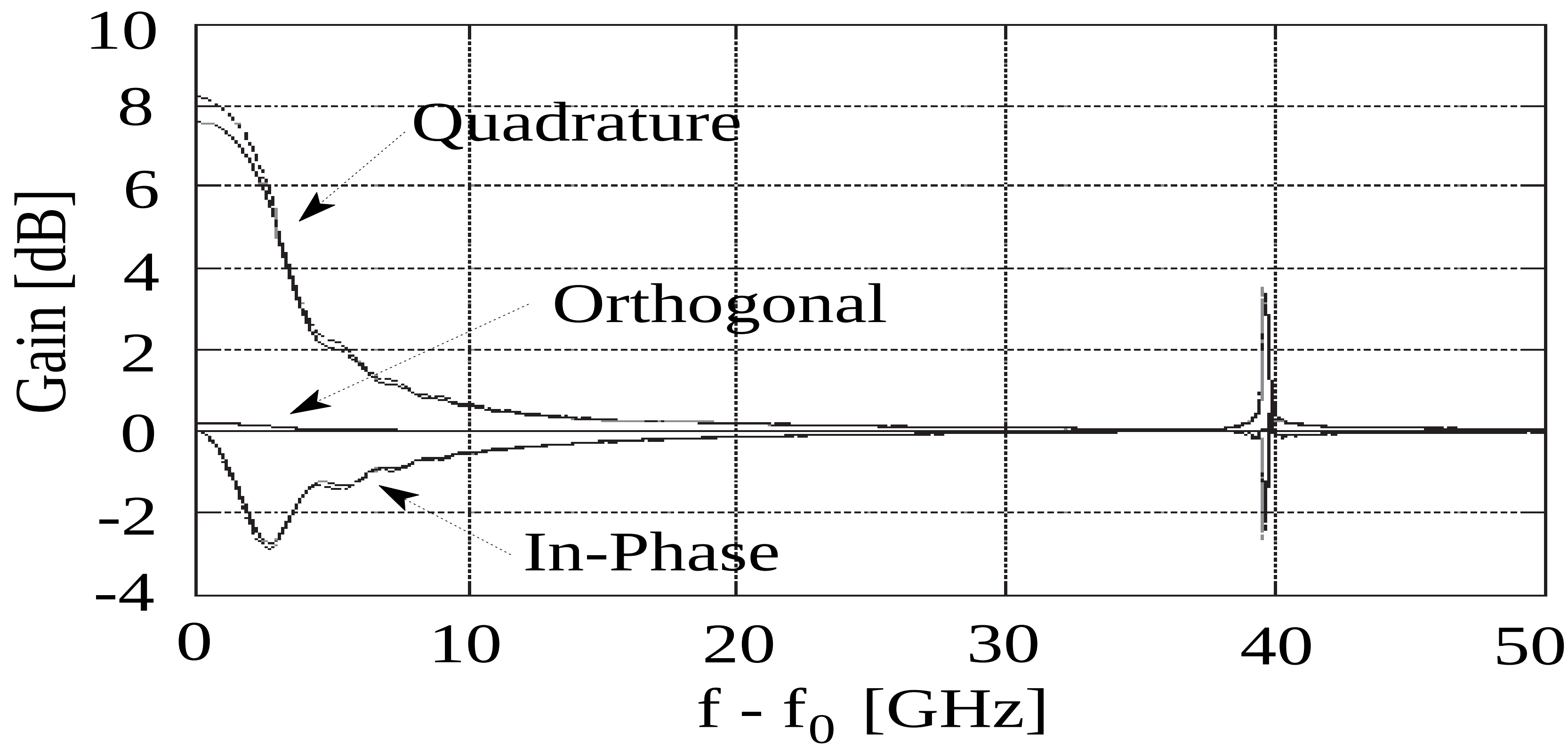
Simulated (dashed) and analytical (solid) in-phase and quadrature ASE noise gain spectra. Anomalous dispersion.

Noise gain L=3,000 km D=-1.6 ps/nm/km



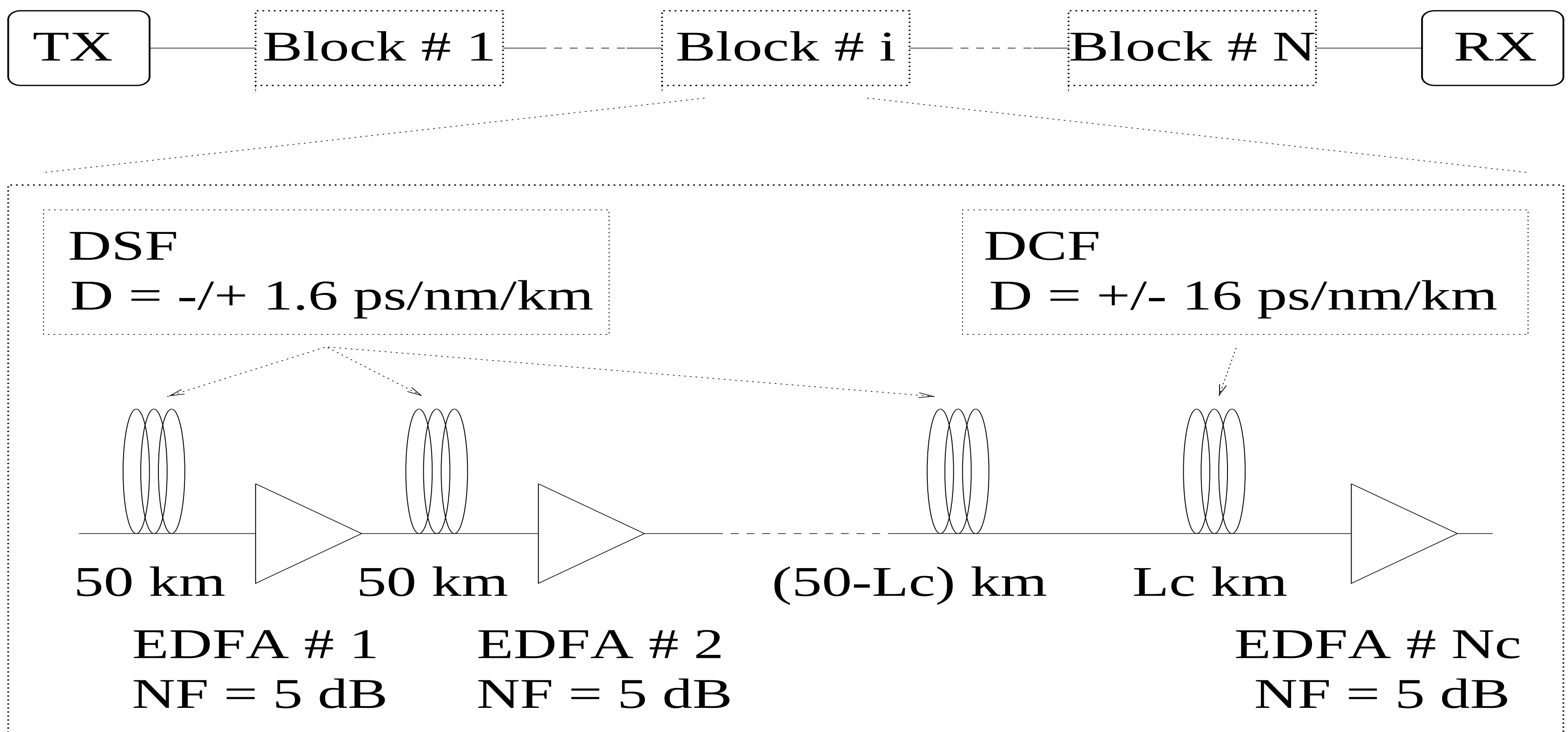
Simulated (dashed) and analytical (solid) in-phase and quadrature ASE noise gain spectra. Normal dispersion.

Parametric Gain and Birefringence



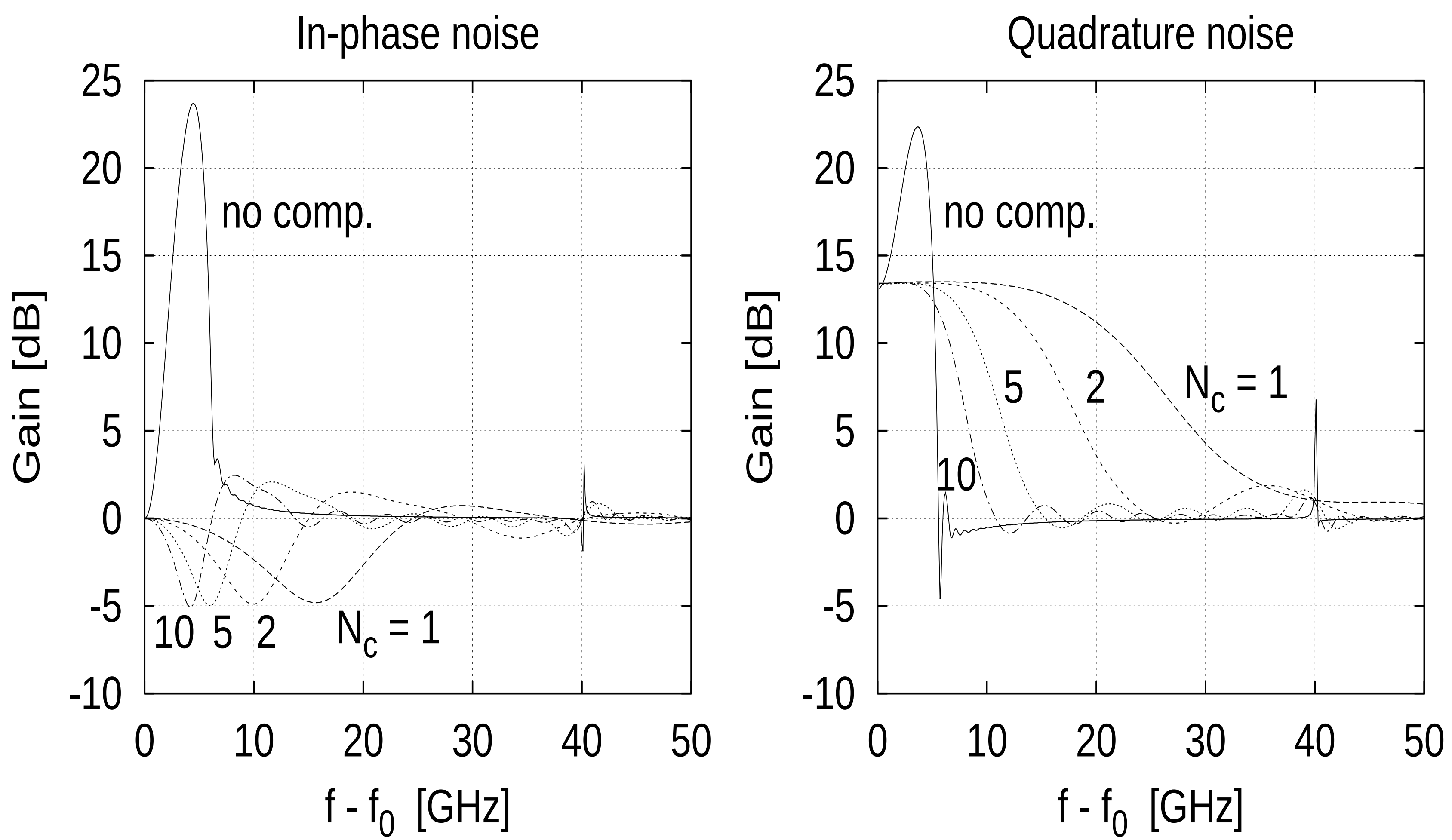
Analytical ASE noise gain spectra with (dashed) and without (solid) birefringence. Normal dispersion.

Compensated Link Configuration

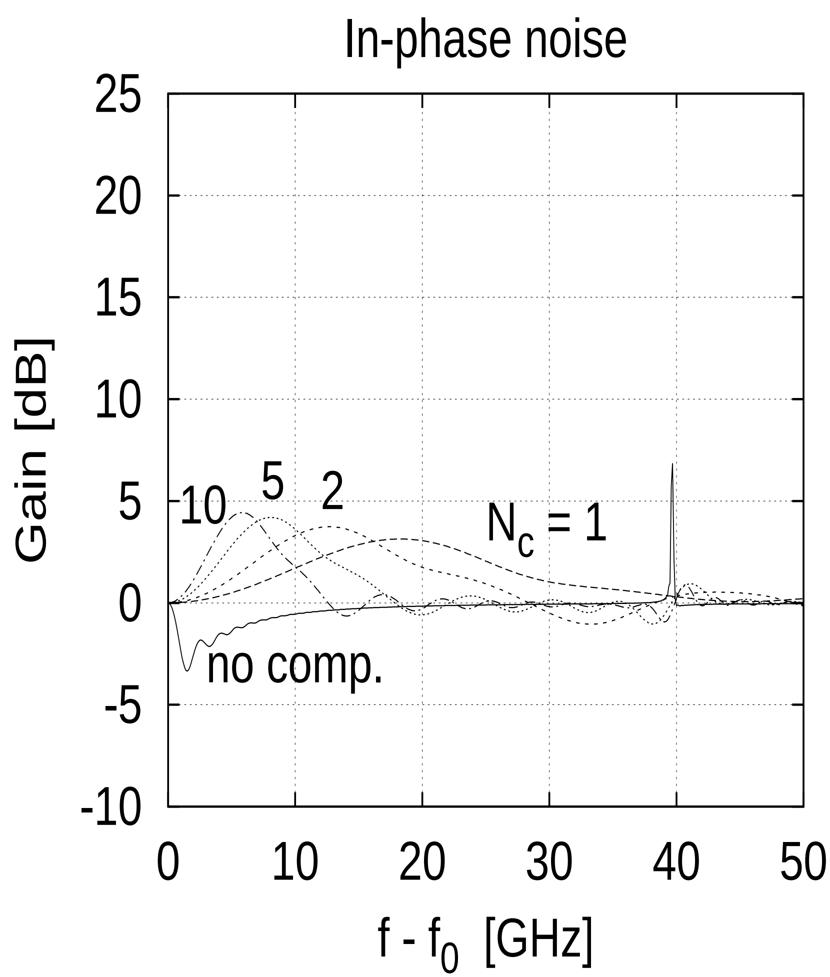


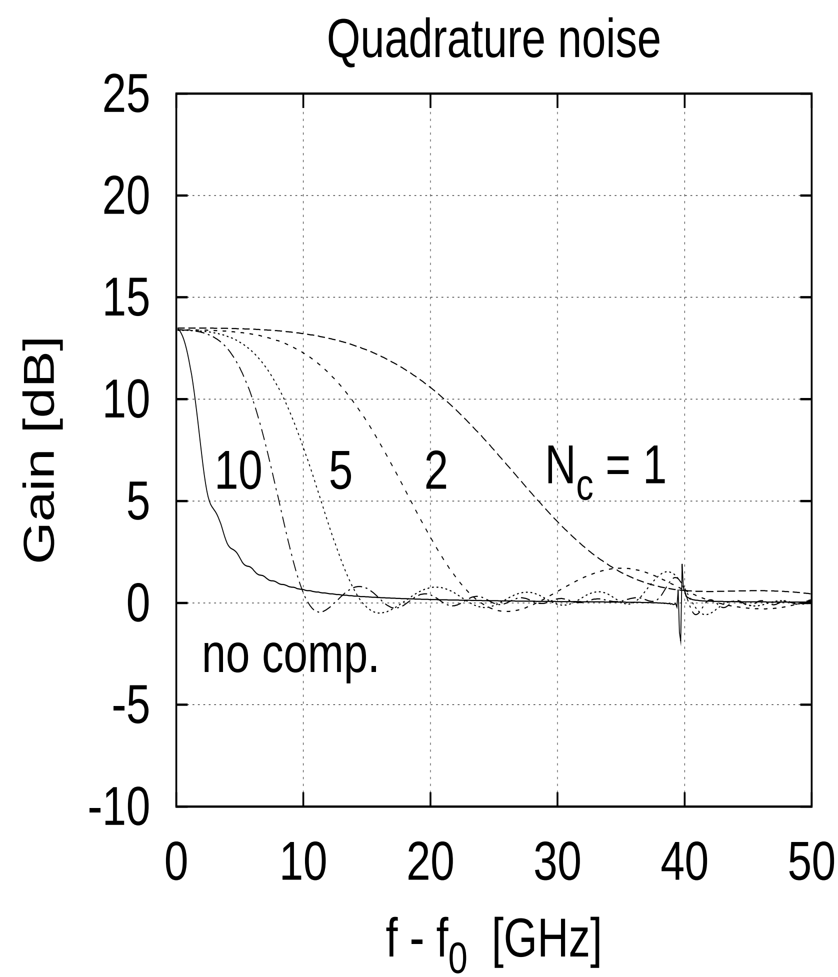
Parameters: CW power: 0 dBm, Fiber loss: $\alpha = 0.22$ dB/km, Fiber nonlinearity: $\gamma = 2$ W^{-1}km^{-1}.

Prevalent Anomalous Dispersion L=6,000 km

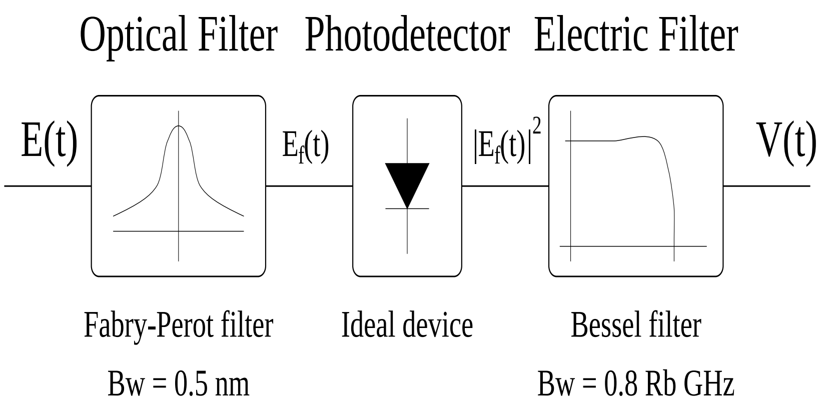


Prevalent Normal Dispersion L=6,000 km





Analitycal Evaluation of Q-parameter

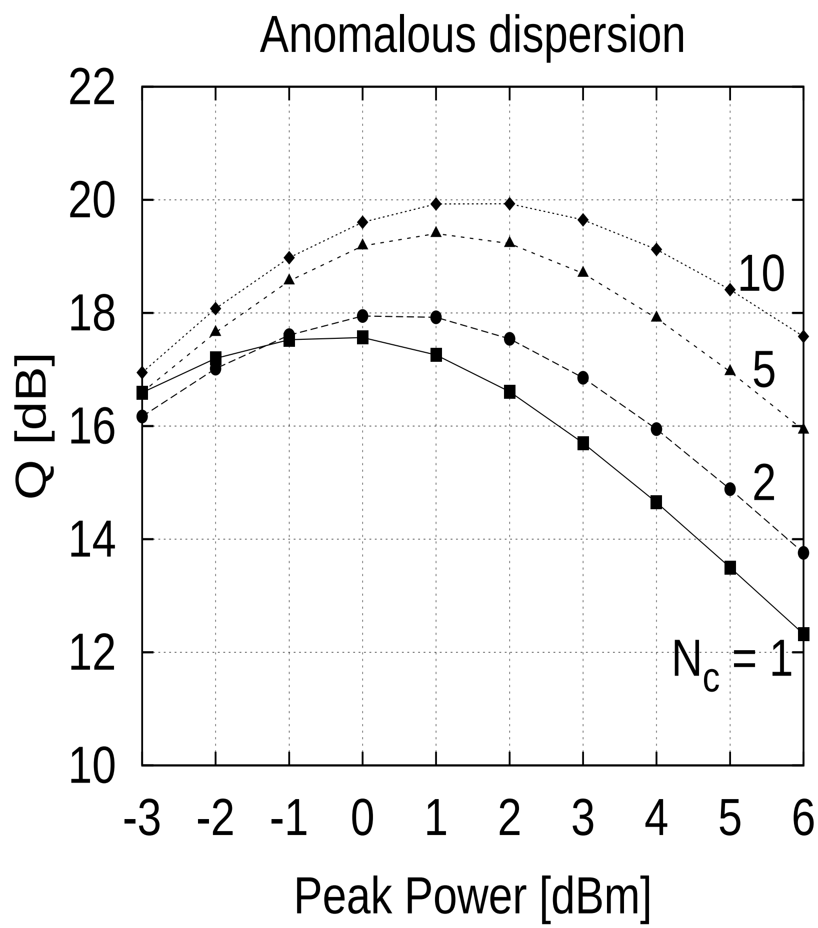


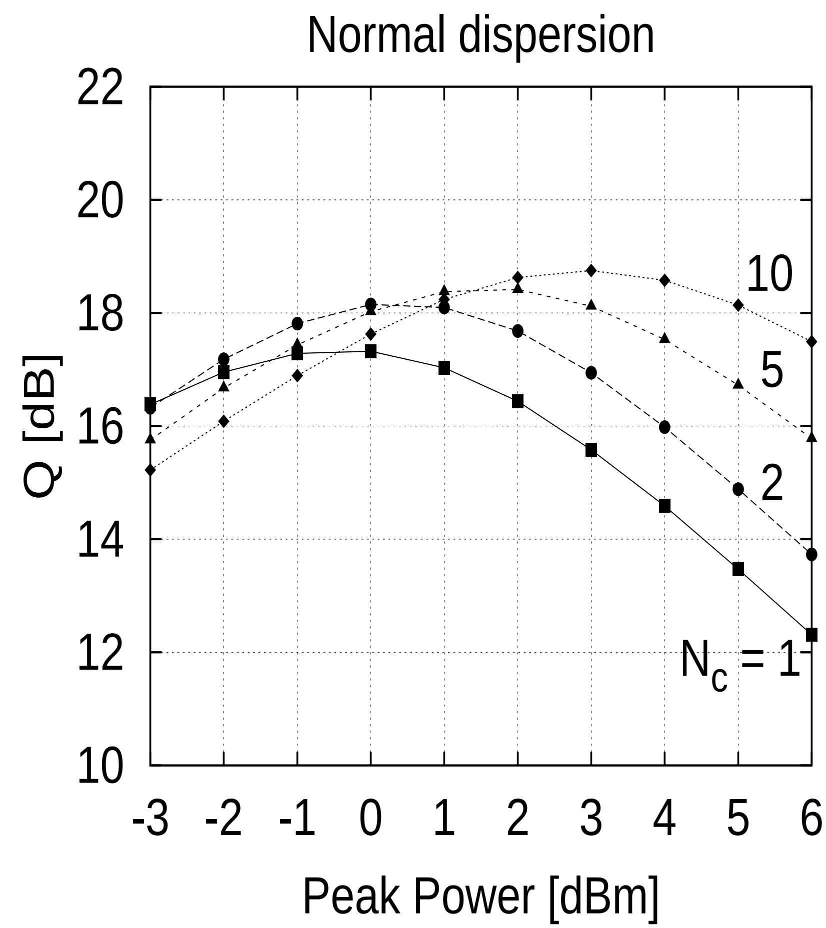
$$E(t) = \left[\sqrt{P_{ric}} + a_r(t) + \jmath a_i(t)\right] e^{\jmath\varphi}$$

$$Q = \frac{\mu_1 - \mu_0}{\sigma_1 + \sigma_0}$$

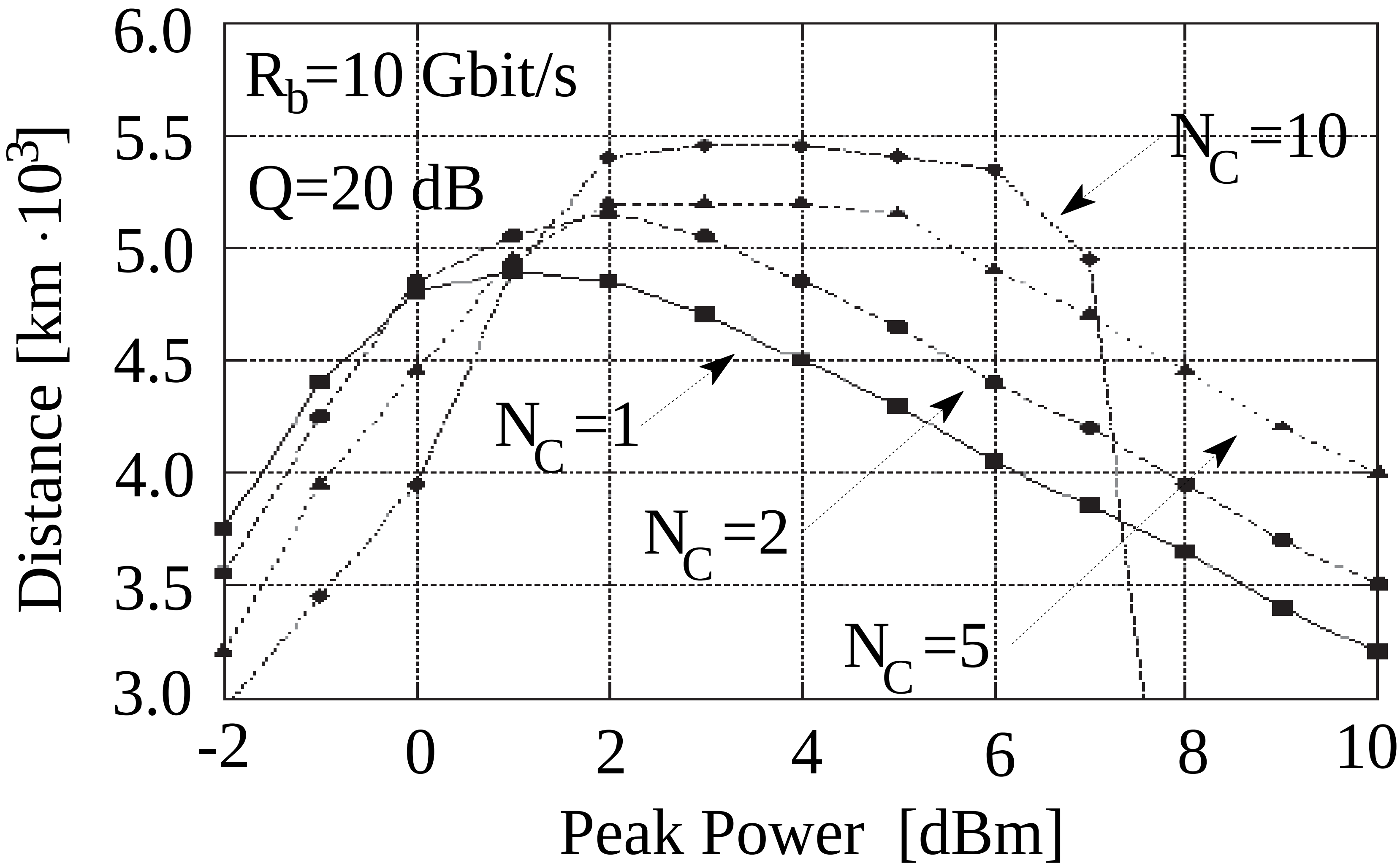
- For transmitted "1"'s PG effects on ASE noise are analytically evaluated.
- For transmitted "0"'s linear propagation of ASE noise is assumed.
- Distorsion of the signal is neglected.

Q vs. Power - L=6,000 km - R_b=10 Gbit/s

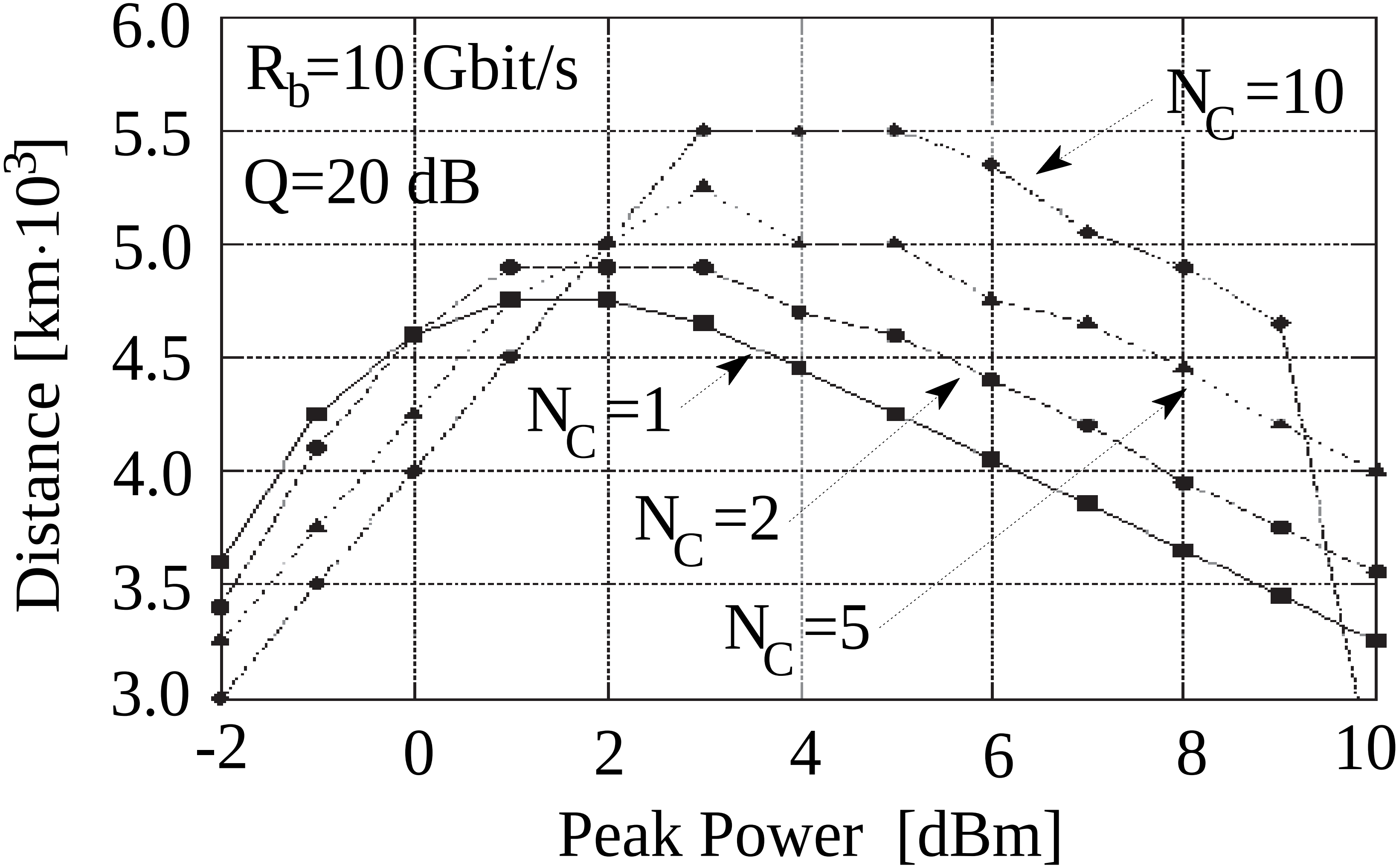




Max Distance vs. Peak Power - Anomalous Dispersion



Max Distance vs. Peak Power - Normal Dispersion



Conclusions

- An analytical tool to evaluate the nonlinear noise enhancement due to parametric gain has been presented.
- PG modifies noise spectra in both dispersion regions.
- Signal intensity and fiber dispersion determine the phenomenon characteristics.
- Dispersion map and power budget must be carefully designed to reduce the impact of PG.
- Considering the noise impact only, a longer distance can be reached increasing the distance between DCF spans.

The authors would like to thank: