Parametric Gain on Dispersion Compensated Fiber Links

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Outline

- Introduction.
- The origin of Parametric Gain (PG) and its system impact.
- Description of the Transfer Matrix analytical tool developed for both dispersion regions.
- Phenomenon characteristics.
- Evaluation of the Q-parameter and optimization of the dispersion map on a 6,000 km long link.
- 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.
- In the anomalous dispersion region PG causes Modulation Instability (MI).
- PG characteristics strongly depend on the dispersion map.
- PG can be detrimental in long-haul amplified systems.

Analytical Formalism (I)

Evolution of a CW signal with power P_0 together with the ASE noise $a(z,T)$.

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

Substituting in the Schrödinger equation and neglecting the terms containing $|a|^2$ we get the linear evolution equation of ASE noise:

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

We analyze in-phase and quadrature components of the ASE noise in the spectral domain.

$$A_r(z,\Omega) = \mathcal{F}\{\mathcal{R}e[a(z,T)]\} \qquad A_i(z,\Omega) = \mathcal{F}\{\mathcal{I}m[a(z,T)]\}$$

Analytical Formalism (II)

The solution has the following Transfer Matrix form:

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

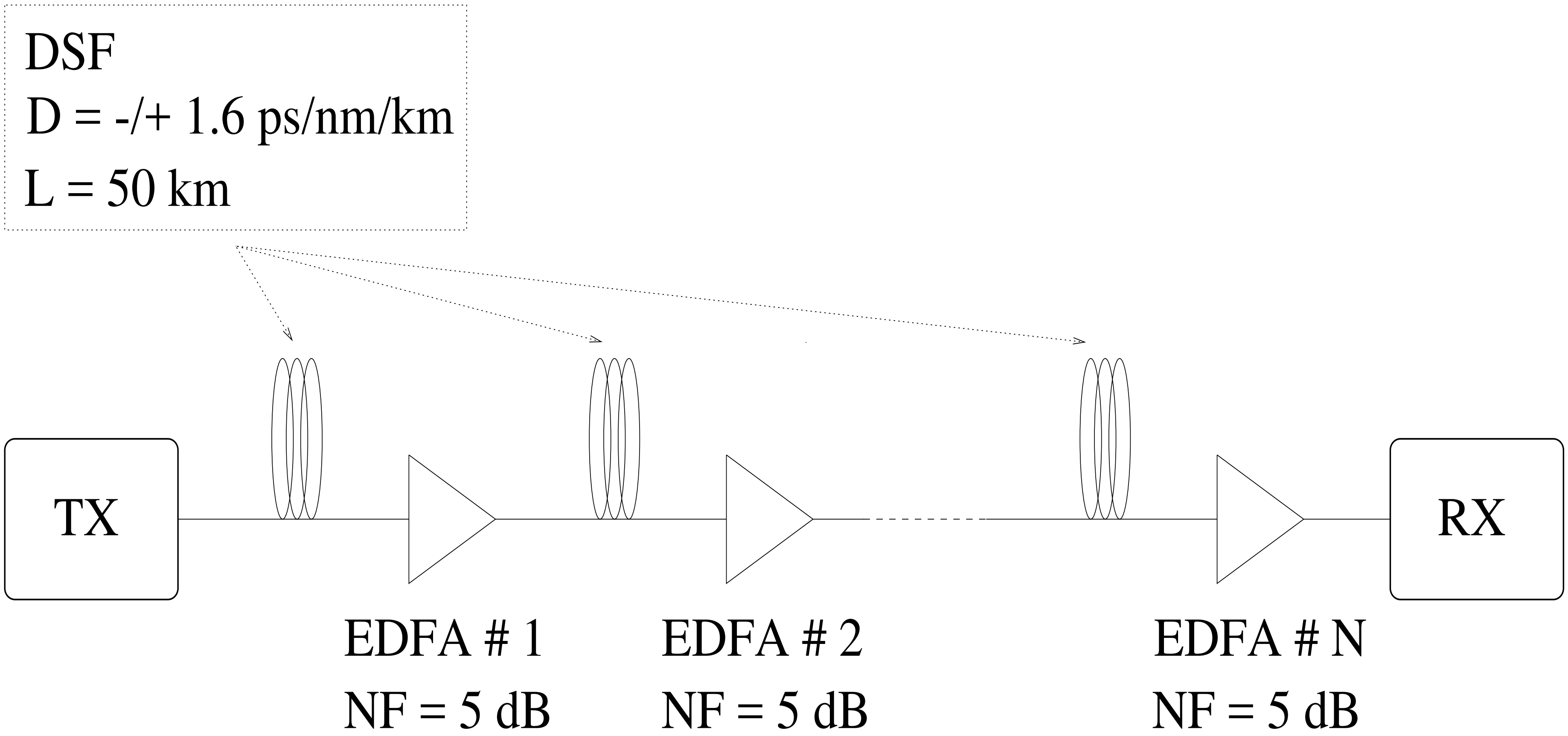
where the T_{ij}'s are expressed using Hankel's functions.

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

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

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

Uncompensated 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 after 3,000 km, D=+1.6 ps/nm/km

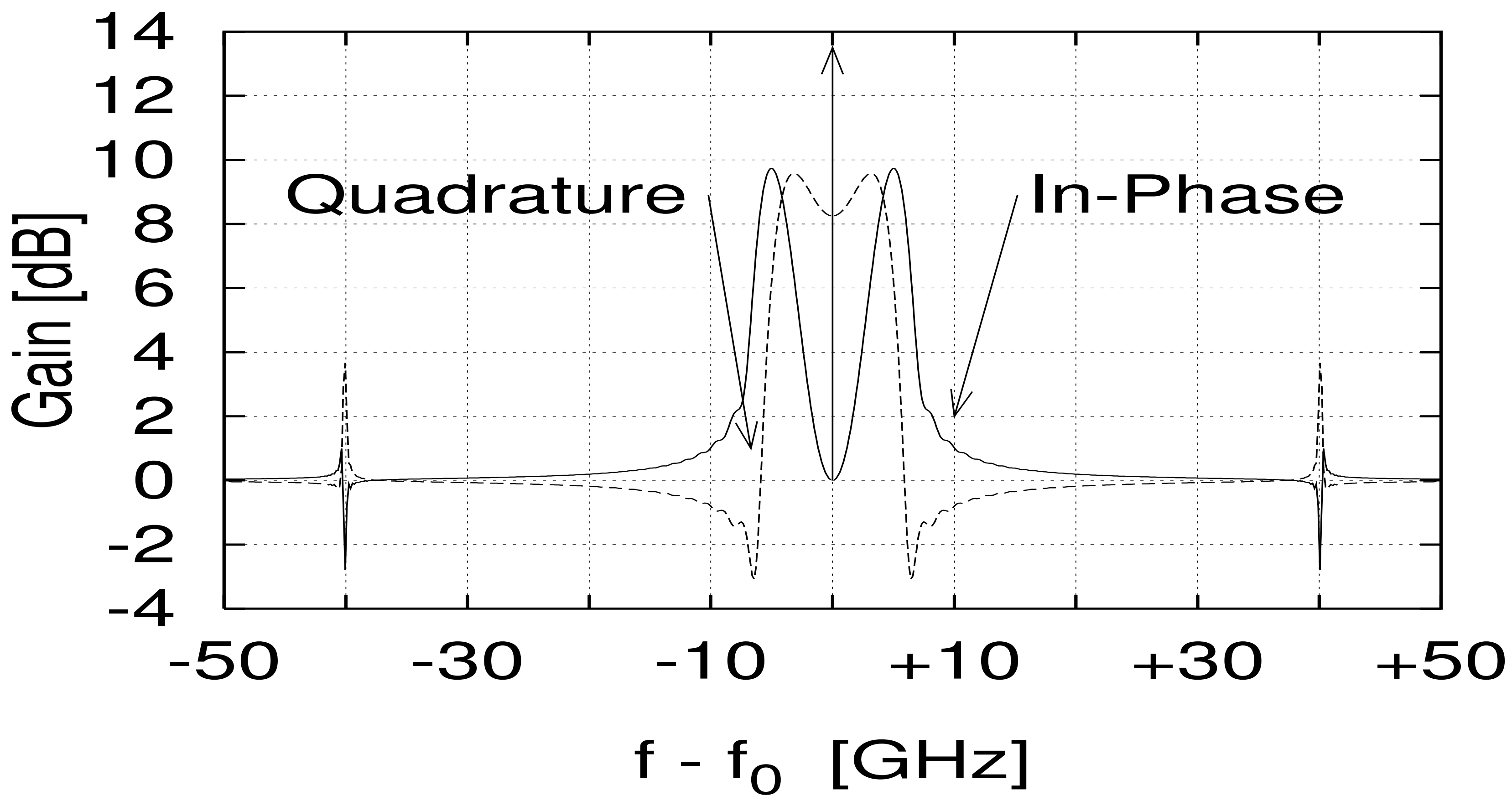


Figure 1: In-phase and quadrature ASE noise gain spectra. Anomalous dispersion.

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

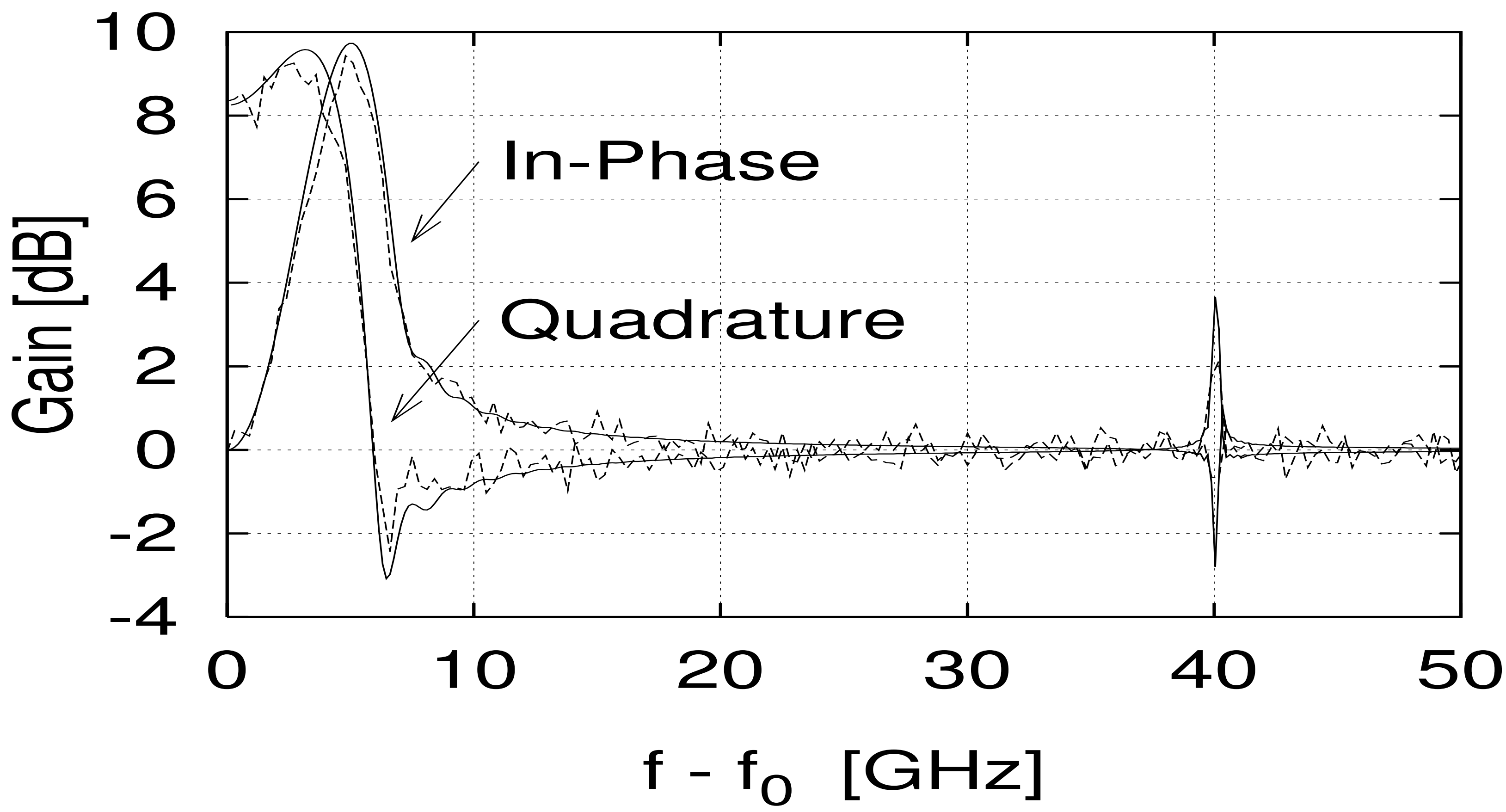


Figure 1: Simulated (dashed) and analytical (solid) in-phase and quadrature ASE noise gain spectra. Anomalous dispersion.

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

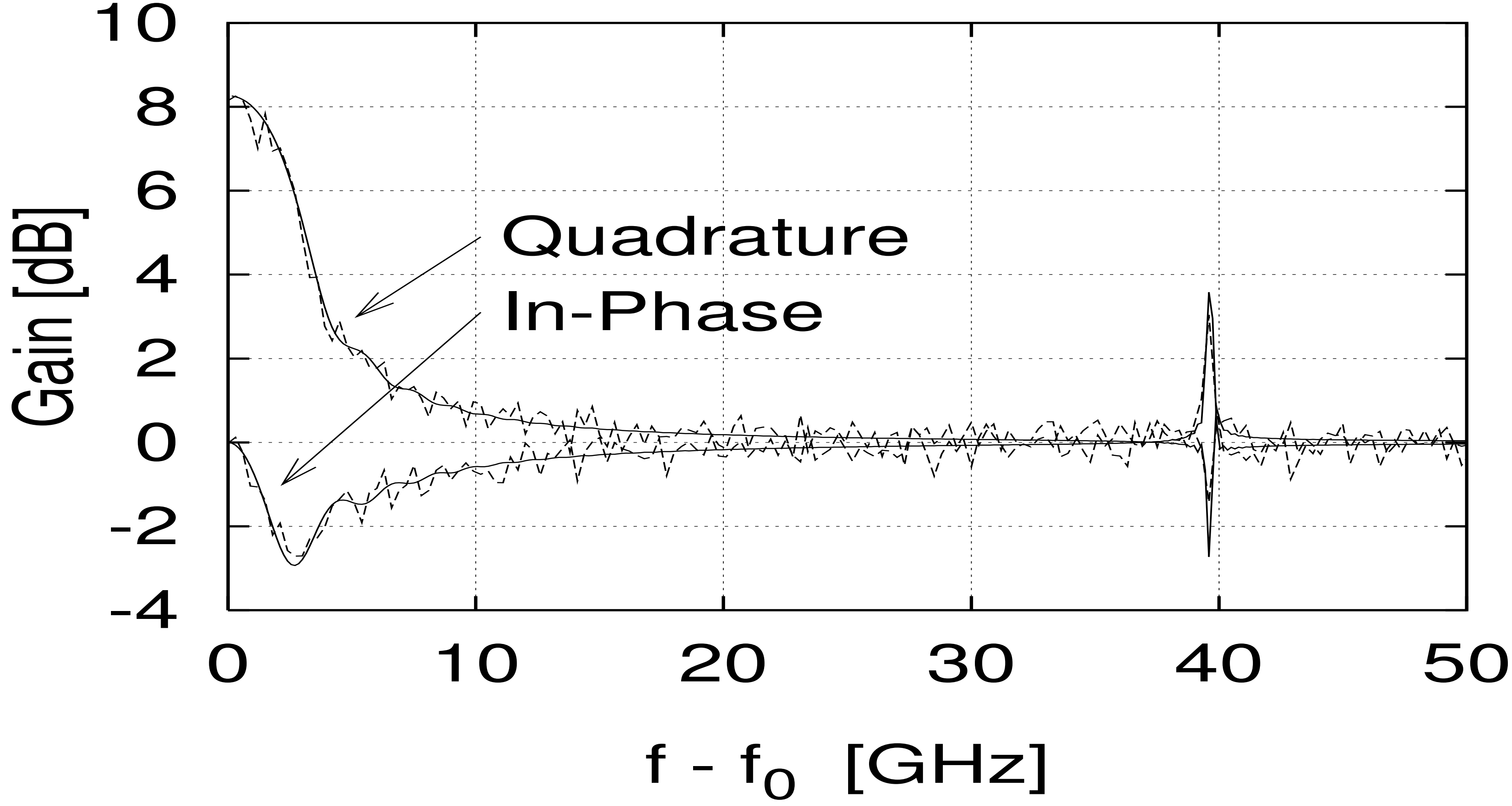
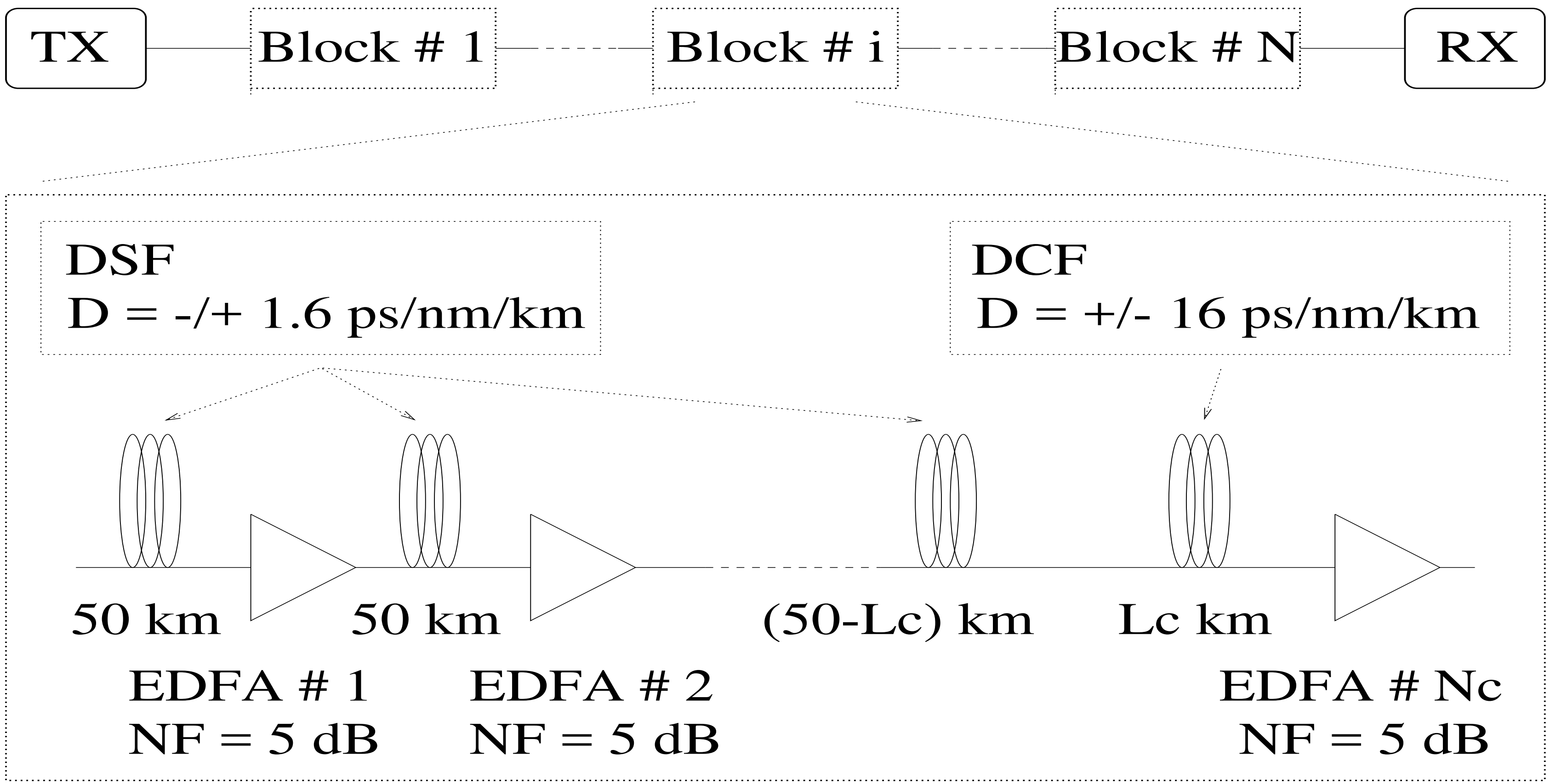


Figure 2: Simulated (dashed) and analytical (solid) in-phase and quadrature ASE noise gain spectra. Normal dispersion.

Compensated Link - L=6,000 km



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

Prevalent Anomalous Dispersion

Figure 6: In-phase noise

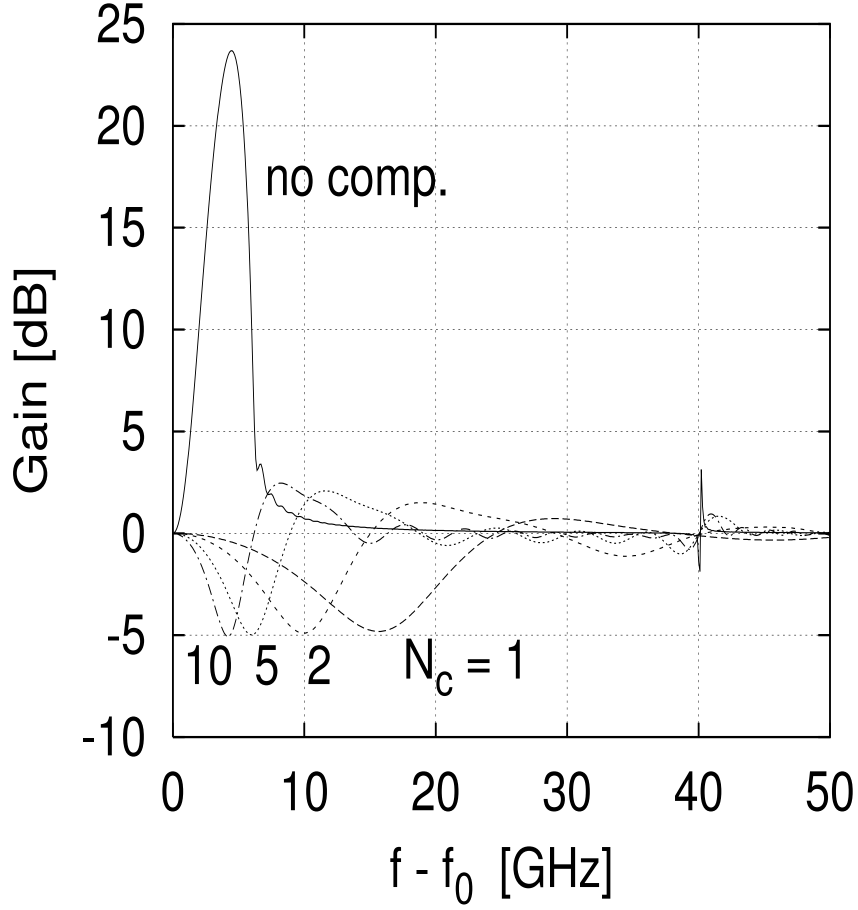
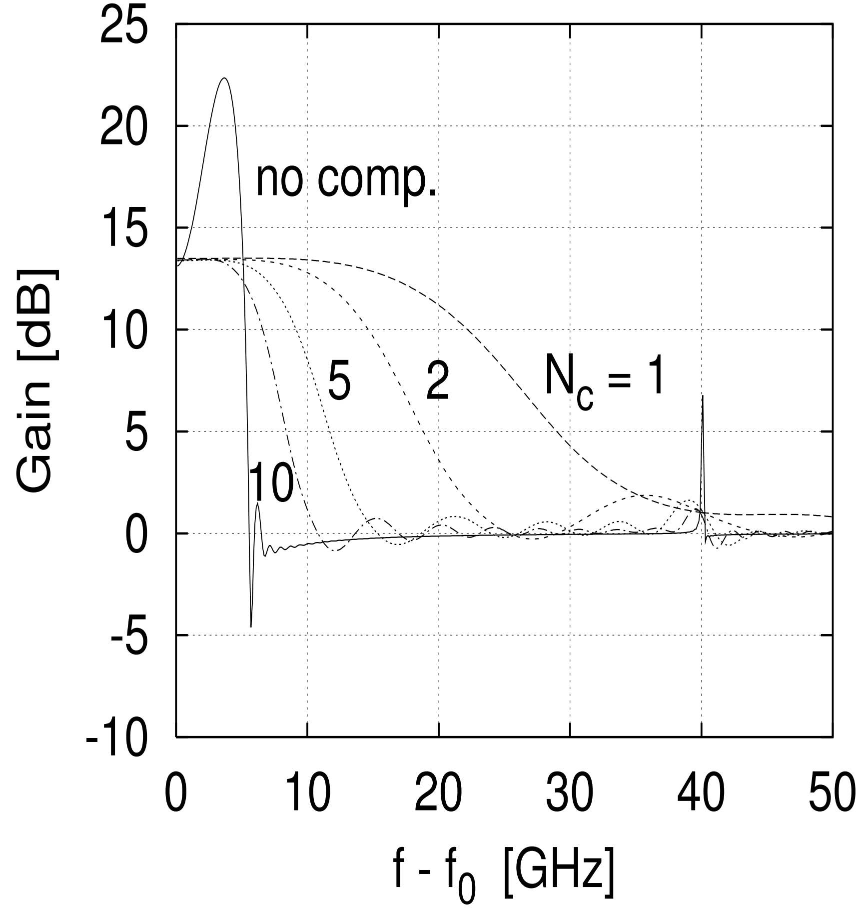


Figure 7: Quadrature noise



Prevalent Normal Dispersion

Figure 4: In-phase noise

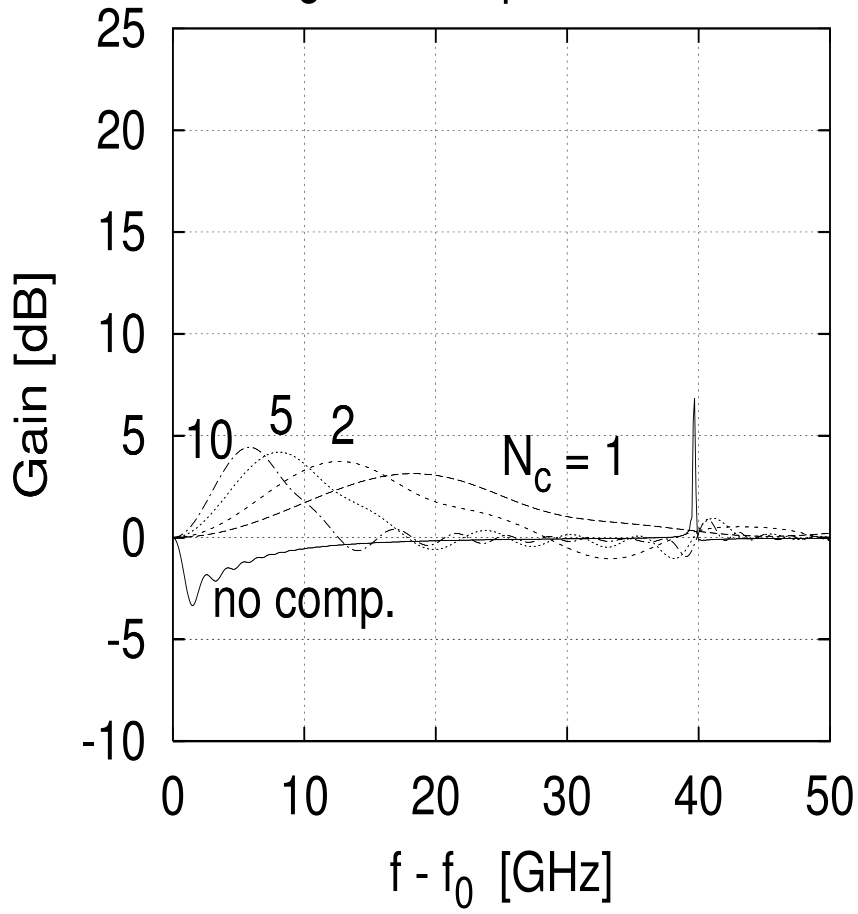
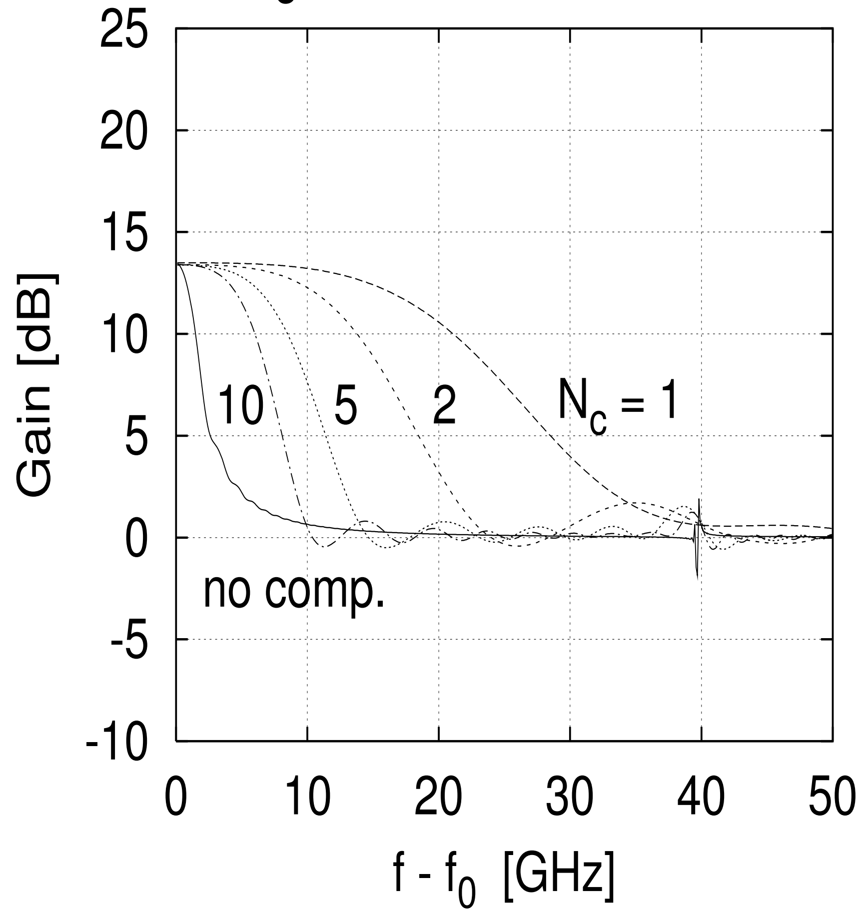
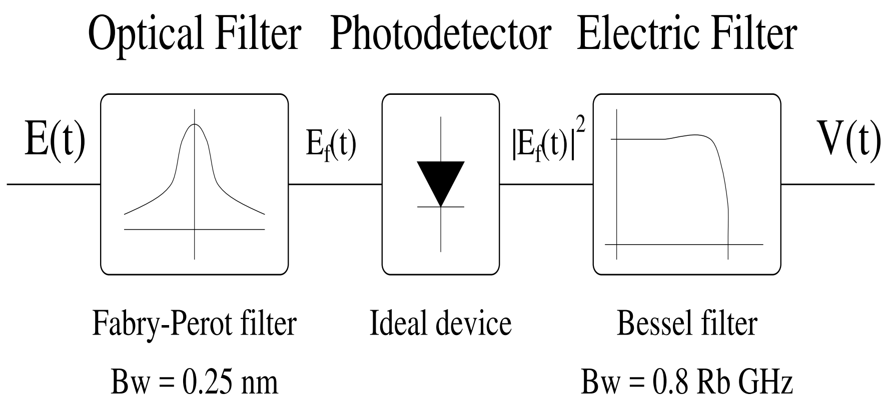


Figure 5: Quadrature noise



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=2.5 Gbit/s

Figure 8: Anomalous dispersion

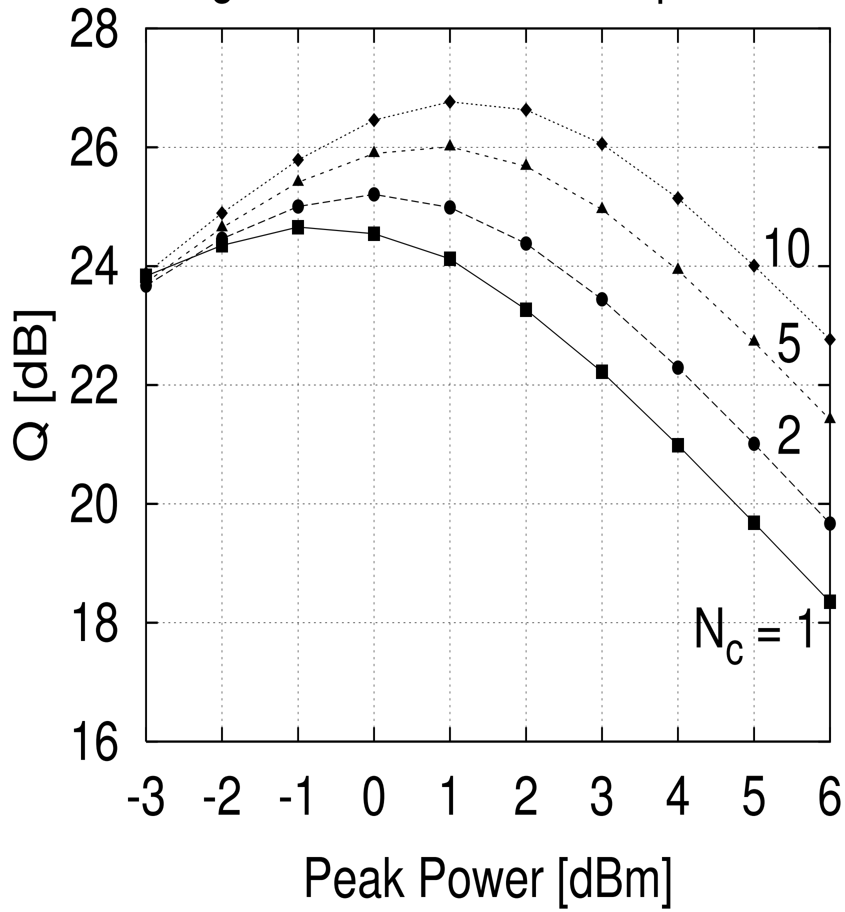
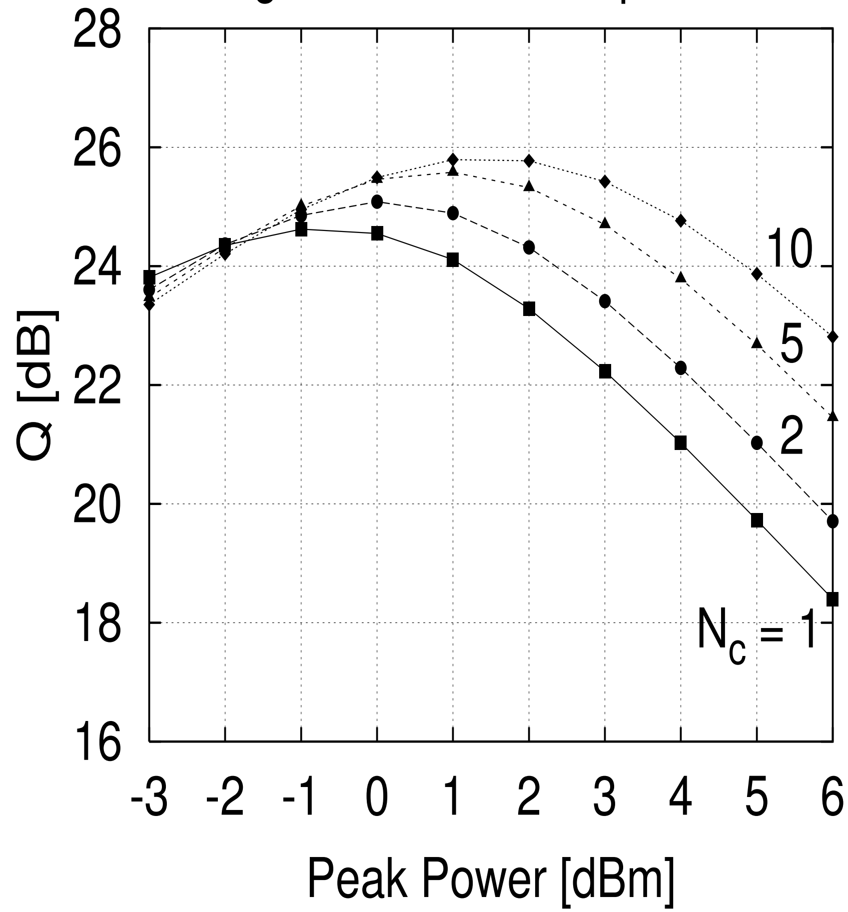


Figure 9: Normal dispersion



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

Figure 10: Anomalous dispersion

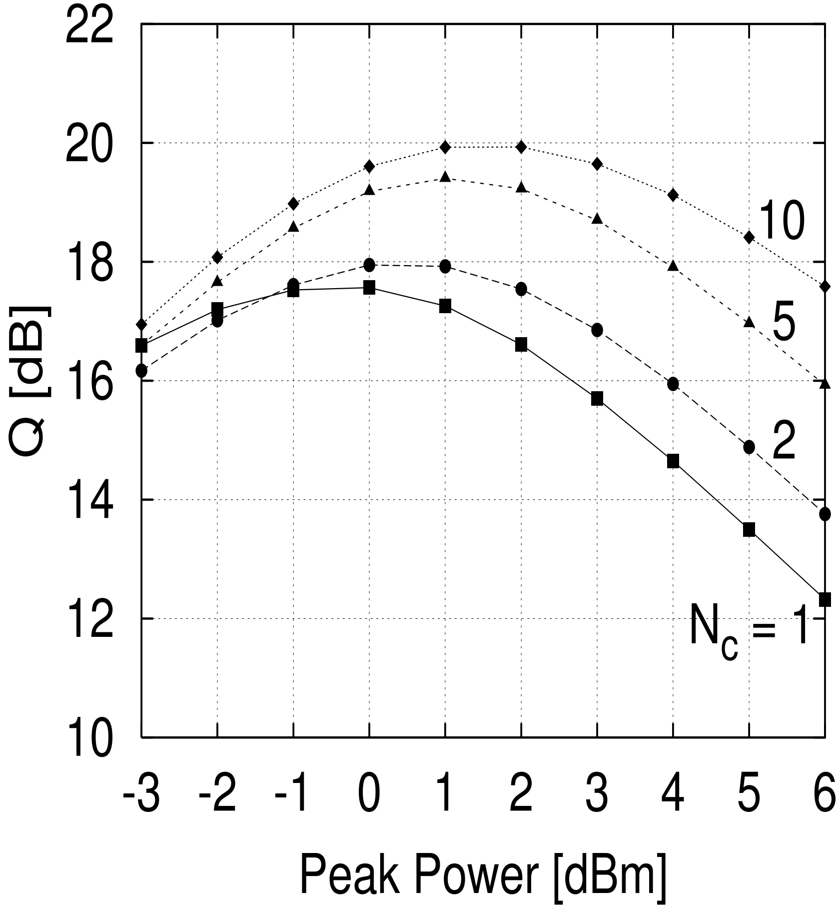
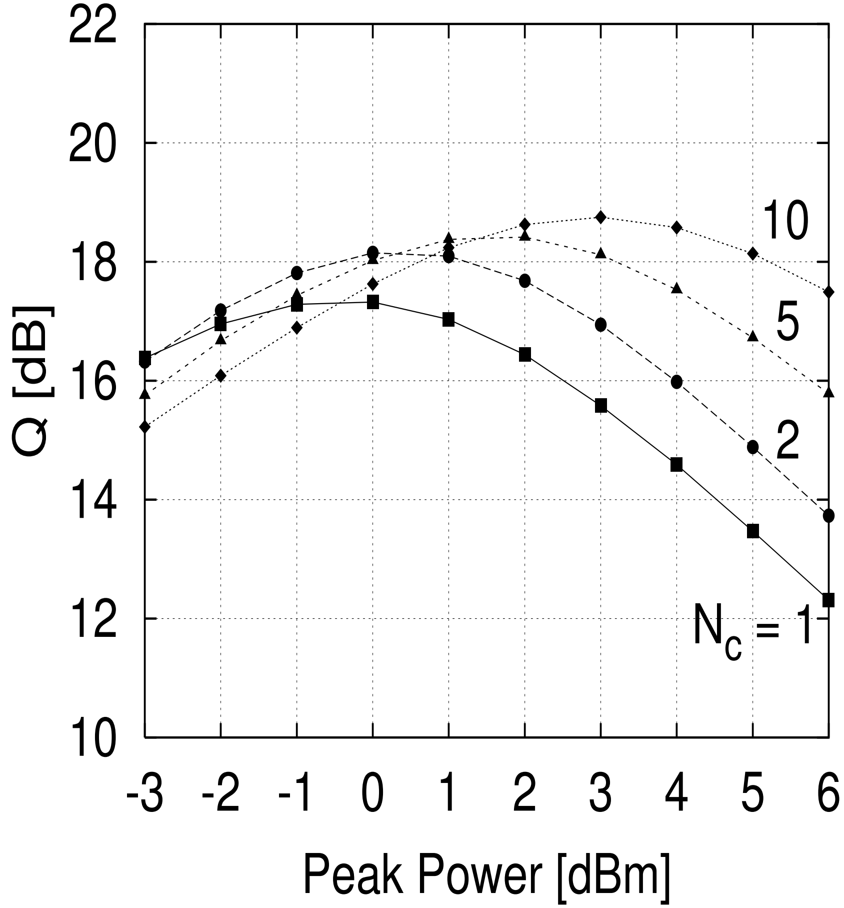


Figure 11: Normal dispersion



Conclusions

- In long-haul systems PG can be one of most important limiting phenomena.
- PG characteristics are determined by signal intensity and fiber dispersion.
- Dispersion map and power budget must be carefully designed to reduce the impact of PG.
- A new analytical tool for the evaluation of the impact of PG has been derived.

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Parametric Gain and Birefringence

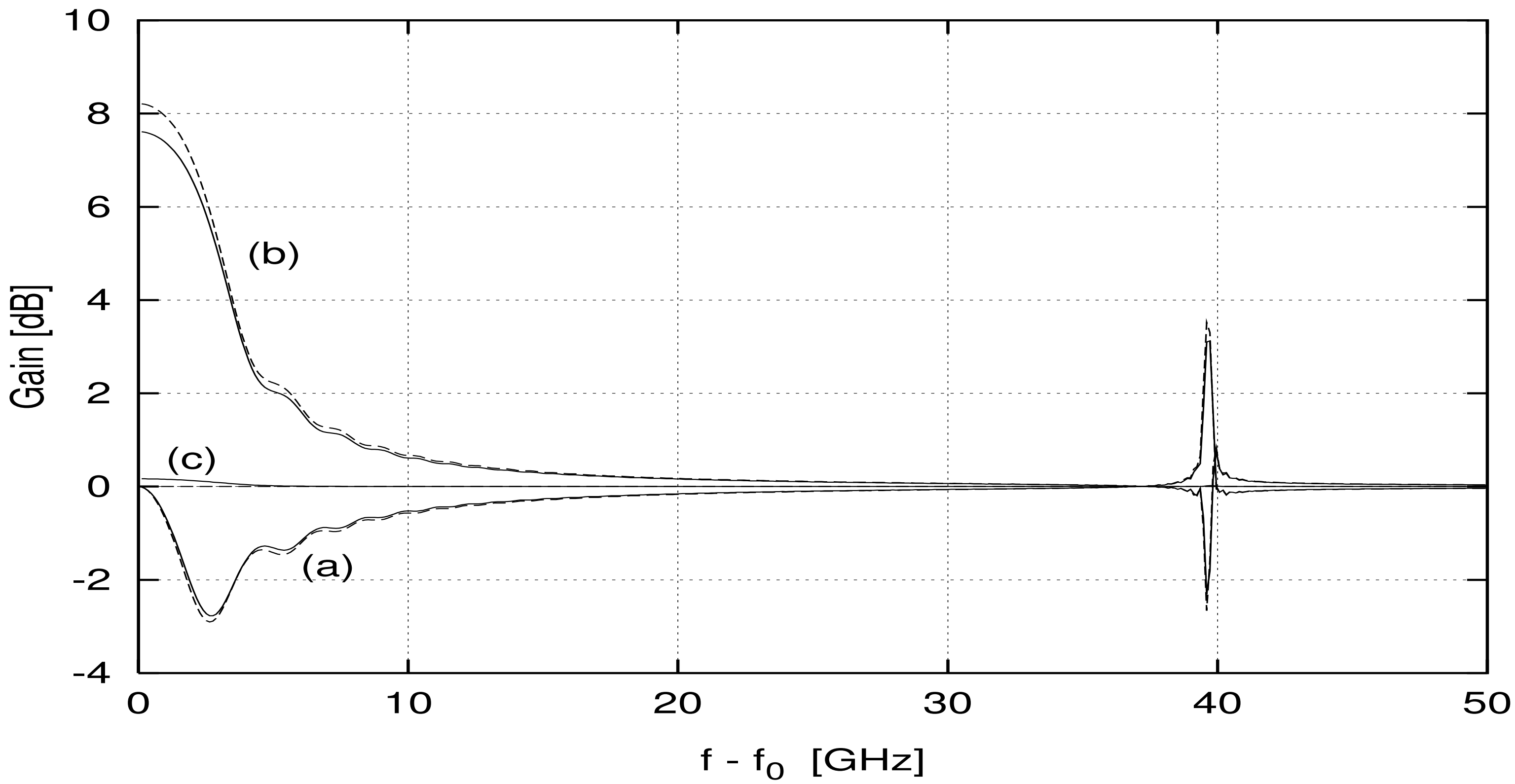

Figure 3: Noise gain curves obtained using the scalar model (dashed curve) and the vectorial model, for in phase (a), quadrature (b) and orthogonal (c) components.