# *40 Gb/ s systems in SMF*

1. *Basic physical effects*
    - ⇒ *linear and nonlinear effects*
    - ⇒ *GVD compensation:*
        - *dispersion compensation fiber*
        - *nonlinear compensation – optical solitons*
2. *Single channel transmission at 10 Gb/s in SMF*
    - ⇒ *RZ versus NRZ transmission*
3. *Single channel transmission at 40 Gb/s in SMF*
    - ⇒ *RZ versus NRZ transmission*
    - ⇒ *influence of the noise and SPM on the transmission*
    - ⇒ *dispersion compensation schemes*
4. *WDM transmission at 4 $\times$40 Gb/s in SMF – example*
5. *Conclusions*

1. *Basic physical effects*

   $\Rightarrow$ *linear and nonlinear effects*

   $\Rightarrow$ *group velocity dispersion (GVD):*

$D$ = (16 ps/nm.km) at 1.55 $\mu m$ $\Rightarrow$ *basic limitation with SMF !*

*Externally Modulated DFB lasers*

*RZ, duty cycle = 0.5*

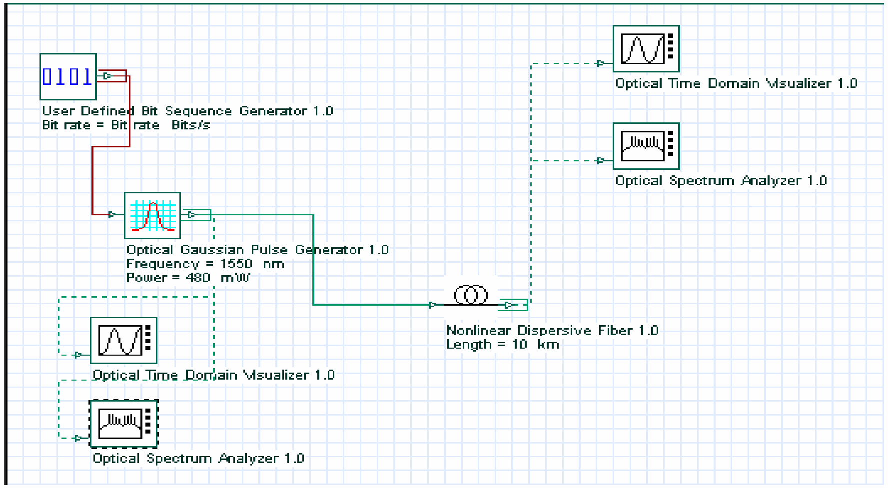
*How does reduce the dispersion length $L_D$ increasing B in SMF?*

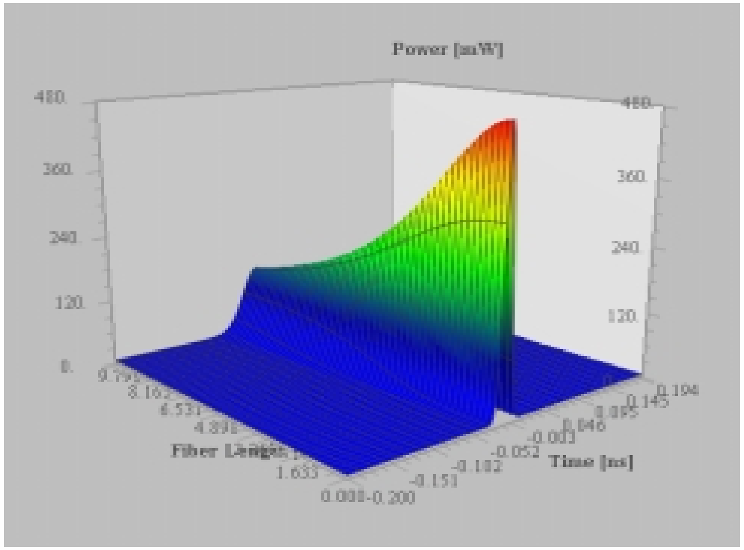
$B = 2.5$ Gb/s $\Rightarrow T_B = 400$ ps $\Rightarrow T_{FWHM} = 200$ ps $\Rightarrow L_D = 693$ km

$B = 10$ Gb/s $\Rightarrow T_B = 100$ ps $\Rightarrow T_{FWHM} = 50$ ps $\Rightarrow L_D = 40$ km

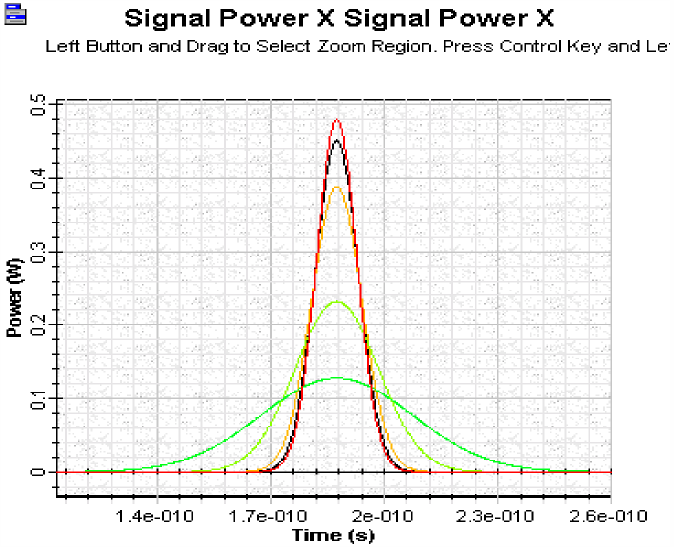
$B = 40$ Gb/s $\Rightarrow T_B = 25$ ps $\Rightarrow T_{FWHM} = 12.5$ ps $\Rightarrow L_D = 2.5$ km

## ⇒ *Group velocity dispersion (GVD):*



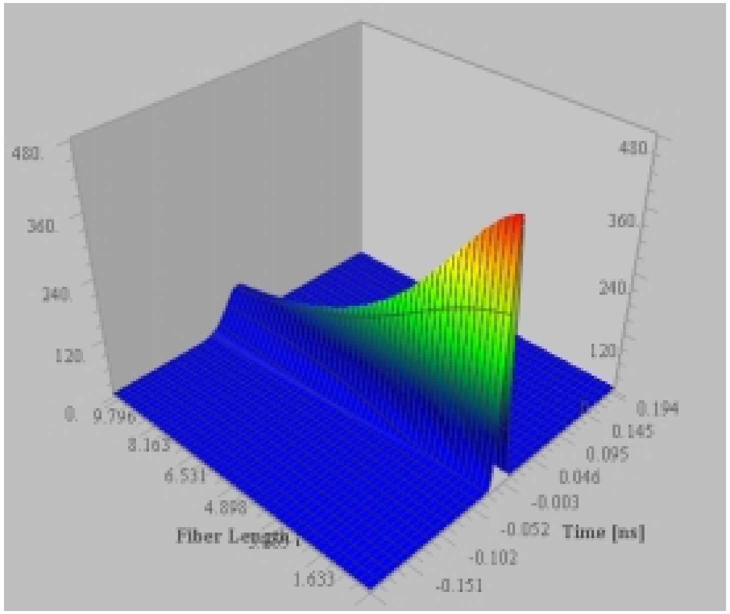



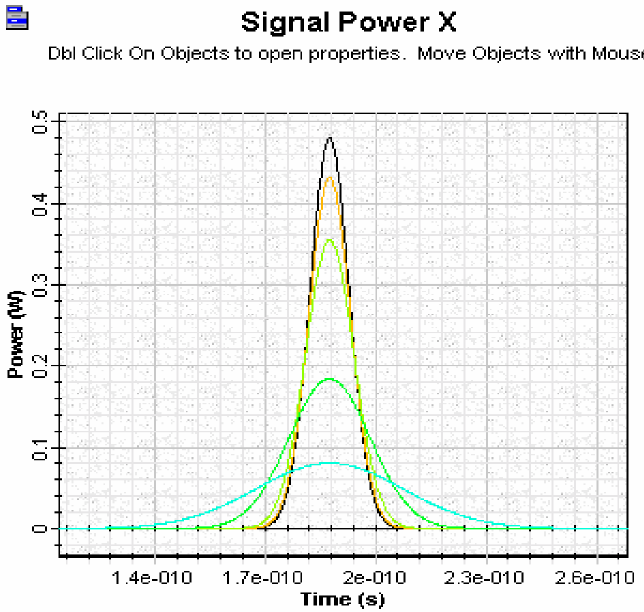

*Evolution of the pulse shape*




*Pulse shape at 1, 2, 5 and 10 km*

$\Rightarrow$ *linear losses* $\Rightarrow$ *periodic amplification*




*Evolution of the pulse shape*

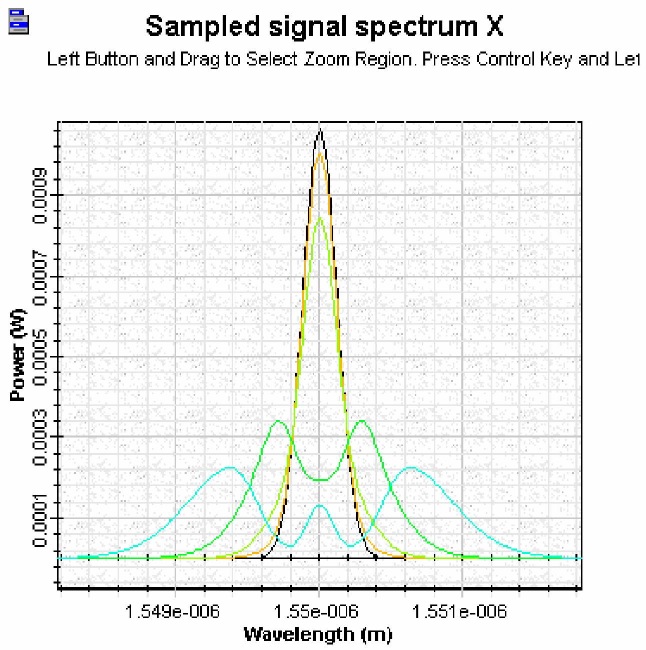
*Pulse shape at 0, 1, 2, 5 and 10 km*

*G.P.Agrawal, "Nonlinear Fiber optics", third edition, Academic Press, 2001.*

1. *Basic physical effects*

⇒ *linear and nonlinear effects*

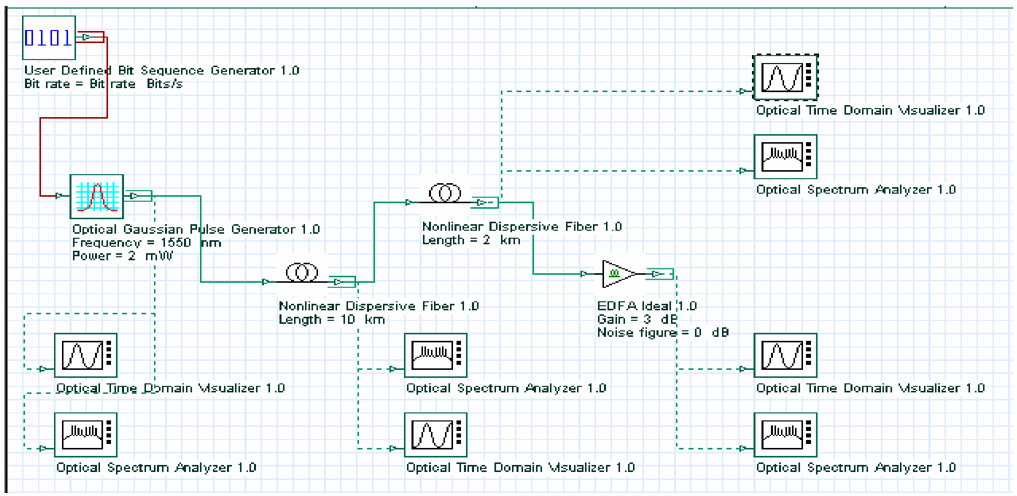
⇒ *self-phase modulation*




*Pulse spectrum at 0, 1, 2, 5 and 10 km*

# 1. Basic physical effects

## ⇒ GVD compensation: DCF

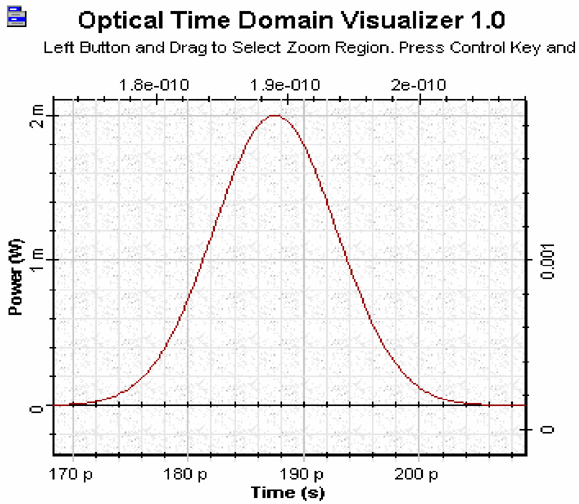



$D_{SMF}$ = 17 (ps/nm. km), $\partial D_{SMF} / \partial \lambda$ = 0.08 (ps/nm$^2$ .km), $\gamma_{SMF}$ = 1.31 (1 / km. W),

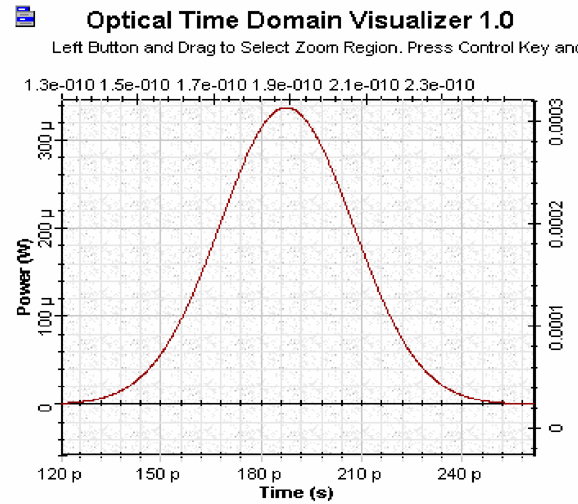
$\alpha_{SMF}$ = 0.2 (dB / km), $L_{SMF}$ = 10 km

$D_{DCF}$ = -80 (ps/nm. km), $\partial D_{DCF} / \partial \lambda$ = 0.08 (ps/nm$^2$ .km), $\gamma_{DCF}$ = 5.24 (1 / km. W),

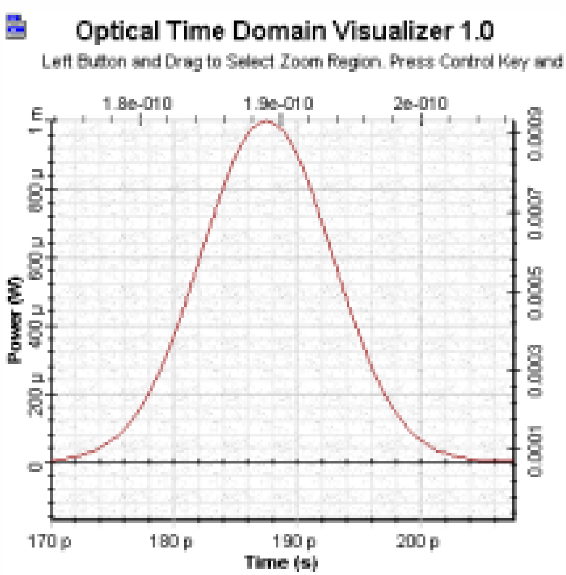
$\alpha_{DCF}$ = 0.5 (dB / km), $L_{DCF}$ = 2 km



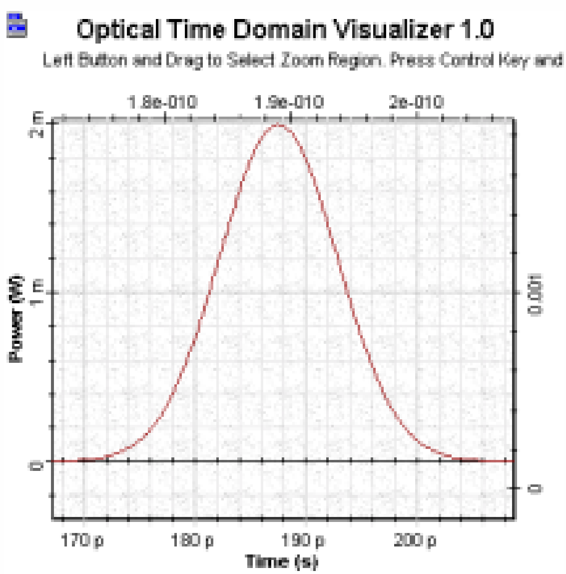

*Initial Gaussian pulse, 2 mW*



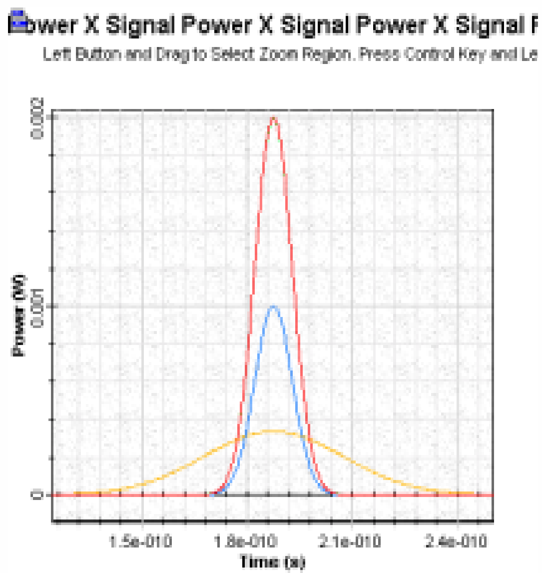

*Pulse after 10 km SMF*




*Pulse after 2 km DCF*




*Pulse after amplification NF =0*



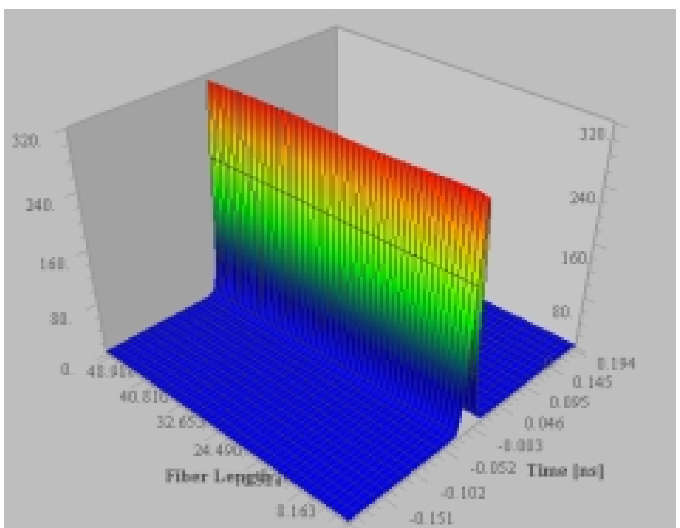

*Pulse shapes together*

1. *Basic physical effects*

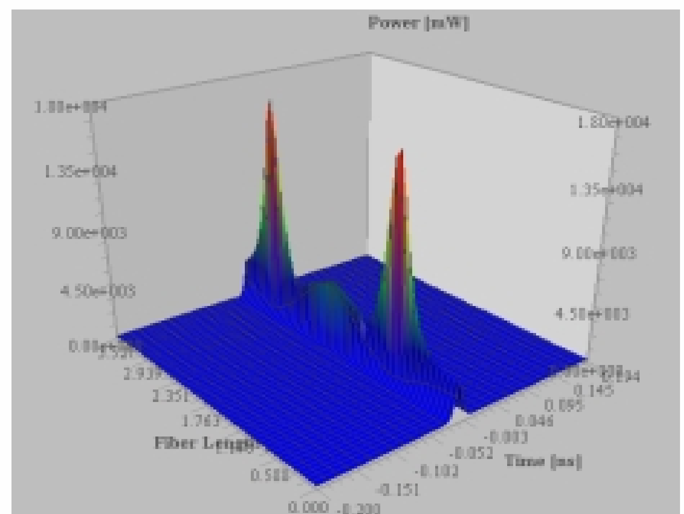
$\Rightarrow$ *GVD compensation:*

*nonlinear compensation – optical solitons*

$$B = 40\ Gb/s \Rightarrow L_D = 2.5\ km\ ,\ \gamma = 1.36\ (1/km.W) \Rightarrow P \sim 305\ mW$$




*The soliton shape evolution after 50 km propagation in SMF*

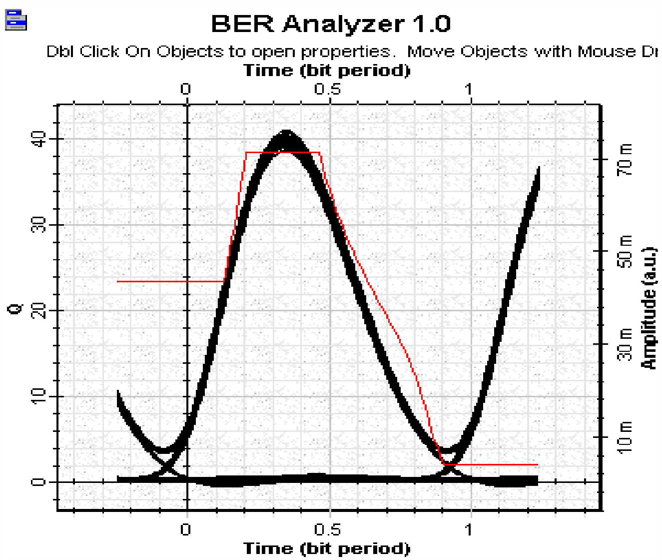



*Temporal evolution for the third-order soliton*

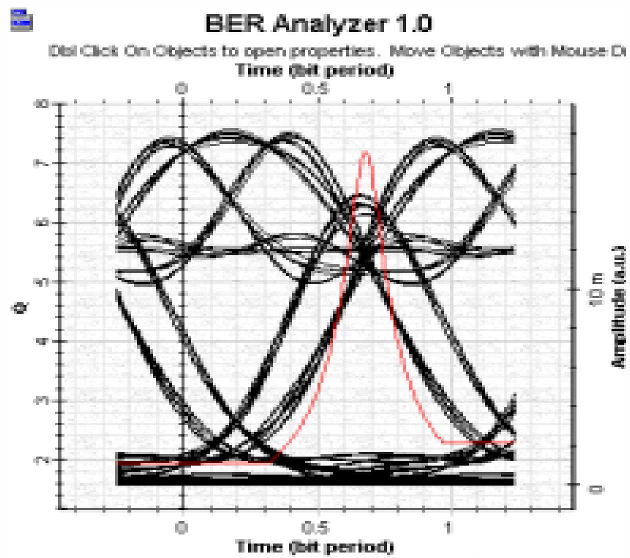
# 2. Single channel transmission at 10 Gb/s in SMF

## ⇒ RZ versus NRZ transmission

- ♦ *transmission over 100 km lossless SMF at 10 Gb/s*



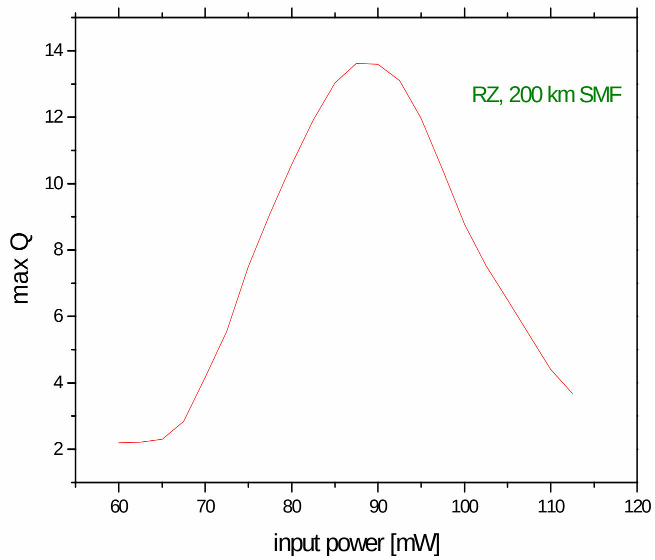

*P = 190 mW, duty ratio =0.25*



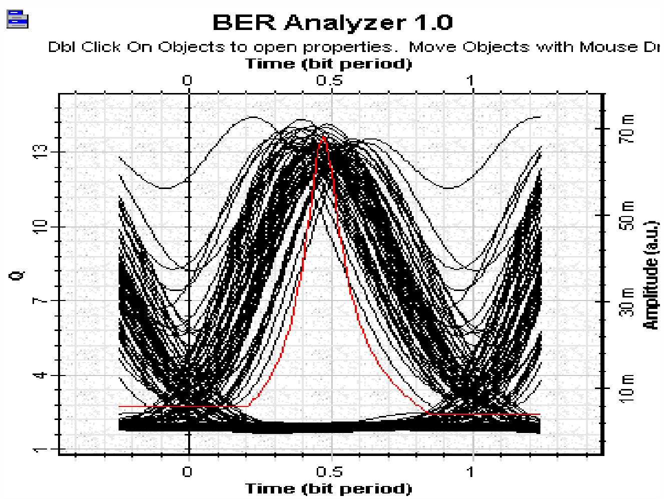

*P=15.84 mW*

♦ *transmission over SMF at 10 Gb/s. Periodic amplification*

*RZ, duty ratio =0.5; 8 loops × 25 km; Gain = 5 dB; NF =6 dBm*

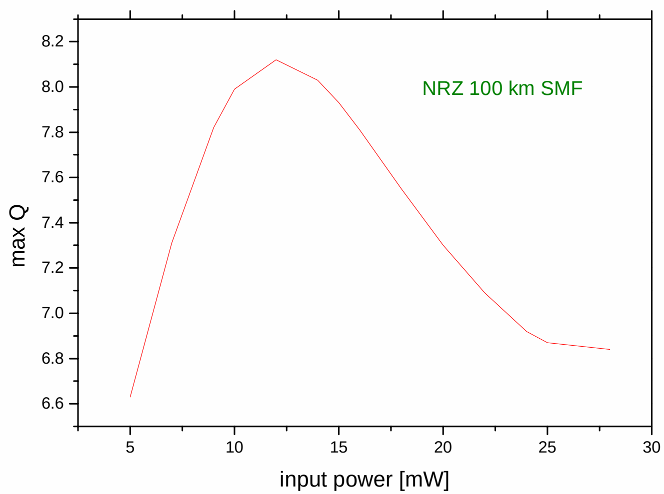



*max Q factor as a function from P*

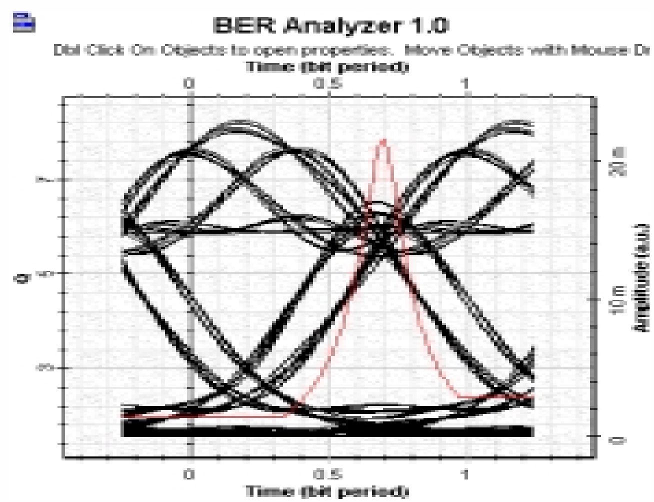



*P = 87.5 mW*

## *NRZ, 4 loops × 25 km, Gain = 5 dB, NF = 6 dBm*




*max Q factor as a function from P*




*P = 15 mW*

*RZ-modulation format is superior compared to conventional NRZ ⇒ for $L_A$ = 25 km at 10 Gb/s the maximum transmiision length for RZ (duty cycle = 0.5) ~ 200 km, whereas for NRZ ~ 100 km, or the*

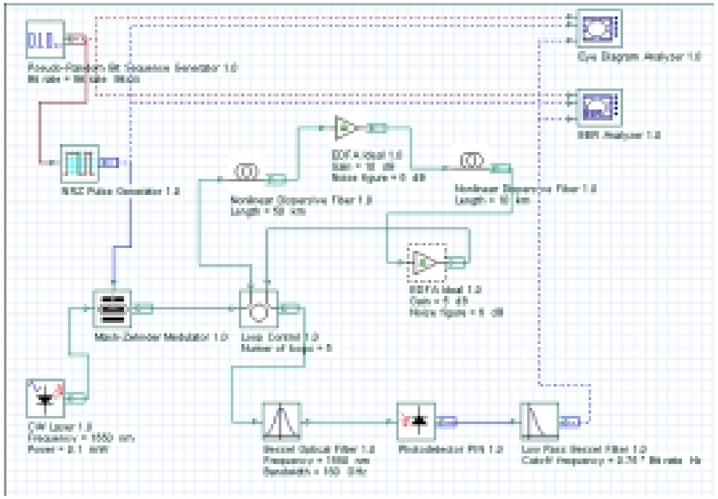
*K. Ennser and K. Petermann, IEEE Photon. Technol. Lett., vol. 8, pp.443-445, 1996.*

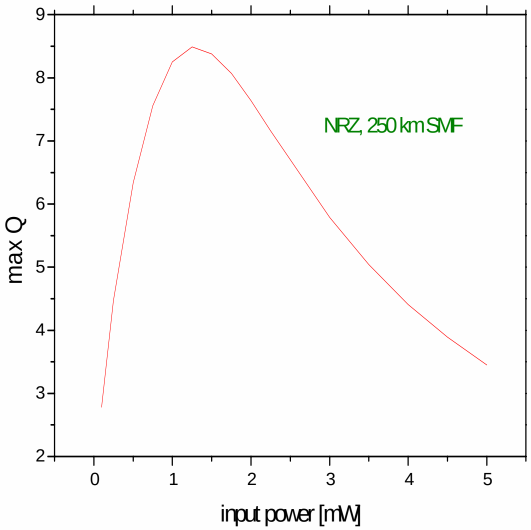
*M.I. Hayee and A.E. Willner, IEEE Photon. Technol. Lett., vol. 11, pp.991-993, 1999.*

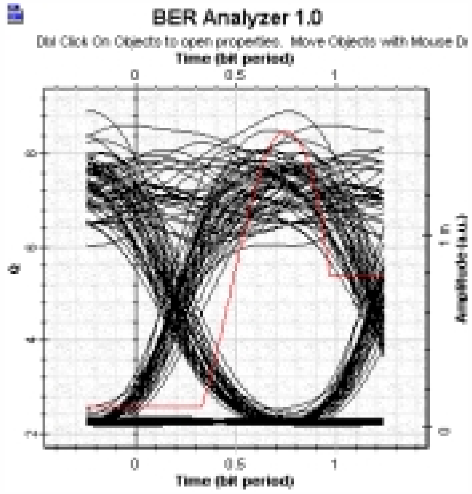
# 3. Single channel transmission at 40 Gb/s in SMF

## ⇒ RZ versus NRZ transmission

## NRZ at 40 Gb/s over 250 km






*NRZ*

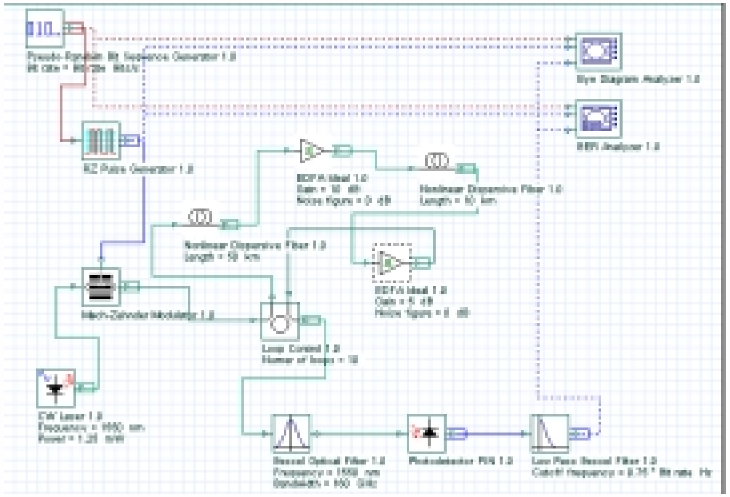
*max Q as a function of P*

*P = 1.25 mW*

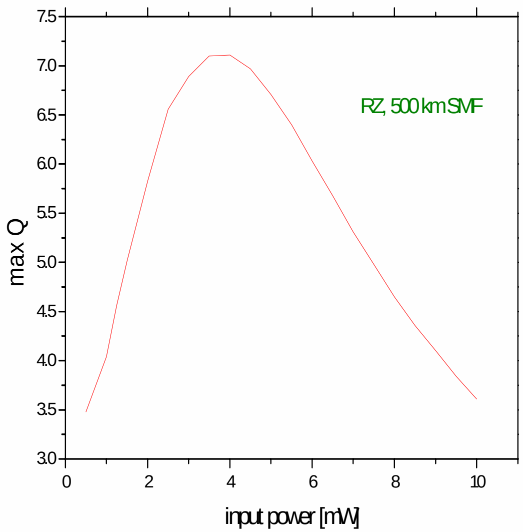
# 3. Single channel transmission at 40 Gb/s in SMF

## ⇒ RZ versus NRZ transmission

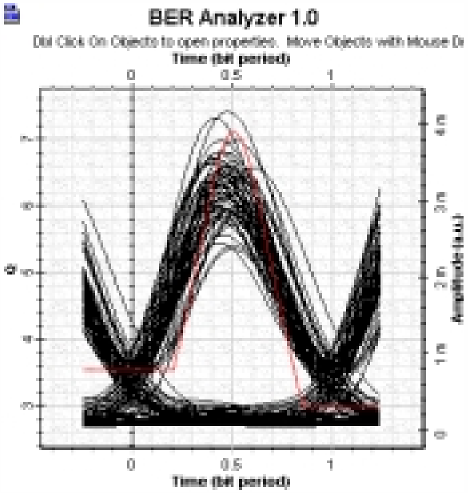
## RZ at 40 Gb/s over 500 km



RZ



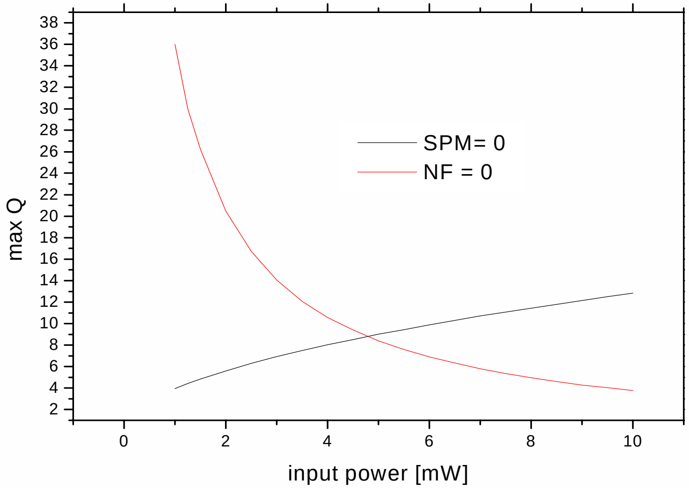

Max Q as a function of P




P = 4 mW

# 3. Single channel transmission at 40 Gb/s in SMF

⇒ *influence of the noise and SPM on the transmission*




*RZ at 40 Gb/s over 500 km, NF = 0 and SFM = 0*

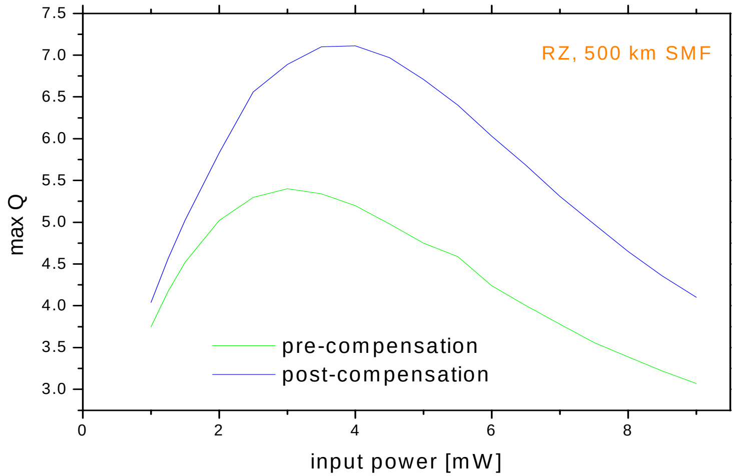
⇒ *at low power levels , the performance is hampered by ASE*
*at high power levels, the transmission distance is reduced due to SPM*


*D. Breuer and K. Petermann, IEEE Photon. Technol. Lett., vol. 9, pp.398-400, 1997.*

*M.I. Hayee and A.E. Willner, IEEE Photon. Technol. Lett., vol. 11, pp.991-993, 1999.*

# 3. Single channel transmission at 40 Gb/s in SMF

## ⇒ dispersion compensation schemes




*RZ at 40 Gb/s over 500 km in SMF*

⇒ *post-compensation scheme is superior compared to pre-compenstaion scheme in dispersion compensated systems at 40 Gb/s*


*C.M. Weinert, R. Ludvig, W. Papier, H.G. Weber, D. Breuer, K. Petermann and F. Kuppers, Journal of Lightwave Technology, vol. 17, pp.2276-2284, 1999.*

# 4. WDM transmission at 4 ×40 Gb/s in SMF – Example

$\lambda_1 = 1548.8\ \mu m,\ \Delta\lambda_1 = -1.2\ nm,\ D_{SMF}(\lambda_1) = 15.904\ (ps/nm.km),$

$D_{DCF}(\lambda_1) = -79.748\ (ps/nm.km)$

$\lambda_2 = 1549.6\ \mu m,\ \Delta\lambda_2 = -0.4\ nm,\ D_{SMF}(\lambda_2) = 15.968\ (ps/nm.km),$

$D_{DCF}(\lambda_2) = -79.916\ (ps/nm.km)$

$\lambda_3 = 1550.4\ \mu m,\ \Delta\lambda_3 = 0.4\ nm,\ D_{SMF}(\lambda_3) = 16.032\ (ps/nm.km),$

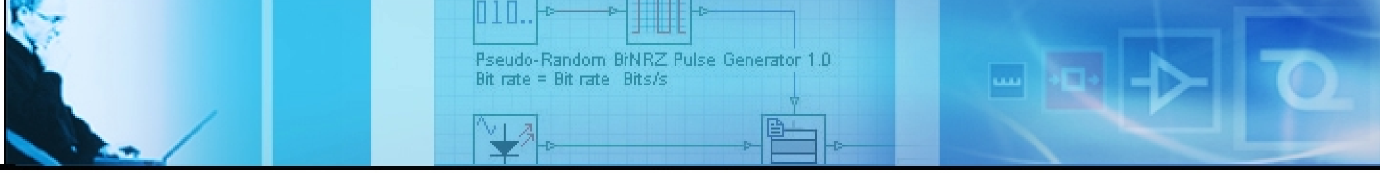
$D_{DCF}(\lambda_3) = -80.084\ (ps/nm.km)$

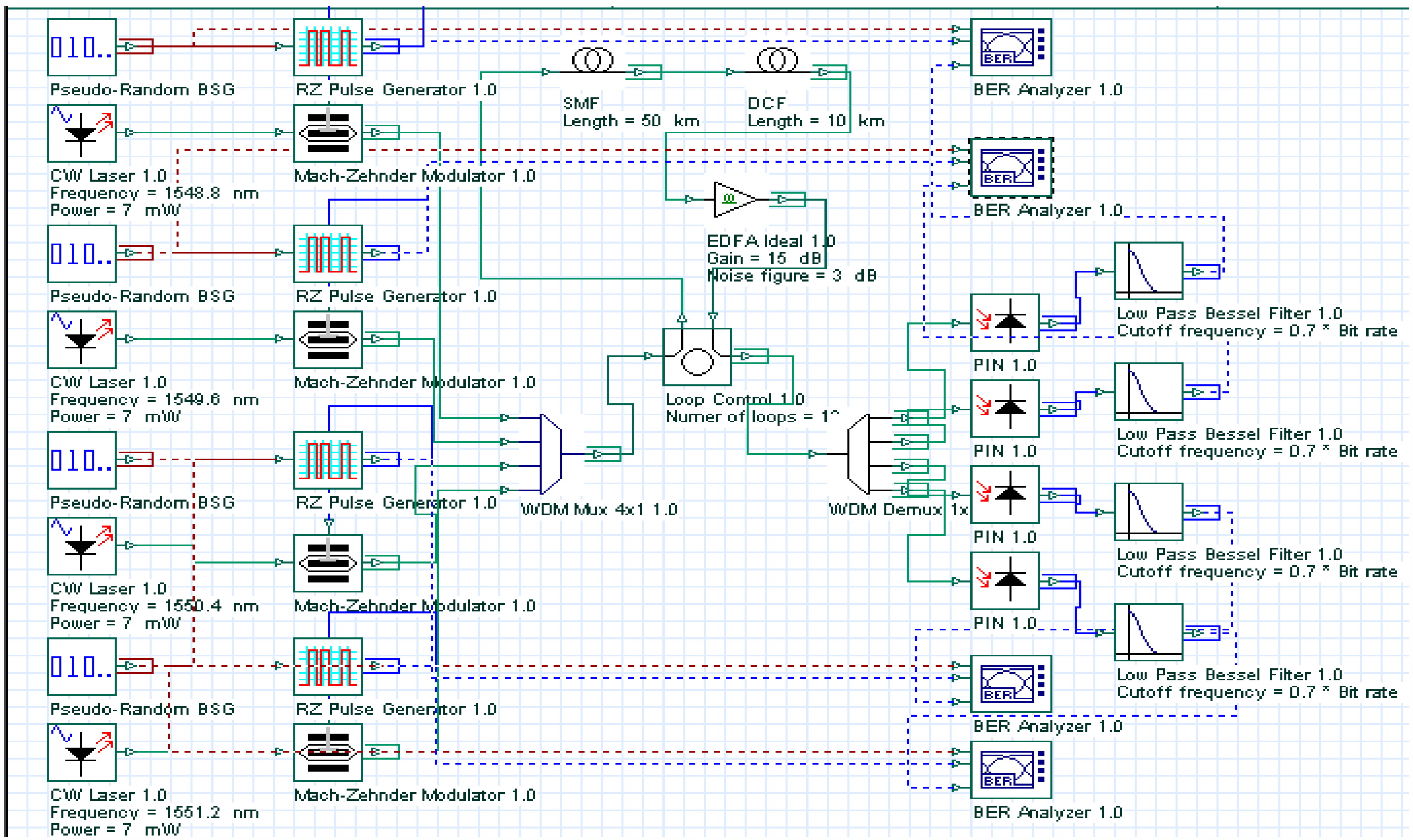
$\lambda_4 = 1551.2\ \mu m,\ \Delta\lambda_4 = 1.2\ nm,\ D_{SMF}(\lambda_4) = 16.096\ (ps/nm.km),$

$D_{DCF}(\lambda_4) = -80.252\ (ps/nm.km)$

$\partial D_{SMF} / \partial \lambda = 0.08\ (ps/nm^2.km),\ \partial D_{DCF} / \partial \lambda = -0.21\ (ps/nm^2.km),$

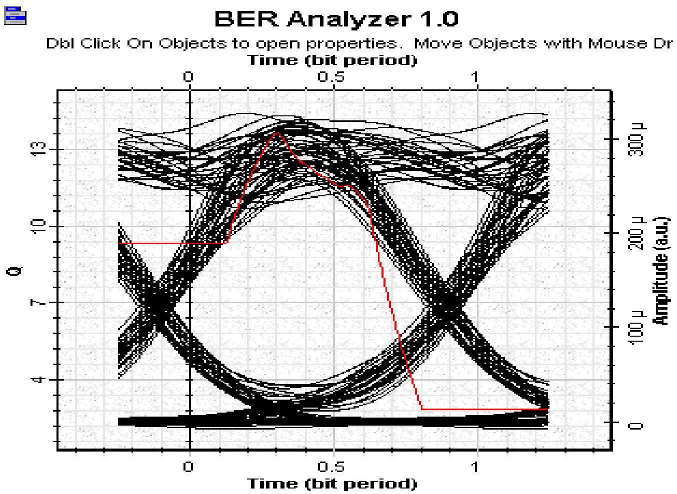
Optiwave



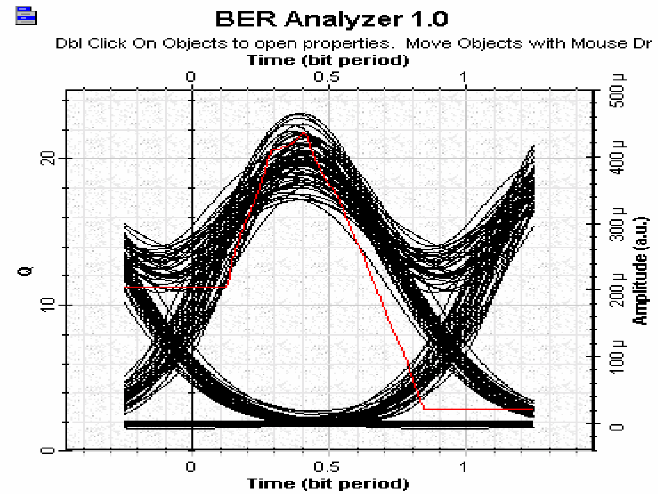




*WDM transmission at 4 ×40 Gb/s in SMF*

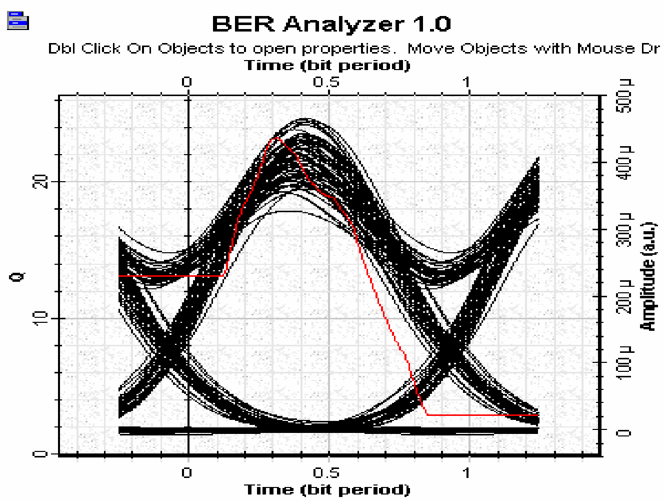
# *P in all channels = 4  mW*



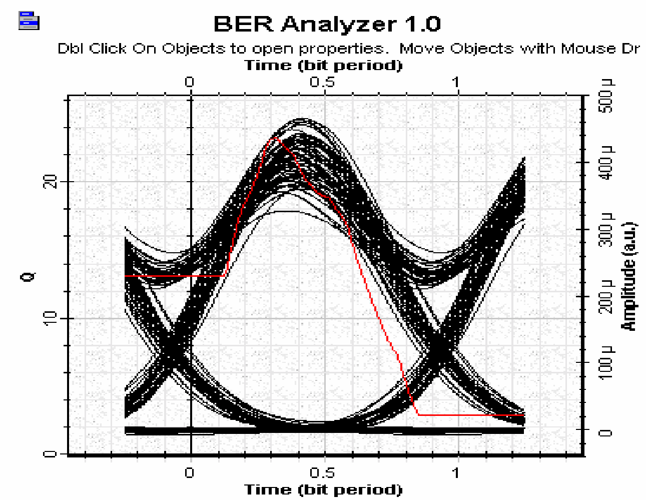

*CH.1*




*CH.2*




*CH.3*




*CH.4*

# *5. Conclusions:*

*For upgrading the existing standard-fiber network at 1.55 μm at 40 Gb/s single channel with dispersion managed systems*

*⇒ RZ- modulation format is superior compared to conventional NRZ – modulation format*

*⇒ at low power levels, the performance is mainly hampered by the accumulated amplifier noise at higher input powers, the transmission distance is significantly reduced by nonlinear self-phase modulation.*

*⇒ post-compensation scheme is superior compared to pre-compensation scheme*