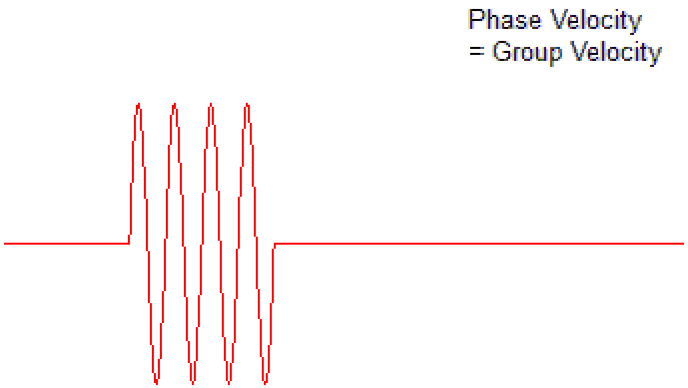
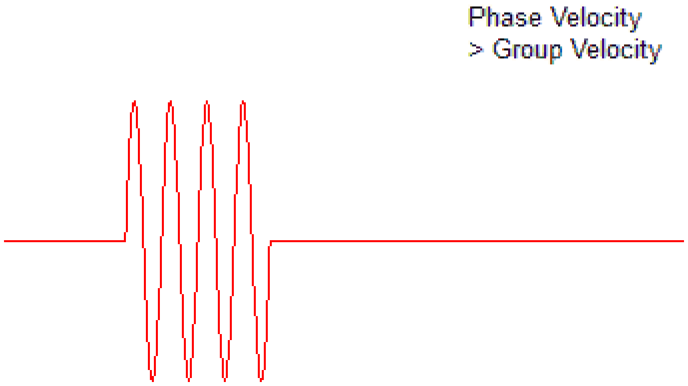
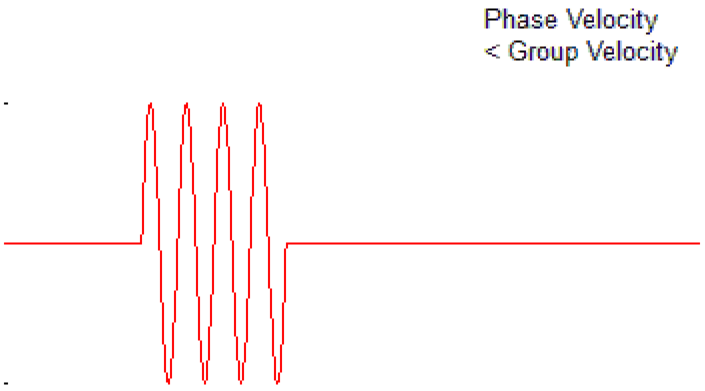
Phase and Group Velocity



Phase and Group Velocity

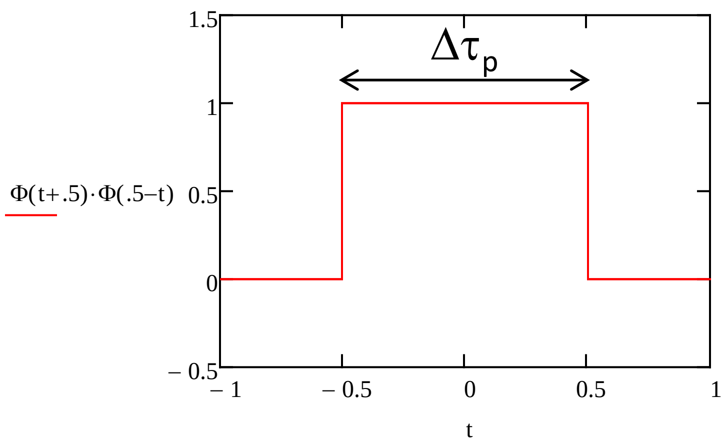


Phase and Group Velocity

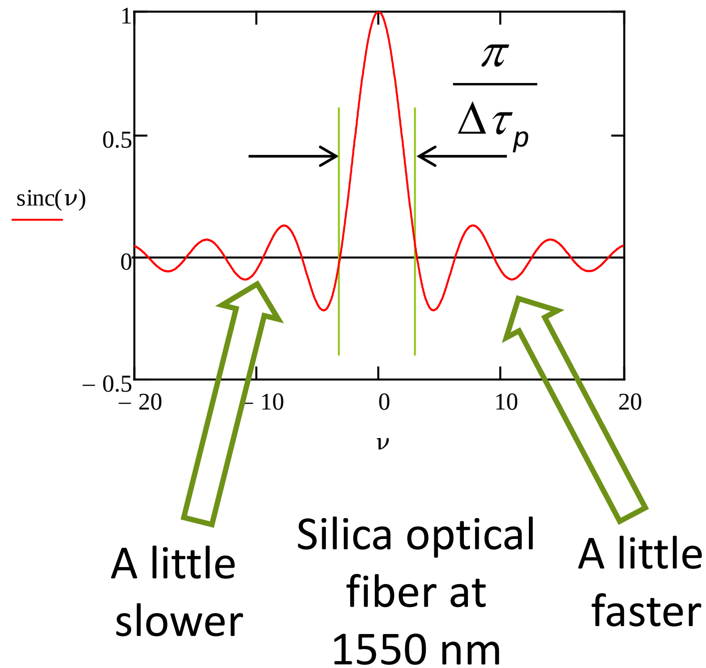


Group Velocity Dispersion

Temporal Pulse



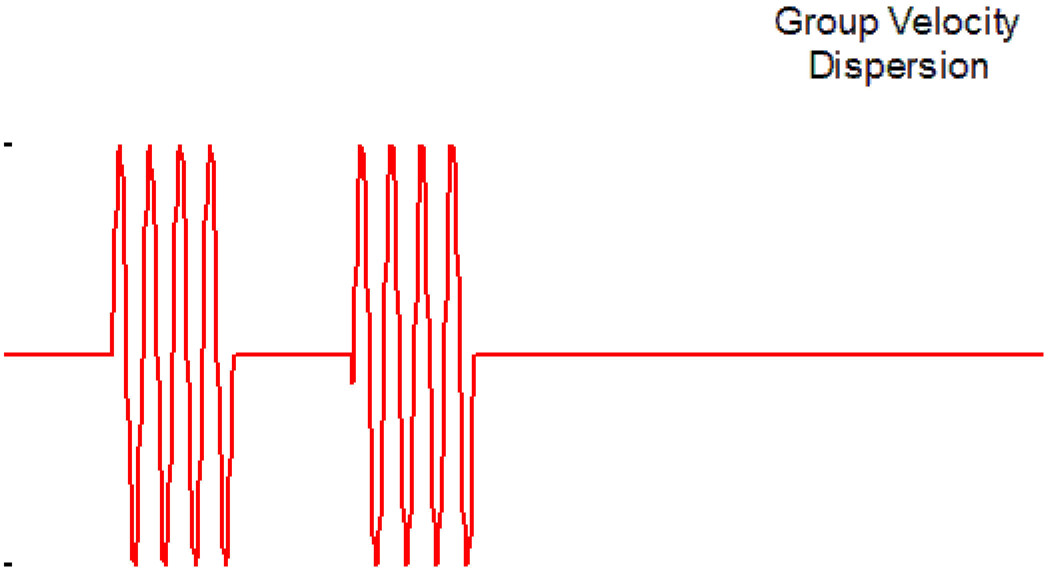
Fourier Transform



10 Gbits/sec
$\rightarrow \Delta\tau_p$ = 100 psec
$\rightarrow \pi/\Delta\tau_p$ = 31 GHz
$\rightarrow \Delta\lambda_0$ = 0.25 nm (@ 1550 nm)

$$D \approx 16 \frac{ps}{km \cdot nm}$$

Group Velocity Dispersion



GVD Expressions

$$\text{Phase Velocity} \equiv \frac{\omega}{\beta} = \frac{c}{n_{eff}}$$

$$\text{Group Velocity:} \quad v_g \equiv \frac{d\omega}{d\beta} = \frac{c}{n_g}$$

$$\text{Group Delay:} \quad \tau \equiv \frac{1}{v_g} = \frac{d\beta}{d\omega} = \frac{1}{c}\frac{d\beta}{dk_0}$$

$$\text{Dispersion Parameter:} \quad \mathrm{D} \equiv \frac{d\tau}{d\lambda_0}$$

Chromatic Dispersion – Expression for Group Velocity

$$\vec{E}_{\beta_0}(\vec{r},t) = A_0 \vec{E}(r,\phi) e^{j(\beta_0 z - \omega_0 t)}$$

$$\vec{E}_{\beta}(\vec{r},t) = A(\beta) \vec{E}(r,\phi) e^{j(\beta(\omega) z - \omega(\beta) t)}$$

$$\vec{E}(\vec{r},t) = \int_{-\infty}^{\infty} \vec{E}_{\beta}(\vec{r},t)\, d\beta$$

$$= \int_{-\infty}^{\infty} A(\beta) \vec{E}(r,\phi) e^{j(\beta z - \omega t)} d\beta$$

$$= \underbrace{\int_{-\infty}^{\infty} A(\beta) e^{j(\beta - \beta_0) z - j(\omega - \omega_0) t} d\beta}_{A(z,t)} \cdot \vec{E}(r,\phi) e^{j(\beta_0 z - \omega_0 t)}$$

Chromatic Dispersion – Expression for Group Velocity

$$\vec{E}(\vec{r},t)=\int_{-\infty}^{\infty}A(\beta)e^{j(\beta-\beta_0)z-j\left(\left(\frac{d\omega}{d\beta}\right)_{\beta_0}(\beta-\beta_0)+\frac{1}{2}\left(\frac{d^2\omega}{d\beta^2}\right)_{\beta_0}(\beta-\beta_0)^2+\ldots\right)t}d\beta\;\cdot\vec{E}(r,\phi)e^{j(\beta_0 z-\omega_0 t)}$$

$$\approx\int_{-\infty}^{\infty}A(\beta)e^{j(\beta-\beta_0)z-j\left(\left(\frac{d\omega}{d\beta}\right)_{\beta_0}(\beta-\beta_0)\right)t}d\beta\;\cdot\vec{E}(r,\phi)e^{j(\beta_0 z-\omega_0 t)}$$

$$\approx\underbrace{\int_{-\infty}^{\infty}A(\beta)e^{j(\beta-\beta_0)\left((z-\underbrace{\left(\frac{d\omega}{d\beta}\right)_{\beta_0}}_{v_g}t)\right)}d\beta}_{A\left(z-v_g t\right)}\;\cdot\vec{E}(r,\phi)e^{j(\beta_0 z-\omega_0 t)}$$

The GVD “D” Parameter

$$\vec{E}_{\omega_0}\left(\vec{r},t\right) = A_0\vec{E}\left(r,\phi\right)e^{j\left(\beta_0 z-\omega_0 t\right)}$$

$$\vec{E}_{\omega}\left(\vec{r},t\right) = A\left(\omega\right)\vec{E}\left(r,\phi\right)e^{j\left(\beta(\omega)z-\omega(\beta)t\right)}$$

$$\vec{E}\left(\vec{r},t\right) = \int_{-\infty}^{\infty} A\left(\omega\right)\vec{E}\left(r,\phi\right)e^{j\left(\beta z-\omega t\right)}d\omega$$

The GVD “D” Parameter

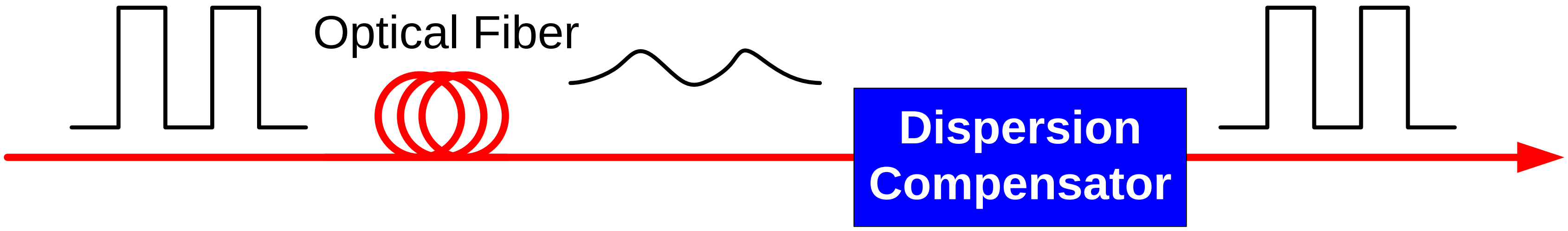
$$\vec{E}(\vec{r},t) = \int_{-\infty}^{\infty} A(\omega) e^{j\left(\left(\frac{d\beta}{d\omega}\right)_{\beta_0}(\omega-\omega_0)+\frac{1}{2}\left(\frac{d^2\beta}{d\omega^2}\right)_{\beta_0}(\omega-\omega_0)^2+\ldots\right)z-j(\omega-\omega_0)t} d\omega \cdot \vec{E}(r,\phi) e^{j(\beta_0 z-\omega_0 t)}$$

$$\approx \int_{-\infty}^{\infty} A(\omega)\, e^{j\left(\left(\frac{d\beta}{d\omega}\right)_{\beta_0}(\omega-\omega_0)+\frac{1}{2}\left(\frac{d^2\beta}{d\omega^2}\right)_{\beta_0}(\omega-\omega_0)^2\right)z-j(\omega-\omega_0)t} d\omega \cdot \vec{E}(r,\phi) e^{j(\beta_0 z-\omega_0 t)}$$

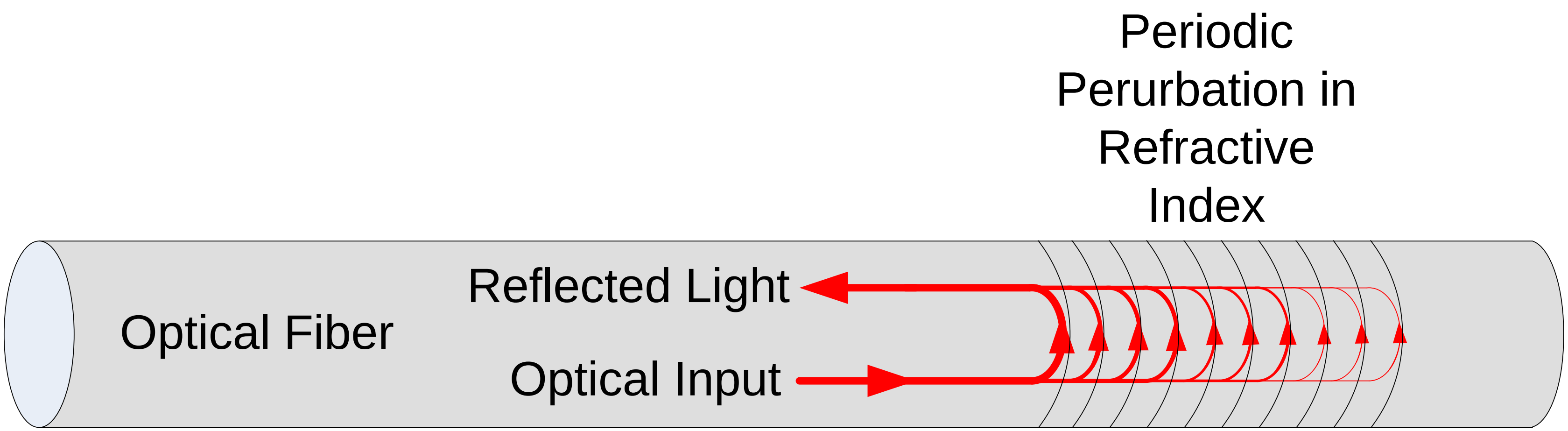
$$= \int_{-\infty}^{\infty} A(\omega) e^{j(\omega-\omega_0)\left(\left(\underbrace{\underbrace{\left(\frac{d\beta}{d\omega}\right)_{\beta_0}}_{\tau}+\frac{1}{2}\left(\frac{d^2\beta}{d\omega^2}\right)_{\beta_0}((\omega-\omega_0))}_{\tau'}\right)z-t\right)} d\omega \cdot \vec{E}(r,\phi) e^{j(\beta_0 z-\omega_0 t)}$$

$$\tau' = \tau + \frac{1}{2}\left(\frac{d^2\beta}{d\omega^2}\right)_{\beta_0}(\omega-\omega_0) = \tau - \frac{1}{2}\left(\frac{d}{d\lambda_0}\frac{d\beta}{d\omega}\right)_{\beta_0}\frac{\lambda_0}{\omega}(\omega-\omega_0) = \tau + \frac{1}{2}D(\lambda-\lambda_0)$$

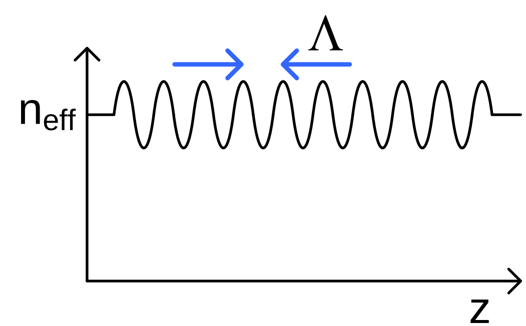
Dispersion Compensation



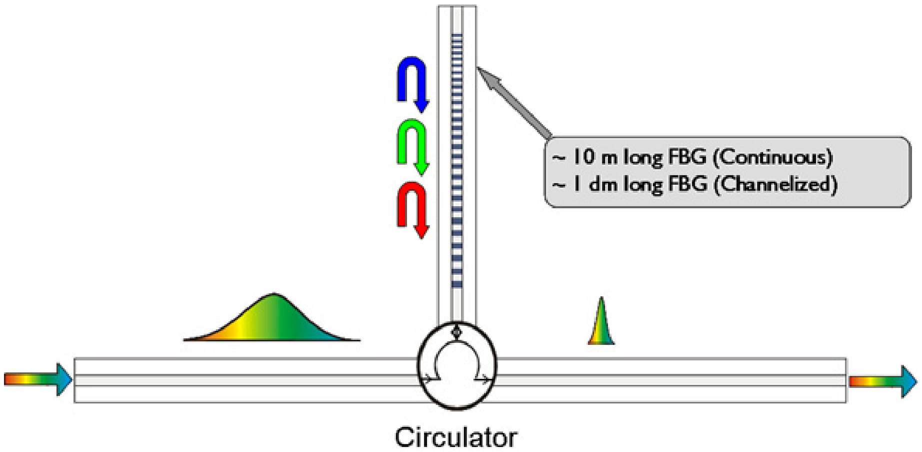
Fiber Bragg Gratings



$$\lambda_{Bragg} = \frac{\Lambda}{2 n_{eff} m} \quad m = 1, 2, \ldots$$



Fiber Bragg Grating Compensator

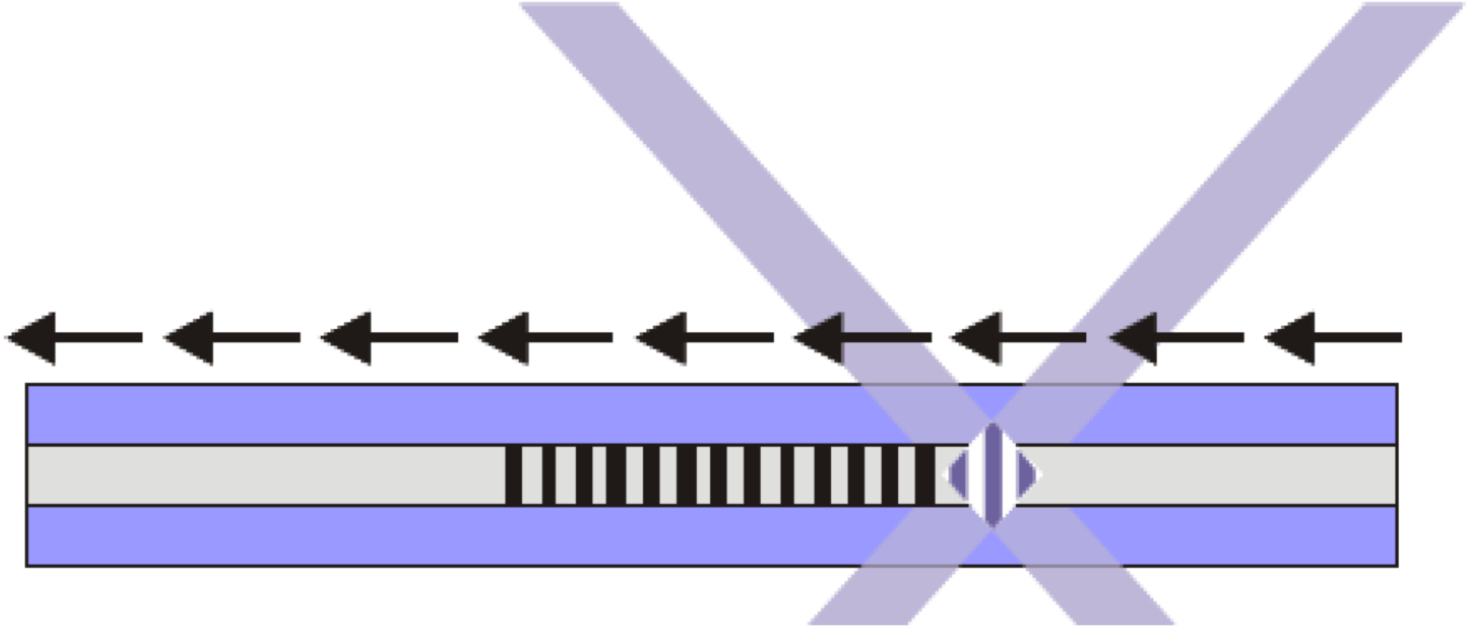


Two main types of FBG based dispersion compensators are commercially available today, multi-channel (or channelized) and continuous. The channelized version provides channel spacing specific, or grid specific, compensation whereas the continuous type provides, in much the same manner as a DCF, continuous compensation throughout the C-band, hence providing total channel plan independency.

1530-1565nm

From web site for Proximion (Sweden), www.proximion.com

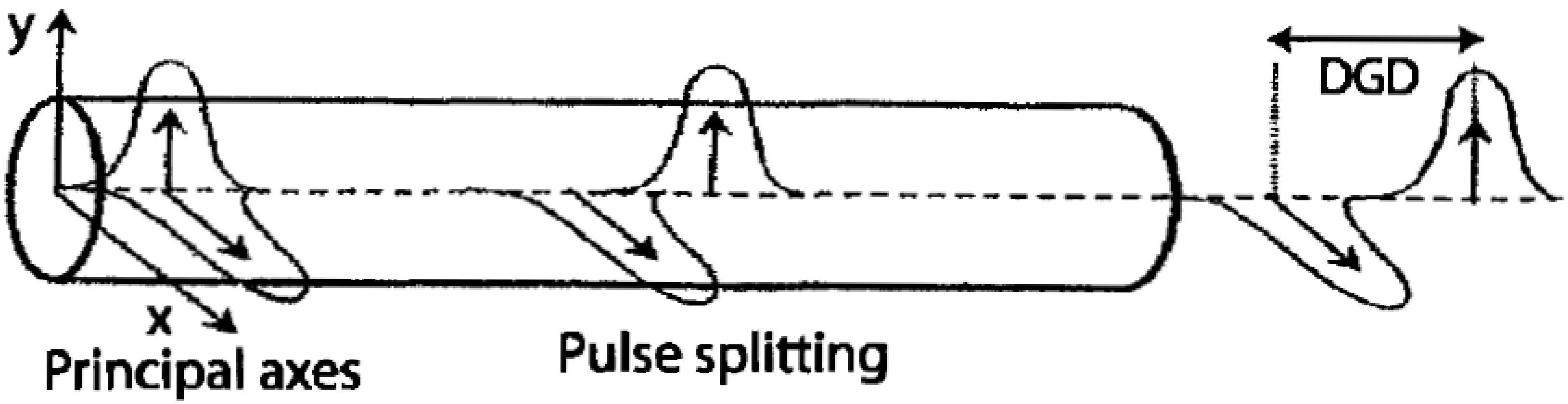
Fabricating a “Chirped” Fiber Bragg Grating



Two ultraviolet laser beams interfere, resulting in a fringe pattern. By accurately controlling the motion of the fiber many successive fringe patterns can be added into very long gratings such as the truly unique FBG’s used in our continuous dispersion compensators

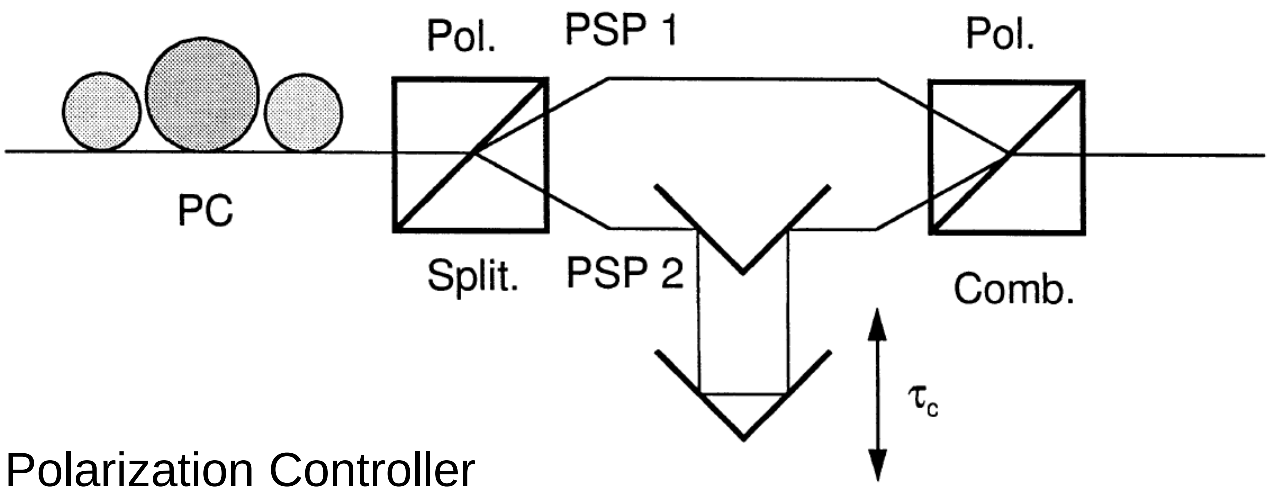
From web site for Proximion (Sweden), www.proximion.com

Polarization Mode Dispersion (PMD)



From “Lightwave Technology: Telecommunication Systems,” Govind P. Agrawal, p. 84 (Wiley, 2005)

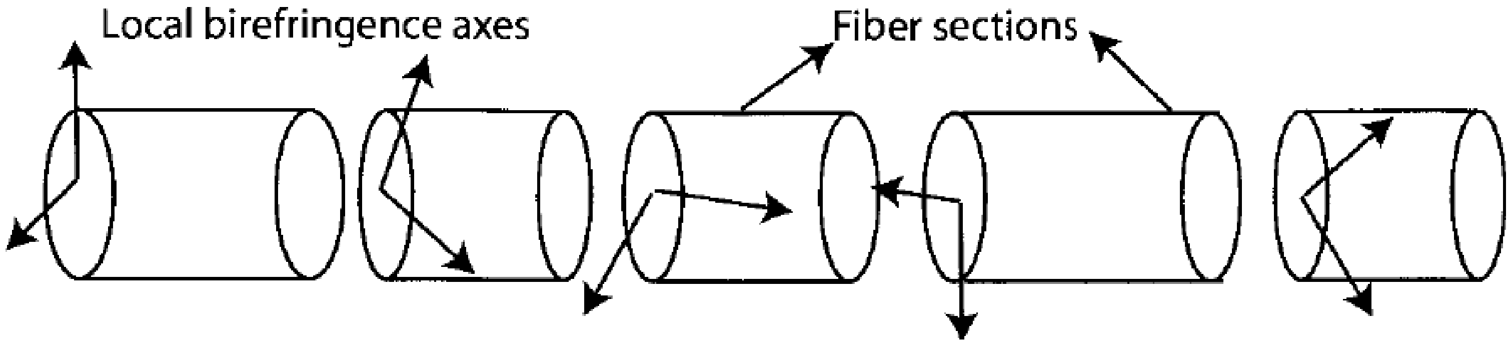
PMD Compensation



PC = Polarization Controller
Pol. Spit. = Polarization Splitter
PSP 1 = Principle State of Polarization 1
PSP 2 = Principle State of Polarization 2
Pol. Comb. = Polarization Combiner

From "Comparison of PMD-compensation techniques at 10 Gbit/s using an optical first-order compensator and electrical transversal filter," T. Merker, N. Hahnenkamp, P. Meissner, Optics Communications, Vol. 182, 2000, pp. 135–141

PMD – Random Birefringence



- Long optical fibers (> 10 meters) have random birefringence.
- This makes causes pulse spreading for both states of polarization and makes compensation difficult.
- Fortunately, the random nature of the birefringence also results in less PMD

DGD = Differential Group Delay ~ 0.1 – 1 ps/(km)$^{1/2}$
- Most significant for data rates > 10 Gbits/sec

Figure from "Lightwave Technology: Telecommunication Systems," Govind P. Agrawal, p. 84 (Wiley, 2005)

PMD – Random Birefringence

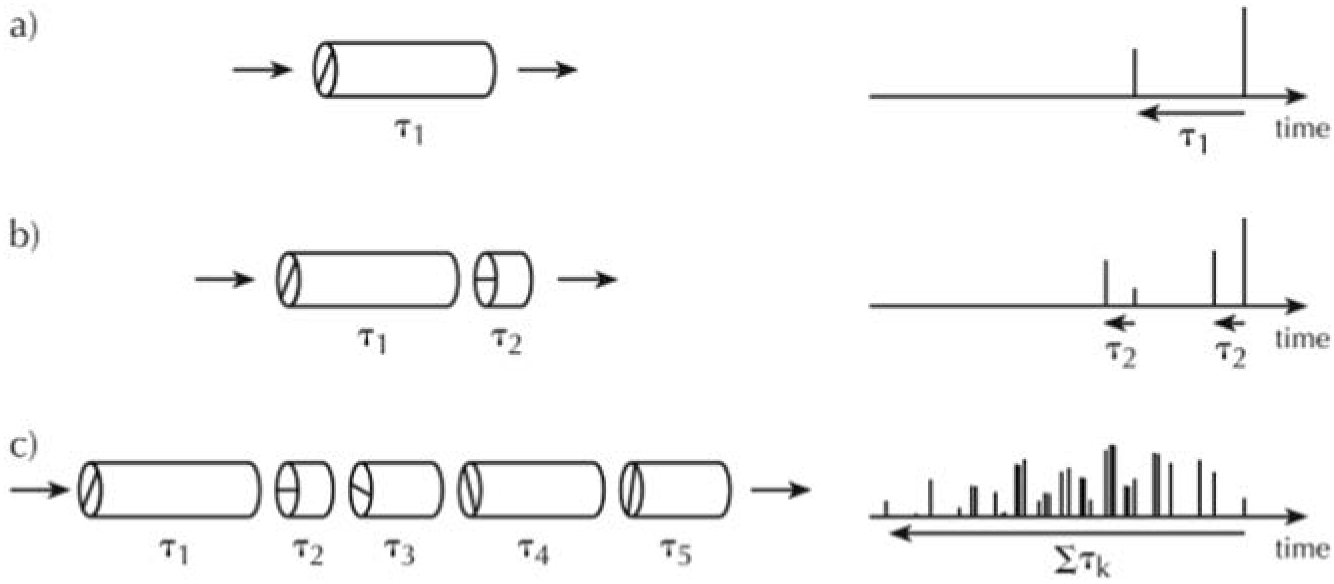


Fig. 8.17. Impulse response from one or more birefringent elements. The polarization of the impulses has been abstracted. a) Impulse response from one stage alone. An input impulse is split along the two birefringent axes and one pulse is delayed with respect to the other by τ_1. b) Impulse response from two stages. The two impulses from the first stage are each divided into two parts, the slow components are then delayed by τ_2. c) Impulse response from five stages generates 2^5 or 32 impulses. There is a first and last pulse, and the time response is FIR. (finite impulse response)

From "Polarization optics in telecommunications," Jay N. Damask (Springer, 2005)