Fiber Optic Communications

Ch 5. Dispersion Management

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Dispersion management

- Dispersion compensating fibers (DCF)
- Fiber Bragg gratings (FBG)
- Dispersion-equalizing filters
- Optical phase conjugation (OPC)
- Electronic dispersion compensation (EDC)

The dispersion problem and solutions

- Using optical amplification, dispersion (not loss) is the major limitation
  - In general, dispersion is important at bit rates > 5 Gbit/s
    - Even if the source is chirp-free and the fiber is single-mode
  - With a narrow source spectrum and without third-order dispersion, we have

$$4B\sqrt{|\beta_2|L} \leq 1$$

  - Dispersion must be compensated for
    - Then noise and nonlinearities become the major limitations
- Compensation can be in
  - Optical domain: DCF, FBG, filters, OPC, and (previously) solitons
  - Electrical domain: Pre- or post-compensation, often using DSP

The aim of dispersion compensation is to cancel the phase factor

$$A(z,t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \tilde{A}(0,\omega)\exp\left[\frac{i}{2}\beta_2\omega^2 z + \frac{i}{6}\beta_3\omega^3 z - i\omega t\right]d\omega$$

Compensation in the optical domain

- In general, an optical device with field transfer function

$$H(\omega) = |H(\omega)| \exp[i\phi(\omega)] \approx |H(\omega)| \exp\left[i(\phi_0 + \phi_1\omega + \tfrac{1}{2}\phi_2\omega^2 + \tfrac{1}{6}\phi_3\omega^3)\right]$$

will modify the electric field to

$$A(L,t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \tilde{A}(0,\omega) H(\omega) \exp\left(\frac{i}{2}\beta_2\omega^2 L + \frac{i}{6}\beta_3\omega^3 L - i\omega t\right) d\omega$$

- The dispersion is perfectly canceled if

$$|H(\omega)| = 1, \ \ \phi_2 = -\beta_2 L, \ \ \phi_3 = -\beta_3 L$$

  - ϕ_0 only changes the absolute phase
    - Is of no consequence
  - ϕ_1 introduces a delay
    - Important to keep small to avoid latency

The dispersion of the fiber acts as an all-pass filter

Dispersion compensation can be placed anywhere if nonlinearities are small

Dispersion-compensating fibers

A ***dispersion-compensating fiber*** (DCF)

- Has normal dispersion, $D < 0 \Rightarrow$ Can compensate GVD perfectly
- Has a tailored dispersion relation that allows TOD compensation
  - Curvature is almost opposite of SMF value $\Rightarrow$ some residual TOD

Denoting the two transfer functions by H_{f1} (SMF) and H_{f2} (DCF), we get

$$A(L,t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \tilde{A}(0,\omega) H_{f1}(L_1,\omega) H_{f2}(L_2,\omega) \exp(-i\omega t)\, d\omega$$

The conditions for compensation after SMF + DCF are

$$\beta_{21}L_1 + \beta_{22}L_2 = 0, \quad \beta_{31}L_1 + \beta_{32}L_2 = 0$$

- First condition is most important
- Second condition is important for a broad-band (WDM) signal

When nonlinearities are important, DCF position is important

- Otherwise, DCF can be put anywhere

Dispersion maps

DCFs can be placed in different ways

Figure: Different ***dispersion maps***

- Precompensation
- Postcompensation
- Periodic compensation

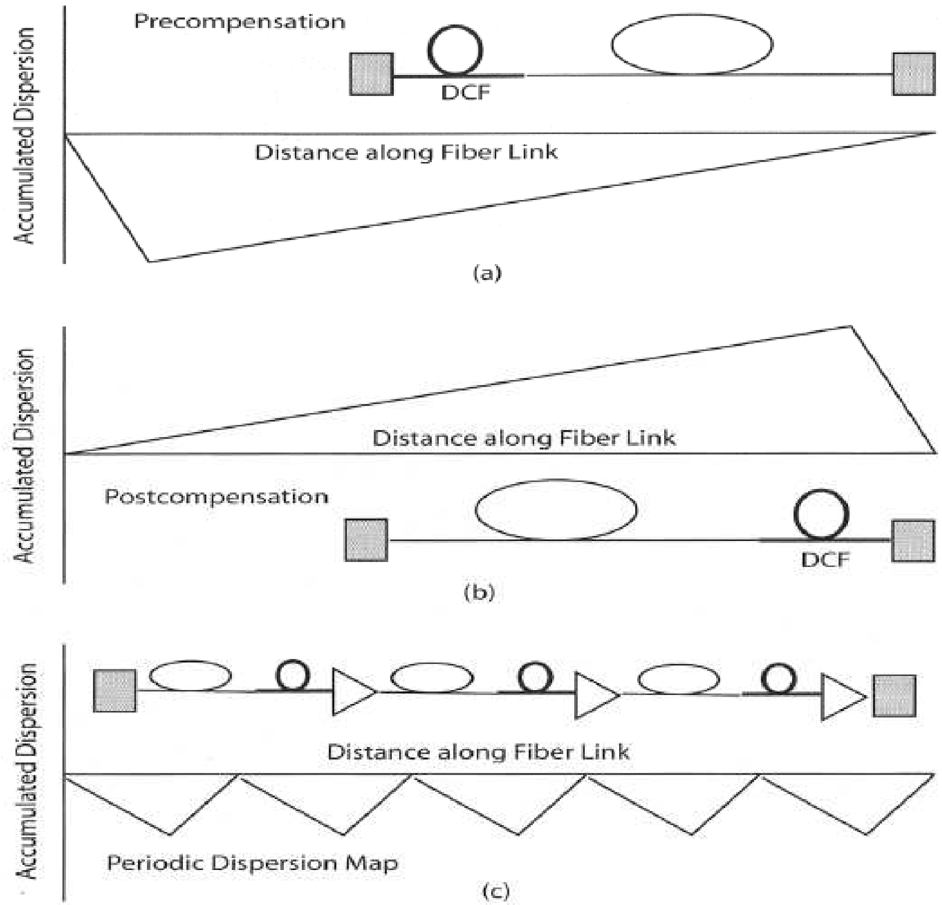
Perform equally well in a linear system

In practice, periodic compensation is often used

- Each piece of fiber is compensated

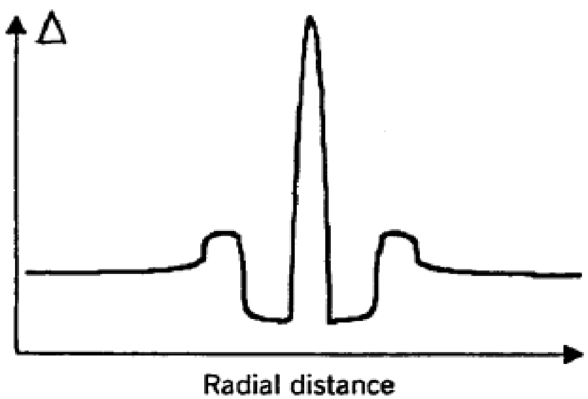
Including nonlinearities, performance can be very different

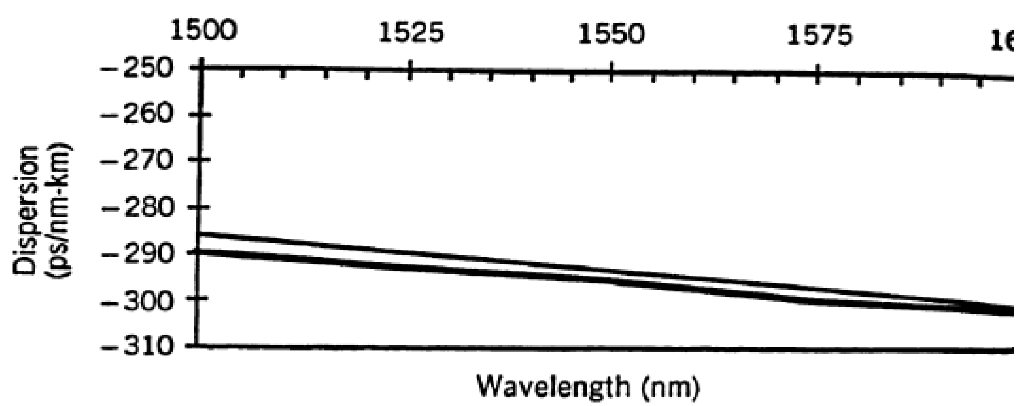
- Dispersion map design is an important tool to combat nonlinearities in OOK systems



DCF design

- Can be made with strong normal dispersion $-D \approx$ 100–300 ps/(nm km
  - A DCF of length 4 km can compensate for ~50 km of SMF
- Loss is relatively high, 0.4–1 dB/km
  - Additional amplification is needed ⇒ noise is increased
- Figures show example DCF radial profile and the *D* value



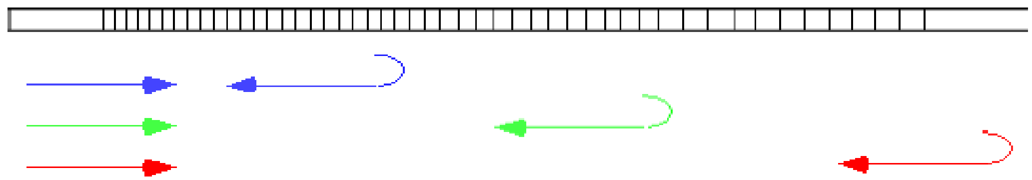


- A figure-of-merit is ”dispersion per loss” M ≈ 100–400 ps/(nm dB)
- The fiber core is small ⇒ the nonlinear coefficient is relatively large
  - Typically, γ = 5 $W^{-1} km^{-1}$ to compare with γ < 2 $W^{-1} km^{-1}$ for SMF

Fiber Bragg gratings (FBG)

In an FBG, the refractive index varies periodically

- Made by holographic UV exposure



In a chirped grating, the period of *n* changes with *z* $\lambda_B = 2n\Lambda$

- The Bragg wavelength (which is reflected) varies along the fiber
- Λ is the distance between two peaks for *n*
- Different frequency components experience different delay

The grating dispersion is

$$D_g = \frac{T_R}{L_g \Delta\lambda} = \frac{2n}{c\Delta\lambda}$$

- T_R = grating round trip time
- L_g = grating length
- Δλ = difference in λ_B at the two grating ends

Example: Δλ = 0.2 nm, D_g = 500 ps/(nm cm), L_g = 10 cm, compensates for 300 km of SMF

There is, for a given length, a trade-off between bandwidth and dispersion

Chirped fiber Bragg gratings

Figure shows measured reflectivity and time delay for a 10 cm long linearly chirped grating

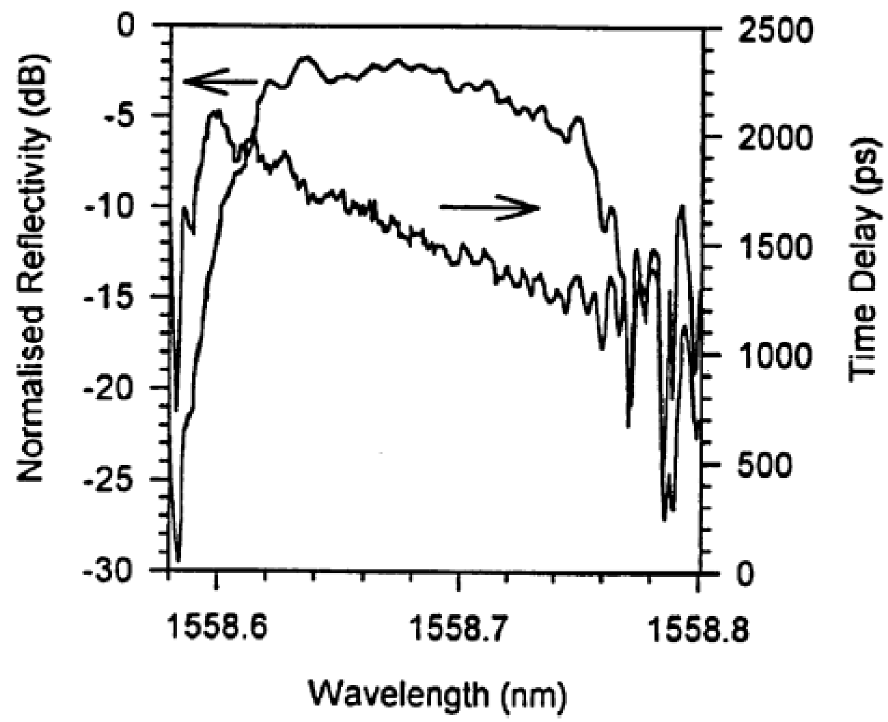
- Dispersion is 5000 ps/nm, equivalent to 300 km SMF
- Optical bandwidth is 0.12 nm, sufficient for 10 Gbit/s if source is chirp free

These devices operate in reflection

- Loss is mainly due to coupling
- Can be improved by using a ***circulator***

Linearly chirped gratings compensate for β_2

Nonlinearly chirped gratings can, in principle, compensate for higher order fiber dispersion (β_3, β_4)



Dispersion-equalizing filters, Mach–Zehnder

Dispersion-equalizing filters can be implemented with ***Mach–Zehnder interferometers*** (MZI)

A single MZI has the transfer function

- τ is the extra delay of the longer arm

$$H_{\mathrm{MZ}}(\omega) = \frac{1+\exp(i\omega\tau)}{2}$$

Transfer function is tailored by cascading many MZIs

High frequencies experience more delay

- Will counteract fiber dispersion

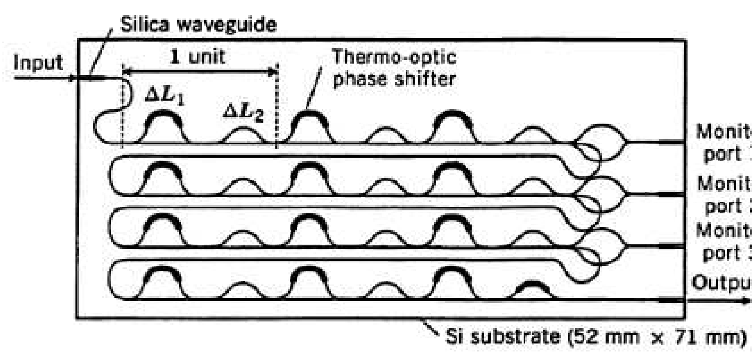
By temperature tuning of the arm lengths the transfer function is controlled

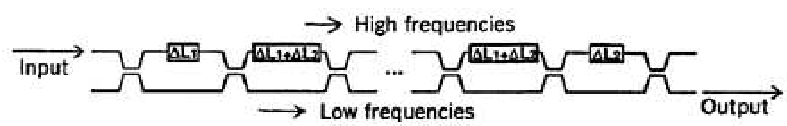
- Both center wavelength and dispersion

The compensator has narrow bandwidth and is polarization-dependent

Typical performance:

- Loss ≈ 10 dB
- GVD ≈ 500–1000 ps/nm





Optical phase conjugation (OPC)

Using OPC, the complex conjugate is generated in the middle of the fiber

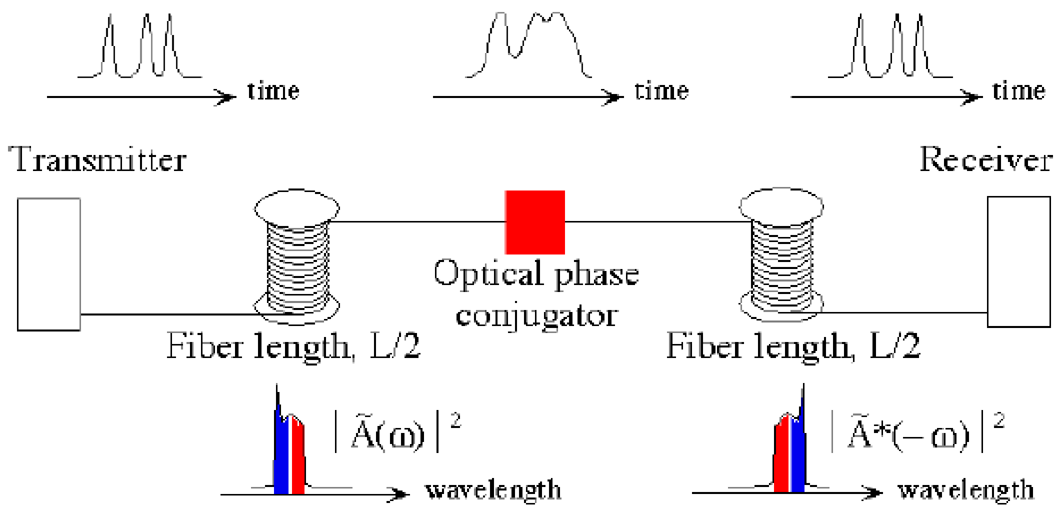
- The conjugate experiences dispersion of opposite sign
- The effect of GVD in the second half cancels the effect of the GVD in the first

Complex conjugating the nonlinear Schrödinger equation, the GVD term changes sign

$$\frac{\partial A^*}{\partial z} - \frac{i\beta_2}{2}\frac{\partial^2 A^*}{\partial t^2} - \frac{\beta_3}{6}\frac{\partial^3 A^*}{\partial t^3} = 0$$

- Equivalent to changing to $-\beta_2$
- TOD term is not changed

We get $A(L,t) = A^*(0,t)$



OPC can compensate for β_2, but not β_3 and β_5 etc.

OPC can compensate for the Kerr nonlinear effects

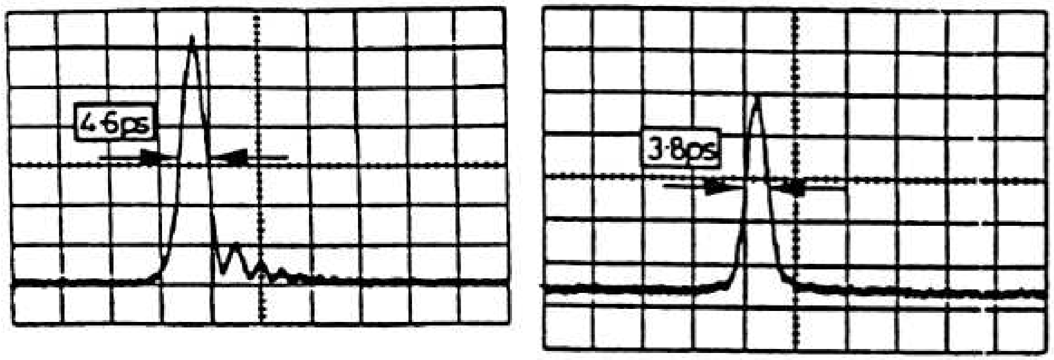
Optical phase conjugation

- The complex conjugate is generated using ***four-wave mixing*** (FWM)
  - The fiber is nonlinear and FWM occurs, but is weak
  - A special highly nonlinear fiber (HNLF) is used
- Neglecting losses, both GVD and SPM are perfectly compensated for
- Considering losses, compensation of SPM is only partial
  - The losses causes the power to change within the fiber
    - The nonlinearities are stronger in the first part than in the second part
  - Cannot be solved by amplification in the middle
    - Power distribution should be symmetric around the center point
  - Possible solution: Combine with Raman amplification
    - Will make the power distribution more even

Channels at high bit rates

For high bit rates, > 40 Gbit/s, TOD/PMD become important

Figure shows 2.1 ps pulses after propagation without and with β_3 compensation



DCFs are designed to compensate for β_3

Optical filters and chirped gratings can be designed to compensate for β_3

In WDM systems, each channel can be compensated individually:

- Filters with periodic characteristics can be used
- Cascaded chirped FBGs optimized for a specific wavelength can be used

PMD is problematic since the transfer function is unknown

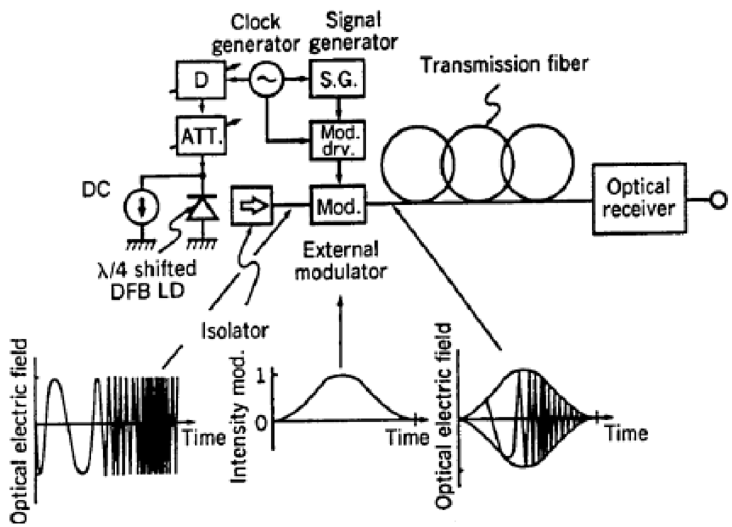
- Optical PMD compensators must do monitoring of the signal to get feedback
- In a coherent receiver, PMD compensation is done by an ***adaptive equalizer*** implemented in DSP

Dispersion compensation by prechirping

- If we can generate a general field, we can compensate the dispersion
  - Set up a field that after propagation gives pulses without ISI
  - Pulse broadening can be significant ⇒ requires superposition of many pulses
- Instead, suppose we introduce a chirp to pulses of unchanged width
- If a Gaussian pulse is chirped, a broadening of √2 is obtained when
  - Maximum reach is $\sqrt{2}L_D$
  - Occurs for C = 1/√2

$$L = \frac{C + \sqrt{1 + 2C^2}}{1 + C^2} L_D, \quad L_D = \frac{T_0^2}{|\beta_2|}$$

- Figure shows example
  - DFB laser is frequency modulated
  - An external modulator synchronously performs intensity modulation
  - 10 Gbit/s over 100 km demonstrated



Prechirping can only compensate for a limited amount of dispersion

Dispersion compensation in a coherent receiver

Can dispersion compensation be done in the receiver?

- In principle: It depends on the detection method
- In practice: It also depends on whether you can make the DSP chip or the corresponding analog implementation

We have been talking mostly about ***direct-detection (DD) receivers***

- Electric current proportional to the optical power
- Phase information is lost

Dispersion changes the phase of the spectrum ⇒ Dispersion compensation cannot be done after DD

Using the information available, some compensation can be done

- Trying to maximize the eye opening in an adaptive equalizer

In DSP, the ***maximum likelihood sequence estimator*** (MLSE) can be used

- Uses the ***Viterbi algorithm***
- Compensates dispersion and PMD by investigating a sequence of bits
- Algorithm has high complexity, compensates a limited amount of dispersion

Dispersion compensation in a coherent receiver

A ***coherent receiver*** performs a linear mapping from the optical field to the electrical signal

- Input: Optical signal from the fiber + light from a ***local oscillator*** (LO) laser
- Output: Two currents proportional to the real and imaginary part of the light

The coherent receiver makes is possible to

- Encode data into the phase
- Improve the signal quality using DSP

The DSP typically used perform

- Electronic dispersion compensation (EDC)
- Tracking of polarization and compensation of PMD
- Tracking of the signal–LO phase evolution

The drawback is that

- Developing an application-specific integrated circuit (ASIC) is very complicated and costly
- An ASIC consumes significant power, EDC consumes a large part of the ASIC

Dispersion compensation in a coherent receiver

When the field and the amount of accumulated dispersion is known, ***electrical dispersion compensation*** (EDC) is straight-forward

Can be done in time or frequency domain

In frequency domain: FFT, shift the phase, IFFT

- Very similar to solution of the Schrödinger equation
- Performed on a limited amount of data
  - Edges are not correctly compensated, must be handled

In time domain: Perform FIR filtering corresponding to GVD

- Continuous time impulse response is

$$h(t) = \sqrt{\frac{2\pi}{id_a}} \exp\left(-\frac{it^2}{2d_a}\right)$$

- Must be discretized at sampling rate, truncated, and delayed to make causal
- For long systems, the FIR filter is long (many hundred taps)

In principle, arbitrary amounts of dispersion can be compensated for

The ”Nortel system”

- commercial coherent system (2007)
  - 40 Gbit/s : QPSK, polarization multiplex.)
- Performs EDC because DCFs add
  - Loss (DCF losses must be compensated for)
  - Nonlinearity (DCF is nonlinear)
  - Cost (DCF modules cost money)
  - Work (Must match fiber lengths)
- Performs adaptive equalization
  - Separates polarizations
  - Compensates PMD, residual dispersion
  - uses the constant-modulus algorithm
- Made coherent systems a strong contender to traditional systems