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Optical Communication Systems (OPT428)

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Chapter 7: Dispersion Management

- Dispersion Problem and Its Solution
- Dispersion-Compensating Fibers
- Dispersion-Equalizing Filters
- Fiber Bragg Gratings
- Optical Phase Conjugation
- Other Techniques
- High-Speed Lightwave Systems

Dispersion Problem and Its Solution

- Systems built during 1980s used standard fibers with their zero-dispersion wavelength near 1.3 μm.
- Standard fibers have large dispersion near 1.55 μm.
- Operation near zero-dispersion wavelength not realistic for WDM systems.
- Even with DFB lasers, transmission distance is limited to

$$L < \frac{1}{16|\beta_2|B^2} = \frac{\pi c}{8\lambda^2|D|B^2}.$$

- $L < 35$ km at B $=$10 Gb/s if we use $|\beta_2| \approx 21$ ps^2/km.
- Dispersion must be compensated or managed using a suitable technique before old systems can be upgraded to 10 Gb/s.

Basic Idea

- Pulse propagation in the linear case is governed by

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

- Using the Fourier-transform method, the solution is

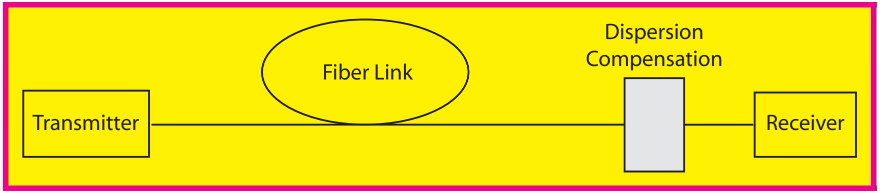
$$A(z,t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \tilde{A}(0,\omega)\exp\left(\frac{i}{2}\beta_2\omega^2 z + \frac{i}{6}\beta_3\omega^3 z - i\omega t\right) d\omega.$$

- Fiber acts as an optical filter with the transfer function

$$H_f(z,\omega) = \exp(i\beta_2\omega^2 z/2 + i\beta_3\omega^3 z/6).$$

- All dispersion-management schemes implement a dispersion compensating "filter" that cancels this phase factor.
- If $H(\omega) = H_f^*(L,\omega)$, the output signal can be restored.

Dispersion-Compensating Filters



- Optical field after the filter is given by

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

- Expanding the phase of $H(\omega)$ in a Taylor series:

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

- Constant phase ϕ_0 and time delay ϕ_1 can be ignored.
- Dispersion compensated when $\phi_2 = -\beta_2 L$ and $\phi_3 = -\beta_3 L$.
- Signal is restored perfectly only if $|H(\omega)| = 1$ and higher-order terms in the expansion are negligible.

Dispersion-Compensating Fibers

- Optical filters with $H(\omega) = H_f^*(L,\omega)$ are not easy to design.
- Simplest solution: Use a fiber as an optical filter because it automatically has the desired form of the transfer function.
- This solution was suggested as early as 1980.
- It provides an all-optical, fiber-based solution to the dispersion problem.
- Special dispersion-compensating fibers (DCFs) developed.
- Such fibers are routinely used for upgrading old fiber links.
- Such a scheme works well even when the nonlinear effects are not negligible as long as the average optical power launched into the fiber link is optimized properly.

Conditions for Dispersion Compensation

- After two fibers of lengths L_1 and L_2, optical field is given by

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

- If second fiber (DCF) is designed such that $H_{f1}(L_1,\omega)H_{f2}(L_2,\omega) = 1$, the pulse will fully recover its original shape.

- Conditions for perfect dispersion compensation are

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

- In terms of dispersion parameter D and dispersion slope S

$$D_1L_1+D_2L_2 = 0, \qquad S_1L_1+S_2L_2 = 0.$$

- First condition sufficient if TOD does not affect a bit stream.

Requirements for DCFs

- Consider the upgrade problem for fiber links made with standard telecommunication fibers.
- Such fibers have $D_1 \approx 16$ ps/(km-nm) near 1.55-μm.
- The DCF must exhibit normal GVD ($D_2 < 0$).
- For practical reasons, L_2 should be as small as possible.
- This is possible only if the DCF has a large negative value of D_2.
- As an example, if we assume $L_1 = 50$ km, we need a 10-km-long DCF when $D_2 = -80$ ps/(km-nm).
- This length can be reduced to 6.7 km if the DCF is designed to have $D_2 = -120$ ps/(km-nm).
- DCFs with larger values of $|D_2|$ are preferred to minimize extra losses incurred inside a DCF.

DCFs for WDM Systems

- For a WDM system, the same DCF must compensate dispersion over for all channels.
- The slope condition, $S_1L_1 + S_2L_2 = 0$ must be satisfied.
- Reason: both D_1 and D_2 are wavelength-dependent.
- The condition $D_1L_1 + D_2L_2 = 0$ is replaced with

$$D_1(\lambda_n)L_1 + D_2(\lambda_n)L_2 = 0 \quad (n = 1, \ldots, N),$$

- Near the ZDWL of a fiber, $D_j(\lambda_n) = D_j^c + S_j(\lambda_n - \lambda_c)$.
- Dispersion slop of the DCF should satisfy

$$S_2 = -S_1(L_1/L_2) = S_1(D_2/D_1).$$

- Ratio S/D, called relative dispersion slope should be the same for both fibers.

Negative-Slope DCFs

- Using $D \approx 16$ ps/(km-nm) and $S \approx 0.05$ ps/(km-nm^2), ratio S/D is positive and about 0.003 nm^{-1} for standard fibers.
- Since D is negative for a DCF, S should also be negative such that $S_2/S_1 = D_2/D_1$.
- For a DCF with $D \approx -100$ ps/(km-nm), dispersion slope S should be -0.3 ps/(km-nm^2).
- The use of negative-slope DCFs offers the simplest solution for WDM systems with a large number of channels.
- Such DCFs were developed and commercialized during the 1990s.
- In 2001, broadband DCFs were used to transmit 101 channels, each operating at 10 Gb/s, over 9,000 km.

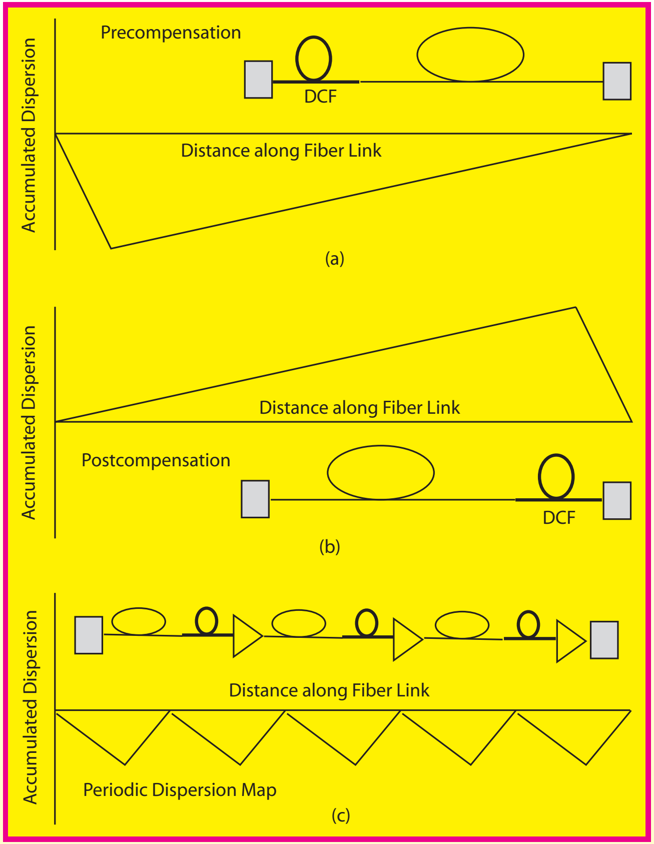
Dispersion Maps

- A fiber link may contain multiple types of fibers with different dispersion characteristics.
- Solution for an arbitrary form of $\beta_2(z)$ is given by

$$A(z,t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \tilde{A}(0,\omega)\exp\left(\frac{i}{2}d_a(z)\omega^2 - i\omega t\right)d\omega.$$

- Total accumulated dispersion $d_a(z) = \int_0^z \beta_2(z')\,dz'$.
- Dispersion management requires $d_a(L) = 0$ at the end of a fiber link so that $A(L,t) = A(0,t)$.
- Three schemes used in practice: (a) precompensation, (b) postcompensation, and (c) periodic compensation.

Dispersion Maps



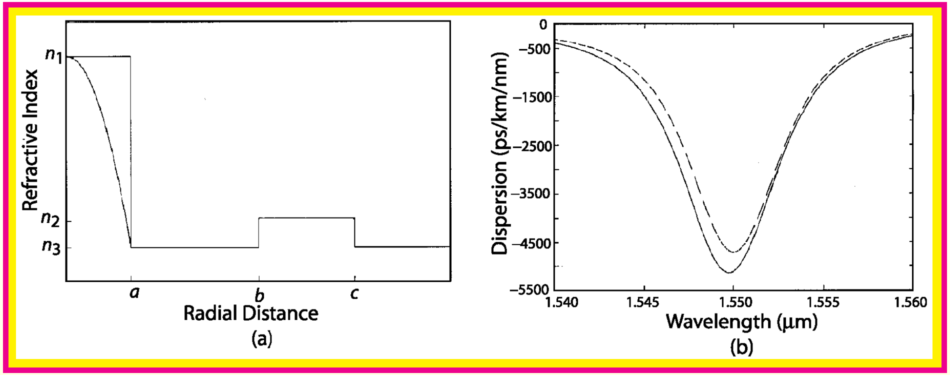
Dispersion Maps

- Precompensation: Dispersion accumulated over the entire link is compensated at the transmitter end.
- Postcompensation: A DCF of appropriate length is placed at the receiver end.
- Periodic compensation: Dispersion is compensated in a periodic fashion all along the link.
- For a truly linear system (no nonlinear effects), all three schemes are identical.
- Three configurations behave differently when nonlinear effects are included.
- System performance improved by optimizing dispersion map.

Single-Mode DCF Design

- In a single-mode design, V parameter is made close to 1.
- Accomplished in practice by reducing the core size (diameter 4–5 μm).
- A large fraction of the mode propagates outside the core.
- Waveguiding contribution to dispersion is enhanced, resulting in large negative values of D.
- Values of $D < -100$ ps/(km-nm) can be realized.
- Such DCFs suffer from two problems, both resulting from their relatively narrow core diameter.
- Relatively high losses ($\alpha = 0.4$–0.6 dB/km).
- Nonlinear parameter γ is larger by about a factor of 4.

Improved DCF Design

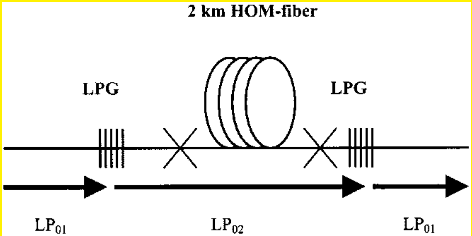


- DCF is designed with two concentric cores, separated by a ring-shaped cladding region.
- Size parameters a, b, and c and refractive indices n_1, n_2, and n_3 optimized to realized desired dispersion characteristics.
- D can be as large as $-5{,}000$ ps/(km-nm) when $a = 1$ μm, $b = 15.2$ μm, and $c = 22$ μm.

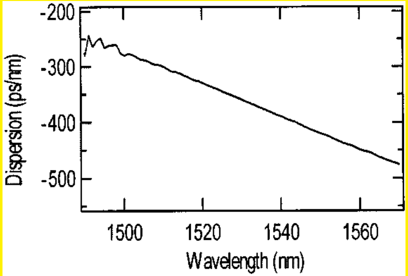
Two-Mode DCF

- Best Solution: Employ a two-mode DCF with $V \approx 2.5$.
- Second mode exhibits large negative values of D.
- A 1-km length can compensate dispersion accumulated over 50 km, while adding little extra loss or nonlinear degradation.
- The use of a two-mode DCF requires a mode-conversion device.
- Mode converter should be polarization-insensitive and operate over a broad bandwidth.
- A long-period grating is used for this purpose.
- Grating period $\Lambda \sim 100\ \mu$m is chosen to match the index difference $\delta\bar{n}$ between two modes ($\Lambda = \lambda/\delta\bar{n}$).

Two-Mode DCF Design



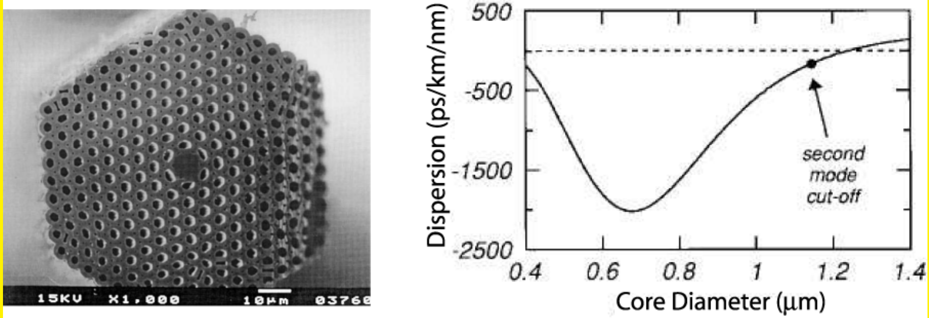
(a)



(b)

- First grating transfers power to higher-order mode.
- Seconds grating transfers power back into fundamental mode.
- Measured dispersion characteristics of such a 2-km-long DCF show $D = -420$ ps/(km-nm) near 1,550 nm.
- Such DCFs are polarization-insensitive, exhibit low insertion loss, and offer dispersion compensation over the entire C band.

Photonic-Crystal Design



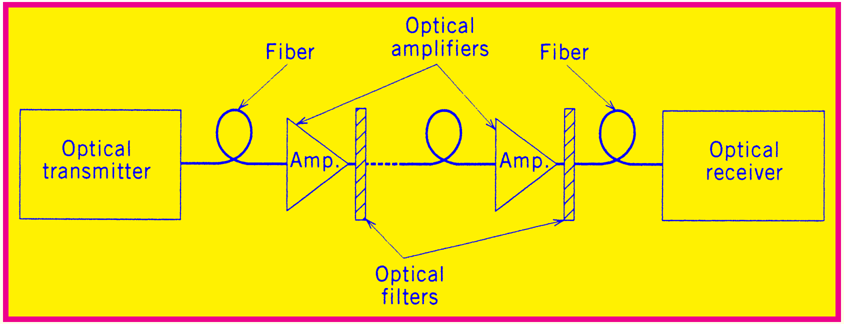
(a) (b)

- Photonic-crystal fibers contain a two-dimensional array of air holes that modify dispersion characteristics.
- D for a PCF is also depends on the core diameter.
- Values as large as $-2{,}000$ ps/(km-nm) are possible with a suitable design.
- Broadband dispersion compensation can be realized by tailoring size and spacing of air holes.

Reverse-Dispersion Fibers

- Such fibers are designed such that the signs of both D and S are reversed compared to standard fibers.
- Dispersion is compensated using fiber sections of same lengths.
- Lengths of fiber sections are reduced below 10 km so that the map period L_m becomes a small fraction of amplifier spacing L_A.
- This technique is referred to as short-period or dense dispersion management.
- Length of fiber drawn from a single perform is close to 5 km.
- Fiber cable is made by combining two types of fibers, resulting in a dispersion-free cable.

Dispersion-Equalizing Filters



- A shortcoming of DCFs is that a relatively long length (>5 km) is required.
- Losses encountered within each DCF add considerably to total link loss.
- Most dispersion-equalizing filters are relatively compact.
- Such a filter can be combined with the amplifier to compensate fiber losses and dispersion simultaneously in a periodic fashion.

Fabry–Perot Filters

- Any interferometer acts as an optical filter because its transmission (or reflection) is frequency dependent.
- A simple example is provided by the Fabry–Perot interferometer.
- The only problem is that its transfer function affects both the amplitude and phase.
- A good dispersion-equalizing filter should affect only the phase of light propagating through it.
- This problem can be solved by using a Gires–Tournois interferometer.
- It is just a FP interferometer whose back mirror is made 100% reflective.

Gires–Tournois Filters

- Transfer function of a GT filter:

$$H_{\rm GT}(\omega) = H_0 \left[\frac{-r + \exp(i\omega T_r)}{1 - r\exp(-i\omega T_r)} \right].$$

- Constant H_0 takes into account all losses, $|r|^2$ is front-mirror reflectivity, and T_r is round-trip time within the cavity.
- If losses are constant over the signal bandwidth, only spectral phase is modified by such a filter.
- Phase $\phi(\omega)$ of $H_{\rm GT}(\omega)$ is far from ideal.
- It is a periodic function, peaking at frequencies that correspond to longitudinal modes of the cavity.
- Near each peak, phase variations are nearly quadratic in ω.

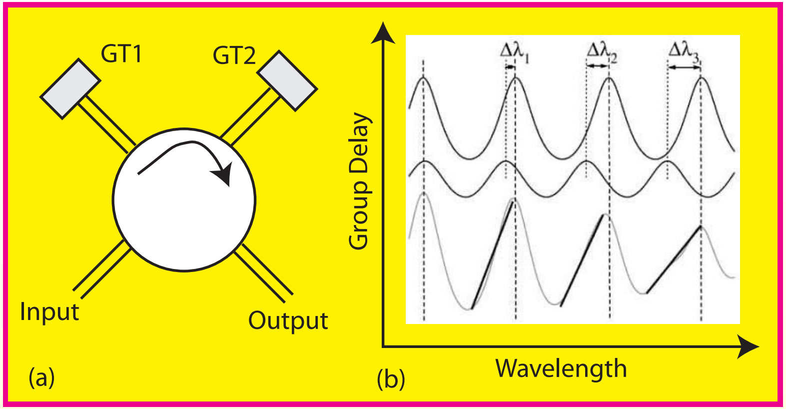
Dispersion of Gires–Tournois Filters

- Group delay $\tau_g = d\phi(\omega)/d\omega$, is also a periodic function.
- $\phi_2 = d\tau_g/d\omega$ is related to the slope of the group delay as

$$\phi_2 = 2T_r^2 r(1-r)/(1+r)^3.$$

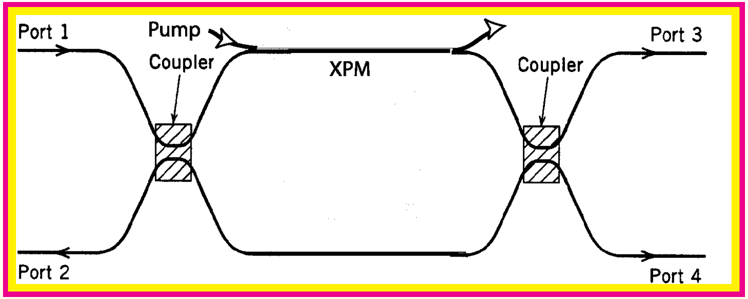
- For a 2-cm-thick GT filter designed with $r = 0.8$, $\phi_2 \approx 2,200$ ps^2.
- Such a filter can compensate dispersion acquired over 110 km of standard fiber.
- A GT filter can compensate dispersion for multiple channels simultaneously as it exhibits a periodic response.
- Periodic nature also indicates that ϕ_2 is same for all channels.
- A GT filter cannot compensate for the dispersion slope of transmission fiber without suitable design modifications.

Dispersion Slope Compensation



- In one approach, two GT filters are cascaded in series.
- Two filters have different cavity lengths and reflectivities, resulting in slightly shifted peaks and different amplitudes.
- Figure shows group delay for individual filters and the total group delay (gray curve). Dark lines show the slope.
- Different slopes indicate different dispersion near each peak.

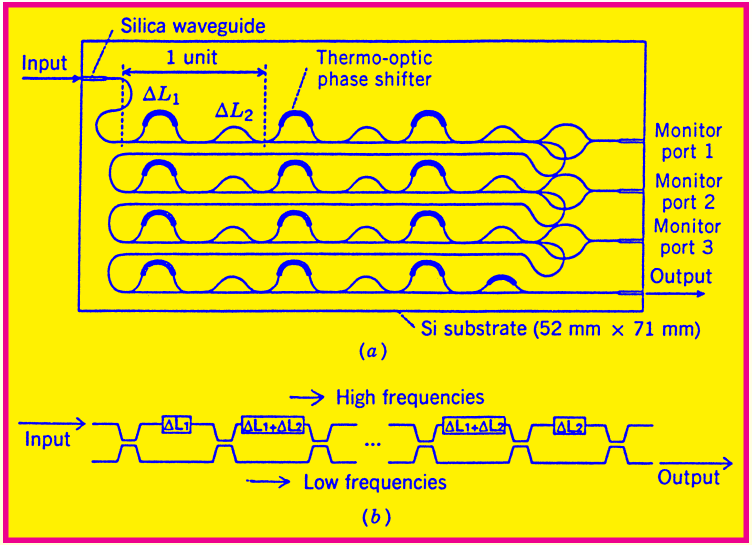
Mach–Zehnder Interferometer



- A MZ interferometer constructed by connecting two 3-dB directional couplers in series.
- First coupler splits input signal into two equal parts.
- Different phase shifts acquired in the MZ arms.
- Two fields interfere at the second coupler.
- Transfer function for the bar port

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

Mach–Zehnder Chain



- A cascaded chain of several MZ interferometers used in practice.
- Fabricated in the form of a planar lightwave circuit using silica-on-silicon technology.
- A chromium heater provides thermo-optic control of phase shift.

Mach–Zehnder Chain

- Functioning of the MZ chain can be understood as follows.
- Higher-frequency components of a pulse propagate in the longer arm of the MZ interferometers.
- Lower-frequency components take the shorter route.
- Relative delay is just the opposite of that introduced by a standard fiber exhibiting anomalous dispersion.
- In a 1994 implementation, a MZ chain with only five MZ interferometers provided a relative delay of 836 ps/nm.
- Such a 5-cm device can compensate dispersion acquired over 50 km.
- Main limitations: Relatively narrow bandwidth (∼10 GHz) and sensitivity to input polarization.

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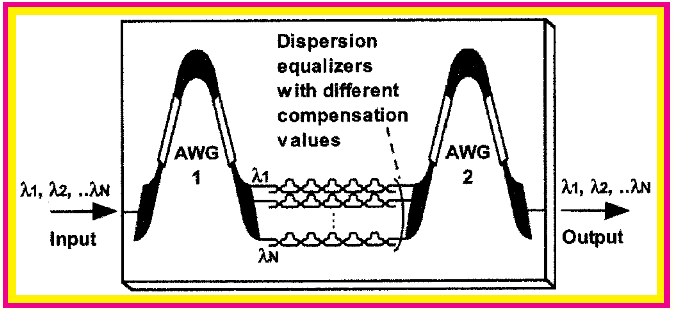
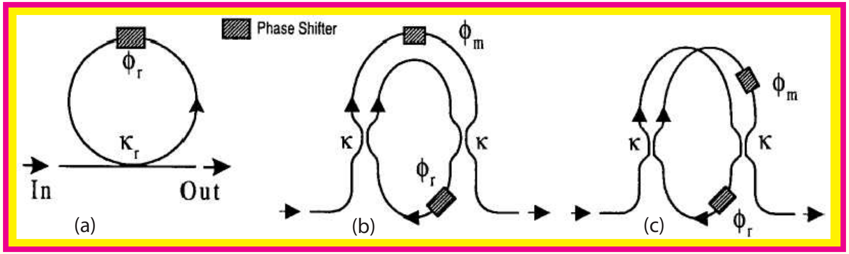
Close

Dispersion-Slope Compensation



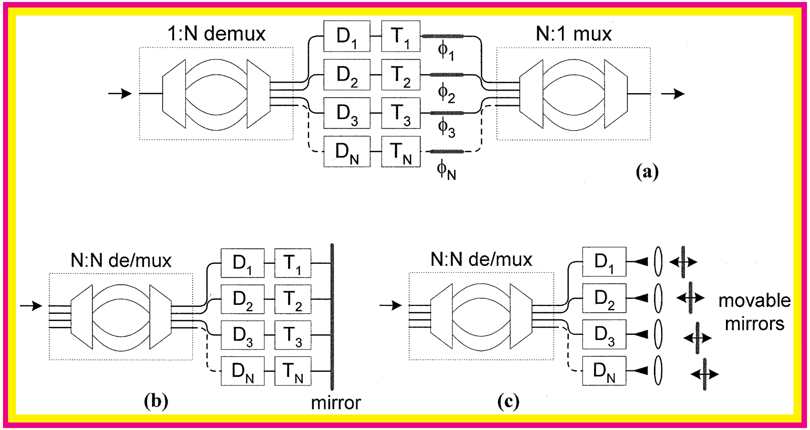
- A planar lightwave circuit capable of compensating both dispersion and dispersion slope is used.
- A separate MZ chain is employed for each WDM channel.
- WDM signal demultiplexed and then multiplexed back using arrayed waveguide gratings (AWGs).
- All components can be integrated on a single chip using silica-on-silicon technology.

All-Pass Filters



- (a) A simple ring resonator with a built-in phase shifter; cascading of multiple rings increases the amount of dispersion.
- An asymmetric or symmetric MZ configuration also acts as an all-pass filter.
- Phase shifters are incorporated using thin-film chromium heaters.
- Such devices can compensate even the dispersion slope of a fiber.
- One device exhibited dispersion that varied from -378 to -3026 ps/nm depending on the channel wavelength.

All-Pass Filters



- (a) A transmissive filter with controllable dispersion for each channel through optical delay lines and phase shifters.
- (b) A reflective filter with a fixed mirror.
- (c) A reflective filter with moving mirrors acting as delay lines.
- Such designs, although complicated, provide the most flexibility.

Fiber Bragg Gratings

- Bragg gratings act as optical filters because of a stop band.
- Light reflected back if its wavelengths falls within stop band.
- Stop band centered at the Bragg wavelength: $\lambda_B = 2\bar{n}\Lambda$.
- Grating period $\Lambda \approx 0.5$ μm near 1.55 μm.
- A holographic technique is used for making Bragg gratings.
- Use of gratings for dispersion compensation proposed in the 1980s.
- Their use became practical after 1990.
- Fiber gratings are available commercially and used routinely for a variety of applications.

Coupled-Mode Equations

- Refractive index varies along the length periodically as $n(z) = \bar{n} + n_g \cos(2\pi z/\Lambda)$.
- Index modulation depth $n_g \sim 10^{-4}$.
- Bragg gratings analyzed using coupled-mode equations

$$dA_f/dz = +i\delta A_f + i\kappa A_b,$$

$$dA_b/dz = -i\delta A_b - i\kappa A_f.$$

- Detuning $\delta = \frac{2\pi}{\lambda_0} - \frac{2\pi}{\lambda_B}$ and coupling coefficient $\kappa = \frac{\pi n_g \Gamma}{\lambda_B}$.
- Transfer function is found to be

$$H(\omega) = r(\omega) = \frac{A_b(0)}{A_f(0)} = \frac{i\kappa \sin(qL_g)}{q\cos(qL_g) - i\delta \sin(qL_g)}.$$

- Dispersion relation $q^2 = \delta^2 - \kappa^2$ (L_g = grating length).

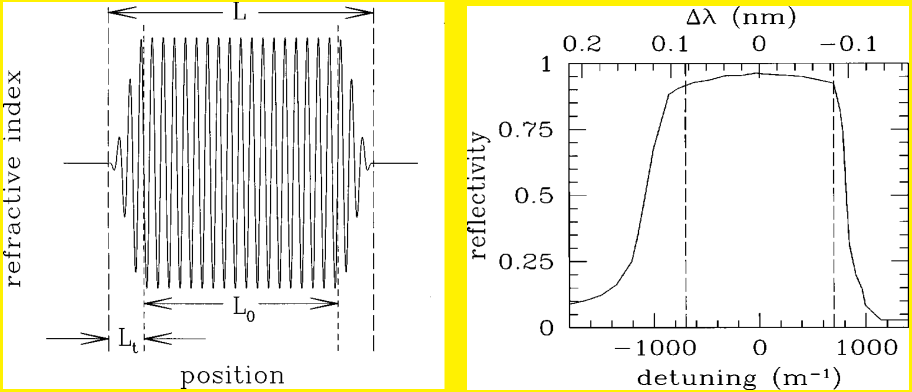
Grating-Induced Dispersion

- Dispersion of the grating is related to the frequency dependence of the phase of $H(\omega)$.
- Grating-induced dispersion exists mostly outside the stop band.
- In this region ($|\delta| > \kappa$), dispersion parameters are

$$\beta_2^g = -\frac{\text{sgn}(\delta)\kappa^2/v_g^2}{(\delta^2 - \kappa^2)^{3/2}}, \qquad \beta_3^g = \frac{3|\delta|\kappa^2/v_g^3}{(\delta^2 - \kappa^2)^{5/2}}.$$

- Grating dispersion normal ($\beta_2^g > 0$) on the "red" side of the stop band (used for dispersion compensation).
- A single 2-cm-long grating can compensate dispersion accumulated over 100 km of fiber.

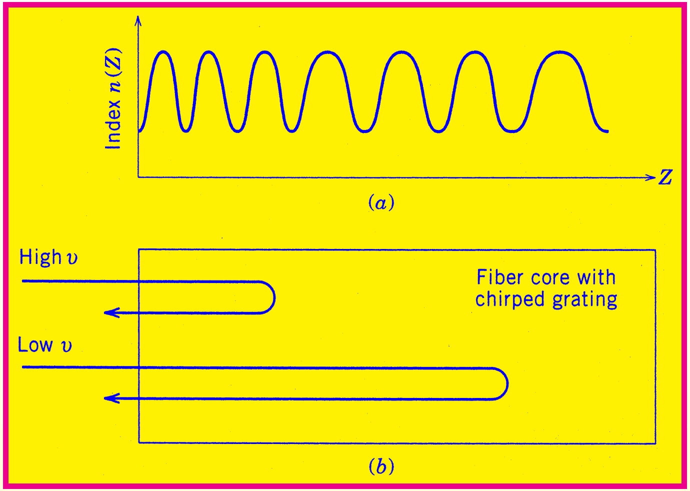
Apodized Gratings



(a) (b)

- An apodization technique is used to improve grating response.
- Index change n_g nonuniform, resulting in a z-dependent κ.
- Reflectivity spectrum of an apodized 7.5-cm-long grating.
- In some gratings κ is varied linearly over length.

Chirped Fiber Gratings



- Period $\bar{n}\Lambda$ of a chirped grating nonuniform over its length.
- Bragg wavelength $\lambda_B = 2\bar{n}\Lambda$ also varies along grating length.
- Equivalent to multiple cascaded gratings with different λ_B.
- Resulting stop band can become quite wide (>1 nm).

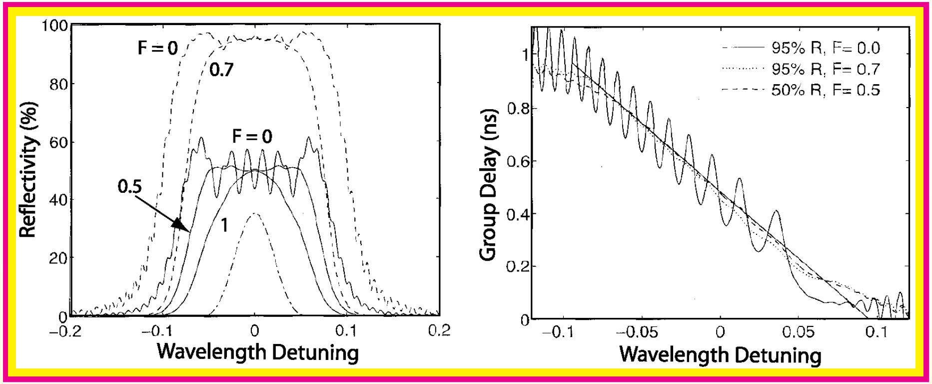
Dispersion of Chirped Gratings

- Origin of Dispersion: Different spectral components of an optical pulse are reflected at different points within the grating where the Bragg condition is satisfied locally.
- Low-frequency components of a pulse are delayed more if optical period increases along the grating.
- This situation corresponds to anomalous GVD.
- The same grating can provide normal GVD if it is flipped.
- Optical period $\bar{n}\Lambda$ of the grating should decrease for it to provide normal GVD.
- Dispersion magnitude determined by the rate at which $\bar{n}\Lambda$ decreases.

Dispersion Parameter

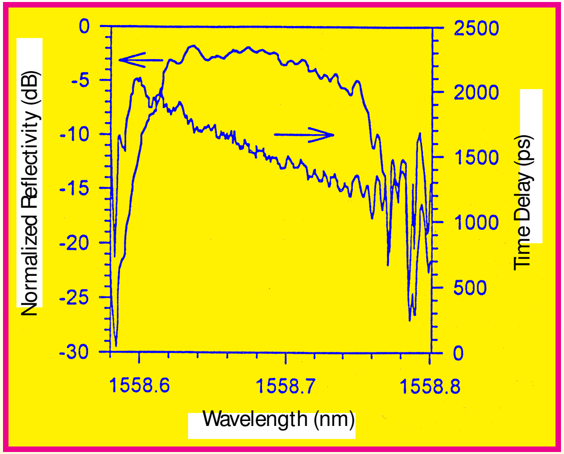
- Dispersion parameter D_g of a chirped grating of length L_g is determined from the relation $T_R = D_g L_g \Delta\lambda$.
- Here T_R is the round-trip time and $\Delta\lambda$ is the difference in the Bragg wavelengths at the two ends of the grating.
- Since $T_R = 2\bar{n}L_g/c$, grating dispersion is given by $D_g = 2\bar{n}/(c\Delta\lambda)$.
- As an example, $D_g \approx 5\times10^7$ ps/(km-nm) for a grating bandwidth $\Delta\lambda = 0.2$ nm.
- Because of such large values of D_g, a 10-cm-long chirped grating can compensate dispersion acquired over 300 km.
- This is remarkable for an optical filter that is only 10 cm long.

Apodized Chirped Fiber Gratings



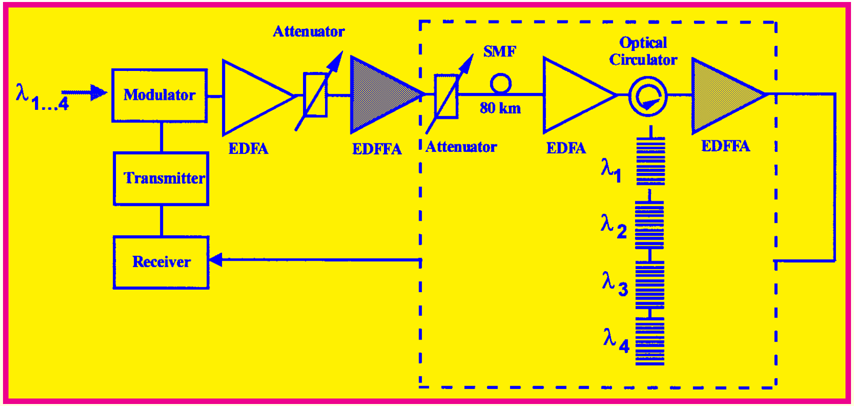
- Fraction F of the grating length over which a chirped grating is apodized plays an important role.
- (a) Reflectivity and (b) group delay for chirped gratings with 50% (solid) or 95% (dashed) reflectivity for different values of F.
- Group delay should vary with wavelength linearly to produce a constant GVD across the signal spectrum.
- It should be as ripple-free as possible.

Mesured Reflectivity Spectrum



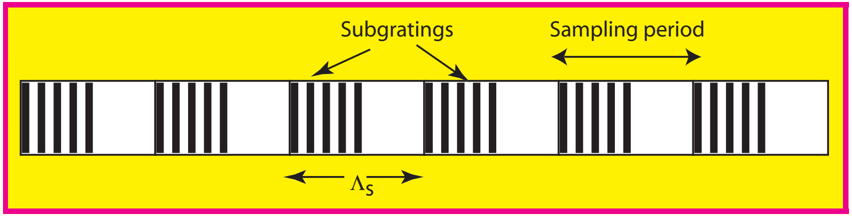
- Measured reflectivity and group delay for a linearly chirped fiber grating with a bandwidth of 0.12 nm.
- In a 1996 experiment, two chirped gratings were cascaded in series to compensate fiber dispersion over 537 km.
- Chirped gratings work as a reflection filter. An optical circulator is used in practice to reduce insertion losses.

Chirped Gratings for WDM Systems



- A chirped grating can have a stop band as wide as 10 nm if it is made long enough.
- When WDM bandwidth is larger than that, several gratings are cascaded in series.
- By 2000, this approach was applied to a 32-channel WDM system with 18-nm bandwidth.

Sampled Gratings



- A sampled or superstructure grating consists of multiple subgratings separated from each other by a section of uniform index.
- Each subgrating is a sample, hence the name "sampled" grating.
- Made by blocking certain regions during fabrication such that $\kappa = 0$ in the blocked regions.
- It can also be made by etching away parts of an existing grating.
- New feature: $\kappa(z)$ varies periodically along z.
- This periodicity modifies the stop band.

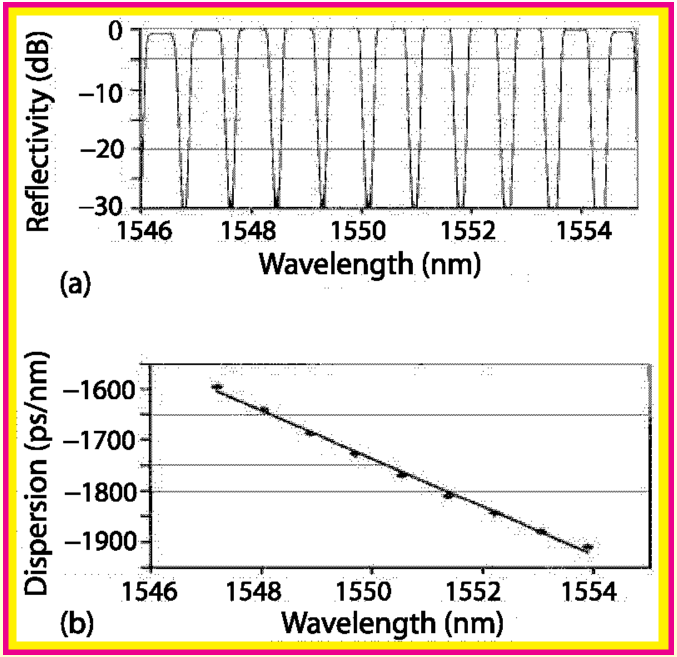
Amplitude-Sampled Gratings

- Coupled-mode equations show that a sampled grating exhibits multiple periodic stop bands.
- Spacing $\Delta\nu_p$ among reflectivity peaks is set by sample period Λ_s as $\Delta\nu_p = c/(2n_g\Lambda_s)$.
- If subgratings are chirped, dispersion of each reflectivity peak is governed by the local chirp.
- Sampling period Λ_s shoud be about 1 mm to ensure that $\Delta\nu_p$ is close to 100 GHz.
- In the simplest kind of grating, sampling function is a "rect" function such that $S(z) = 1$ over each subgrating.

Design of Sampled Gratings

- Shape of the reflectivity spectrum is governed by the Fourier transform of $S(z)$.
- For a "rect" function $S(z)$, reflectivity follows a "sinc" function.
- A constant reflectivity for all peaks can be realized using $S(z) = \sin(az)/az$.
- Dispersion slope can be compensated by introducing a chirp in the sampling period Λ_s, in addition to the grating period.
- Figure shows the reflection and dispersion characteristics of a 10-cm-long grating designed for 8 channels with 100-GHz spacing.

Dispersion of Sampled Gratings



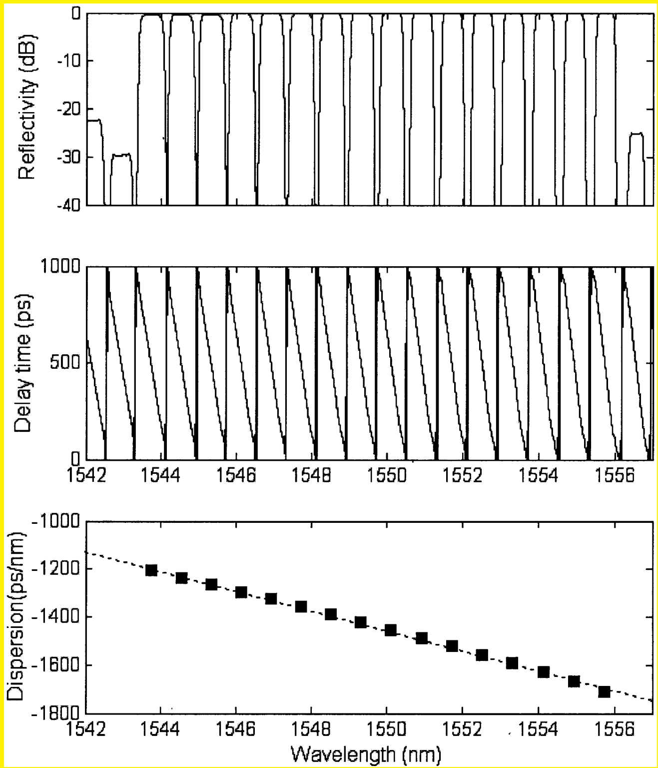
Phase-Sampled Gratings

- Amplitude smapling impractical as the number of WDM channels increases.
- In phase-sampled gratings $S(z)$ modifies phase of κ, rather than its amplitude.
- In contrast with the case of amplitude sampling, refractive index is modulated over the entire grating length.
- Mathematically, index variations are of the form

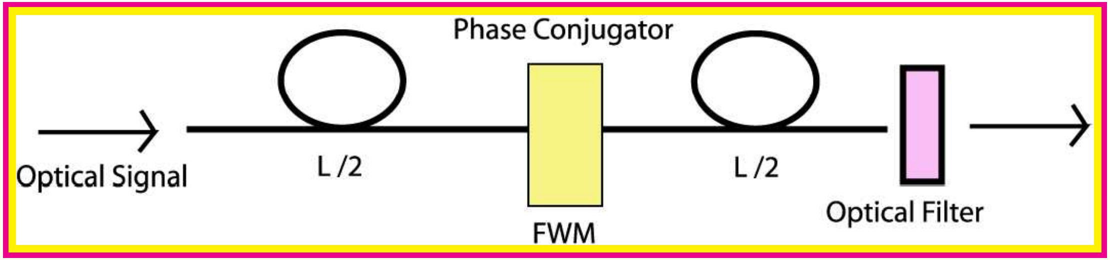
$$n(z) = \bar{n} + n_g \mathrm{Re}\{\exp[2i\pi(z/\Lambda_0) + i\phi_s(z)]\}.$$

- Reflectivity, group delay, and dispersion of a phase-sampled grating designed for 16 WDM channels are shown in the following figure.

Phase-Sampled Gratings



Optical Phase Conjugation



- Four-wave mixing used to generate phase-conjugated idler field in the middle of fiber link.
- β_2 reversed for the phase-conjugated field:

$$\frac{\partial A}{\partial z} + \frac{i\beta_2}{2}\frac{\partial^2 A}{\partial t^2} = 0 \quad \rightarrow \quad \frac{\partial A^*}{\partial z} - \frac{i\beta_2}{2}\frac{\partial^2 A^*}{\partial t^2} = 0.$$

- Pulse shape restored at the fiber end.
- Basic idea patented in 1979.
- First experimental demonstration in 1993.

Thory Behind Phase Conjugation

- Pulse spectrum just before the phase conjugator: $\tilde{A}(L/2,\omega) = \tilde{A}(0,\omega)\exp(i\omega^2\beta_2 L/4)$.
- Pulse spectrum just after phase conjugation:

$$\tilde{A}^*(L/2,\omega) = \tilde{A}^*(0,-\omega)\exp(-i\omega^2\beta_2 L/4).$$

- Spectrum inverted because $\omega_c = 2\omega_p - \omega$.
- Optical field at the end of fiber link:

$$A^*(L,t) = \frac{1}{2\pi}\int_{-\infty}^{\infty}\tilde{A}^*\left(\frac{L}{2},\omega\right)\exp\left(\frac{i}{4}\beta_2 L\omega^2 - i\omega t\right)d\omega.$$

- It is easy to see that $A(L,t) = A^*(0,t)$.
- Pulse shape restored to its input form irrespective of how much pulse broadened in the first section.

SPM Compensation

- Using $A(z,t) = B(z,t)p(z)$, pulse propagation is governed by

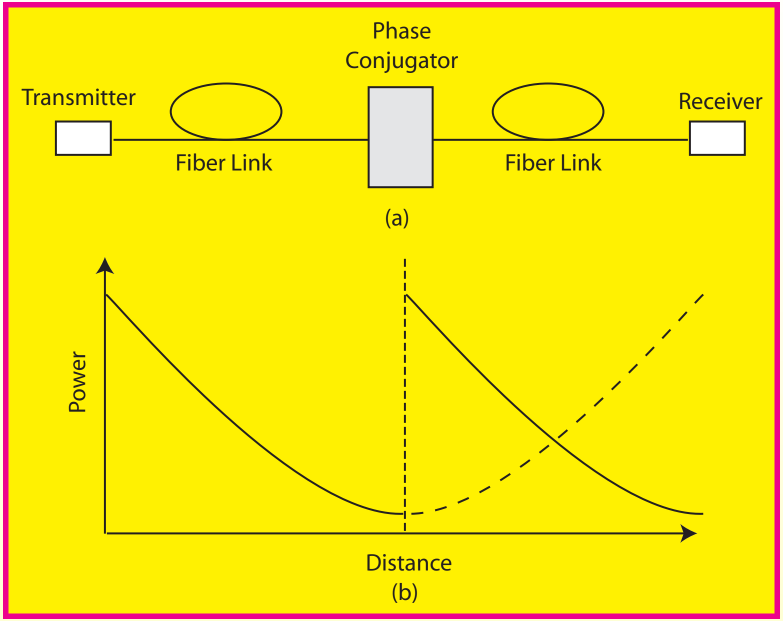
$$\frac{\partial B}{\partial z} + \frac{i\beta_2}{2}\frac{\partial^2 B}{\partial t^2} = i\gamma p(z)|B|^2 B.$$

- Signs of both β_2 and γ change when $B \rightarrow B^*$.
- Both SPM and GVD can be compensated by OPC when $p(z) = 1$.
- Fiber losses destroy this important property of midspan OPC.
- Physical reason: SPM-induced phase shift is power dependent.
- Much larger phase shifts are induced in the first-half of the link than the second half.
- Use of an optical amplifier at $z = L/2$ does not help.

Back

Close

SPM Compensation



- Dashed line shows $p(z)$ required for SPM compensation ($p(z) = p(L-z)$).
- Distributed amplification helps to some extent.

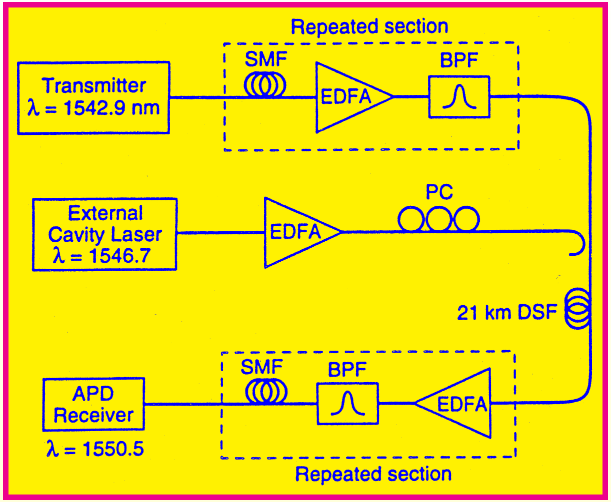
Dispersion-Decreasing Fibers

- Perfect compensation of both GVD and SPM can be realized by employing dispersion-decreasing fibers.
- In such fibers $|\beta_2|$ decreases along fiber length.
- With the transformation $\xi = \int_0^z p(z)\,dz$,

$$\frac{\partial B}{\partial \xi} + \frac{i}{2} b(\xi) \frac{\partial^2 B}{\partial t^2} = i\gamma |B|^2 B.$$

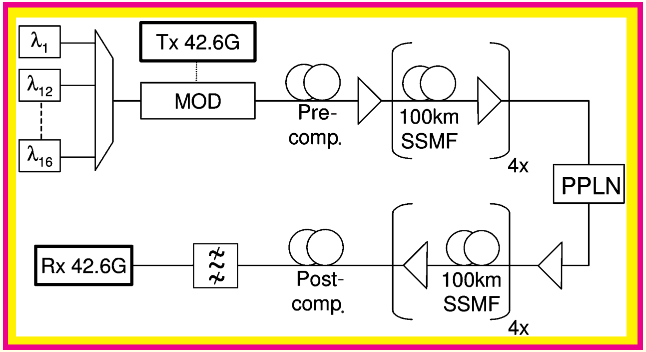
- Effective dispersion parameter $b(z) = \beta_2(z)/p(z)$.
- If $\beta_2(z)$ decreases in exactly the same way as $p(z)$, $b(z)$ becomes independent of z as the ratio remains constant.
- Thus, GVD should decrease as $e^{-\alpha z}$.
- Such fibers can be made by tailoring core radius of the fiber.

Experimental Results



- A long fiber used for OPC in a 1993 experiment.
- Pump wavelength coincided with zero-dispersion wavelength.
- Practical issues: Wavelength shift of OPC signal, polarization sensitivity, insertion losses, higher-order dispersion, etc.

WDM Systems



- A Periodically poled lithium niobate (PPLN) can also act as a phase conjugator.
- It was used in 2004 to demonstrate transmission of 16 channels (at 40 Gb/s) over 800 km of standard fiber.
- A single pump phase-conjugated all 16 WDM channels as it inverted the signal spectrum around the pump wavelength.

Prechirp Technique

- Modifies input pulses before they are launched into fiber link.
- Prechirping of input pulse modifies a Gaussian pulse as

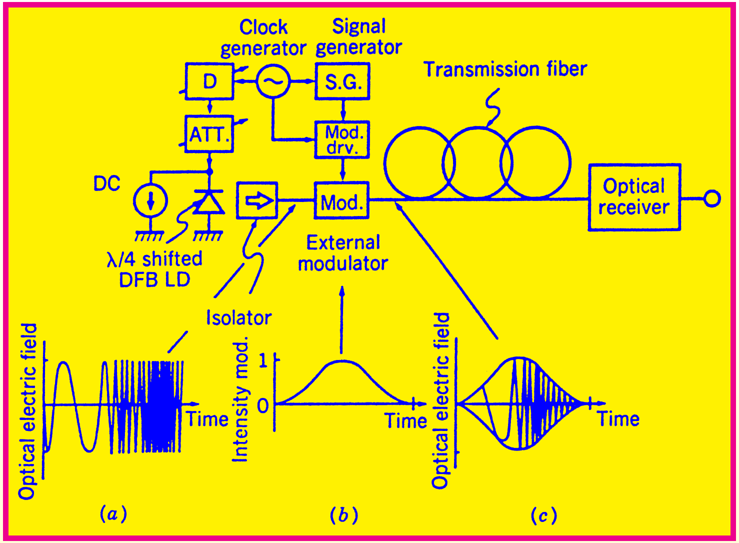
$$A(0,t) = A_0 \exp\left[-\frac{1+iC}{2}\left(\frac{t}{T_0}\right)^2\right].$$

- Suitably chirped pulses can propagate over longer distances before they broaden outside its bit slot.
- Assuming broadening by $\sqrt{2}$ is tolerable,

$$L = \frac{C + \sqrt{1+2C^2}}{1+C^2} L_D.$$

- Maximize L with respect to the chirp parameter C.
- $L = \sqrt{2} L_D$ for $C = 1/\sqrt{2}$ (41% increase).

Prechirp Technique (continued)



- Frequency of DFB laser modulated (FM) through direct current modulation.
- An external modulator modulates envelope (AM).
- Simultaneous AM and FM produces chirped pulses.

Prechirp Technique (continued)

- FM optical signal can be written as

$$E(0,t) = A_0 \exp(-t^2/T_0^2) \exp[-i\omega_0(1+\delta \sin \omega_m t)t],$$

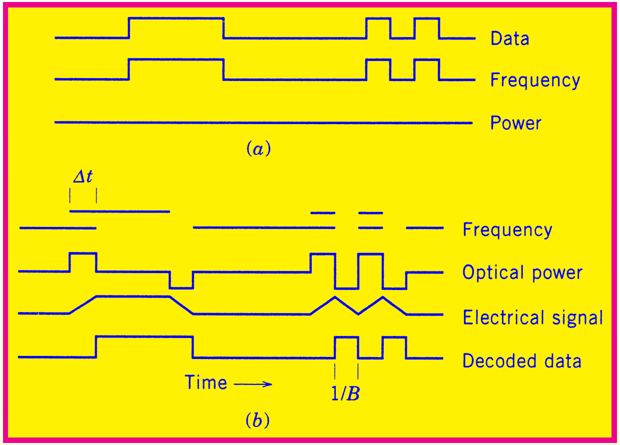
- Near pulse center, $\sin(\omega_m t) \approx \omega_m t$, and

$$E(0,t) \approx A_0 \exp\left[-\frac{1+iC}{2}\left(\frac{t}{T_0}\right)^2\right] \exp(-i\omega_0 t).$$

- Effective Chirp parameter $C = 2\delta\omega_m\omega_0 T_0^2$.
- Both the sign and magnitude of C can be controlled by changing FM parameters δ and ω_m.
- Phase modulation can also be used:

$$E(0,t) = A_0 \exp(-t^2/T_0^2) \exp[-i\omega_0 t + i\delta \cos(\omega_m t)].$$

FSK Format



- FSK: 1 and 0 bits transmitted with different carrier wavelengths.
- Two wavelengths travel at slightly different speeds.
- Wavelength shift $\Delta\lambda$ delays 0 bits by $\Delta T = DL\Delta\lambda$.
- $\Delta\lambda$ chosen such that $\Delta T = T_B = 1/B$.
- This scheme is called dispersion-supported transmission.

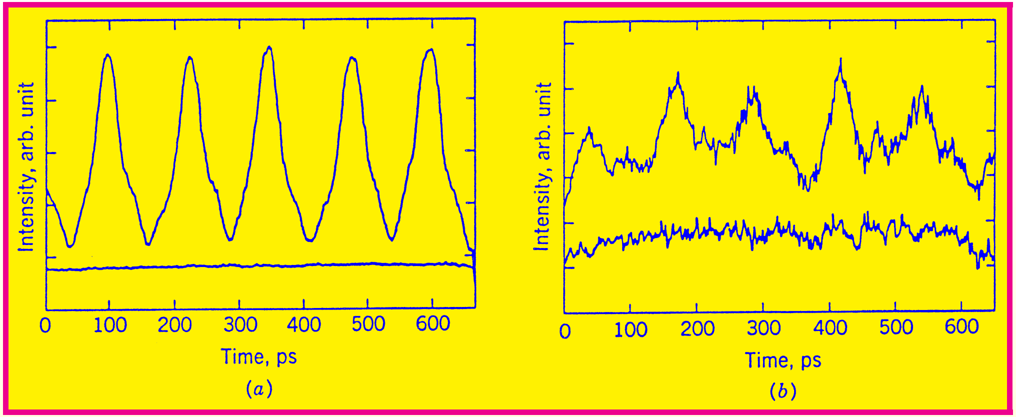
Duobinary Coding

- Duobinary coding reduces signal bandwidth by 50%.
- Dispersive effects reduced for a smaller-bandwidth signal.
- Two successive bits in the digital bit stream summed
  to form a three-level duobinary code at half the bit rate.

$$1+1=2, \quad 0+0=0, \quad 0+1=1, \quad 1+0=1.$$

- Receiver design quite complicated because of the ambiguity between $0+1$ and $1+0$ combinations.
- Phase information is used to distinguish the two.

Nonlinear Prehirping



- Amplify transmitter output using an SOA.
- Gain saturation leads to time-dependent variations in the carrier density, and thus in the refractive index.
- SOA not only amplifies the pulse but also chirps it.
- Input pulse compressed when $\beta_2 < 0$.
- 16-Gb/s signal transmitted over 70 km of standard fiber.

SPM-Induced Prehirping

- Uses self-phase modulation (SPM) for chirping the pulse.
- Transmitter output passed through a fiber of suitable length:

$$A(0,t) = \sqrt{P(t)}\exp[i\gamma L_m P(t)].$$

- In the case of Gaussian pulses

$$A(0,t) \approx \sqrt{P_0}\exp\left[-\frac{1+iC}{2}\left(\frac{t}{T_0}\right)^2\right]\exp(-i\gamma L_m P_0).$$

- Effective SPM-induced hirp parameter: $C = 2\gamma L_m P_0$.
- Transmission fiber itself can be used for chirping the pulse.
- This is the basic idea behind solitons.

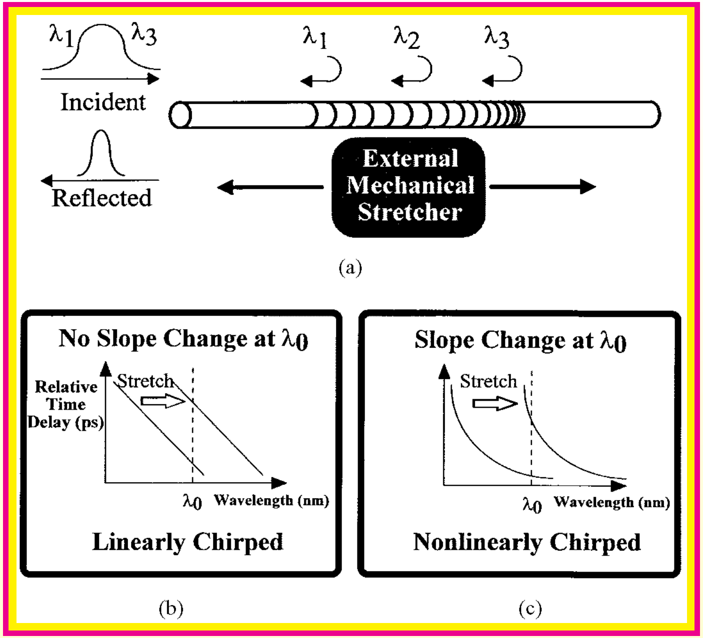
Postcompensation Techniques

- Employs an electronic technique at the receiver.
- Relatively easy to implement if a heterodyne receiver is used.
- Heterodyne receivers first convert data into microwave format.
- A microwave bandpass filter cancel the effects of GVD.
- Much harder to solve the GVD problem for direct detection since all phase information is lost.
- Several nonlinear equalization techniques permit signal recovery.
- They require electronic logic circuits operating at the bit rate.
- Electronic equalization limited to low bit rates and to distances of only a few dispersion lengths.

Tunable Dispersion Compensation

- Not all WDM channels can be compensated perfectly by a single DCF.
- Residual dispersion for each channel needs compensation at the receiver (called postcompensation).
- Precise amount of residual dispersion not known in practice (dispersion variations along fiber length).
- Dynamic variations can occur because of temperature fluctuations.
- Solution: Tunable dispersion compensation

Stretched Fiber Gratings



- Dispersion tuned by stretching a nonlinearly chirped grating.
- Grating is placed on a mechanical stretcher and a piezoelectric transducer is used to stretch it.

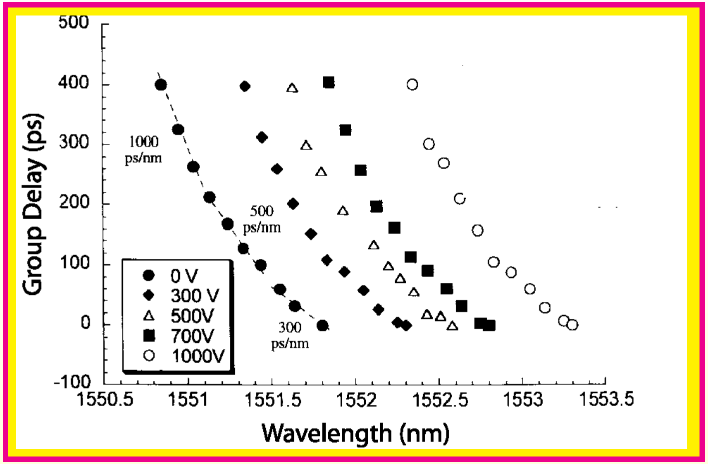
Role of Nonlinear Chirp

- In a chirped grating, group delay $\tau_g = \frac{2}{c}\int_0^{L_g} \bar{n}(z)\,dz$.
- Stress-induced changes in mode index $\bar{n}$ change the local Bragg wavelength as $\lambda_B(z) = 2\bar{n}(z)\Lambda(z)$.
- Slope of group delay at a given wavelength does not change when $\bar{n}$ is a linear function of z.
- Grating dispersion is given by

$$D_g(\lambda) = \frac{d\tau_g}{d\lambda} = \frac{2}{c}\frac{d}{d\lambda}\left(\int_0^{L_g} \bar{n}(z)\,dz\right).$$

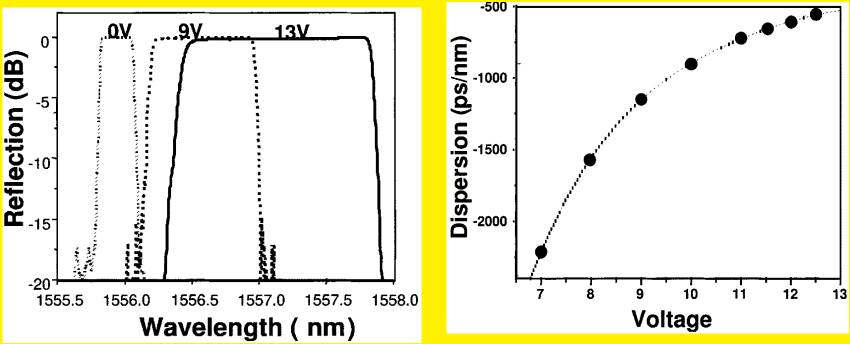
- Value of D_g at any wavelength can be altered by changing mode index $\bar{n}$ (through heating or stretching).

Stretched Fiber Gratings



- Group delay as a function of wavelength at several applied voltages for a 5-cm-long nonlinearly chirped fiber grating.
- For a fixed channel wavelength, dispersion can be changed from −300 to −1,000 ps/nm by changing voltage.
- Tunable compensation for multiple channels possible by using a sampled grating with nonlinear chirp.

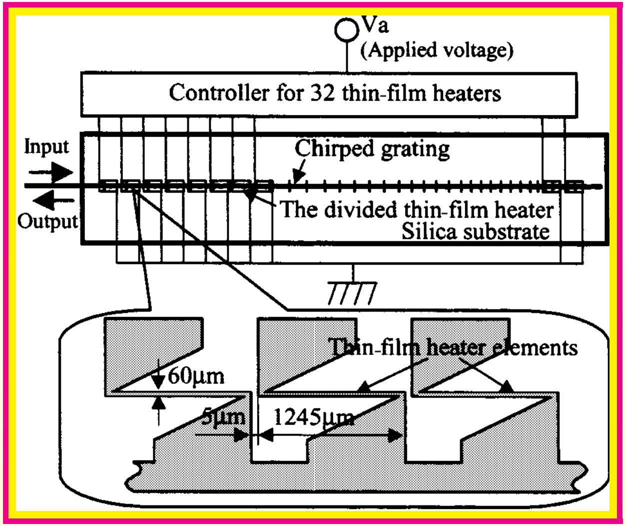
Temperature Tuning



(a) (b)

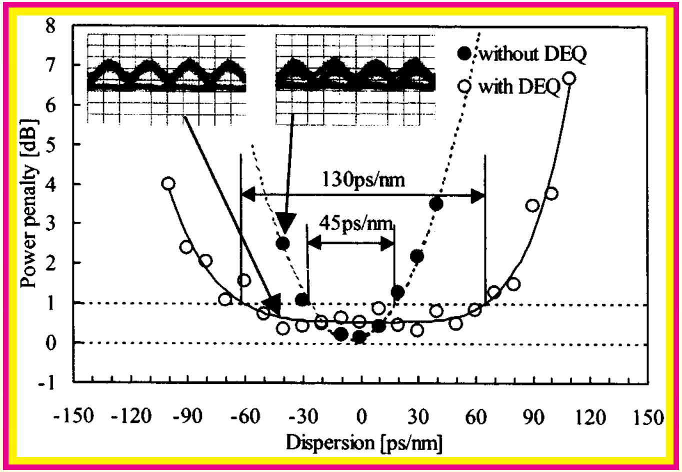
- Grating is made with a linear chirp, and a temperature gradient is used to produce tunable dispersion.
- Distributed heating requires a thin-film heater deposited on the outer surface of the fiber grating.
- (a) Reflection spectrum and (b) total GVD as a function of voltage for a fiber grating with temperature gradient.

Temperature Tuning



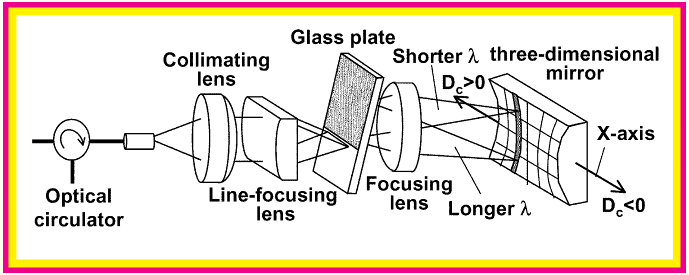
- A segmented thin-film heater provides better temperature control.
- 32 chromium heating elements formed on a silica substrate.
- Only a few volts required to change dispersion slope from +100 to −300 ps/nm^2.

Experimental Results



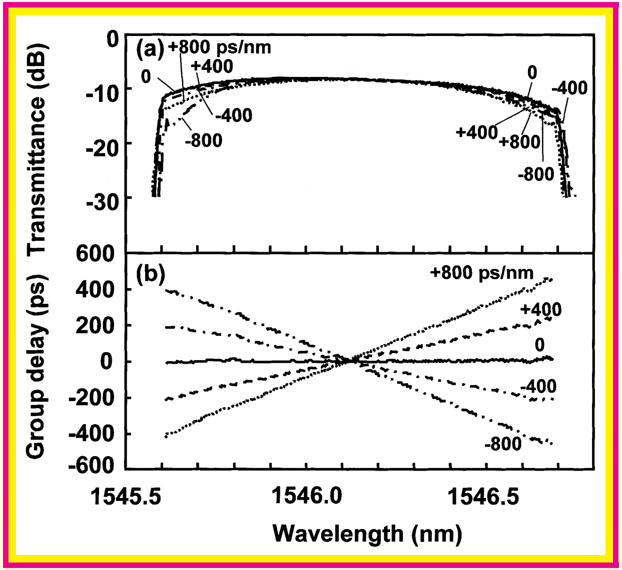
- Solid and dashed curves show power penalties with (filled circles) and without (empty circles) the dispersion equalizer.
- Recorded eye diagrams are shown at two data points (arrows).
- Tolerable dispersion range can be more than doubled.

Virtually Imaged Phased Array



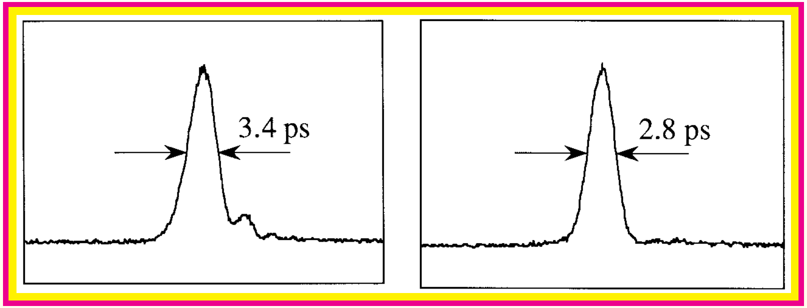
- A virtually imaged phased array can provide tunable dispersion.
- Signal is focused onto a tilted glass plate with 100% and 98% reflecting layers on its front and back surfaces.
- This arrangement creates multiple beams that appear to diverge from an array of virtual images.
- Interference among these beams produces output at an angle that varies with wavelength.

Virtually Imaged Phased Array



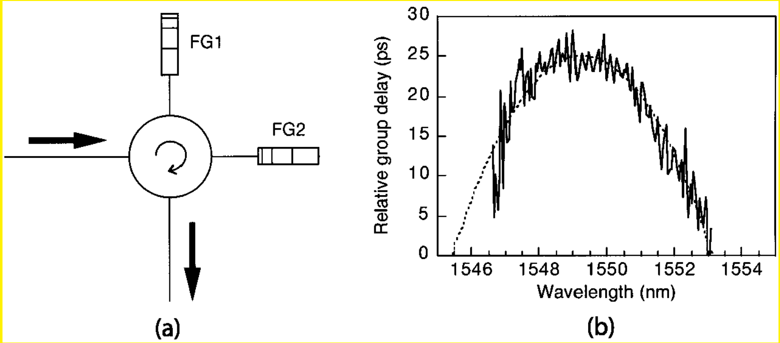
- Light is focused on a mirror that provides controllable wavelength-dependent group delay by moving the mirror along one axis.
- Dispersion can be varied from -800 to $+800$ ps/nm.

Higher-Order Dispersion Management



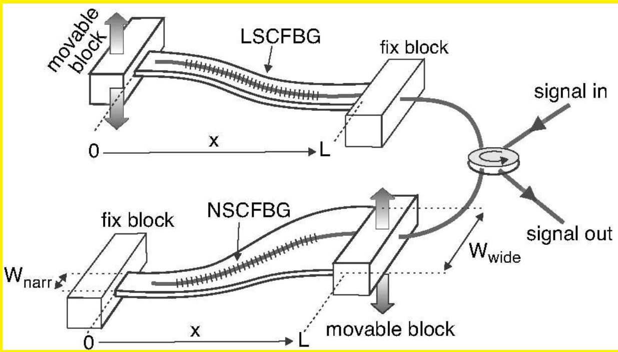
- Third-order dispersion requires $\beta_{31}L_1 + \beta_{32}L_2 = 0$.
- Necessary when short pulses are used at high bit rates.
- Cascaded MZ filters can be used for this purpose.
- Pulse distorted when a 2.1-ps pulse was transmitted over 100 km.
- Equalizing filter eliminated oscillatory tail and reduces pulse width to 2.8 ps.
- Residual increase in the pulse width is due to PMD.

Cascaded Chirped Fiber Gratings



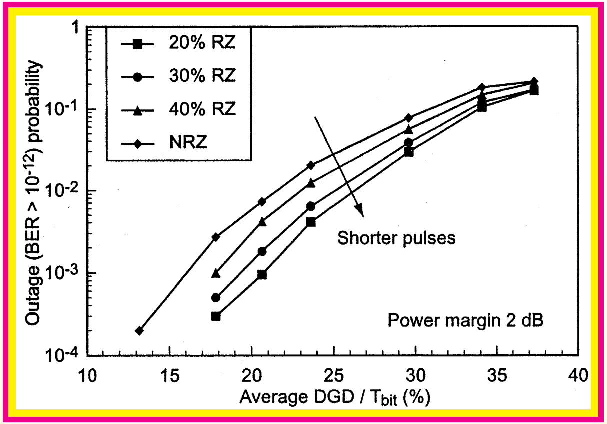
- A nonlinearly chirped fiber grating can compensate TOD.
- Cascading of two chirped gratings ccomensates β_3 without affecting β_2.
- One of the chirped grating is flipped so that the combination provides no net GVD.
- Their TOD contributions add up to produce a nearly parabolic shape for the relative group delay.

Cascaded Chirped Fiber Gratings



- A linearly strain-chirped fiber Bragg grating (LSCFBG) is cascaded with another that is nonlinearly chirped (NSCFBG).
- Both gratings are mounted on a substrate that could be bent by moving a block.
- It was possible to change only dispersion slope from 0 to -58 ps/nm^2 over a bandwidth of 1.7 nm.

PMD Problem



- A PMD-limited system is quantified through outage probability.
- Outage probability depends on data format; performance better for RZ format with shorter pulses.
- Outage probability $< 10^{-5}$ (5 min/year) is required.
- Average DGD should satisfy $\sigma_T < 0.1/B$.

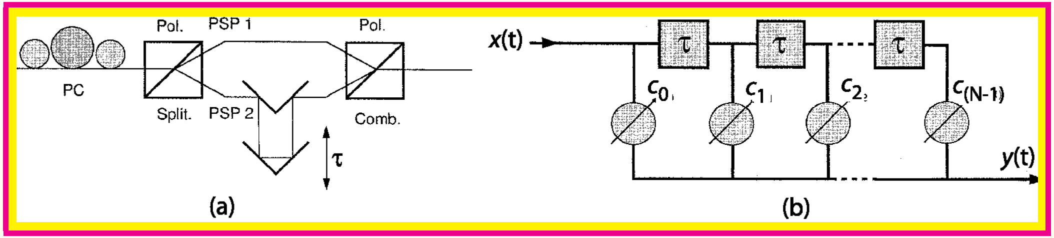
Need for PMD Compensation

- Average pulse broadening governed by the PMD parameter:

$$\sigma_T = D_p \sqrt{L}.$$

- If we use $B\sigma_T = 0.1$, $B^2L < (10D_p)^{-2}$.
- In the case of "old" fiber links, $B^2L < 10^4$ (Gb/s)^2-km, if we use $D_p = 1$ ps/$\sqrt{\text{km}}$ as a representative value.
- Such fibers require PMD compensation at $B = 10$ Gb/s when link length exceeds even 100 km.
- For modern fibers $D_p < 0.1$ ps/$\sqrt{\text{km}}$. As a result, B^2L exceeds 10^6 (Gb/s)^2-km.
- PMD compensation is not necessary at 10 Gb/s but may be required at 40 Gb/s if the link length exceeds 600 km.

PMD Compensation Techniques

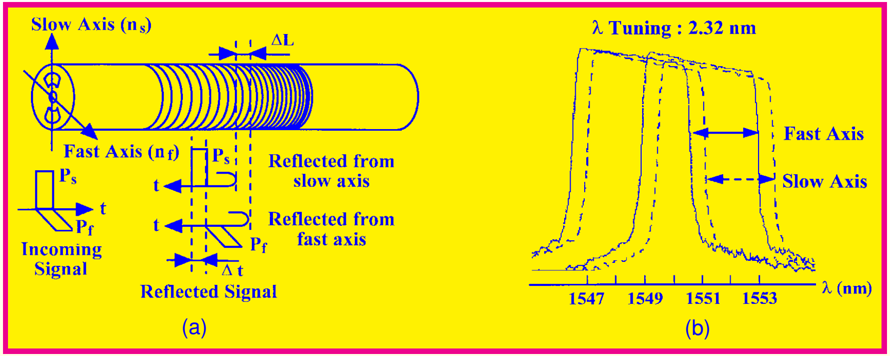


- Schematic illustration of (a) optical and (b) electrical PMD compensators.
- Electrical PMD equalizer corrects for the PMD effects within the receiver using a transversal filter.
- This filter splits electrical signal $x(t)$ into a number of branches using multiple delay lines to form $y(t) = \sum_{m=0}^{N-1} c_m x(t - m\tau)$.
- Error signal for control electronics is based on closing of the "eye" at the receiver.

Optical PMD Compensation

- PMD-distorted signal is separated into two components along PSPs, which are delayed by different amounts before being combined.
- Delay is adjustable in one branch through a variable delay line.
- A feedback loop is used to adjust polarization controller in response to changes in the fiber PSPs.
- The success of this technique depends on $L/L_{\rm PMD}$, where $L_{\rm PMD} = (T_0/D_p)^2$.
- Considerable improvement expected for $L < 4L_{\rm PMD}$.
- $L_{\rm PMD} \sim$ 10,000 km for $D_p \approx 0.1$ ps/ $\sqrt{\rm km}$ and $T_0 = 10$ ps.
- Optical PMD compensators can work over transoceanic distances for 10-Gb/s systems.

Tunable PMD Compensation



- A birefringent chirped fiber grating can be used.
- Because of birefringence, two components have different Bragg wavelengths and slightly shifted stop bands.
- Resulting DGD that can compensate for the PMD-induced DGD.
- This DGD is wavelength-dependent for a chirped grating.
- It can be tuned over 5 nm by stretching the grating.

Chapter 8: Nonlinearity Management

- Role of Fiber Nonlinearity
- Solitons in Optical Fibers
- Dispersion-Managed Solitons
- Pseudo-linear Lightwave Systems
- Intrachannel Nonlinear Effects
- High-Speed Lightwave Systems

Role of Fiber Nonlinearity

- In the absence of nonlinear effects, system performance is only limited by the SNR degradation induced by amplifier noise.
- Since SNR can be improved by increasing input optical power, link length can be made arbitrarily long.
- However, nonlinear effects are not negligible for long-haul systems when power levels exceed a few milliwats.
- Degradation induced by the nonlinear effects depends on the dispersion map employed.
- Different dispersion maps can lead to different Q factors.
- An optimum power level exists at which BER is the lowest and the system performs best.

Nonlinear Schrödinger Equation

- Propagation of an optical bit stream inside a dispersion-managed system is governed by the NLS equation:

$$i\frac{\partial A}{\partial z} - \frac{\beta_2}{2}\frac{\partial^2 A}{\partial t^2} + \gamma|A|^2 A = \frac{i}{2}(g_0 - \alpha)A.$$

- With the transformation $A(z,t) = \sqrt{P_0 p(z)}\,U(z,t)$, this equation becomes

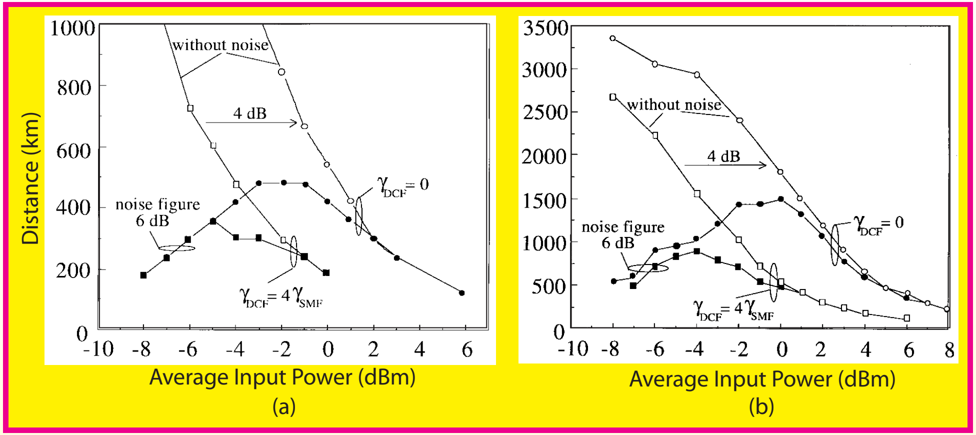
$$i\frac{\partial U}{\partial z} - \frac{\beta_2}{2}\frac{\partial^2 U}{\partial t^2} + \gamma P_0 p(z)|U|^2 U = 0.$$

- P_0 = input peak power; $p(z) = \exp\left(\int_0^z [g_0(z) - \alpha(z)]\,dz\right)$.
- $p(z_m) = 1$, where $z_m = mL_A$ is amplifier location.
- In the case of lumped amplifiers, $p(z) = \exp[-\int_0^z \alpha(z)\,dz]$.

System Design Issues

- Two major design issues exist for a dispersion-managed system:
  - ⋆ What is the optimum dispersion map?
  - ⋆ Which modulation format provides the best performance?
- Both of them studied by solving the NLS equation numerically.
- Dispersion map: 50 km of standard fiber [$D = 16$ ps/(km-nm), $\alpha = 0.2$ dB/km, and $\gamma = 1.31$ W^{-1}/km] followed by 10 km of DCF [$D = -80$ ps/(km-nm), $\alpha = 0.5$ dB/km, and $\gamma = 5.24$ W^{-1}/km].
- Optical amplifiers with 6-dB noise figure placed 60 km apart.
- Maximum transmission distance L calculated at which eye opening is reduced by 1 dB for a 40-Gb/s system.

NRZ versus RZ Format

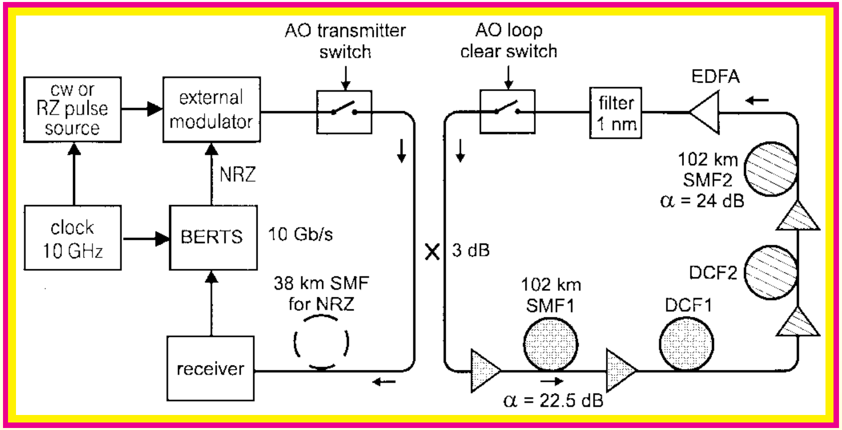


- Results for (a) NRZ and (b) RZ formats.
- Without amplifier noise, distance can be increased by decreasing launched power (empty symbols).
- When noise is included, an optimum power level exists for which link length is maximum.
- This distance is <400 km for the NRZ format.

Nonlinear Effects Within DCF

- Reason: RZ-format pulses spread quickly and their peak power is reduced considerably.
- This reduction in the peak power lowers the impact of SPM.
- Buildup of nonlinear effects within DCFs also affects system performance.
- Even for RZ format, maximum distance is $<$900 km at a power of -4 dBm because of DCF-induced nonlinear degradation.
- Not only DCFs have a larger nonlinear parameter, pulses are also compressed inside them, resulting in much higher peak powers.
- If the nonlinear effects can be suppressed within DCF, maximum distance can be increased close to 1,500 km.

Recirculating Fiber Loop



- Recirculating fiber loop used to demonstrate transmission of a 10-Gb/s signal over 2,040 km of standard fiber.
- Two 102-km sections of standard fiber and two 20-km DCFs used.
- A filter with a 1-nm bandwidth used to reduce ASE noise.
- Two acousto-optic switches control the the loop.

System Design

- Perfect compensation of GVD in each map period is not the best solution in the presence of nonlinear effects.
- A numerical approach is used to optimize the design of dispersion-managed lightwave systems.
- In a 1998 experiment, a 40-Gb/s signal was transmitted over 2,000 km of standard fiber using a novel dispersion map.
- Distance could be increased to 16,500 km at 10 Gb/s by placing amplifier right after the DCF.
- NRZ format can be used at 10 Gb/s but the RZ format is superior for lightwave systems operating at 40 Gb/s or more.

Semianalytic Approach

- Considerable insight possible by adopting a semianalytic approach based on a single Gaussian pulse (an isolated 1 bit).

- Using the moment or variational method, NLS equation is reduced to two coupled equations:

$$\frac{dT}{dz} = \frac{\beta_2(z)C}{T}, \qquad \frac{dC}{dz} = (1+C^2)\frac{\beta_2(z)}{T^2} + \frac{\gamma(z)p(z)E_0}{\sqrt{2\pi}T}.$$

- Details of loss and dispersion managements appear through z dependence of β_2, γ, and p.

- For given values of three input pulse parameters (T_0, C_0, and E_0) these equations can be solved numerically.

- Pulse energy E_0 is related to average power as $P_{\text{av}} = \frac{1}{2}BE_0 = (\sqrt{\pi}/2)P_0(T_0/T_b)$.

Solution in the Linear Case

- Consider first the linear case by setting $\gamma(z) = 0$.
- E_0 plays no role because pulse propagation is independent of input pulse energy.
- Moment equations can be solved analytically:

$$T^2(z) = T_0^2 + 2\int_0^z \beta_2(z)C(z)\,dz, \quad C(z) = C_0 + \frac{1+C_0^2}{T_0^2}\int_0^z \beta_2(z)\,dz.$$

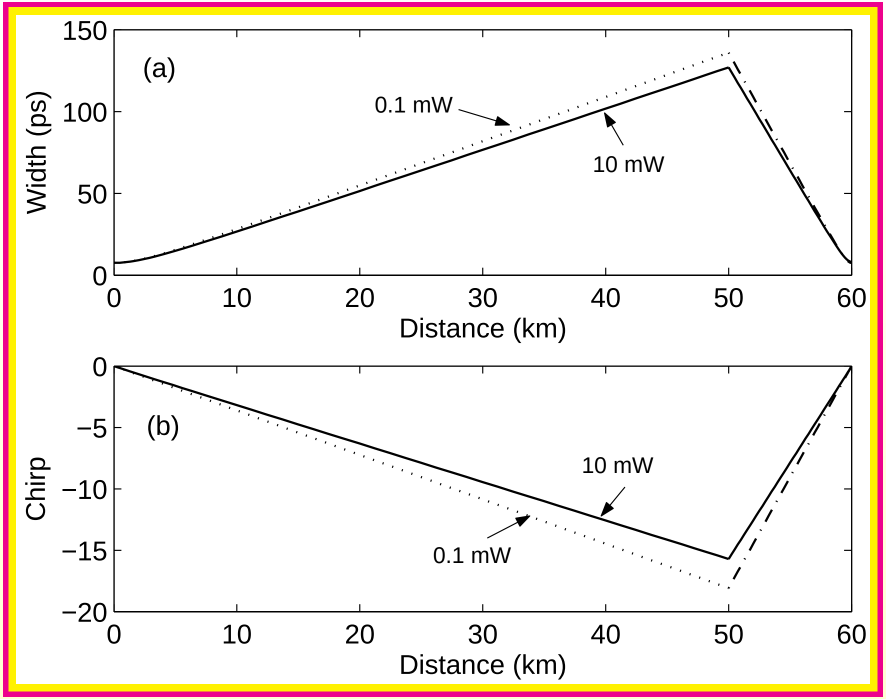
- For a two-section dispersion map values of T and C at the end of the map period $z = L_{\rm map}$ are given by

$$T_1 = T_0[(1+C_0 d)^2 + d^2]^{1/2}, \qquad C_1 = C_0 + (1+C_0^2)d.$$

- Parameter d is defined as $d = \frac{1}{T_0^2}\int_0^{L_{\rm map}} \beta_2(z)\,dz = \frac{\bar{\beta}_2 L_{\rm map}}{T_0^2}$.

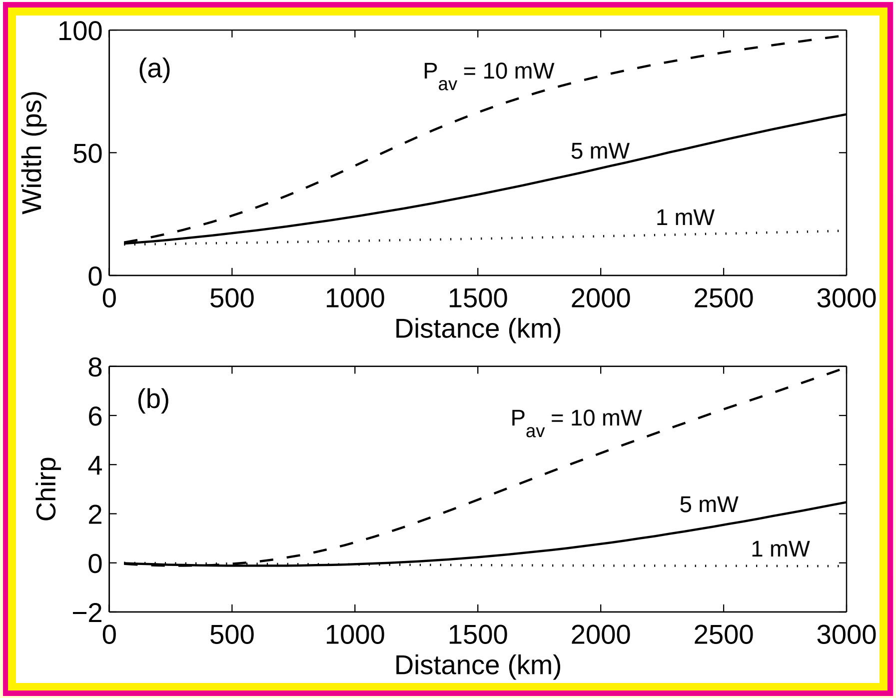
Back
Close

Solution in the Nonlinear Case



- Nonlinear effects modify both width and chirp but changes are not large even for a 10-mW launched power.

Buildup of Nonlinear Effects



- Even for $P_{\text{av}} = 5$ mW, pulse width becomes larger than the bit slot after a distance of 1,000 km.

Soliton and Pseudo-linear Regimes

- Management of nonlinear effects is important.
- Parameters associated with dispersion map can be controlled to manage the nonlinearity problem.
- Two main techniques have evolved: Systems employing them are said to operate in the pseudo-linear and soliton regimes.
- It was noted in several experiments that a nonlinear system performs best when GVD compensation is only 90 to 95% .
- Solitons can form when residual dispersion is anomalous.
- Performance improved if input pulse is initially chirped such that $\bar{\beta}_2 C < 0$.
- This observation led to the adoption of the chirped RZ (CRZ) format used for pseudo-linear systems.

Normalized NLS equation

- Consider a lightwave system in which dispersion is compensated only at the transmitter and receiver ends.
- Introduce two length scales $L_D = T_0^2/|\beta_2|$ and $L_{\rm NL} = (\gamma P_0)^{-1}$.
- Using τ as $\tau = t/T_0$, NLS equation becomes

$$iL_D \frac{\partial U}{\partial z} - \frac{s}{2}\frac{\partial^2 U}{\partial \tau^2} + \frac{L_D}{L_{\rm NL}} p(z)|U|^2 U = 0.$$

- $s = \text{sign}(\beta_2) = \pm 1$ depending on the sign of β_2.
- For $\gamma = 2$ W^{-1}/km, $L_{\rm NL} \sim 100$ km for P_0 of 2 to 4 mW.
- Dispersion length L_D can vary over a wide range (from $\sim$1 to 10,000 km) depending on the bit rate of the system and type of fibers used.

Soliton Regime

- If $L_D \gg L_{\text{NL}}$ and $L < L_D$, dispersive effects play a minor role.
- This is the situation at a bit rate of 2.5 Gb/s or less.
- L_D exceeds 1,000 km at $B = 2.5$ Gb/s even for standard fibers and can exceed 10,000 km for dispersion-shifted fibers.
- If L_D and L_{NL} are comparable, dispersive and nonlinear terms are equally important in the NLS equation.
- This is the situation for 10-Gb/s systems. The use of solitons is most beneficial in the regime.
- A soliton-based system confines each pulse tightly to its bit slot through by a careful balance of GVD and SPM effects.
- Since GVD is used to offset the impact of nonlinear effects, dispersion is never fully compensated in soliton-based systems.

Pseudo-linear Regime

- If $L_D \ll L_{\rm NL}$, dispersive effects dominate locally, and nonlinear effects can be treated in a perturbative manner.
- This situation is encountered at a bit rate of 40 Gb/s or more.
- If T_0 is $<$10 ps, L_D is reduced to below 5 km.
- Input pulses spread quickly over several neighboring bits.
- Extreme broadening reduces their peak power by a large factor.
- Nonlinear effects are reduced considerably because of averaging that produces a nearly constant total power in all bit slots.
- Overlapping of neighboring pulses enhances *intrachannel* nonlinear effects.

Soliton in Optical Fibers

- Solitons maintain their shape by balancing the dispersive and nonlinear effects.
- GVD broadens optical pulses except when the pulse is initially chirped such that $\beta_2 C < 0$.
- SPM imposes a chirp on the optical pulse such that $C > 0$.
- Soliton formation possible only when $\beta_2 < 0$.
- SPM and GVD can cooperate when input power is adjusted such that SPM-induced chirp just cancels GVD-induced broadening.
- Nonlinear Schrödinger Equation

$$i\frac{\partial A}{\partial z} - \frac{\beta_2}{2}\frac{\partial^2 A}{\partial t^2} + \gamma |A|^2 A = 0.$$

Properties of Solitons

- Introducing $\xi = z/L_d$, $\tau = t/T_0$, and $U = A/\sqrt{P_0}$:

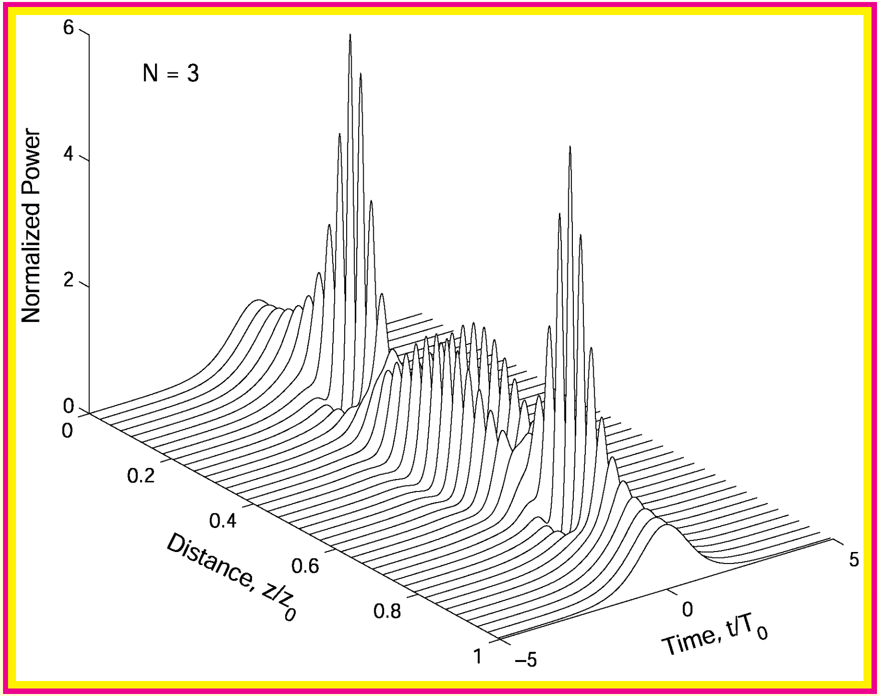
$$i\frac{\partial U}{\partial \xi} \pm \frac{1}{2}\frac{\partial^2 U}{\partial \tau^2} + N^2|U|^2U = 0.$$

- Its solution depends on a single parameter N defined as

$$N^2 = L_D = L_D/L_{\rm NL} = \gamma P_0 T_0^2/|\beta_2|.$$

- Dispersive and nonlinear lengths: $L_D = \frac{T_0^2}{|\beta_2|}$, $L_{\rm NL} = \frac{1}{\gamma P_0}$.
- The two are balanced when $L_{\rm NL} = L_D$ or $N = 1$.
- Input pulses of the form $u(0,\tau) = N\,\mathrm{sech}(\tau)$ evolve in a periodic fashion (inverse scattering method).

Soliton Evolution



- Pulses shape invariant for $N = 1$ (Fundamental soliton).
- Periodic evolution for $N > 1$ with period $z_0 = \frac{\pi}{2} L_D = \frac{\pi}{2} \frac{T_0^2}{|\beta_2|}$.

Fundamental Soliton Solution

- For fundamental solitons, NLS equation becomes

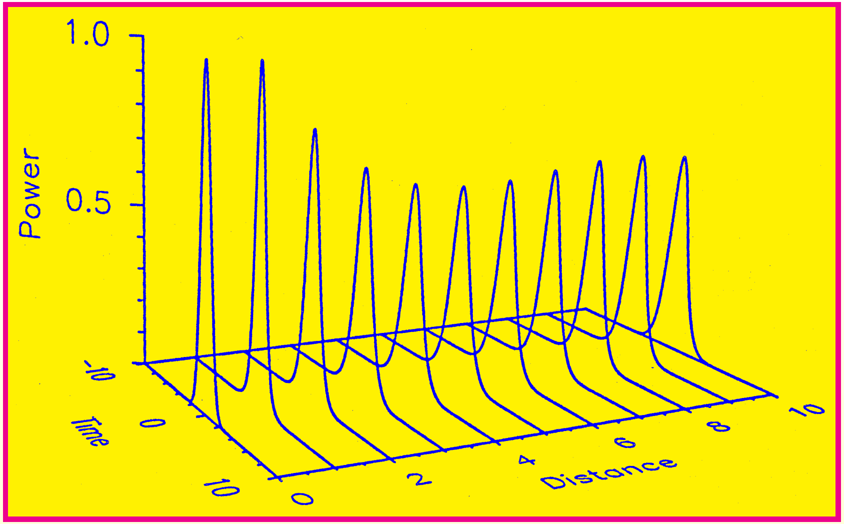
$$i\frac{\partial u}{\partial \xi} + \frac{1}{2}\frac{\partial^2 u}{\partial \tau^2} + |u|^2 u = 0.$$

- If $u(\xi,\tau) = V(\tau)\exp[i\phi(\xi)]$, V satisfies $\frac{d^2V}{d\tau^2} = 2V(K - V^2)$.
- Multiplying by $2(dV/d\tau)$ and integrating over τ,

$$(dV/d\tau)^2 = 2KV^2 - V^4 + C.$$

- $C = 0$ from the boundary condition $V \to 0$ as $|\tau| \to \infty$.
- Constant $K = \frac{1}{2}$ using $V = 1$ and $dV/d\tau = 0$ at $\tau = 0$.
- Final Solution: $u(\xi,\tau) = \text{sech}(\tau)\exp(i\xi/2)$.

Stability of Fundamental Solitons



- Evolution of a Gaussian pulse with $N = 1$.
- Very stable; can be excited using any pulse shape.
- Nonlinear index $\Delta n = n_2 I(t)$ larger near the pulse center.
- Solitons is a temporal mode of a SPM-induced waveguide.

Loss-Managed Solitons

- Fiber losses destroy the balance needed for solitons.
- Soliton energy and peak power decrease along the fiber.
- Nonlinear effects become weaker and cannot balance dispersion completely.
- Pulse width begins to increase.

- Solution: Compensate losses periodically using amplifiers.
- Solitons sustained through periodic amplification are called loss-managed solitons.
- They must be launched with a higher energy.

Path-Averaged Solitons

- The NLS equation with losses included through $p(z)$:

$$i\frac{\partial u}{\partial \xi} + \frac{1}{2}\frac{\partial^2 u}{\partial \tau^2} + p(z)|u|^2 u = 0.$$

- Rapid variations in $p(z)$ can destroy a soliton if its width changes rapidly.
- Solitons evolve little over a distance short compared with L_D.
- If $L_A \ll L_D$, width of a soliton remains virtually unchanged even if its peak power varies between two amplifiers.
- In effect, replace $p(z)$ by its average value $\bar{p} = L_A^{-1} \int_0^{L_A} e^{-\alpha z} dz$.
- Fundamental soliton can be excited if input peak power P_s is larger by a factor of $1/\bar{p}$.

Energy Enhancement Factor

- Energy enhancement factor for loss-managed solitons is given by

$$f_{\mathrm{LM}} = \frac{P_s}{P_0} = \frac{1}{\bar{p}} = \frac{\alpha L_A}{1 - \exp(-\alpha L_A)} = \frac{G \ln G}{G - 1}.$$

- Launched peak power must be larger by a factor f_{LM} for solitons to survive in lossy fibers.
- As an example, $G = 10$ and $f_{\mathrm{LM}} \approx 2.56$ when $L_A = 50$ km and $\alpha = 0.2$ dB/km.
- Condition $L_A \ll L_D$ must be satisfied for such soliton systems.
- The moment method can be used to study how fiber losses affect evolution of solitons.

Soliton Evolution in Lossy Fibers

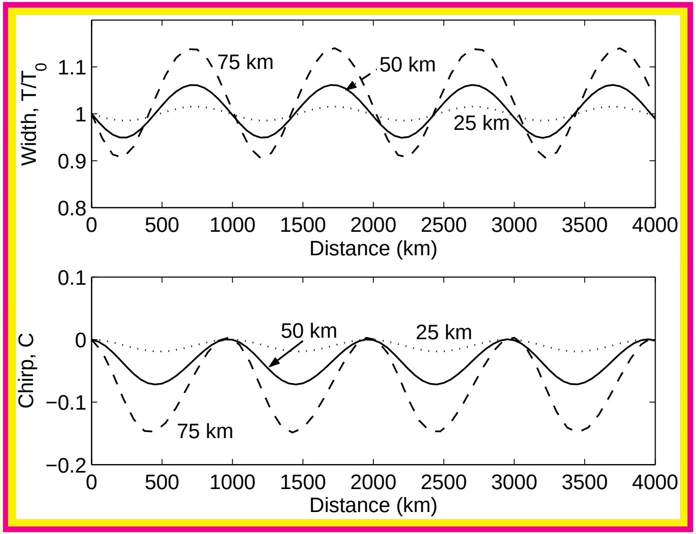
- Assume $U(z,t) = a\,\mathrm{sech}(t/T)\exp(-iCt^2/T^2 + i\phi)$.
- Using the moment method, we obtain:

$$\frac{dT}{dz} = \frac{\beta_2 C}{T}$$

$$\frac{dC}{dz} = \left(\frac{4}{\pi^2} + C^2\right)\frac{\beta_2}{T^2} + \frac{2\gamma p(z) E_0}{\pi^2 T}.$$

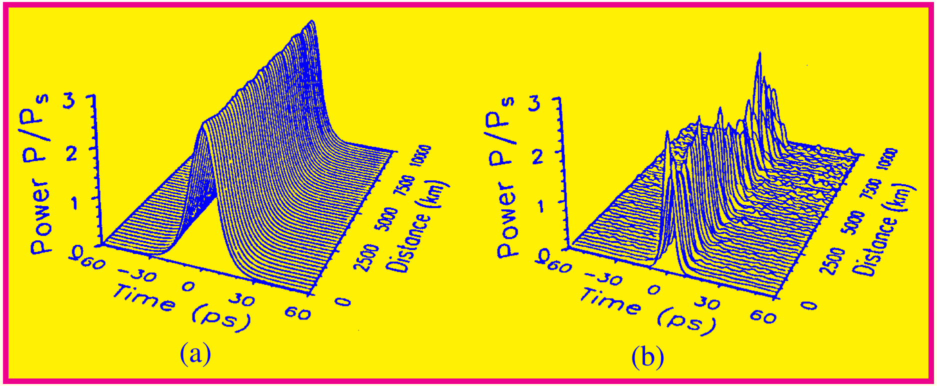
- Losses included through $p(z) = \exp(-\alpha z)$.
- If $\alpha = 0$, both derivatives vanish at $z = 0$ if $\beta_2 < 0$, $C = 0$ and $E_0 = 2|\beta_2|/(\gamma T_0)$.
- Using $E_0 = 2P_0T_0$, this occurs for $N = L_D/L_{\mathrm{NL}} = 1$.

Soliton Evolution in Lossy Fibers



- Evolution of pulse with and chirp for when $L_D = 100$ km.
- For $L_A = 25$ km, width and chirp remain close to input values.
- Width can change by more than 10% when $L_A = 75$ km.
- If $L_A/L_D > 1$, pulse width starts to increase exponentially.

Numerical Evolution over Long Fiber Links



- Evolution of a loss-managed soliton over 10,000 km.
- Amplifier spacing is fixed at $L_A = 50$ km.
- Dispersion length L_D is varied by changing T_0.
- When $L_D = 200$ km, soliton is preserved even after 10,000 km.
- If dispersion length is reduced to 25 km, soliton is unable to sustain itself.

Design of Soliton Systems

- Condition $L_A < L_D$ with $L_D = T_0^2/|\beta_2|$ leads to $T_0 > \sqrt{|\beta_2| L_A}$.
- T_0 must be a small fraction of $T_b = 1/B$ to ensure that neighboring solitons are well separated.
- This requirement can be used to relate T_0 to the bit rate B using $T_b = 2q_0 T_0$.
- Typically, q_0 exceeds 4 to ensure pulse tails do not overlap.
- Using $T_0 = (2q_0 B)^{-1}$, we obtain $B^2 L_A < (4q_0^2|\beta_2|)^{-1}$.
- For $\beta_2 = -2$ ps^2/km, $L_A = 50$ km, and $q_0 = 5$, we obtain $T_0 > 10$ ps and $B < 10$ Gb/s.
- To operate at 10 Gb/s, one must reduce L_A if β_2 is kept fixed.

Design of Soliton Systems

- Condition $L_A \ll L_D$ can be relaxed considerably by employing distributed amplification.
- A distributed-amplification scheme provides a nearly lossless fiber by compensating losses locally at every point along fiber link.
- Distributed Raman amplification was used by 1985.
- A 1988 experiment transmitted solitons over 4000 km using periodic Raman amplification.
- This experiment was the first to demonstrate that solitons can be transmitted over transoceanic distances.
- Main drawback is that Raman amplification requires pump lasers emitting more than 500 mW of power near 1.46 μm.

Dispersion-Managed solitons

- Dispersion management is employed commonly for modern WDM systems.
- Solitons can form even when β_2 varies along the link but their properties
  are quite different.
- A scheme proposed in 1987 relaxes the restriction $L_A \ll L_D$ by employing a new kind of fiber in which GVD varies along its length.
- Such fibers are called *dispersion-decreasing* fibers (DDFs).
- They are designed such that the decreasing GVD counteracts the reduced SPM experienced by solitons weakened from fiber losses.

Dispersion-Decreasing Fibers

- In the NLS equation β_2 is a function of z.
- Introducing $\xi = T_0^{-2} \int_0^z \beta_2(z)\, dz$ and $\tau = t/T_0$,

$$i\frac{\partial U}{\partial \xi} + \frac{1}{2}\frac{\partial^2 U}{\partial \tau^2} + N^2(z)|U|^2 U = 0.$$

- Here, $N^2(z) = \gamma P_0 T_0^2 p(z)/|\beta_2(z)|$.
- If $|\beta_2(z)| = |\beta_2(0)| p(z)$, N becomes a constant.
- Fiber losses then have no effect on a soliton.
- L_A can exceed L_D if GVD decreases between two amplifiers as $|\beta_2(z)| = |\beta_2(0)| \exp(-\alpha z)$.
- Under such conditions, a fundamental soliton maintains its shape and width even in a lossy fiber.

Dispersion-Decreasing Fibers

- Fibers with a nearly exponential GVD profile have been fabricated.
- A practical technique for making DDFs consists of reducing core diameter along fiber length during fiber-drawing process.
- Variations in fiber diameter reduce $|\beta_2|$.
- GVD can be varied by a factor of 10 over a length of 20 to 40 km with an accuracy better than 0.1 ps^2/km.
- Propagation of solitons in DDFs has been observed in several experiments.
- Exponential GVD profile can be approximated with a staircase by splicing together several constant-dispersion fibers.
- Benefits of DDFs can be realized using just four fiber segments.

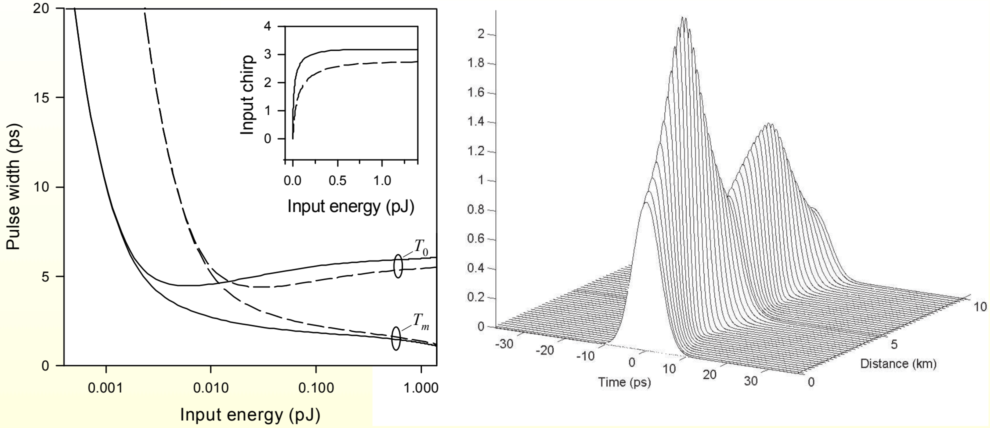
Periodic Dispersion Maps

- Use of dispersion management forces each soliton to propagate in the normal-dispersion regime of a fiber.
- At first sight, such a scheme should not even work because the normal-GVD fibers do not support solitons.
- It turns out that new kinds of solitons (called dispersion-managed solitons) can still form.
- Pulses then evolve in a linear fashion over a single map period.
- On a longer length scale, solitons form if SPM effects are balanced by the average dispersion.
- Not only the peak power but also the width and shape of such solitons oscillate in a periodic fashion.

Input Pulse Parameters

- Moment Equations can be used to study dispersion-managed solitons.
- Width and chirp equations should be solved with the periodic boundary conditions to ensure that a DM soliton recovers its initial state after each amplifier.
- Periodic boundary conditions fix the initial width T_0 and chirp C_0 of input pulses at $z = 0$.
- A new feature of DM solitons is that the input pulse width depends on the dispersion map and cannot be chosen arbitrarily.
- In general, input pulses must be chirped appropriately.
- Pulse parameters depends on the dispersion map used and should be determined numerically.

Input Pulse Parameters



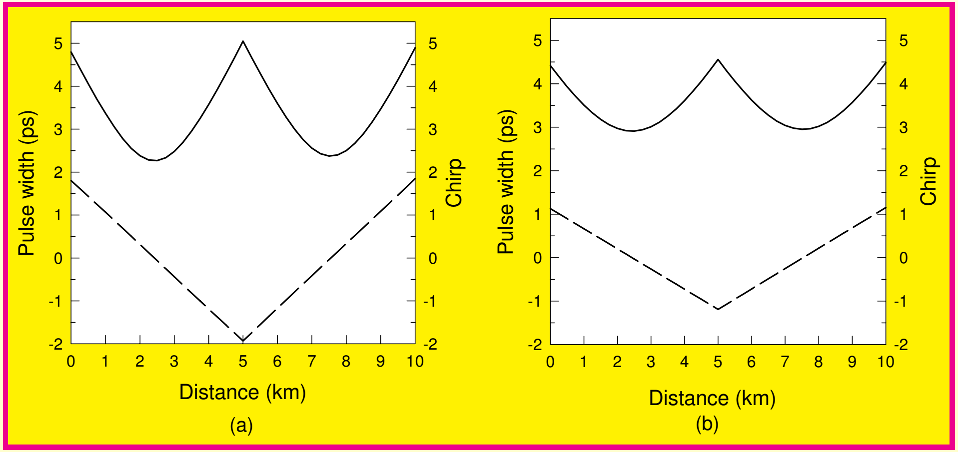
(a)

(b)

- (a) Changes in T_0 and T_m for $\alpha = 0$ (solid lines) and 0.25 dB/km (dashed lines). Inset shows input chirp C_0.
- (b) Evolution of DM soliton over one map period for $E_0 = 0.1$ pJ. Dispersion Map: Two 5-km fiber sections with $\beta_2 = \mp 4$ ps^2/km.
- Minimum pulse width T_m occurs in the anomalous-GVD section.

Periodic Width and Chirp Variations

- Both T_0 and T_m decrease rapidly as pulse energy is increased.
- T_0 attains its minimum value at a certain pulse energy E_c.
- T_0 and T_m differ by a large factor for $E_0 \gg E_c$.
- Pulse width changes considerably in each fiber section when this regime is approached. (a) $E_0 = 0.1$ pJ; (b) E_0 close to E_c.



Soliton System Design

- Many different DM solitons coexist for the same map with different values of E_0, T_0, and C_0.
- How should one choose among these multiple solutions?
- Pulse energies much smaller than E_c should be avoided because a low average power would lead to SNR degradation.
- When $E_0 \gg E_c$, large variations in pulse width induce XPM-induced interaction between neighboring solitons.
- Region near $E_0 = E_c$ is most suited for designing DM soliton systems.
- Numerical solutions of the NLS equation confirm this conclusion.

Optimum Pulse Width

- Optimum values of T_0 can be found from the moment equations:

$$T_0 = T_{\text{map}}\sqrt{\frac{1+C_0^2}{|C_0|}}, \qquad T_{\text{map}} = \left(\frac{|\beta_{2n}\beta_{2a}l_n l_a|}{\beta_{2n}l_n - \beta_{2a}l_a}\right)^{1/2}.$$

- T_{map} is a parameter with dimensions of time involving only the map parameters.
- It provides a time scale associated with an arbitrary dispersion map.
- Minimum value of T_0 occurs for $|C_0| = 1$ and is given by $T_0^{\text{min}} = \sqrt{2}T_{\text{map}}$.
- Minimum pulse width $T_m = T_{\text{map}}$ under such conditions.

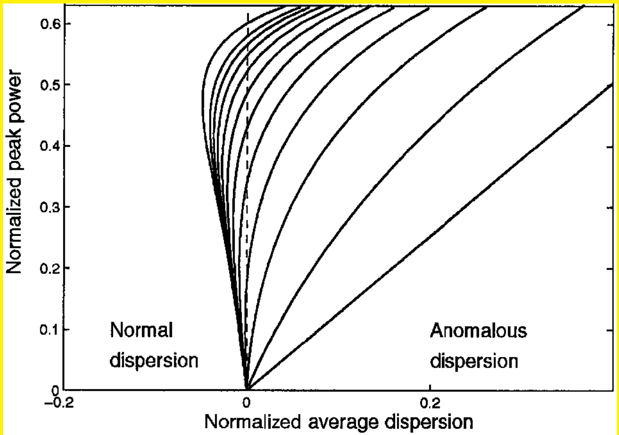
Map Strength

- It is useful to look for other combinations of map parameters that play an important role in designing a DM soliton system.
- Two useful parameters are defined as

$$\bar{\beta}_2 = \frac{\beta_{2n} l_n + \beta_{2a} l_a}{l_n + l_a}, \qquad S_{\rm map} = \frac{\beta_{2n} l_n - \beta_{2a} l_a}{T_{\rm FWHM}^2}.$$

- $T_{\rm FWHM} \approx 1.665 T_m$ is the minimum FWHM.
- $\bar{\beta}_2$ represents average GVD of the entire link.
- Map strength $S_{\rm map}$ is a measure of how much GVD changes abruptly between two fibers in each map period.
- DM solitons can exist even when average GVD is normal provided map strength exceeds a critical value $S_{\rm cr}$.

Map Strength



- Peak power of DM solitons as a function of $\bar{\beta}_2/\beta_{2a}$.
- Map strength is zero for the rightmost curve, increases in step of 2 until 20, and becomes 25 for the leftmost curve.
- Periodic solutions in the normal-GVD regime exist if S_{map} exceeds 4.8.

Experiments with DM Solitons

- In a 1996 experiment, a periodic dispersion map enabled transmission of 20-Gb/s soliton bit stream over 5520 km.
- In another 20-Gb/s experiment, solitons were transmitted over 9,000 km.
- In a 1997 experiment, a 10-Gb/s signal was transmitted over 28,000 km using a fiber loop consisting of 100 km of normal-GVD fiber and 8 km of anomalous-GVD fiber.
- By 1999, 10-Gb/s DM solitons could be transmitted over 16,000 km of standard fiber.
- Solitons system work quite well at 10 Gb/s but their performance is less satisfactory at 40 Gb/s.

Timing Jitter

- Timing jitter problem severe for soliton-based systems.
- In the case of DM solitons, the moment method provides the following expression for it:

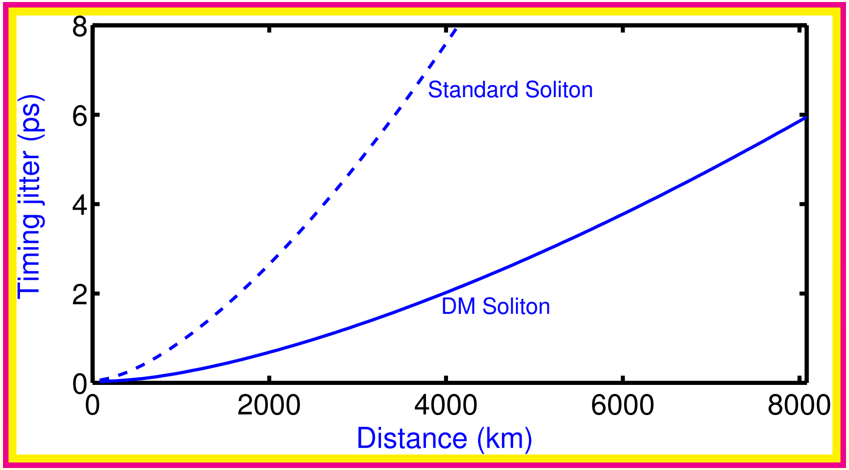
$$\sigma_t^2 = \frac{S_{\mathrm{ASE}} T_m^2}{E_0} [N_A(1+C_0^2) + N_A(N_A-1)C_0 d + \tfrac{1}{6} N_A(N_A-1)(2N_A-1)d^2]$$

- N_A = Number of amplifiers; $d = \frac{1}{T_m^2}\int_0^{L_A} \beta_2(z)\,dz = \frac{\bar{\beta}_2}{T_m^2} L_A = \frac{L_A}{L_D}$.
- For $N_A \gg 1$, jitter is approximately given by

$$\frac{\sigma_t^2}{T_m^2} \approx \frac{S_{\mathrm{ASE}}}{3E_0} N_A^3 d^2 = \frac{S_{\mathrm{ASE}} L_T^3}{3E_0 L_D^2 L_A},$$

- $L_D = T_m^2/|\bar{\beta}_2|$ and $N_A = L_T/L_A$.

Timing Jitter

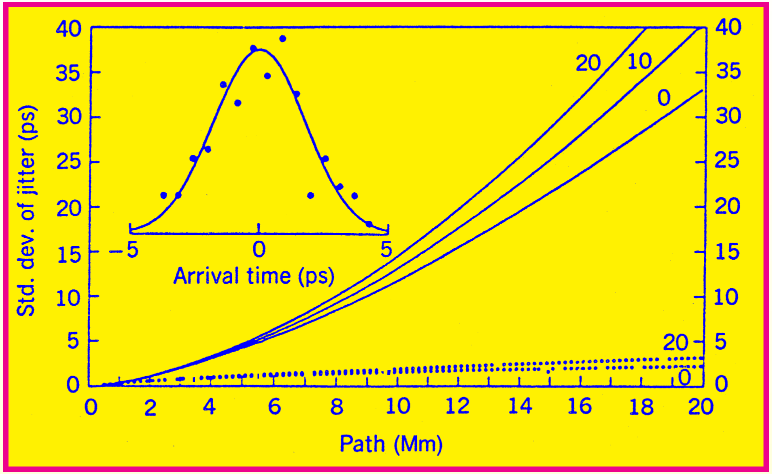


- ASE-induced timing jitter for a 20-Gb/s system.
- Jitter should be less than 10% of the bit slot (< 5 ps).
- Dispersion map consists of 10.5 km of anomalous-GVD fiber and 9.7 km of normal-GVD fiber [$D = \pm 4$ ps/(km-nm)].

Control of Timing Jitter

- Optical filters can reduce timing jitter of solitons.
- Soliton bit stream passes through the filter but most of ASE is blocked by it.
- If an optical filter is placed after each amplifier, it improves the SNR as well as timing jitter.
- Filter technique can be improved by allowing the center frequency of filters to slide slowly along the link.
- Such *sliding-frequency* filters avoid accumulation of ASE within the filter bandwidth.
- As filter passband shifts, solitons shift their spectrum to minimize filter-induced losses.
- ASE noise accumulated over a few amplifiers is filtered out later.

Sliding-Frequency Filters



- Timing jitter with (dotted curves) and without (solid curves) sliding-frequency filters.
- Inset shows a Gaussian fit to numerically simulated jitter at 10,000 km for a 10-Gb/s system.
- Bit-rate dependence is due to contribution of acoustic waves.

Synchronous Modulation

- Soliton jitter can also be controlled using synchronous amplitude modulation (implemented using a $LiNbO_3$ modulator).
- Technique works by introducing additional losses for those solitons that have shifted from their original position.
- Modulator forces solitons to move toward its transmission peak where the loss is minimum.
- This technique can also be implemented using a phase modulator.
- A frequency shift is associated with all time-dependent phase variations.
- Since a change in soliton frequency is equivalent to a change in the group velocity, phase modulation leads to temporal displacement.

Postcompensation of Dispersion

- Postcompensation of accumulated dispersion can be used for reducing timing jitter.
- Cubic jitter term depends on the accumulated dispersion.
- If accumulated dispersion is compensated using fiber of length L_c and GVD β_{2c}, jitter becomes

$$\sigma_c^2 = N_A^3 d^2 T_m^2 (S_{\text{ASE}}/E_0)(y^2 - y + 1/3).$$

- $y = -d_c/(N_A d)$ is the fraction by which accumulated dispersion $N_A d$ is compensated.
- Minimum value occurs for $y = 0.5$. Timing jitter of solitons can be reduced by a factor of 2 by postcompensating accumulated dispersion by 50%.

Pseudo-linear Lightwave Systems

- Local dispersion length is much shorter than nonlinear length in all fiber sections of a pseudo-linear system.
- This approach is most suitable for systems operating at bit rates of 40 Gb/s or more.
- Relatively short pulses spread quickly over multiple bits.
- This spreading reduces peak power and lowers the impact of SPM.
- In one design, pulses spread throughout the link and are compressed back at the receiver end.
- In another, pulses are spread even before they are launched using a DCF (precompensation).

Design of Pseudo-linear Systems

- It is not essential to compensate dispersion only once at the transmitter or the receiver end.
- A periodic dispersion map can also be used.
- It is made such that the pulse broadens by a large factor in the first section and is compressed back in the second section.
- A small amount of dispersion is left uncompensated in each map period.
- This residual dispersion per span can be used to control the impact of intrachannel nonlinear effects.
- Combination of pre- and post-compensation is employed to improve further system performance.

Intrachannel Nonlinear Effects

- Optical pulses spread considerably outside their assigned bit slot in all pseudo-linear systems.
- They overlap and interact with each other through the nonlinear term in the NLS equation.
- Enhanced nonlinear interaction among the 1 bits of the same channel produces intrachannel nonlinear effects.
- If left uncontrolled, they limit performance of all pseudo-linear systems.
- Important question is whether pulse spreading helps to lower the overall impact of fiber nonlinearity.
- The answer to this question turned out to be yes.

Origin of Intrachannel Effects

- In a numerical approach, NLS equation is solved using a pseudo-random bit stream with the input $U(0,t) = \sum_{j=1}^{M} U_j(0,t-t_j)$.
- Considerable physical insight can be gained with a semi-analytic approach focusing on three neighboring pulses.
- Writing $U = U_1 + U_2 + U_3$ in the NLS equations, we obtain

$$
\begin{aligned}
i\frac{\partial U_1}{\partial z} - \frac{\beta_2}{2}\frac{\partial^2 U_1}{\partial t^2} + \gamma P_0 p(z)[(|U_1|^2 + 2|U_2|^2 + 2|U_3|^2)U_1 + U_2^2 U_3^*] &= 0,\\
i\frac{\partial U_2}{\partial z} - \frac{\beta_2}{2}\frac{\partial^2 U_2}{\partial t^2} + \gamma P_0 p(z)[(|U_2|^2 + 2|U_1|^2 + 2|U_3|^2)U_2 + 2U_1 U_2^* U_3] &= 0,\\
i\frac{\partial U_3}{\partial z} - \frac{\beta_2}{2}\frac{\partial^2 U_3}{\partial t^2} + \gamma P_0 p(z)[(|U_3|^2 + 2|U_1|^2 + 2|U_2|^2)U_3 + U_2^2 U_1^*] &= 0.
\end{aligned}
$$

- Last nonlinear term corresponds to four-wave mixing.

Intrachannel XPM

- Consider two isolated 1 bits by setting $U_3 = 0$:

$$i\frac{\partial U_n}{\partial z} - \frac{\beta_2}{2}\frac{\partial^2 U_n}{\partial t^2} + \gamma P_0 p(z)(|U_n|^2 + 2|U_{3-n}|^2)U_n = 0.$$

- Over a distance Δz, XPM shifts the phase by

$$\phi_n(z,t) = 2\gamma P_0 p(z)\Delta z|U_{3-n}(z,t)|^2.$$

- As this phase shift depends on pulse shape, it produces frequency chirp

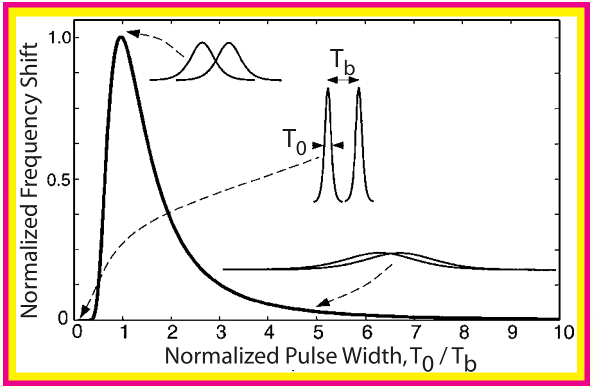
$$\delta\omega_n \equiv -\frac{\partial \phi_n}{\partial t} = -2\gamma P_0 p(z)\Delta z\frac{\partial}{\partial t}|U_{3-n}(z,t)|^2.$$

- Similar to an ASE-induced frequency shift, XPM-induced frequency shift translates into a timing jitter.

XPM-Induced Timing Jitter

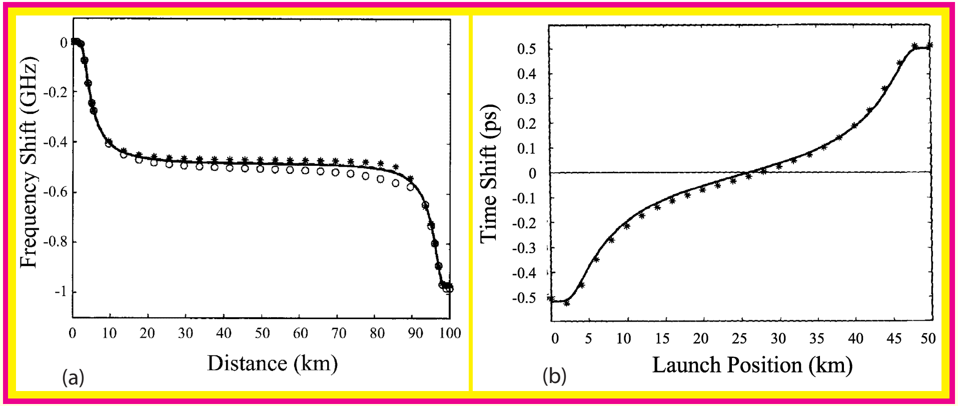
- If all pulses were to shift in time by the same amount, this effect would be harmless.
- Because of XPM, time shift depends on the pattern of bits surrounding each pulse.
- This shift varies from bit to bit depending on the data transmitted.
- Pulses shift in their respective bit slots by random amounts (timing jitter).
- XPM also introduces amplitude fluctuations.
- A quantitative analysis of the XPM effects can be carried out with the moment method.
- Results of this approach reveal several interesting features.

XPM-Induced Frequency Shift



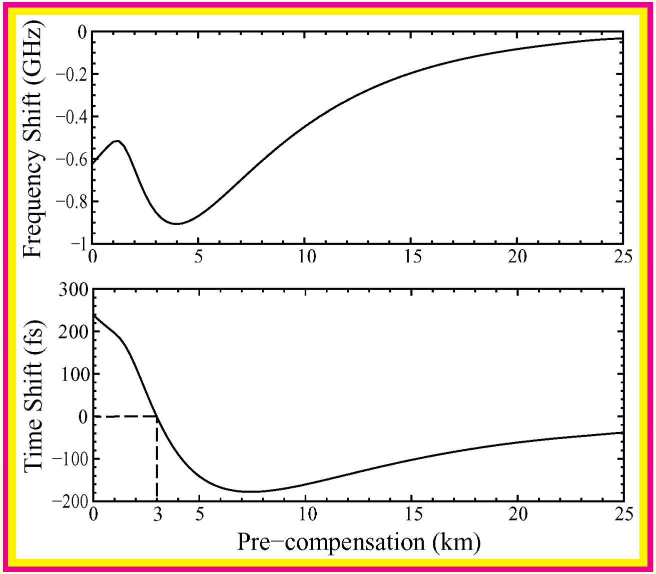
- Consider two Gaussian pulses separated by T_b.
- Frequency shift is largest when $T_0 \approx T_b$.
- Surprisingly, $\Delta\nu$ is small for wide pulses.
- Frequency chirp depends on dP/dt. This slope is smaller for wider pulses and changes sign, resulting in an averaging effect.
- Stretching of optical pulses over multiple bit slots helps.

Frequency and Temporal Shifts



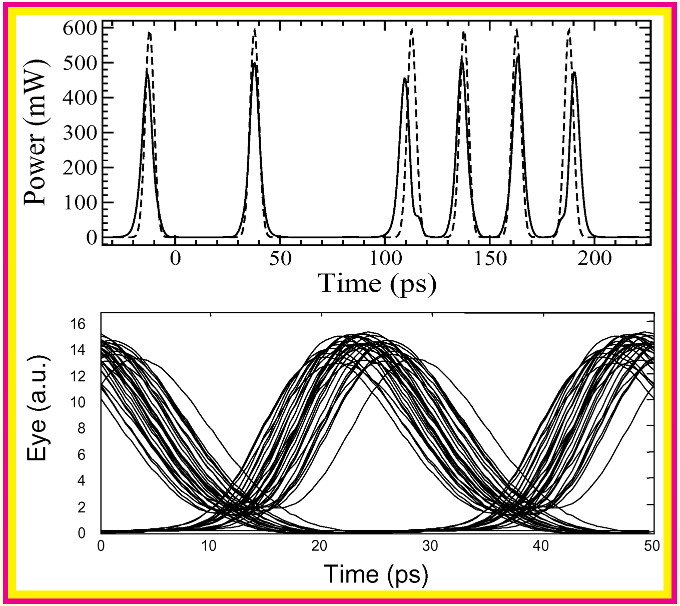
- A 100-km link with two 50-km sections ($D = \pm 10$ ps/km/nm).
- (a) Frequency shift for two 5-ps pulses separated by 25 ps.
- (b) Change in pulse spacing as a function of launch position.
- Pulse position does not shift for a symmetric dispersion map as timing shifts produced in the two sections cancel each other.

Frequency and Temporal Shifts



- Frequency and time shifts after 100 km as a function of DCF length used for chirping input pulses.
- XPM-induced time shift can be cancelled by suitably chirping input pulses.

XPM-Induced Degradation

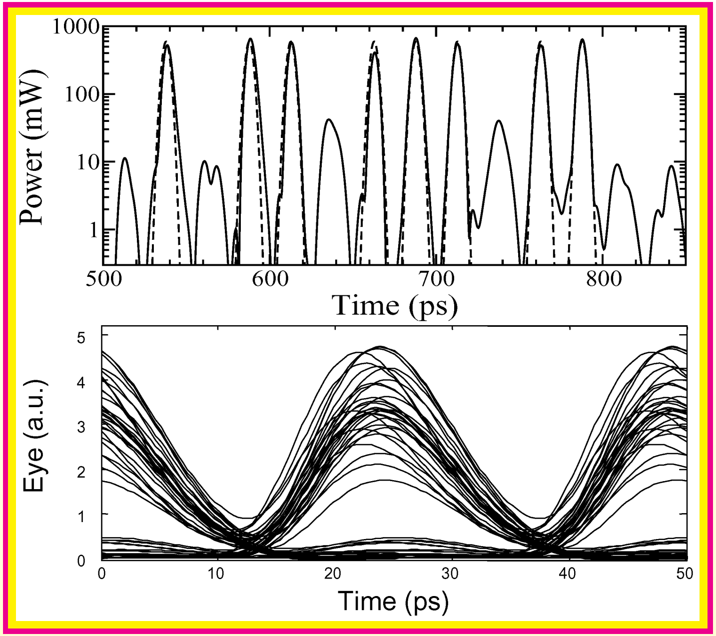


- 40-Gb/s bit stream in 80-km fiber with $D = 4$ ps/(km-nm).
- Dashed curve shows for comparison the input bit stream.
- Output bit stream exhibits both amplitude and timing jitters.

Intrachannel FWM

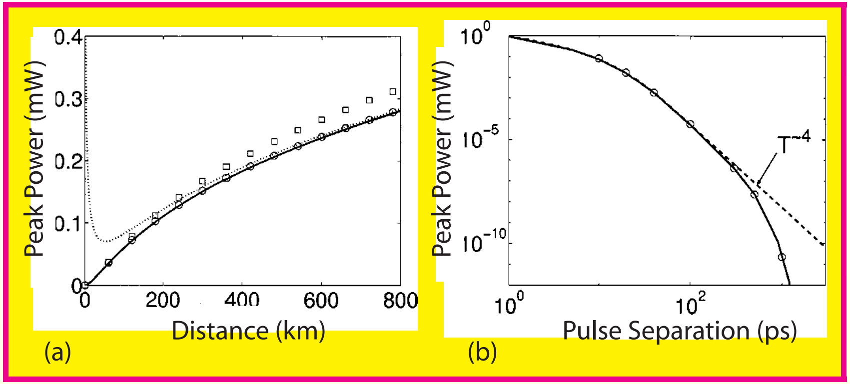
- Intrachannel FWM is of concern because it transfers energy from one pulse to neighboring pulses.
- It can create new pulses in bit slots that represent 0's and contain no pulse initially.
- Such FWM-generated pulses (called ghost pulses) are undesirable because they can lead to additional errors.
- Numerical simulations are often used to predict the impact of such ghost pulses.
- As an example, consider a 40-Gb/s system designed using 80 km of standard fiber with $D = 17$ ps/(km-nm).
- 5-ps chirped Gaussian input pulses propagate through the link.
- Bit stream is severely degraded only after 80 km.

FWM-Induced Degradation



- 40-Gb/s bit stream in 80-km fiber with $D = 17$ ps/(km-nm).
- Dashed curve shows for comparison the input bit stream.
- Ghost pulses degrade the eye diagram considerably.

Intrachannel FWM

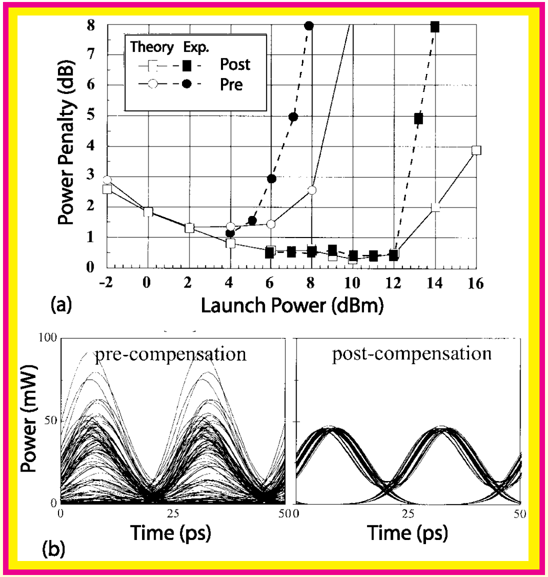


- Peak power of ghost pulse as a function of (a) link length L and (b) pulse separation T_b obtained analytically (solid curves).
- Dotted curves show an asymptotic approximation.
- Symbols show the results of numerical simulations.
- Total peak power at the end of a link of length L grows as $P_t(L) = P_g(L_{\text{map}})(L/L_{\text{map}})^2$.

Control of Intrachannel Nonlinear Effects

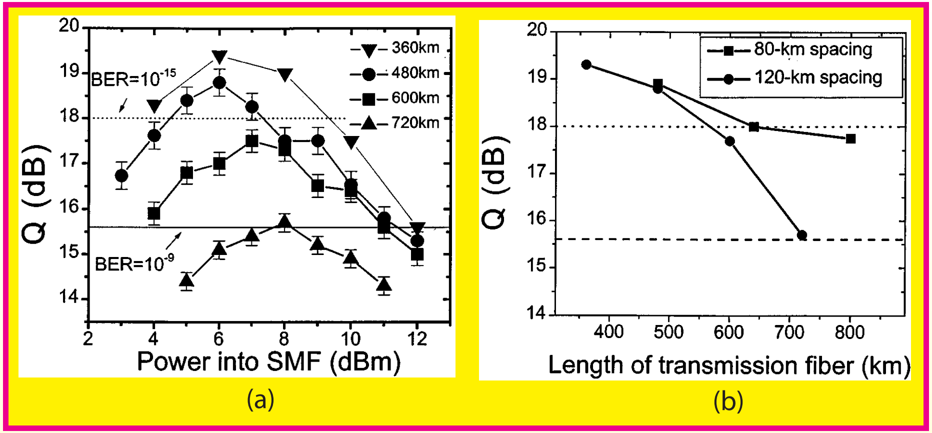
- Optimization of dispersion map can reduce the impact of intrachannel nonlinear effects.
- Two main choices: (i) dispersion accumulates along the link and is compensated using DCFs at the transmitter and receiver ends.
- (ii) Dispersion is compensated periodically at least partially.
- Both types of dispersion maps have been used for 40-Gb/s systems.
- In the first case, one has the choice of pre- or post-compensation.
- Next figure shows measured and calculated power penalties as a function of launched power for two choices.

Cmparison of Pre- and Post-compensation



- Eye diagrams are simulated numerically.
- Much higher powers could be launched in the case of post-compensation, while keeping the penalty below 0.5 dB.

Role of Amplifier Spacing



- This experiment used standard fibers and compensated dispersion only at the receiver end.
- It employed 2.5-ps pulses at 40-Gb/s with $L_A = 120$ km (left).
- For $L_A = 120$ km, system length was limited to 720 km.
- Longer distances could be realized by reducing L_A to 80 km.

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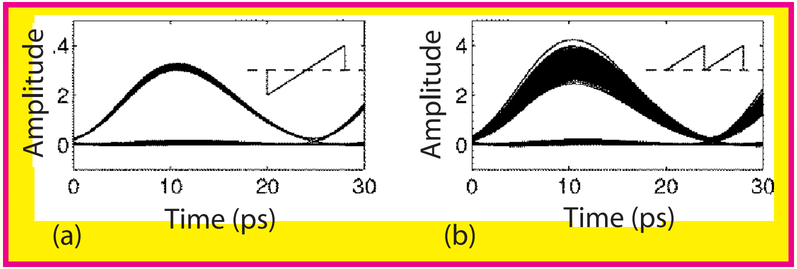
Optimization of Dispersion maps

- Optimization of a dispersion map is not a trivial task.
- It involves a large number of design parameters (lengths and dispersion of individual fibers used to make the map, the amount of pre- and post-compensation employed, pulse width, etc.).
- Extensive numerical simulations reveal several interesting features.
- When fiber dispersion is relatively small [$D < 4$ ps/(km-nm)], soliton regime works best with an RZ duty cycle near 50%.
- When dispersion is large along most of the link, pseudo-linear regime is more desirable for designing a 40-Gb/s system.
- Pseudo-linear systems are most suitable for old links made with standard fibers.

Symmetric Dispersion maps

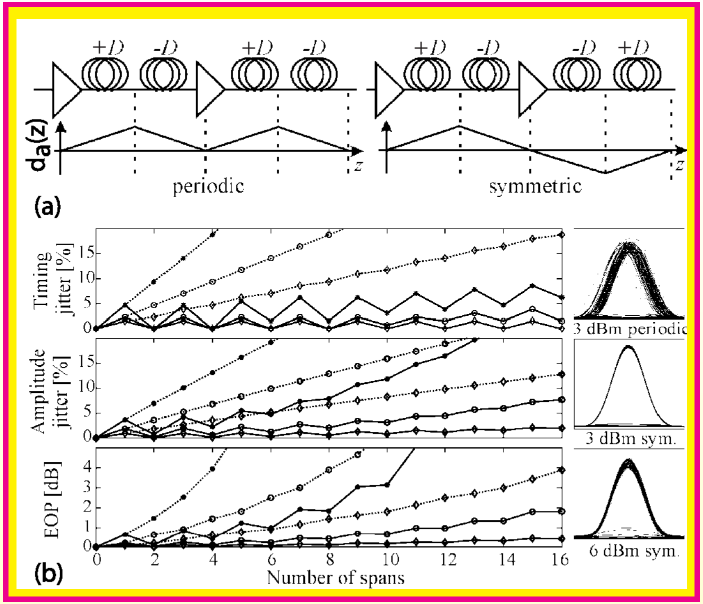


- Can intrachannel nonlinear effects be controlled by optimizing a dispersion map? Answer: Yes.
- Both amplitude and timing jitter are reduced if dispersion map is symmetric: $d_a(z) = d_a(L - z)$, where $d_a(z) = \int_0^z D(z)\,dz$.
- This can be realized by compensating 50% of dispersion at transmitter and remaining 50% at receiver.
- Numerical simulations show eye diagrams for 2.5-ps pulses with a 25-ps bit slot propagated over 1,600 km of standard fiber.

Optimization of Dispersion maps

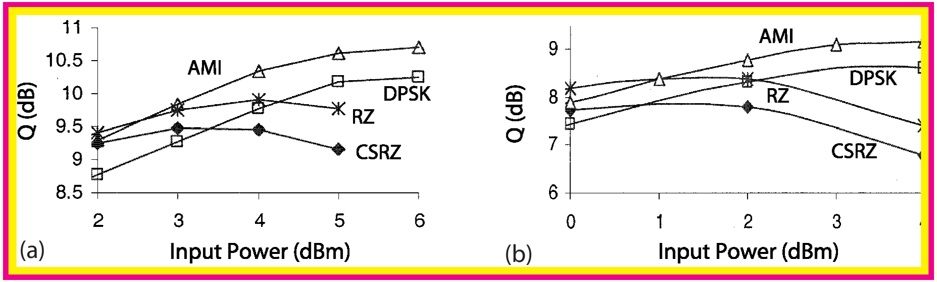
- Timing jitter results from XPM-induced frequency shifts that cancel for a symmetric map.
- Indeed, timing jitter would vanish in the absence of losses $[p(z) = 1]$.
- Residual jitter is due to variations in the average power along the link when lumped amplifiers are used.
- How one one symmetrize the dispersion map?
- If a periodic dispersion map is made with two fiber sections of equal lengths, reversing two fibers in every alternate map period makes the map symmetric.

Symmetric Dispersion maps



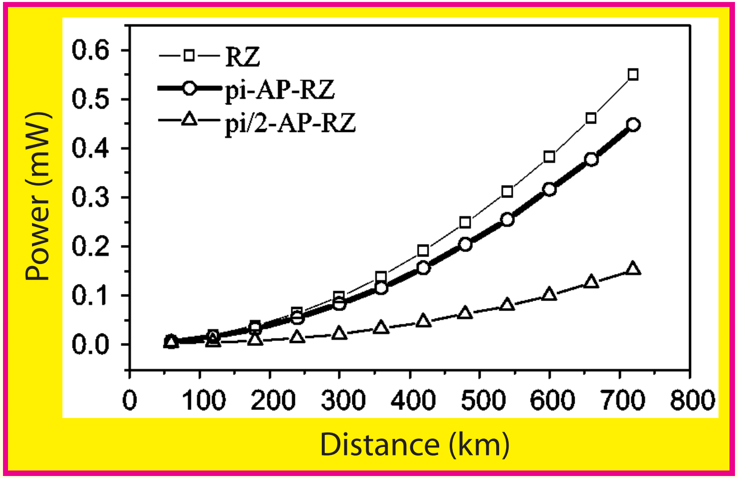
- Timing and amplitude jitter over 16 spans (each 80 km long) for symmetric (solid) and asymmetric (dashed) links.
- Launched powers are 3, 6, and 9 dBm for diamonds, circles, and squares, respectively.

Phase-Alternation Techniques



- Power dependence of Q factor found numerically for a 40-Gb/s channel at a distance of 1,000 km for four modulation formats.
- In (a) $D = 19$ ps/(km-nm) for the first and third 30-km sections but $D = -28$ ps/(km-nm) for the 40-km-long middle section.
- Map (b) employs 100 km of standard fiber with $D = 17$ ps/(km-nm) whose dispersion is compensated using DCFs.
- DPSK and AMI formats provide better performance compared with RZ and CSRZ formats.

Growth of Ghost-Pulse Power

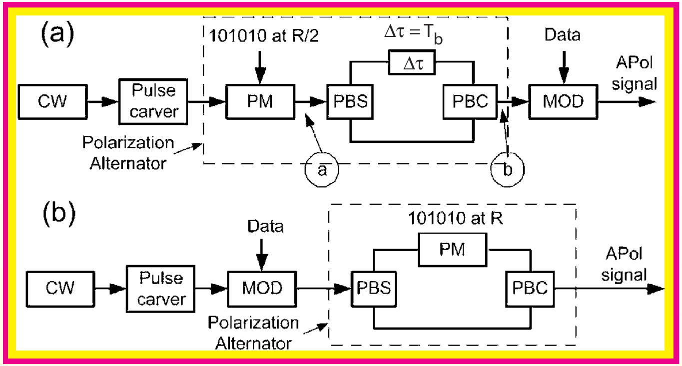


- Growth of power with distance for a 40-Gb/s signal (6.25-ps pulses) and three RZ-type formats.
- Power of ghost pulses depends on phases of neighboring bits.
- AP-RZ format works best because a $\pi/2$ phase difference minimizes buildup of ghost pulses.

Polarization Bit Interleaving

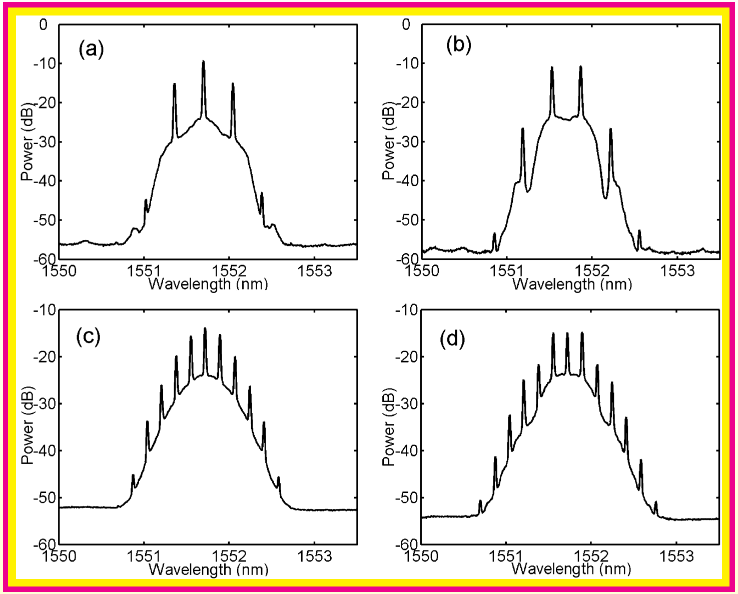
- This technique alternates polarization of neighboring bits.
- Both XPM and FWM processes depend on the state of polarization of interacting waves.
- If neighboring bits are polarized orthogonally, their impact is reduced considerably.
- Bit interleaving was first used in 1991 for reducing interaction between neighboring solitons.
- In a different approach, neighboring channels in a WDM system are orthogonally polarized to reduce channel crosstalk.
- Reduction of Intrachannel nonlinear effects requires that neighboring bits of the same channel be polarized orthogonally.

Polarization Bit Interleaving



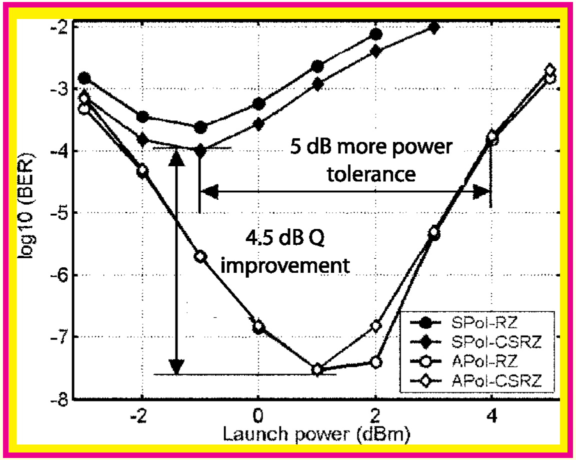
- Two schemes used for for polarization bit interleaving.
- In (a) phase modulator first imposes phase shift on pulse train.
- This train is split into polarization components that are combined back after one bit delay. A data modulator codes the RZ signal.
- In (b) pulse train is first coded with data, then split into its components that are combined back after a phase modulator imposes phase shift on one of the components.

Spectra for Four Modulation Formats



- Spectra of standard (a) RZ and (b) CSRZ signals.
- Modified spectra of (c) RZ and (d) CSRZ signals when neighboring bits are orthogonally polarized.

Polarization Bit Interleaving

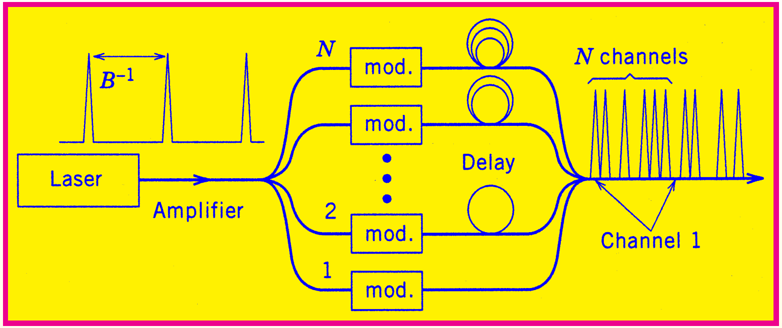


- BER at a distance of 2,000 km for the four formats whose spectra are shown in previous Figure.
- Q^2 factor improves by 4.5 dB when neighboring bits are orthogonally polarized.
- With polarization alternation, intrachannel nonlinear impairments are reduced significantly and lead to a much lower BER.

High-Speed Lightwave Systems

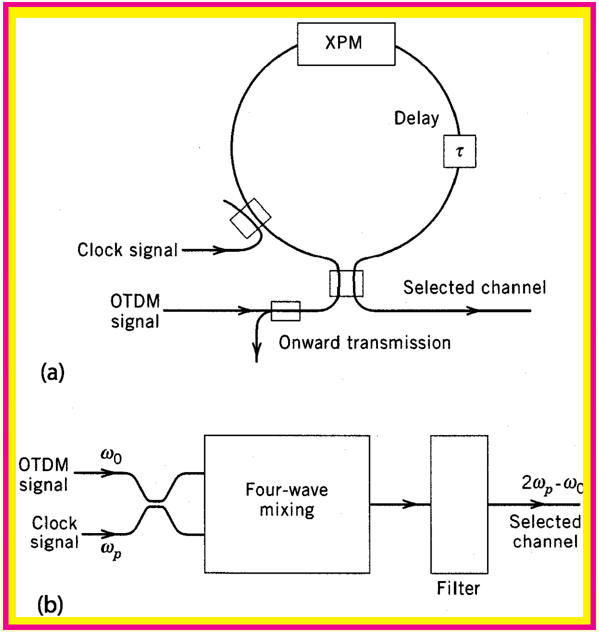
- If intrachannel nonlinear effects can be controlled, it is possible to increase the bit rate beyond 40 Gb/s.
- Such optical signals cannot be generated electrically because of limitations imposed by high-speed electronics.
- Time-division multiplexing (TDM) is employed to create bit streams at data rates higher than 40 Gb/s.
- Optical TDM (OTDM) has been used to transmit data at a single carrier wavelength at bit rates as high as 1.128 Tb/s.
- Use of OTDM requires new types of transmitters and receivers for all-optical multiplexing and demultiplexing.

OTDM Transmitters



- A laser emitting a pulse train at bit rate B is used.
- Pulse width T_p shouls satisfy $T_p < T_b = (NB)^{-1}$ to ensure that each pulse will fit within its allocated time slot T_b.
- Laser output is split into N branches.
- Bit stream in the nth branch is delayed by $(n-1)/(NB)$.
- The output of all branches is combined to form a composite signal.

OTDM Receivers

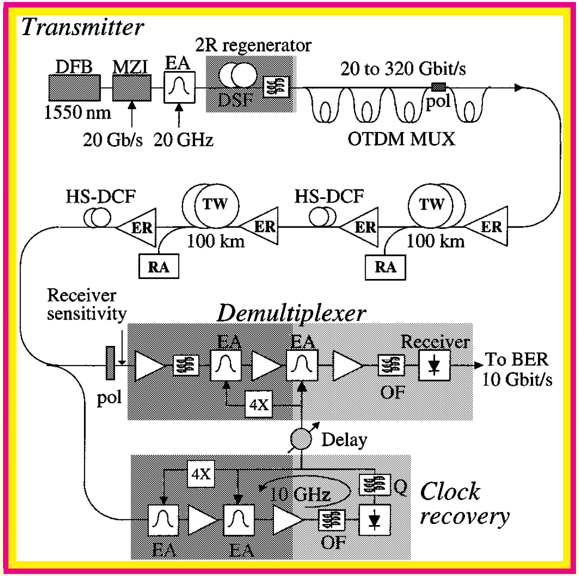


- Demultiplexing schemes: (a) XPM within a Sagnac interferometer and (b) FWM inside a nonlinear medium.
- A semiconductor optical amplifier also used in place of fiber.

Performance of OTDM Systems

- Transmission distance of OTDM systems is limited by fiber dispersion because of the use of short optical pulses.
- A 200-Gb/s system is limited to <50 km even even when $\beta_2 = 0$.
- OTDM systems require simultaneous compensation of both second- and third-order dispersions.
- Even then, PMD is a limiting factor and its compensation is necessary.
- Intrachannel nonlinear effects also limit performance.
- By 1999, operation at 3 Tb/s was realized by combining 19 channels operating at 160 Gb/s.

Performance of OTDM Systems



- Schematic of a 320-Gb/s OTDM experiment over 200 km.
- In 2000, a 1.28-Tb/s ODTM signal was transmitted over 70 km, but it required compensation of fourth-order dispersion.