초고속 광통신에서의 색분산 문제 완화 기술의 현황

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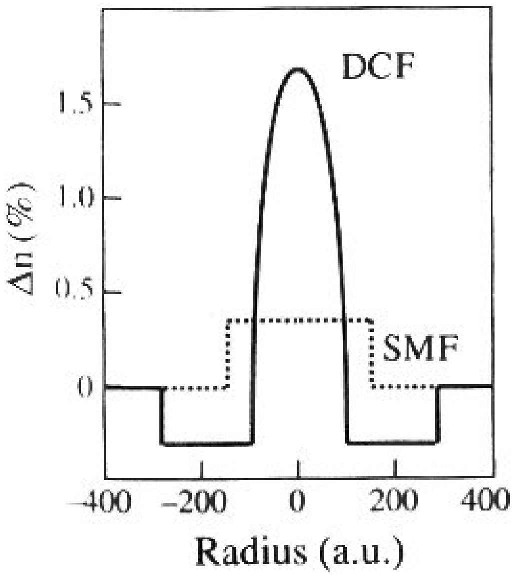
Outline

- Fixed Chromatic Dispersion Compensation Methods

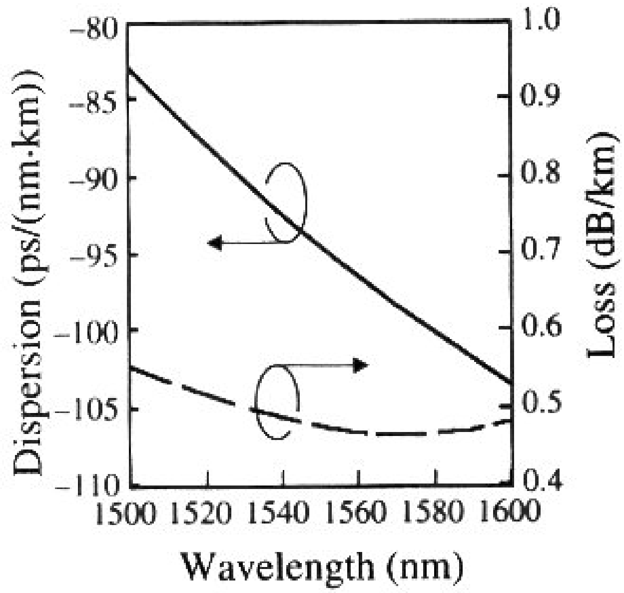
- Tunable Chromatic Dispersion Compensation Methods

Fixed Chromatic Dispersion Compensation Methods

Dispersion-Compensating Fiber (DCF)



Refractive index profile of dispersion compensating fiber (Δ n is defined as refractive index relative to the cladding)



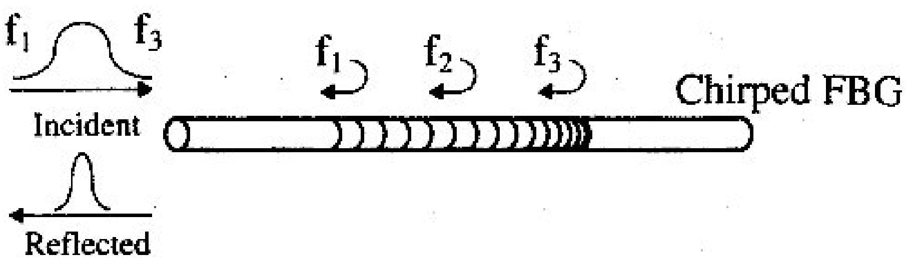
The loss and dispersion as a function of wavelength (negative chromatic dispersion)

✓ Limitation

- **Higher nonlinearity from high power density (due to smaller cross-section)**
- **Higher splicing loss**
- **Higher bending loss**
- **Additional optical loss from long required length**
- **Only one channel compensation owing to dispersion slope mismatch**

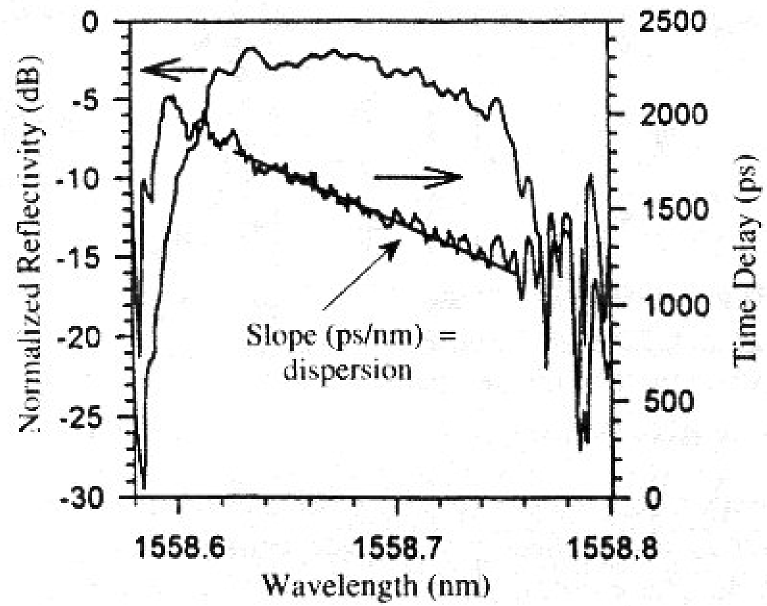
I. Kaminow and T. Li, *Optical Fiber Communications IV B*, Academic Press (2002)

Chirped Fiber Bragg Gratings (CFBGs)



CFBGs reflect different frequency components at different locations within the grating.

They can be used for dispersion compensation when the time delay for the grating is the inverse of the delay caused by dispersion.

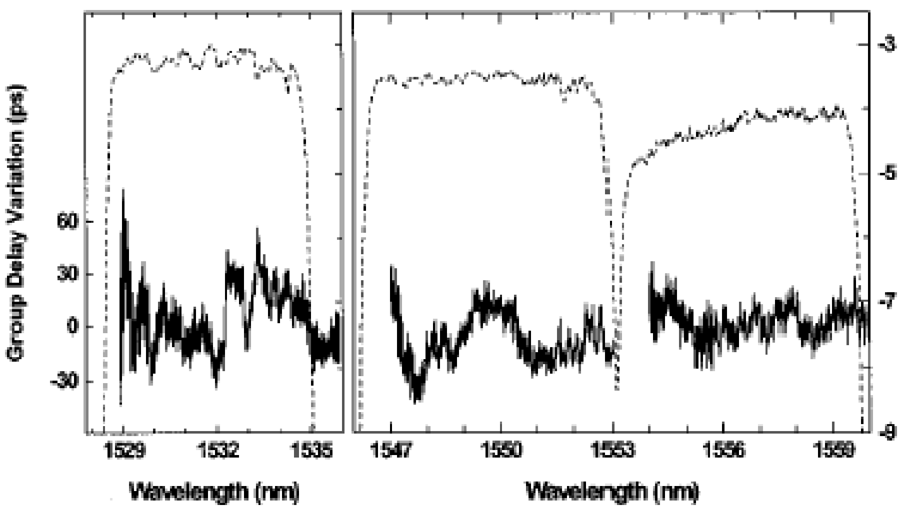


Normalized reflectivity and time delay for a linearly CFBG.

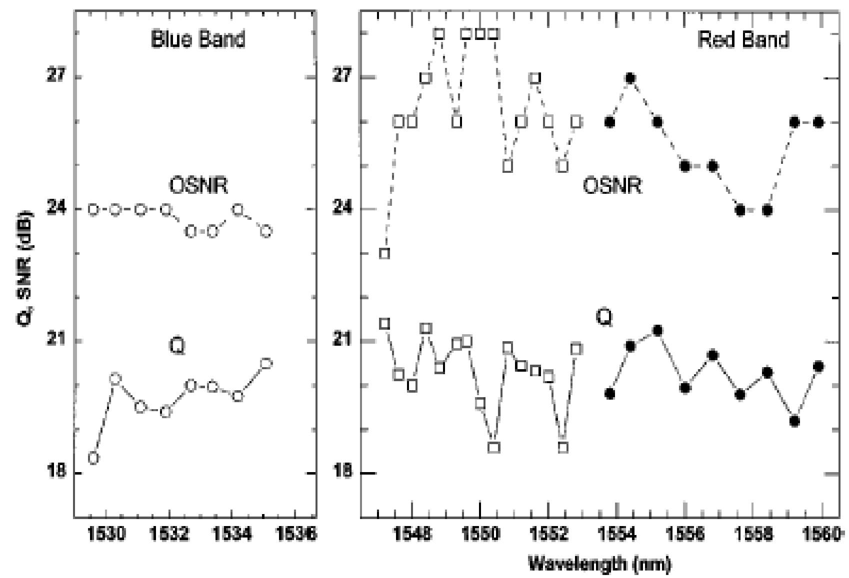
Oscillatory and random ripple should be minimized for the best system performance.

I. Kaminow and T. Li, *Optical Fiber Communications IV B*, Academic Press (2002)

Long-Length Broadband CFBGs



Group delay ripple and insertion loss characteristics of typical blue- and red-band dispersion compensation modules.
(three 1 m-long CFBGs)



Measured Q-value and optical SNR (OSNR) of each channel after 375-km transmission
(10-Gb/s NRZ transmission)

IEEE Photon. Technol. Lett., vol. 12, no. 3, pp 356-358, 2000 (AT&T)

Continued…

32-channel 10 Gb/s over 375 km experiment

18 nm bandwidth

CFBG dispersions: -1300 ps/nm, -1330 ps/nm

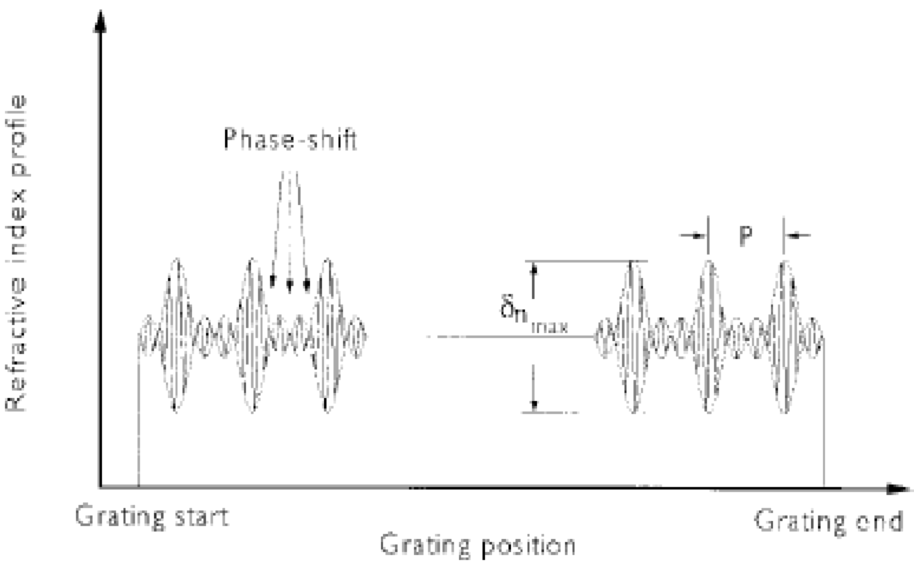
Insertion loss of module: < 3.7 dB (average: 3.2 dB)

PMD: 1.4 ~ 2.4 ps (average: 1.5 ps)

PDL: < 0.3 dB

No temperature stabilization in the experiment
(cf. Typical thermal sensitivity of FBG: ~13 pm/^{o}C)

Multi-Channel CFBGs



Refractive index and phase profile of equal-strength sampled fiber gratings

IEEE Photon. Technol. Lett., vol. 10, no. 6, pp 842-844, 1998 (Univ. of Southampton)

UV

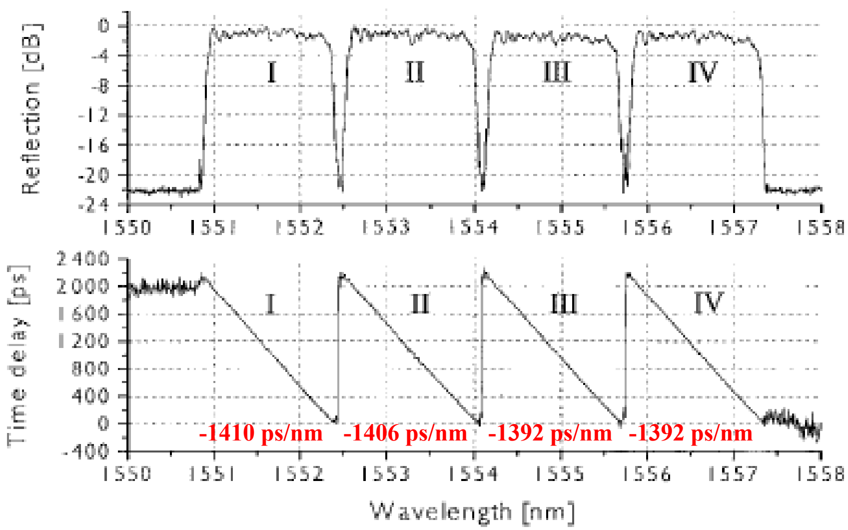
Sinc Periodic Sampling

+

Chirped Phase Mask

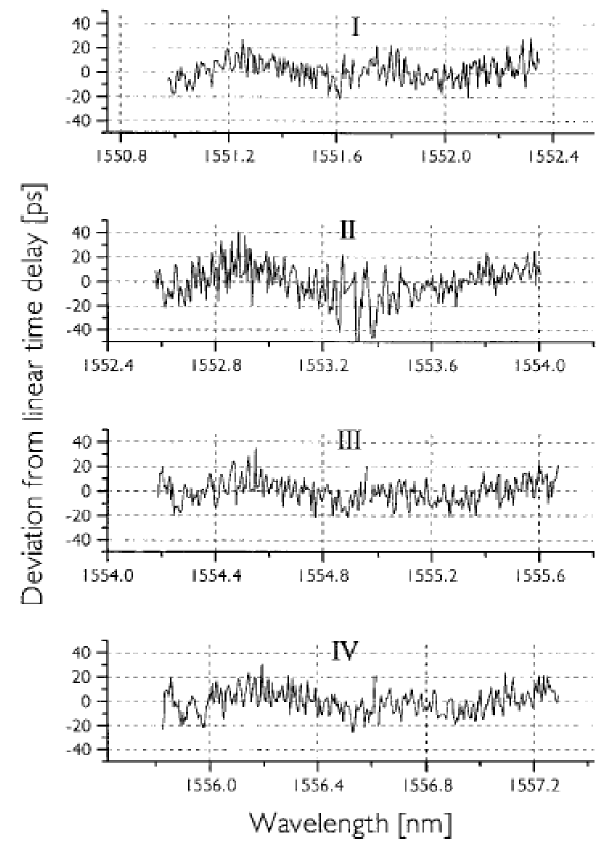
Sinc-Sampled Chirped Fiber Bragg Grating

Continued…



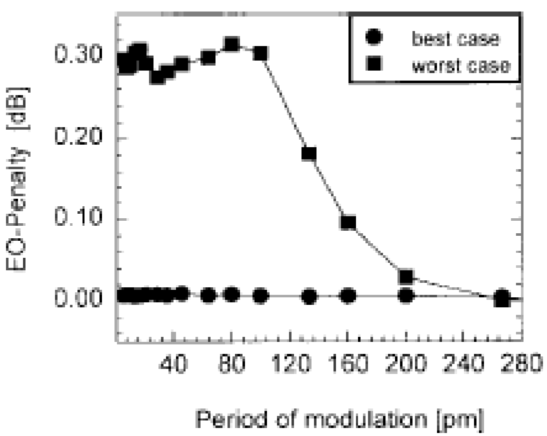
Measured reflection and time delay characteristics of a 22.5-cm-long continuously chirped fiber grating with four wavelength channels separated by 1.6 nm (200 GHz) and channel bandwidths of 1.6 nm.

D = -1410, -1406, -1392, -1392 ps/nm

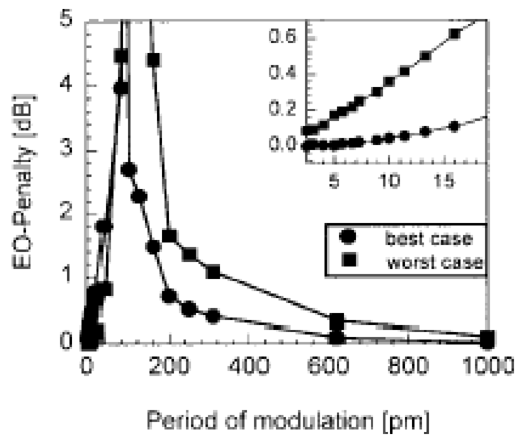


Measured deviations from linear time delay for channels I, II, III, and IV

Influence of Non-Ideal CFBG Characteristics on Dispersion Cancellation



Maximum and minimum eye opening(EO)-penalty as a function of the period of modulation in the reflection spectra of CFBG. Peak-to-peak amplitude of modulation is 1 dB.



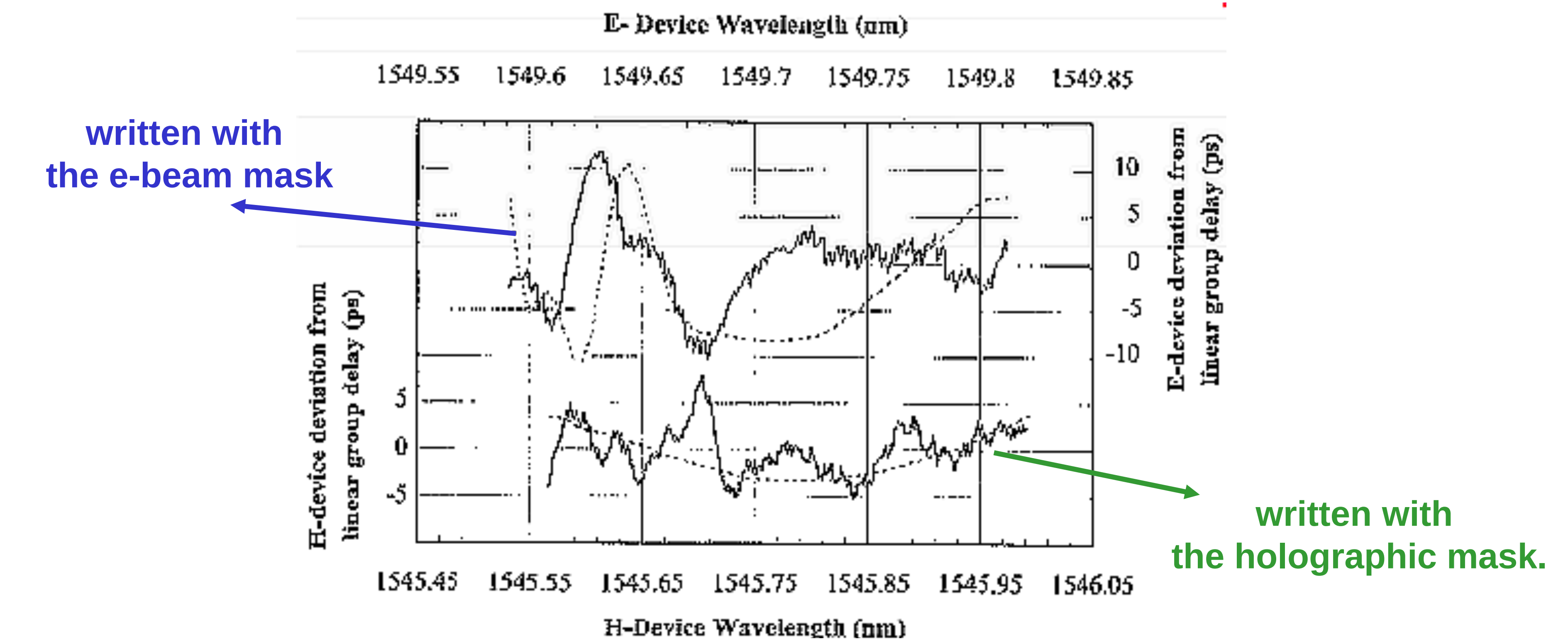
Maximum and minimum EO-penalty as a function of the period of modulation in the time delay (phase). Peak-to-peak modulation is about 120 ps. The insert is a blowup of the data for small periods.

10-Gb/s NRZ transmission system simulation

Random ripple of CFBG can be decomposed into various frequency components.
The effects of ripple on the signal are bit rate dependent.

IEEE Photon. Technol. Lett., vol. 10, no. 10, pp 1476-1478, 1998 (Univ. of Southampton)

The Cause of Random Delay Ripples
– Random Stitch Error of E-beam Phase Mask



IEEE Photon. Technol. Lett., vol. 11, no. 5, 1999
(Communications Research Center, Canada)

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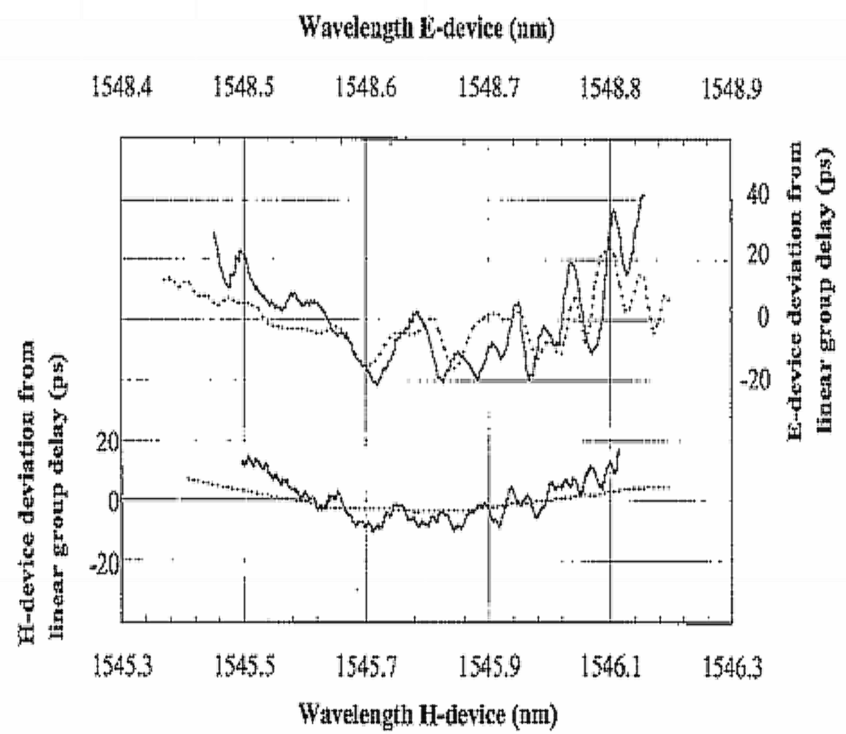
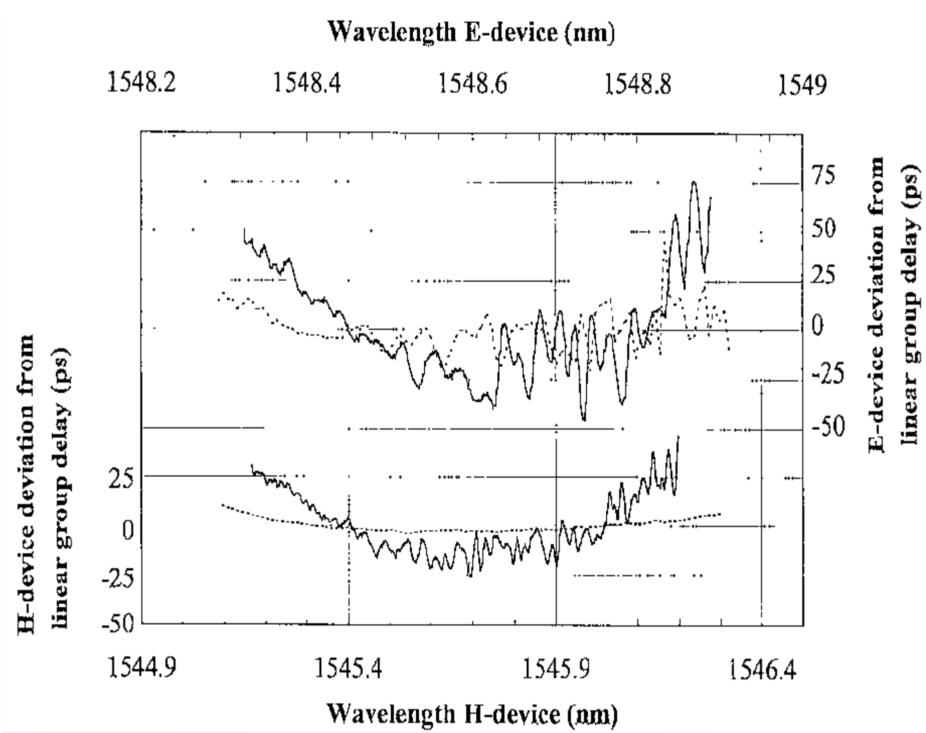
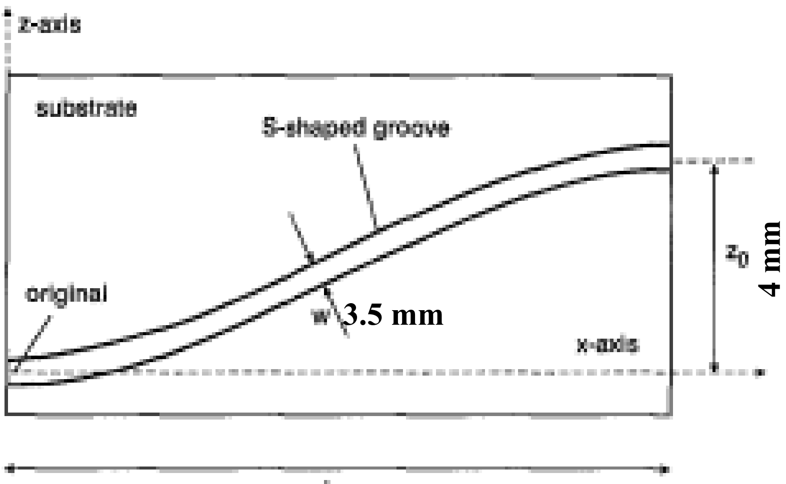




Fully ($cos^2(x)$) apodized 100-mm gratings
Riplple : ±7ps (holographic mask)
± 23ps (E-beam mask)

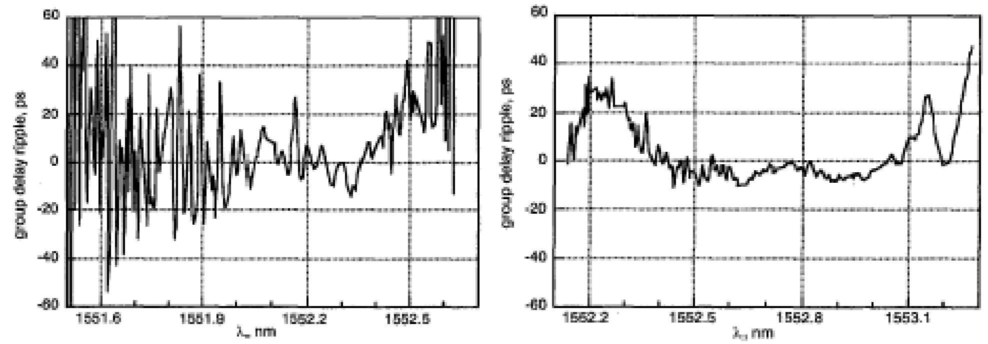
Partially ($exp(-10x^2)cos2(x)$) apodized 100-mm gratings
Riplple : ±10ps (holographic mask)
± 28ps(E-beam mask)

Reduction of Group Delay Ripple of CFBGs



Substrate on which S-shaped groove is formed.
100 mm-long grating, GDR less than +/-3 ps

Electron. Lett., vol. 37, no. 7, pp 449-451, 2001 (NTT)



(a) (b)

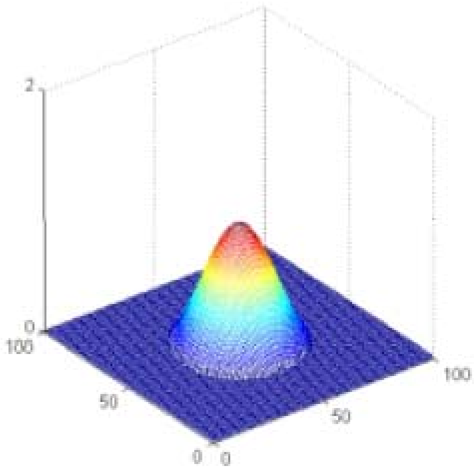
Group delay ripple characteristic of CFBG-A and CFBG-B

(a) CFBG-A, fabricated using conventional step-chirped phase mask

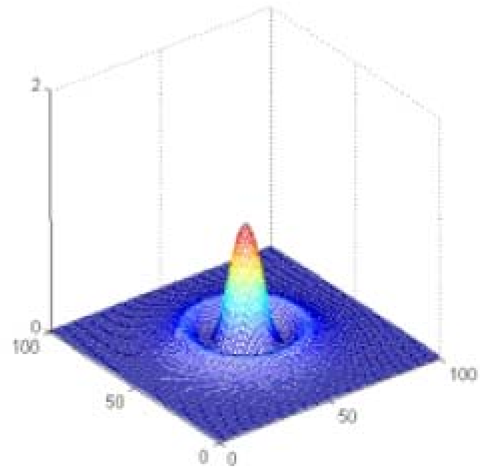
(b) CFBG-B, realized by inserting beam containing a fiber Bragg grating (fabricated using uniform phase mask) and a metal rod into S-shaped groove

LP Modes Intensity Pattern

LP01 Mode

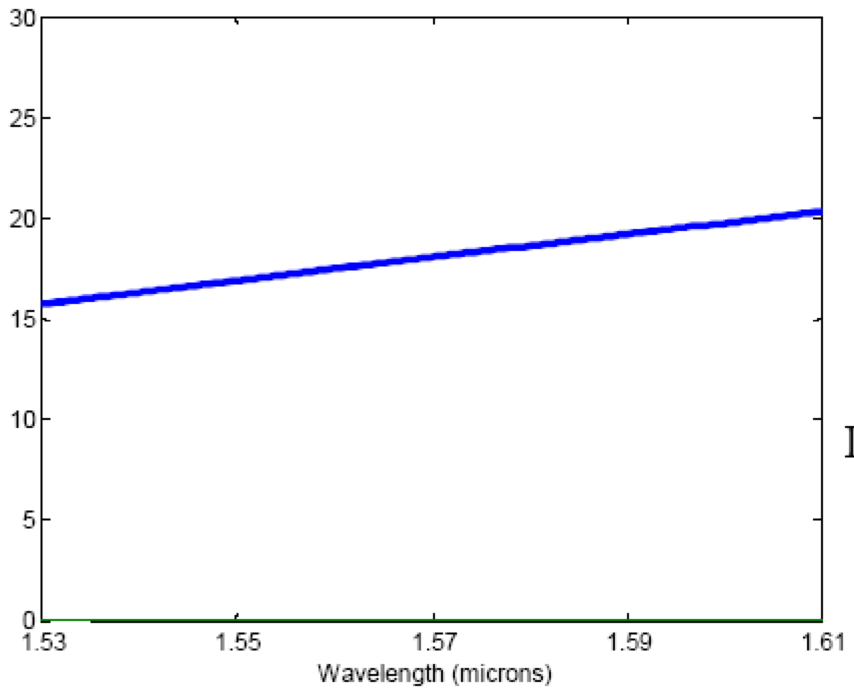


LP02 Mode



LP01 Mode Dispersion

D in units of ps/nm-km



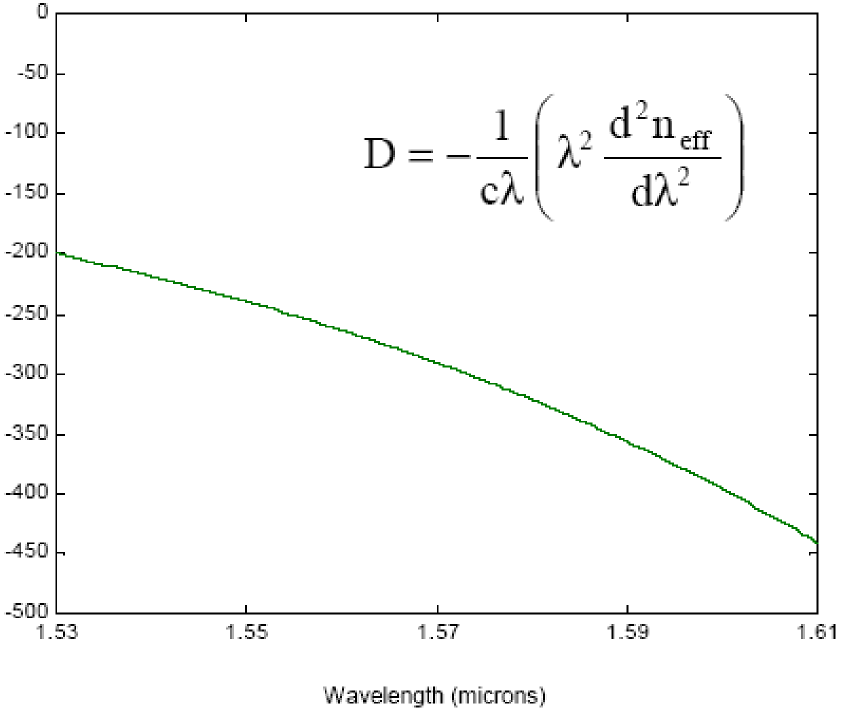
a=4.7 micron
core index=1.4628
clad index=1.46

$$D = -\frac{1}{c\lambda}\left(\lambda^2 \frac{d^2 n_{eff}}{d\lambda^2}\right)$$

The GVD consists of waveguide dispersion and material dispersion.
For silica fibers @ l = 1550 nm, material dispersion is about 20 ps/nm-km, while the waveguide dispersion is about - 3 ps/nm-km.

LP02 Mode Dispersion

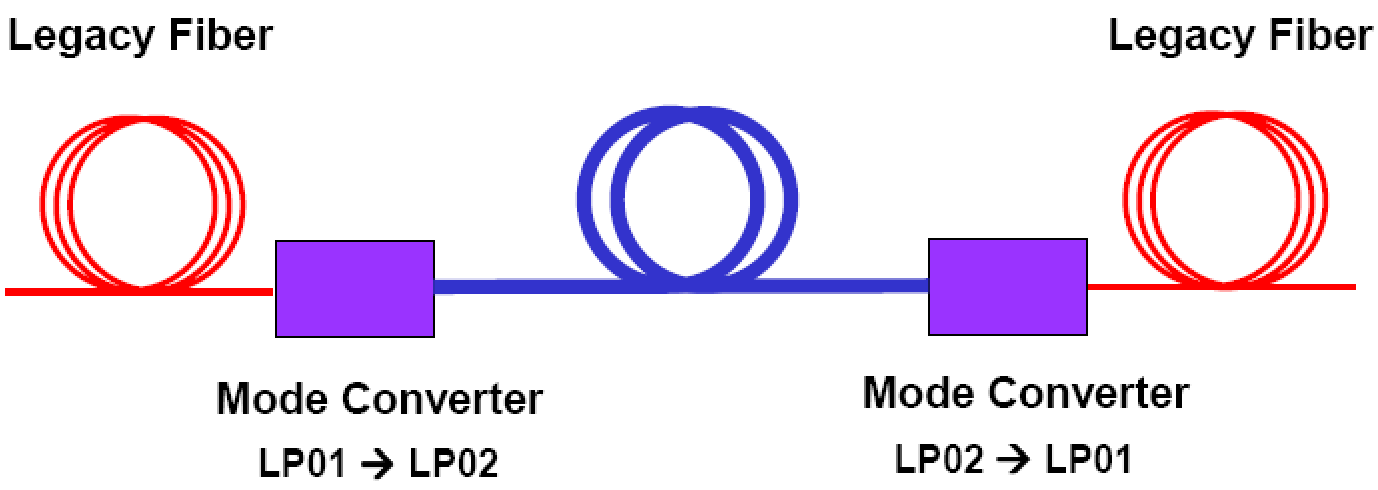
D in units of ps/nm-km



$$D = -\frac{1}{c\lambda}\left(\lambda^2 \frac{d^2 n_{eff}}{d\lambda^2}\right)$$

LP02 mode dispersion
n1=1.477;
n2=1.46;
a=4.7 microns;

2-Mode Fibers

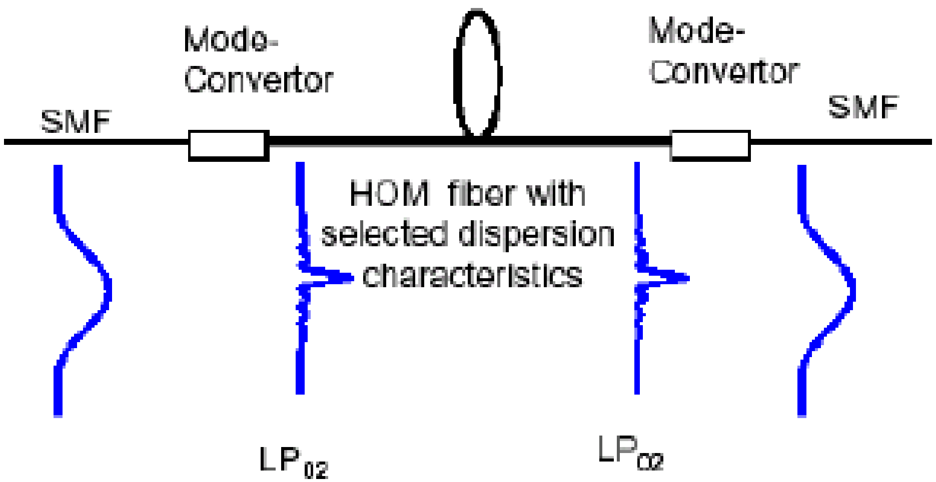


Group Velocity Dispersion (GVD)

D_{LP01} = +17 ps/nm-km (Legacy Fiber)

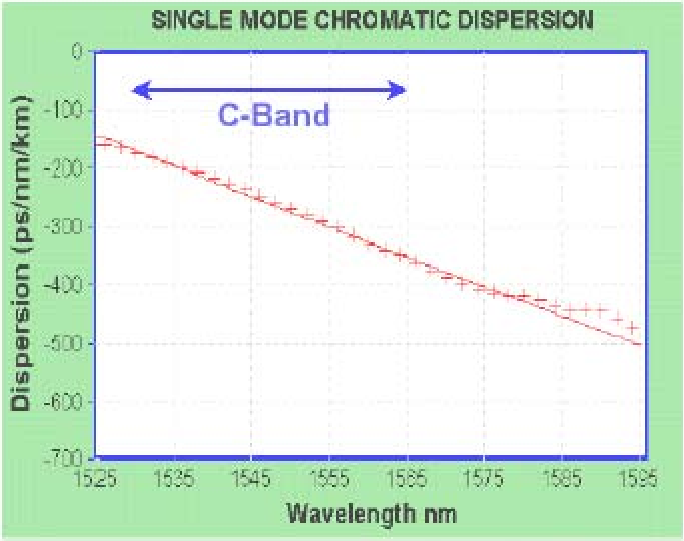
D_{LP02} = -500 ps/nm-km (2-mode Fiber)

Higher-Order-Mode (HOM) Dispersion Compensation Fiber



HOM Dispersion Management Device (DMD)

http://www.lasercomm-inc.com/media/WP_Full-Band_40_NFOEC_08-28-2000.pdf



Dispersion compensation performance of HOM-based DMD

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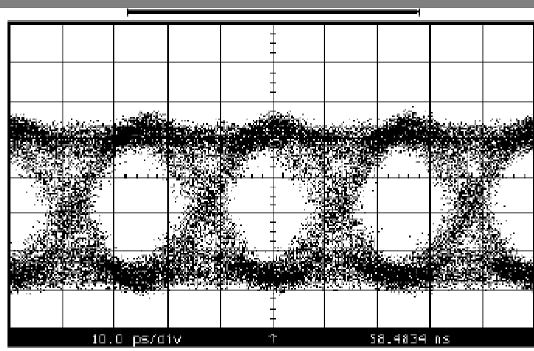
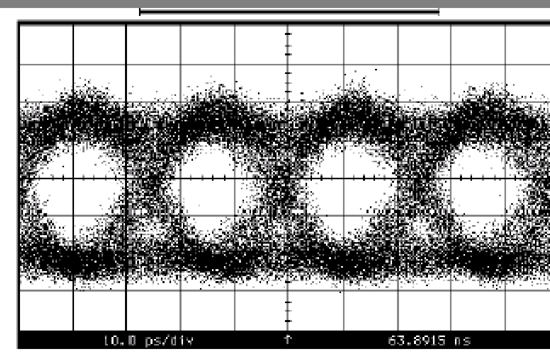
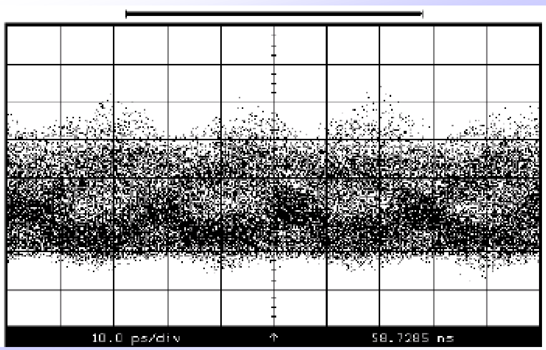


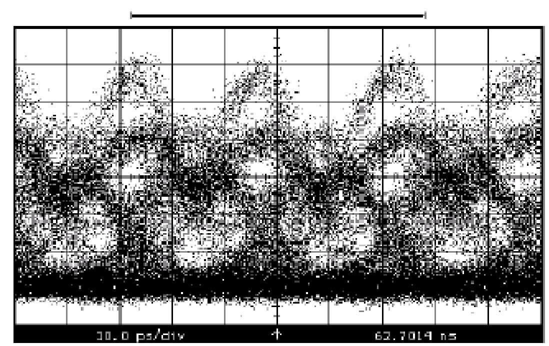
40 Gb/s signal at the Transmitter (Back-to-back)



DCF compensation for a 40 Gb/s signal after 80 km NZDSF @1550 nm



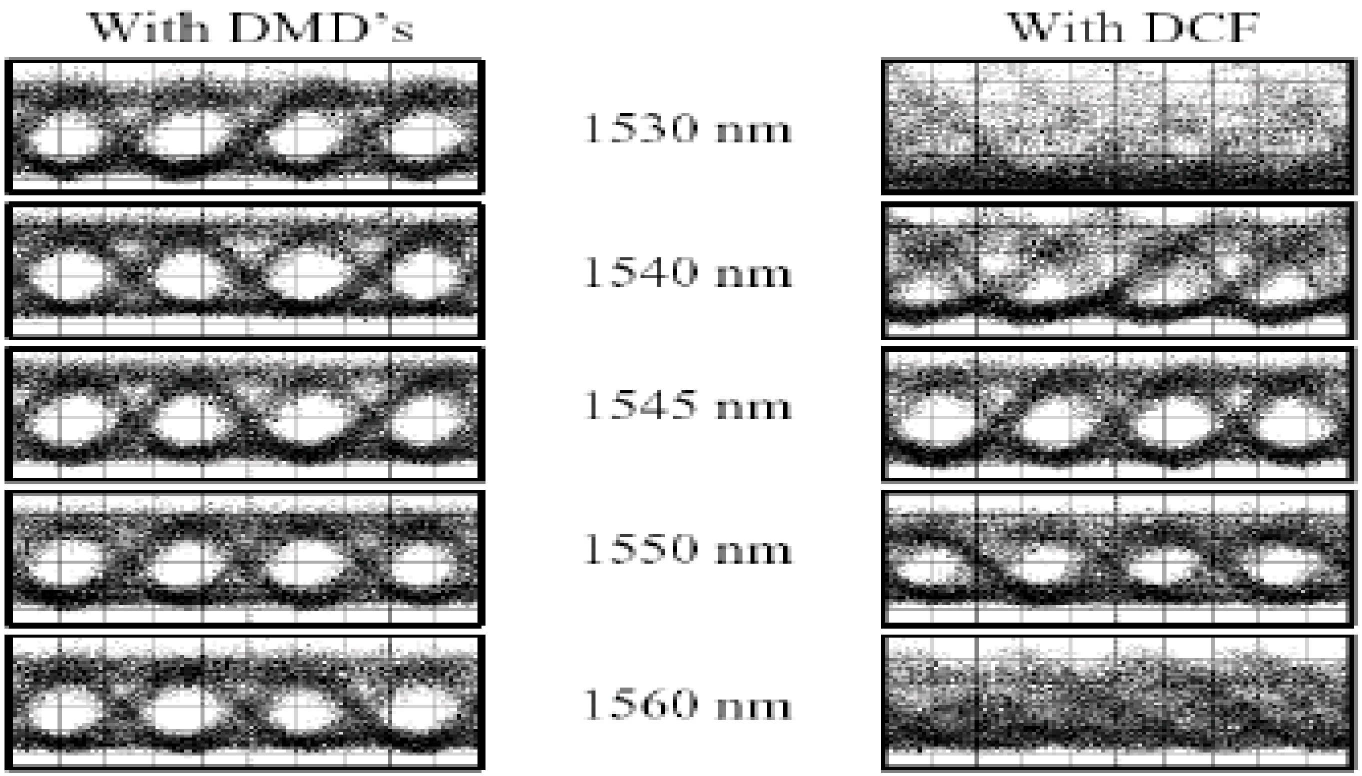
40 Gb/s signal after traversing 80 km of NZDSF without compensation (total dispersion = +210 ps/nm)



DCF compensation for a 40 Gb/s signal after 80 km NZDSF @1530 nm

Continued …

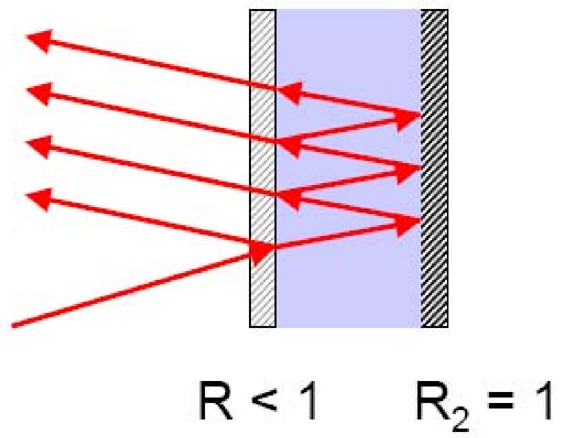
Comparison of DMD and DCF Dispersion Compensation



Performance Specifications (Hi-Mode DMD)

Operating Spectrum	C-Band L-Band
Channelization	N/A (continuous broadband)
Dispersion	-100 ps/nm to -2300 ps/nm
Dispersion Slope	-2.5 ps/nm^2 to -40 ps/nm^2
Insertion Loss	4 dB to 10 dB (dispersion dependent)
Wavelength Dependent Loss	1.0 dB cross-spectrum
Polarization Mode Dispersion	0.5 to 1.0 ps (dispersion dependent)
Electrical Power Requirements	N/A (passive optical device)
Optical Power Handling	20 dBm
Operating Temperature	0º to 65º C
Dimensions (Rackmount Model) (Cardmount Model)	12” x 21” x 1.72” 10” x 10” x 1.6”

Gires-Tournois Etalons



Front mirror reflectivity < 1
Rear mirror reflectivity = 1
All frequency components are totally reflected
Phase shift is a periodic function of frequency

Gires-Tournois Etalons

The phase shift of a Gires-Tournois etalon can be written

$$\Phi = 2\tan^{-1}(\sigma \tan\phi)$$

where

$$\sigma = \frac{1+\sqrt{R}}{1-\sqrt{R}}$$

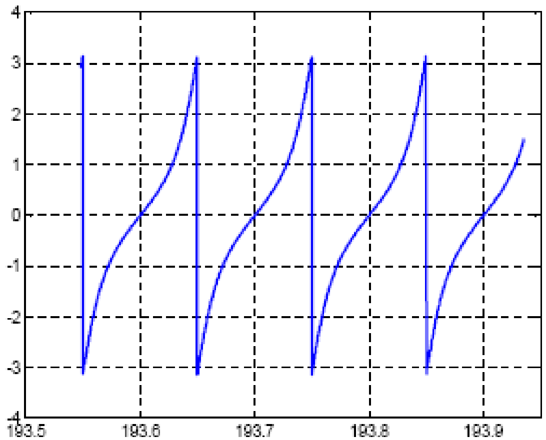
R is the reflectivity of the front mirror, f is the phase shift,

$$\phi = \frac{\omega}{c} nd$$

where d is the space between the mirror, n is the index of refraction of the medium.

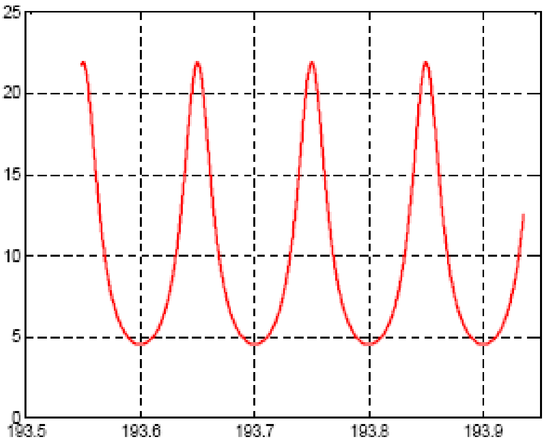
Single Gires-Tournois etalon

Phase shift



Frequency in units of THz

Group delay (ps)

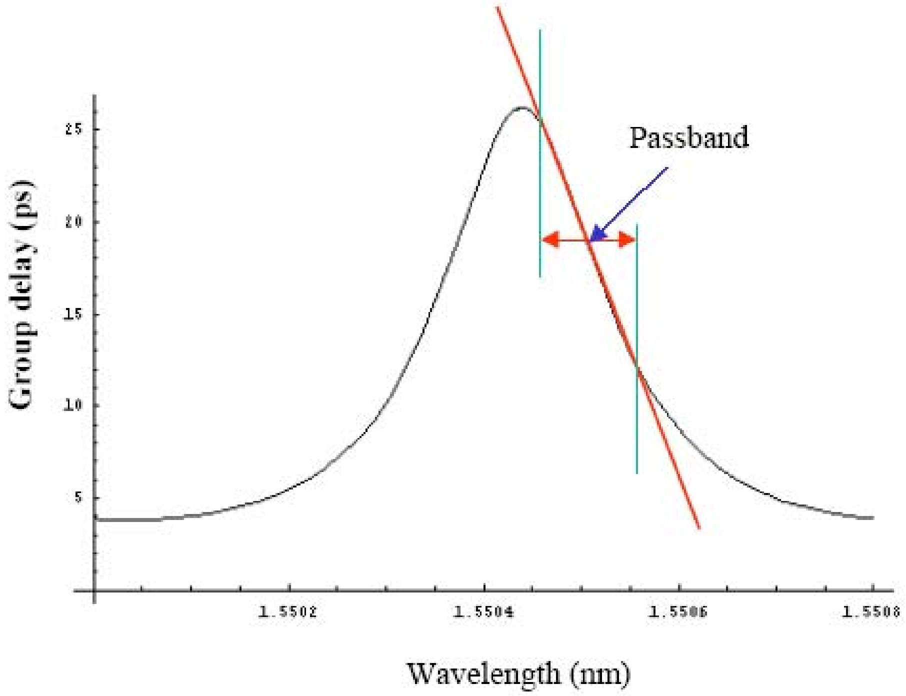


Frequency in units of THz

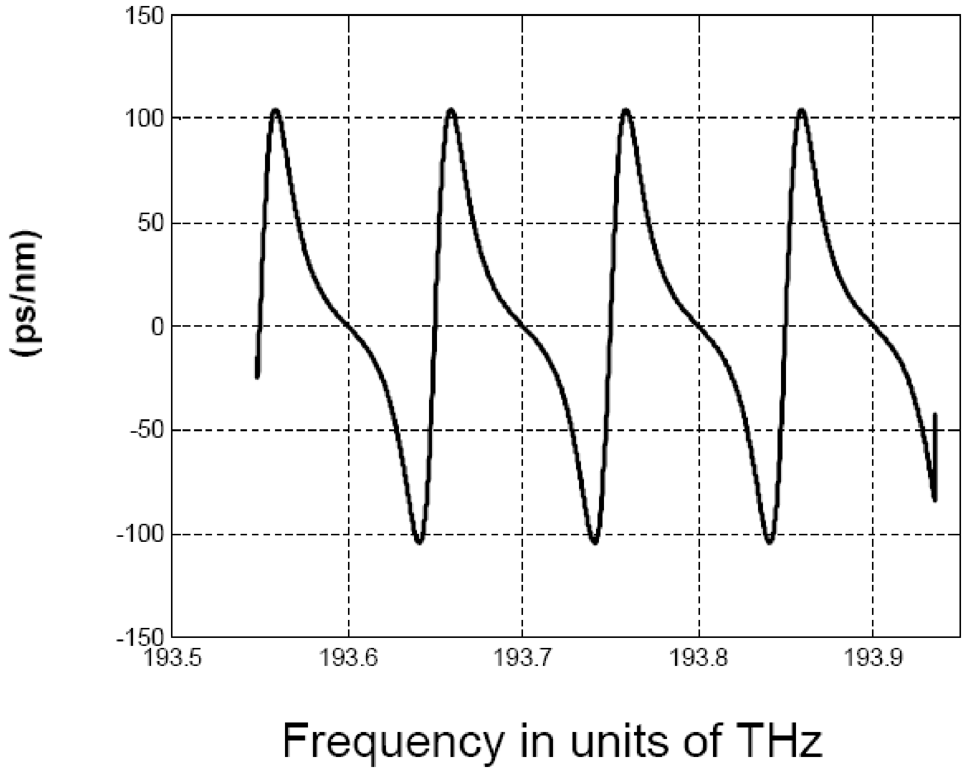
$$\Phi = 2\tan^{-1}\left(\frac{1+\sqrt{R}}{1-\sqrt{R}}\tan\phi\right)$$

$$\tau = \frac{\sigma}{1+(\sigma^2-1)\sin^2\phi}\tau_0$$

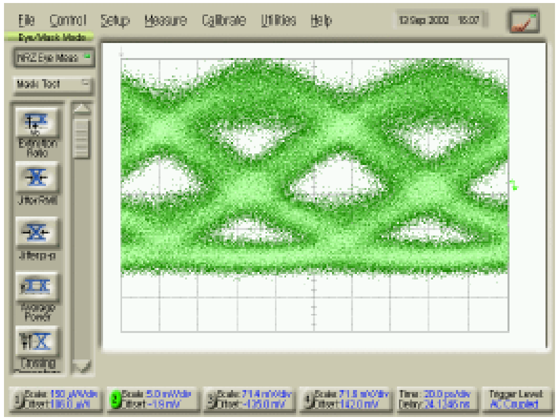
Group Delay of Single Stage GTI Dispersion Compensator



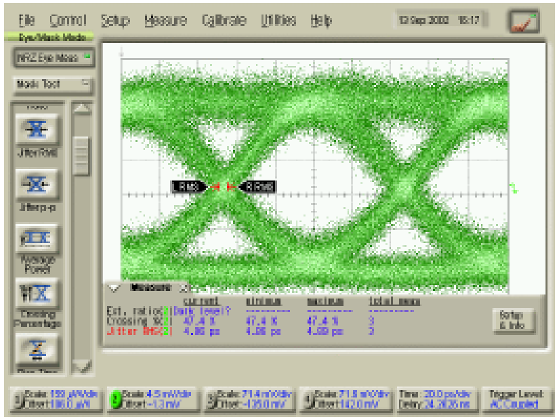
Dispersion of a Single Etalon



Optical Transmission through 100km of fiber (-3.50 dBm laser power)



Without DCM



With Accumux DCM

Eye-diagrams obtained using a GTran 10 Gb/s @193.7 THz transmitter (with pre-chirp)

Bit-Error-Rate

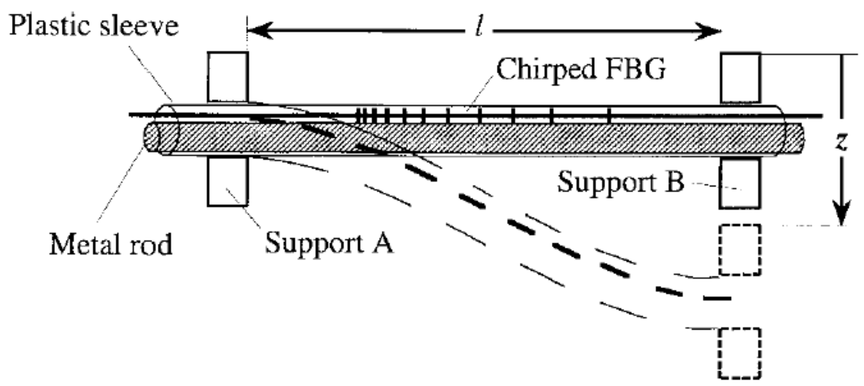
	Without DCM	With Accumux DCM
120km-fiber system, @ -23.00 dBm	No signal	10^{-13}
100km-fiber system, @ -23.50dBm	1.4×10^{-9}	Less than 10^{-15}
100km-fiber system, @ -25.10dBm	No signal	1.4×10^{-9}

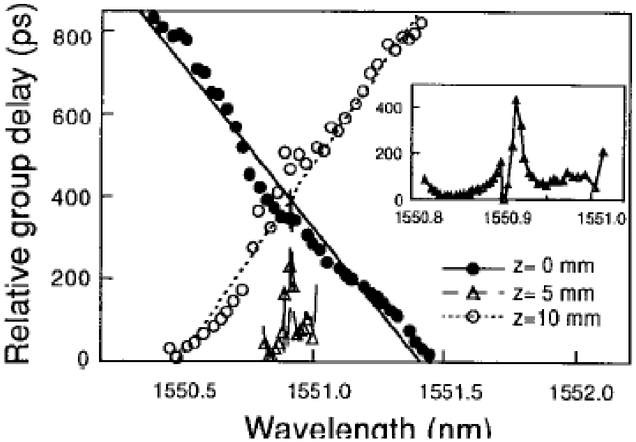
BER obtained using a GTran 10 Gb/s @193.7 THz transmitter (with pre-chirp)

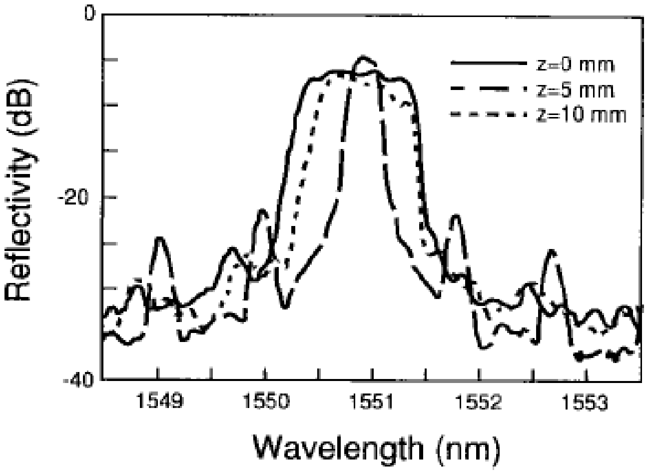
Note: 1 dBm = 1 mW; -20 dBm = 0.01 mW

Tunable Chromatic Dispersion Compensation Methods

Tunable Nonlinear Strain Distribution
- Linearly Chirped FBG Mounted on a Cantilever Beam



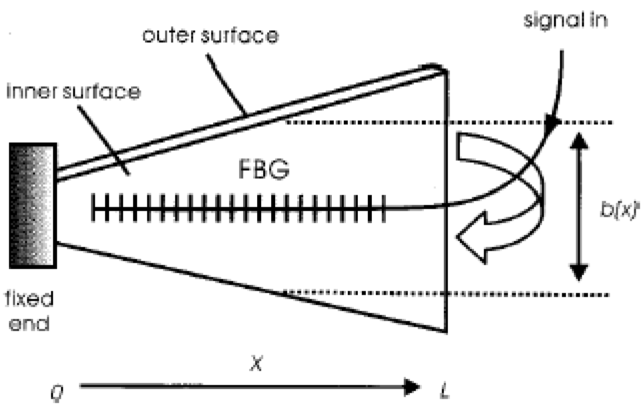


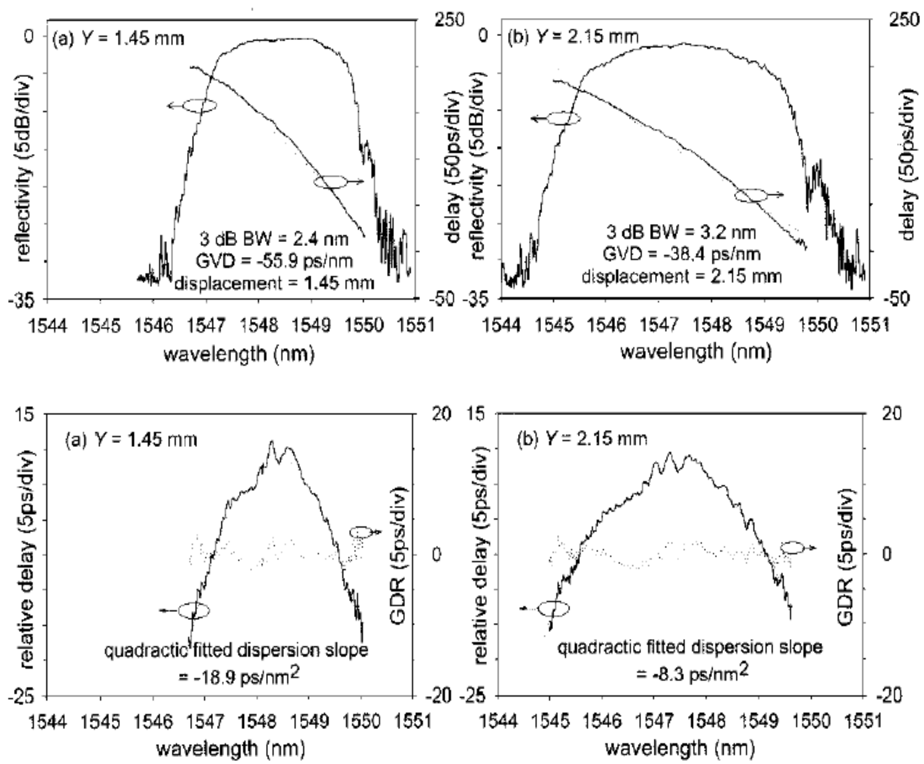


- **Nonlinear strain distribution along the bent cantilever**
- **Cantilever beam rotation prevented**
  - **– fixed grating center wavelength (variation: ~0.09 nm)**
- **-791 ps/nm ~ +932 ps/nm with 10 mm variation in z (10-mm-long linearly chirped FBG)**

IEEE Photon. Technol. Lett., vol. 10, no. 6, pp 845-847, 1998 (NTT)

Tunable Nonlinear Strain Distribution
- Deflecting Tapered Beam

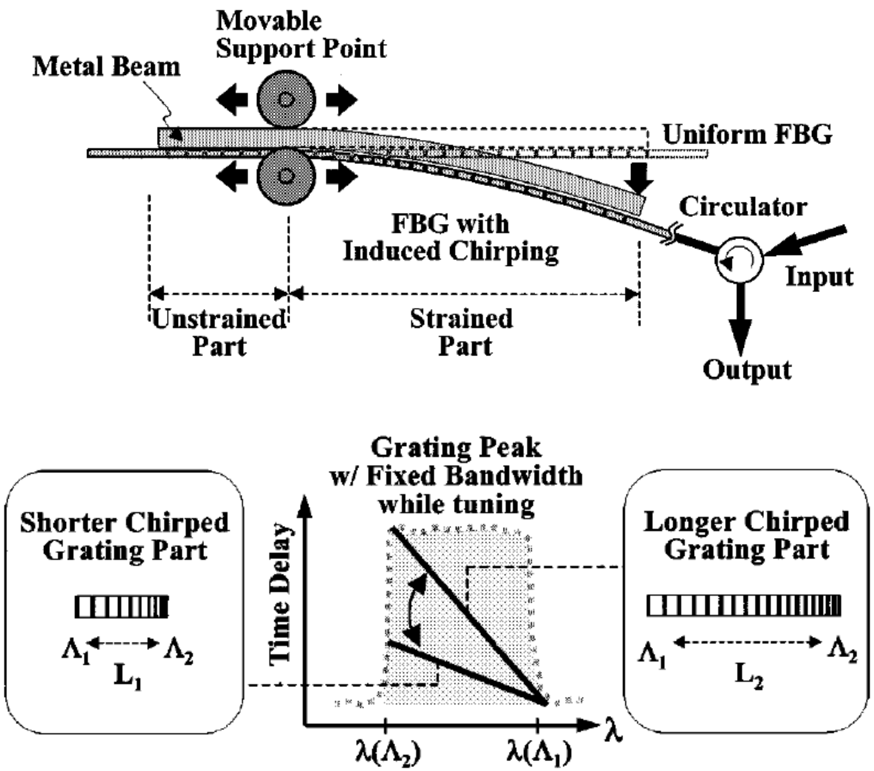


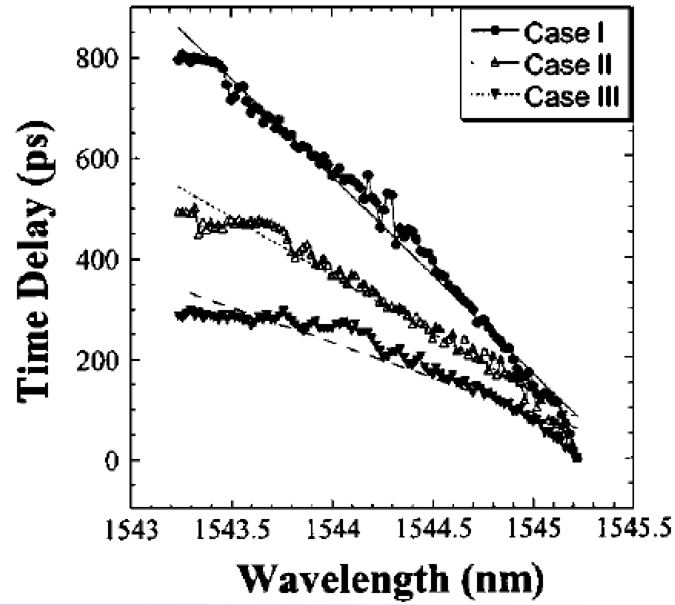


- The nonlinear chirp on the FBG was induced by simple deflection of a linearly tapered beam.
- The dispersion slope can be controlled over a range up to -18.9 ps/nm^2 with a bandwidth in excess of 2.5 nm. (Sufficient to compensate for the DS of a 270-km DSF with DS of 0.07 ps/ nm^2 /km.
- Group delay ripple of +/- 3 ps

IEEE Photon. Technol. Lett., vol. 14, no. 5, pp 663-665, 2002
(Univ. of Tokyo)

Tunable Nonlinear Strain Distribution
- Fixed Bandwidth and Passband Center with Uniform FBG

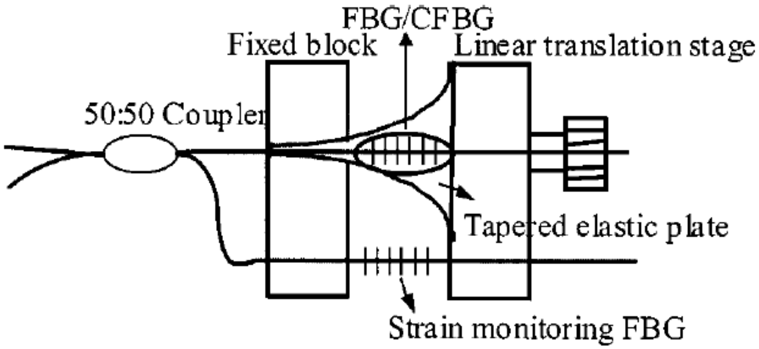




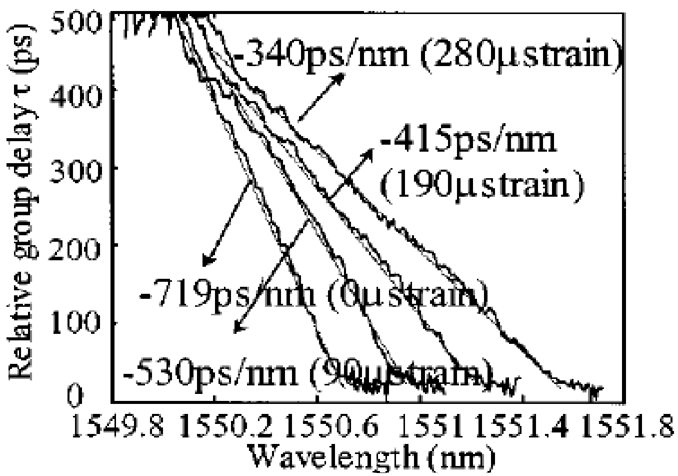
- Controllable strained part length of FBG
- -150ps/nm~- 400 ps/nm for a fixed 2-nm bandwidth
- Disadvantage : unstrained part reflection

IEEE Photon. Technol. Lett., vol. 14, no. 8, pp 1193-1195, 2002
(Univ. of Southern Calif.)

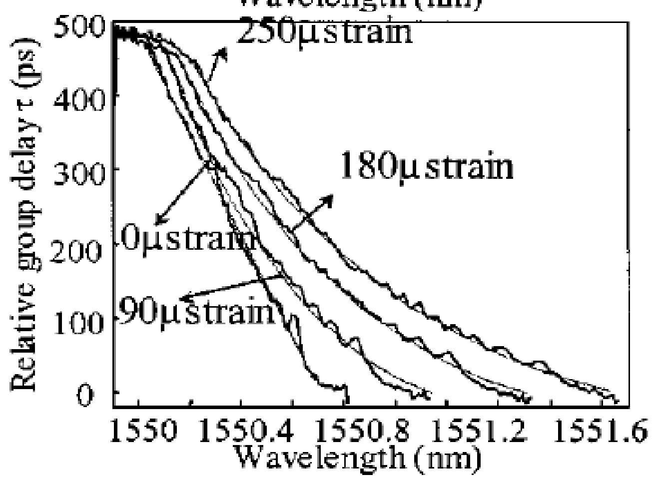
Tunable Nonlinear Strain Distribution
- FBG Mounted on a Tapered Elastic Plate



Hyperbolic plate



Quadratic Plate

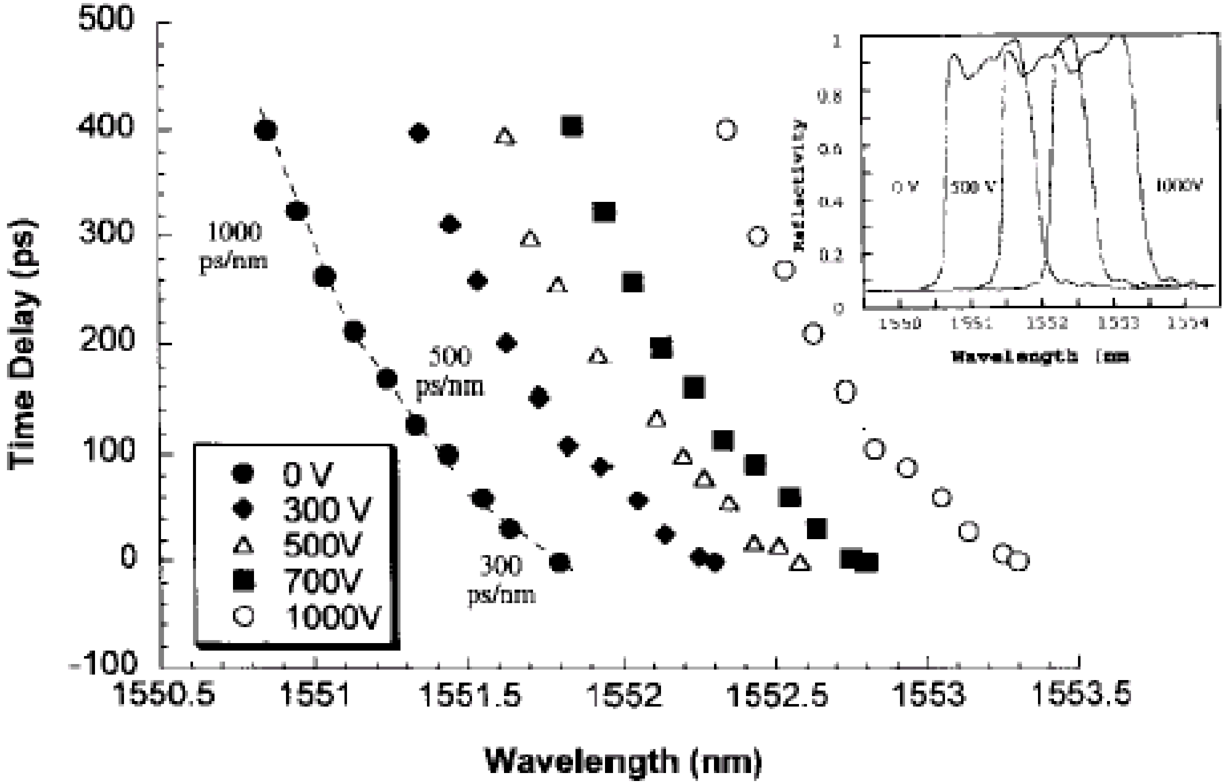


- **Strain distribution depends on the elastic plate tapering profile, elastic coefficient profile**
- **Suitable for higher order dispersion compensation**
- **Repeatability guaranteed with monitoring FBG**
- **-340 ps/nm ~ -720 ps/nm for linear case**

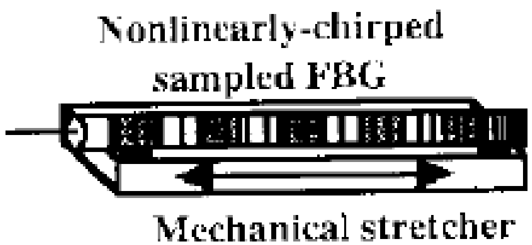
IEEE Photon. Technol. Lett., vol. 14, no. 10, pp 1433-1435, 2002
(Seoul National University)

Group Delay of Nonlinearly Chirped Grating with PZT Voltage Variation

K.-M. Feng *et al., IEEE PTL.* 11, 373 (1999)

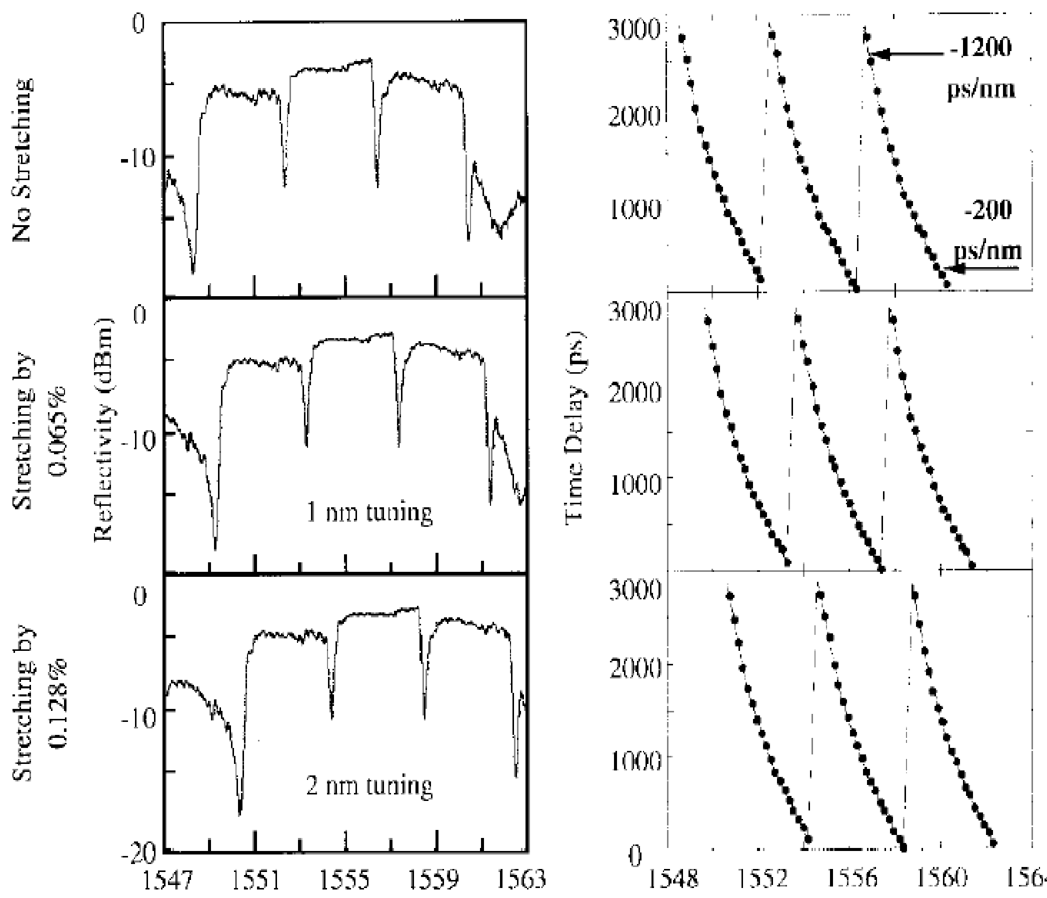


Multi Channel Nonlinearly Chirped Grating Tuned with Uniform Strain



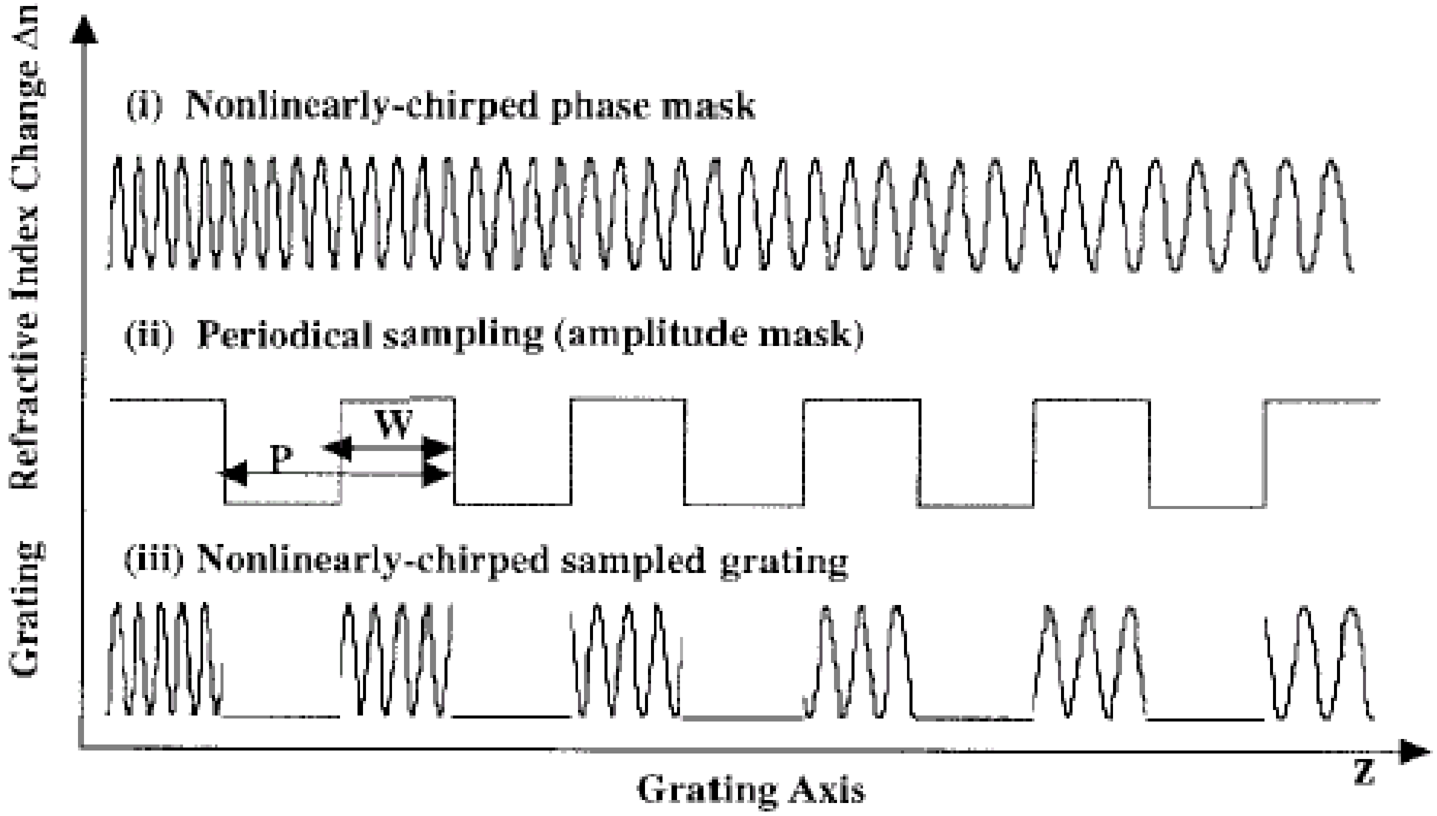
- Uniform strain
- 3 channel simultaneous tuning (10 Gb/s 120 km experiment)
- -200 ps/nm ~ -1200 ps/nm
- Ripple < 40 ps, reflectivity difference < 2 dB

IEEE Photon. Technol. Lett., vol. 11, no. 11, pp 1455-1457, 1999 (Univ. of Southern Calif.)

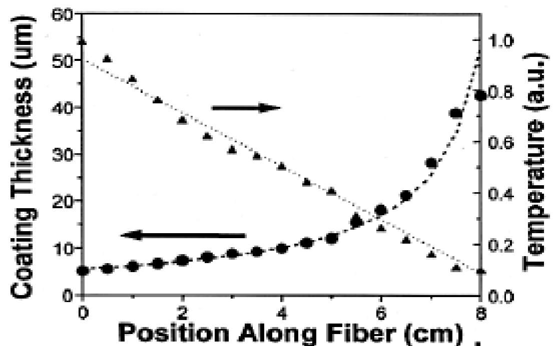


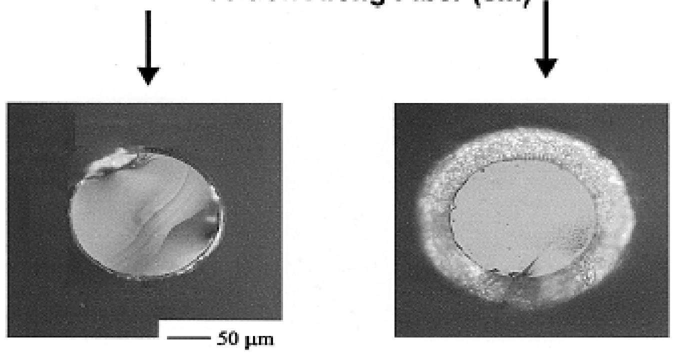
Sampled Nonlinearly Chirped Grating

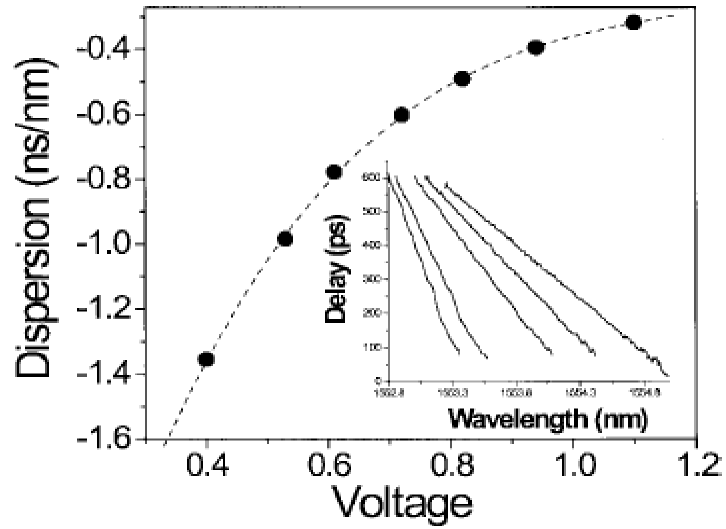
J.-X. Cai *et al.*, *IEEE PTL.* 11, 1455 (1999)



Tunable Nonlinear Temperature Distribution - Tapered Metal Film



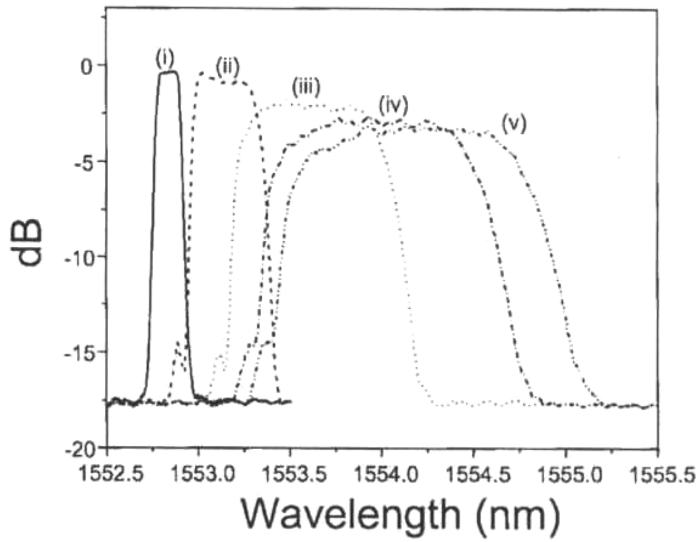




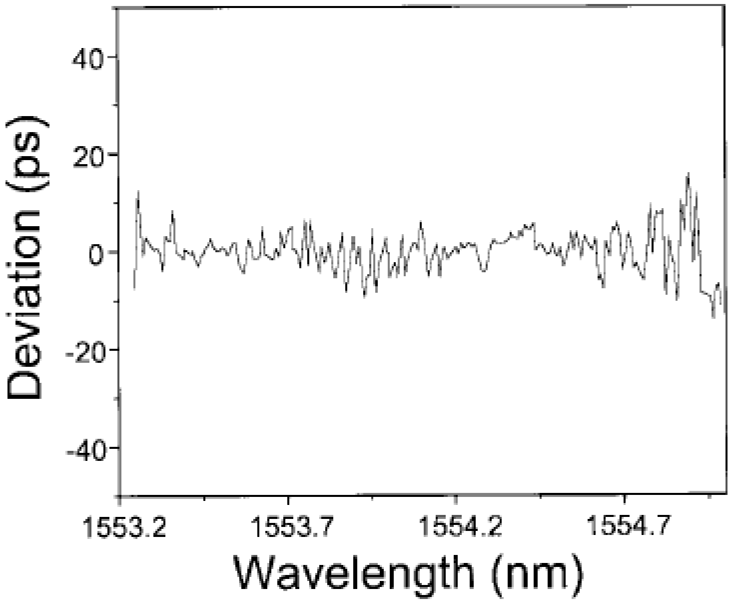
- Advantage : no moving part
- Disadvantage : 1. slow tuning speed
  2. accurate metal deposition
  3. large power consumption
- -300 ps/nm ~-135 0 ps/nm with 7.5-cm grating (power consumption 1W)

IEEE Photon. Technol. Lett., vol. 11, no. 7, pp 854-856, 1999 (Lucent)

Reflection Spectra Change and Delay Ripples

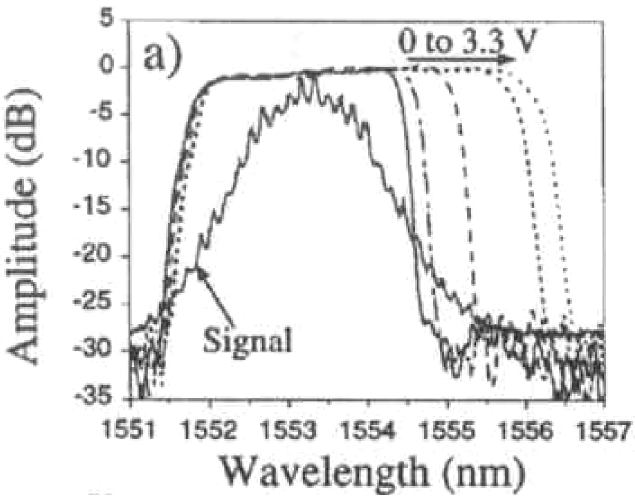


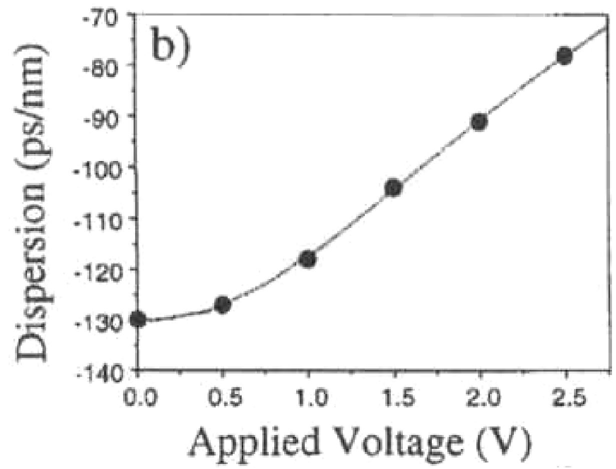
Reflectivity spectra for fiber grating device for increasing values of applied voltage: (i) 0 V (unchirped), (ii) 0.50 V, (iii) 0.81 V, (iv) 1.0 V, and (v) 1.1 V.

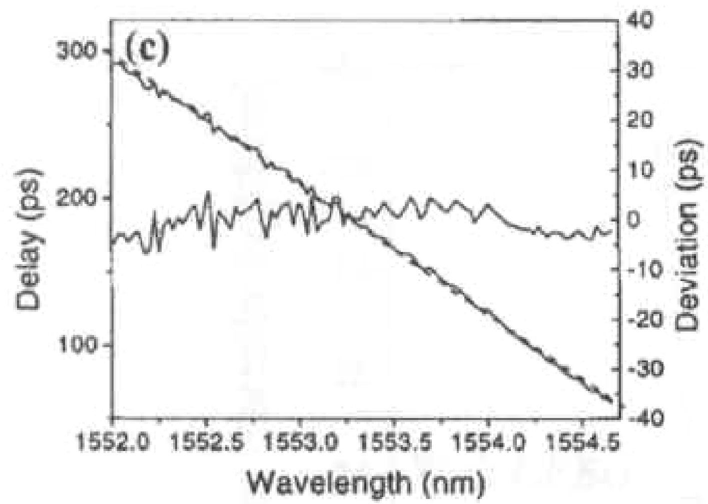


- Ripple ~ 10 ps peak to peak

Variable Dispersion Compensation for 160 Gb/s (Lucent)







B. J. Eggleton *et al.*, *IEEE PTL.* 12, 1022 (2000)

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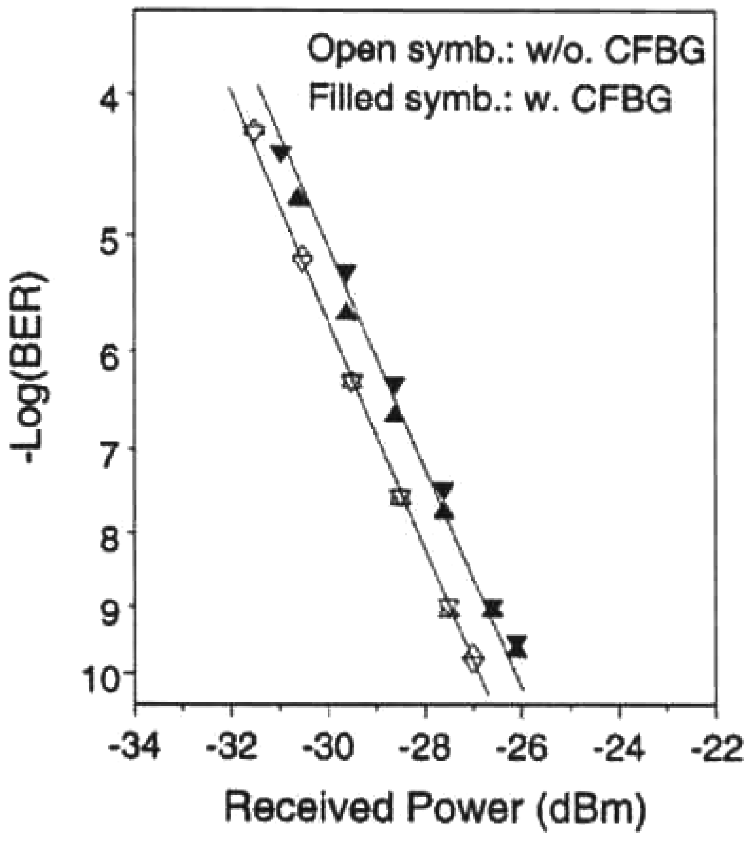


B. J. Eggleton *et al.*, *IEEE PTL.* 12, 1022 (2000)

Measured BER at 160 Gb/s with and without tunable CFBG.

Net dispersion is zero in both cases.

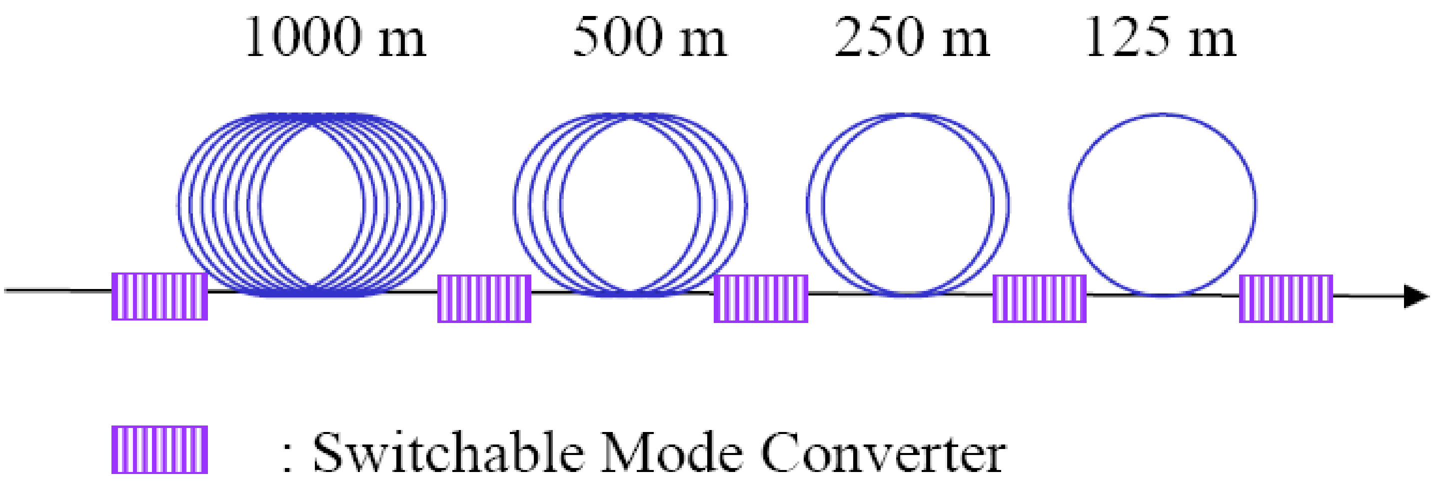
JDS Uniphase Fiber Grating Tunable Dispersion Compensator (Thermal Tuning)

Specifications

Parameter[1]		40 Gb/s	10 Gb/s
Wavelength range		C and L band	
Dispersion tuning range	Typical	-300 to -700 ps/nm	-350 to -1150 ps/nm
Optical loss BW	Minimum	85 GHz	40 GHz
GDR BW	Minimum	85 GHz	40 GHz
GDR (peak to peak)	Maximum	10 ps (note[2])	40 ps
Insertion loss	Maximum	1.7 dB	
Insertion loss ripple	Maximum	0.5 dB	
Polarization dependent loss	Maximum	0.3 dB	
Polarization mode dispersion	Maximum	0.5 ps	1 ps
Maximum power		4 W	
Dimensions (W x H x L)		17 x 12 x 150 mm	
Operation temperature		-5 to 70 °C	
Storage temperature		-40 to 85 °C	

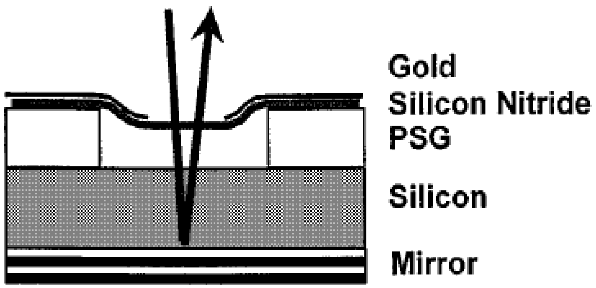
1. All specifications are rated over operation life and polarization effects.
2. Moving average window of 100 pm.

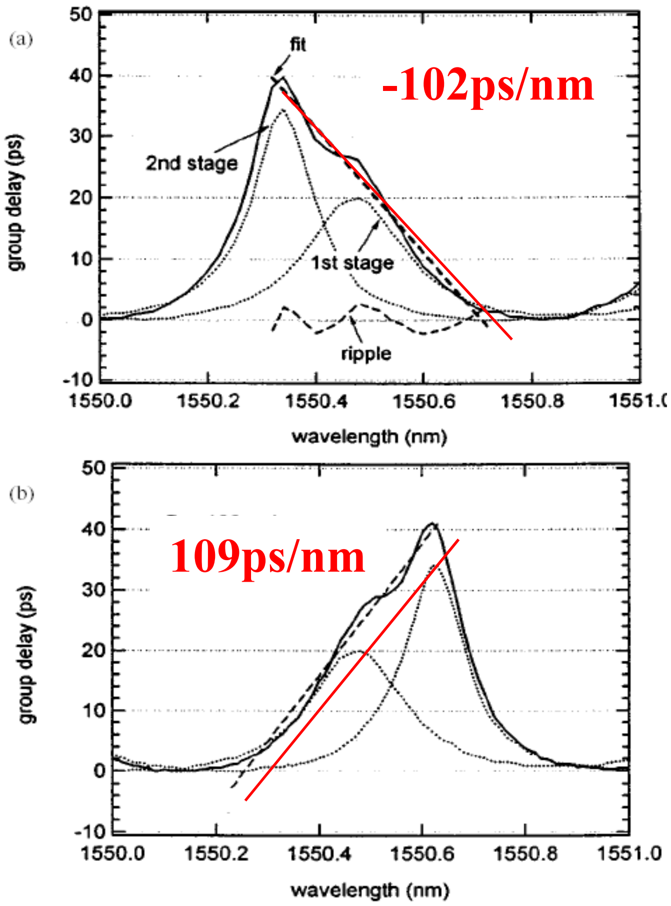
Hi-Mode Fiber



S. Ramachandran, S. Ghalmi, S. Chandrasekhar, Fellow, IEEE, I. Ryazansky, M. F. Yan, F. V. Dimarcello, W. A. Reed, and P. Wisk
IEEE PHOTONICS TECHNOLOGY LETTERS, VOL. 15, NO. 5, MAY 2003

MEMS Actuated Resonant Cavity All-Pass Filter

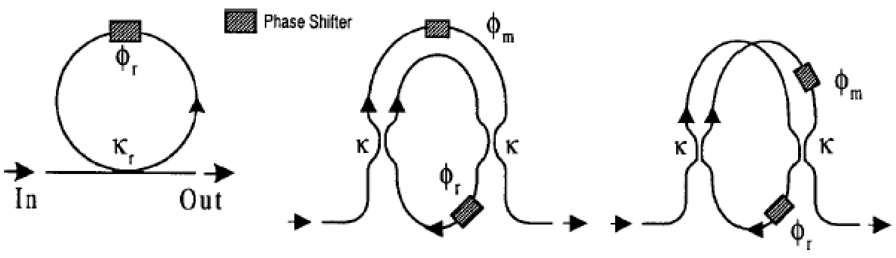


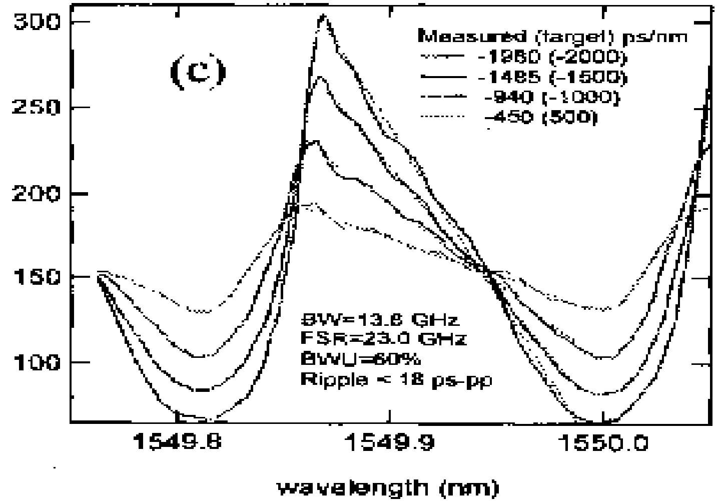


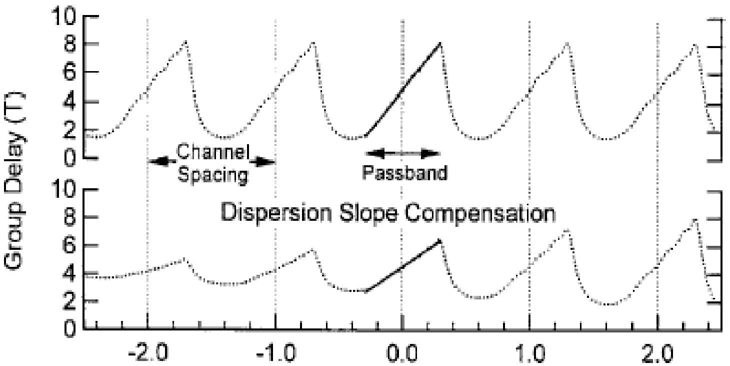
- -100 ps/nm ~ +100 ps/nm with two stage device
- 50 GHz passband
- Ripple < ~3ps
- Passband to channel spacing range (i.e. fill facter) can be increased by cascading several stages
- Excess loss < 2 dB/stage
- PDL < 0.1 dB

IEEE Photon. Technol. Lett., vol. 12, no. 6, pp 651-653, 2000

Waveguide All-Pass Filter



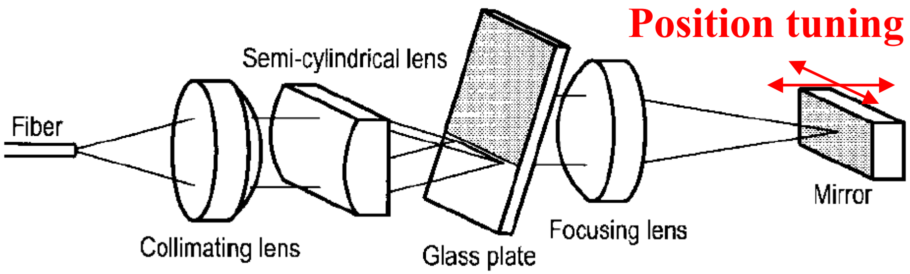


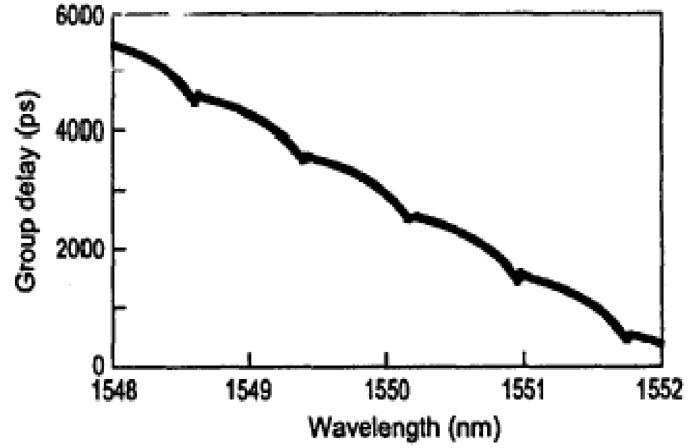


- Phase-only all pass filter
- Two thermooptic chromium phase shifter
  - change the coupling ratio
  - tune the resonant wavelength
- Small channel spacing limited due to the limitation on the bend radius of about 1mm
  - FSR < ~25GHz, passband < ~14GHz
- For a 25-GHz FSR, single-stage filter of max GDR of +/-10 ps over –800 ~ -50 ps/nm.

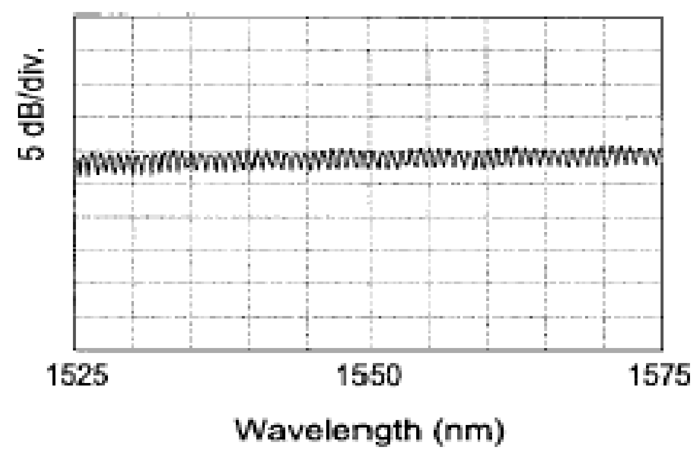
IEEE Photon. Technol. Lett., vol. 11, no. 12, pp 1623-1625, 1999.
OFC 2002, Paper TuT1 (Lucent)

VIPA (Virtually Imaged Phased Array)





- Large angular dispersion
- Dispersion tuning
  - moving the mirror or focusing mirror
  - changing the profile of the mirror
- Dispersion can be tuned from positive to negative
- Fairly large insertion loss due to free-space design
- Non-flat passband (1dB bandwidth ~0.4nm)



IEEE Photon. Technol. Lett., vol. 9, no. 12, pp 1598-1600, 1997 (Fujitsu)

Continued…

- 10 Gb/s 110 km transmission was compensated experimentally.

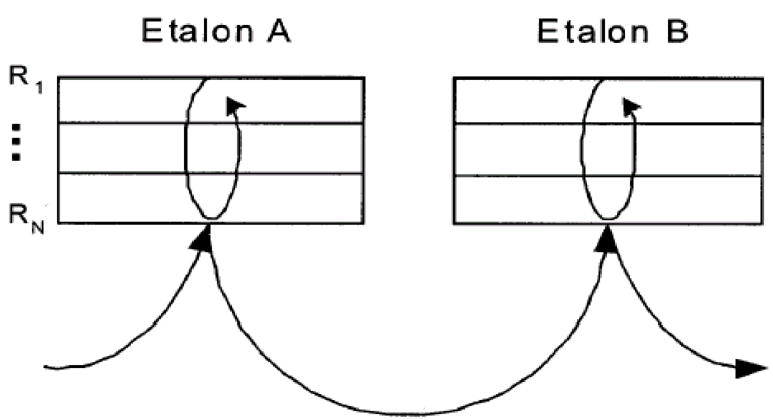
- The losses at the center wavelengths for over 60 channels with 0.8 nm spacing within 50 nm wavelength are almost constant.
  - moving the mirror or focusing mirror
  - changing the profile of the mirror

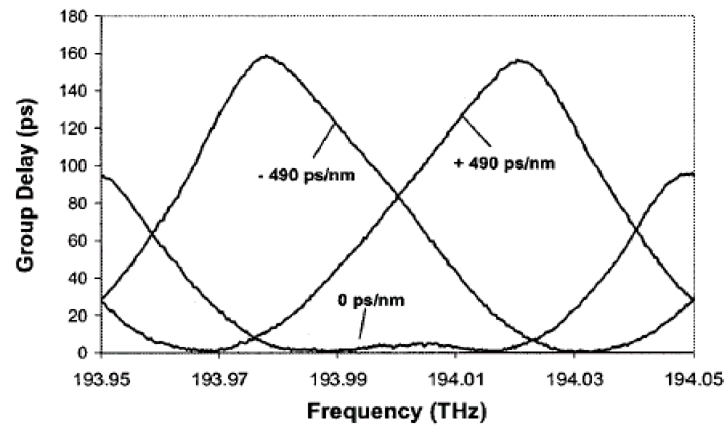
- Insertion loss: ~13 dB (Could be ~5 dB theoretically)

- Polarization dependence < 0.1 dB

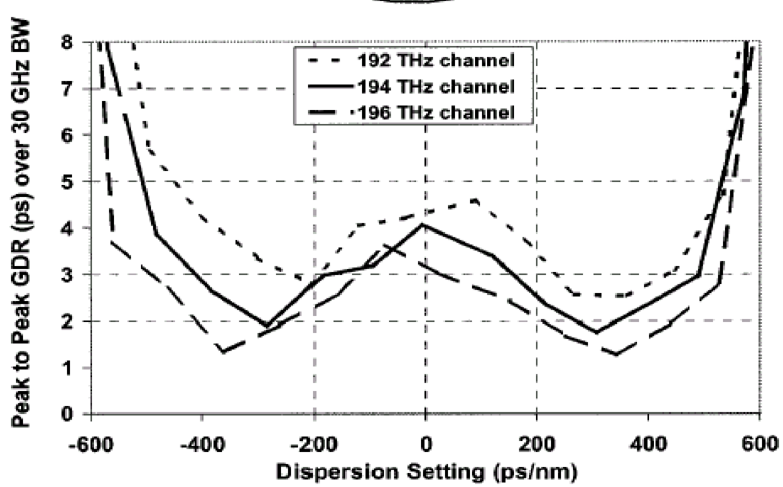
All-pass Multicavity Etalons

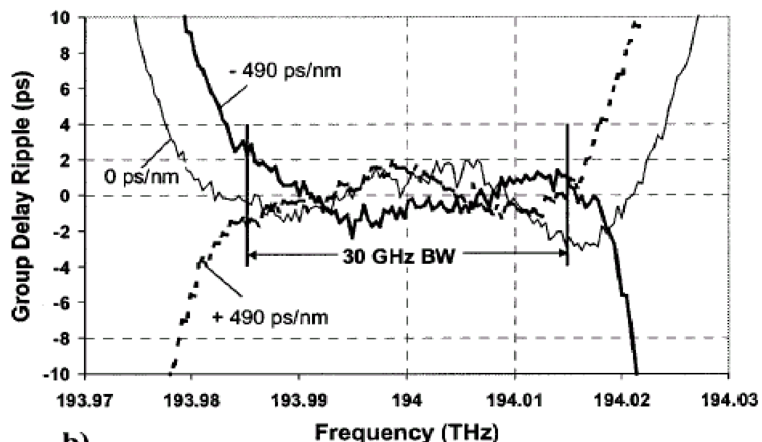
OFC 2002, Paper TuT2 (JDS Uniphase)





a)





b)

Continued…

- Cascaded etalons with different dispersions
- Thermal tuning
- Insertion loss ripple: 0.1 ~ 0.4 dB

FSR	BW	Range	GDR	Loss
50 GHz	25 GHz	+/-800 ps/nm	+/-4.0 ps	4.4 dB
100 GHz	30 GHz	+/-500 ps/nm	+/-3.0 ps	5.3 dB

A Growing Optical Challenge