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UV-written Bragg gratings

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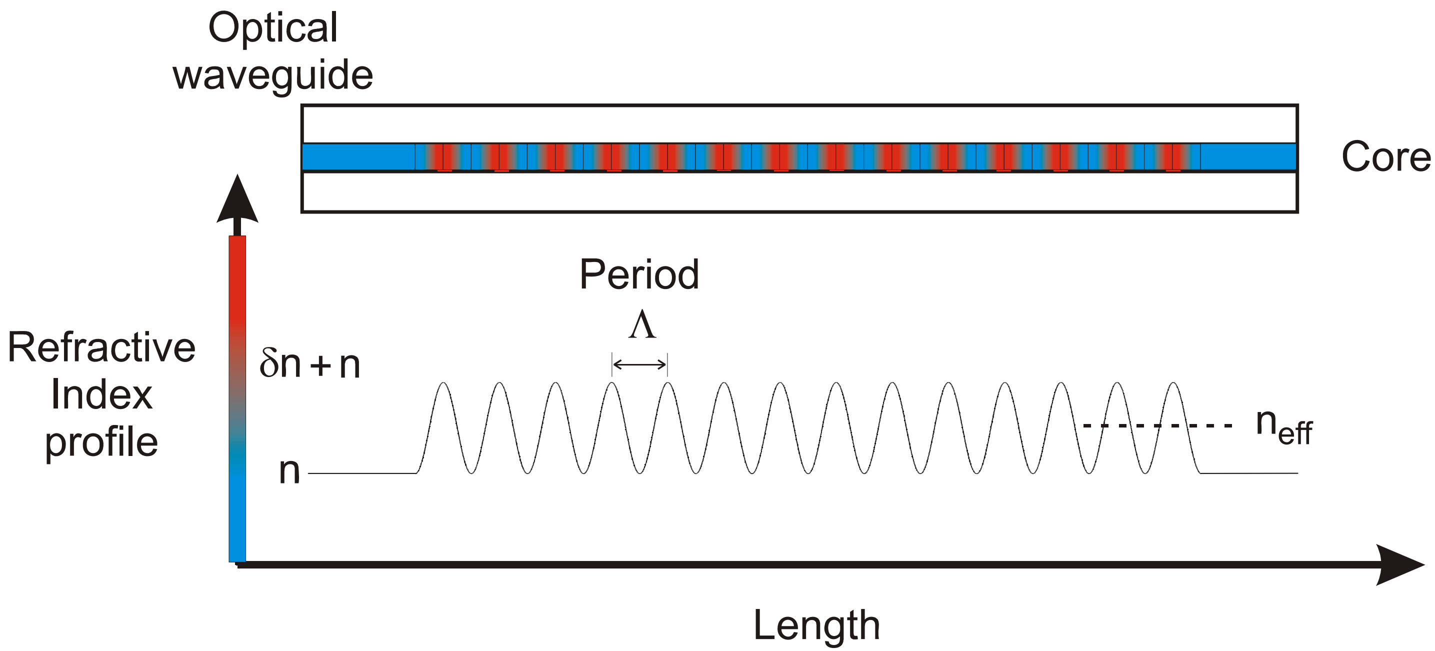
~ Outline ~

- Introduction to Bragg gratings.
  - Fundamentals.
  - History.
- Application areas of Bragg gratings.
  - Dispersion-free gratings for add-drop filtering in high-speed systems.
  - Gratings for optical code division multiple access (O-CDMA) systems.
  - Short gratings for dispersion management in high-speed systems.
- Future trends.
- Summary.

~ Bragg grating fundamentals ~

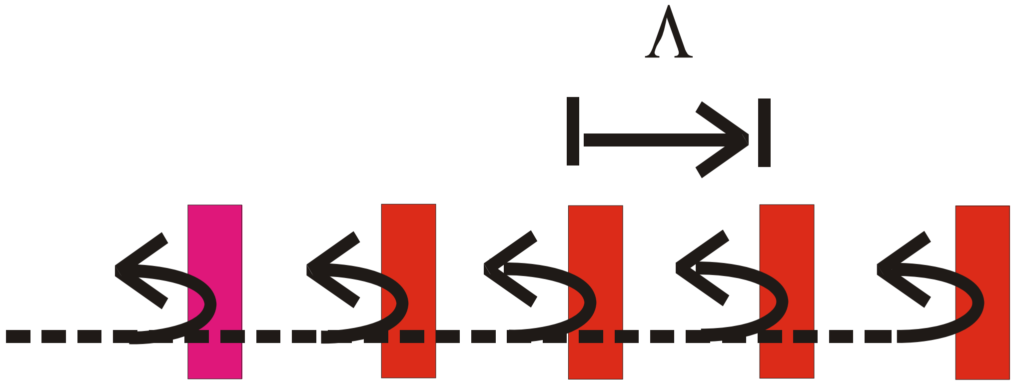
- What is a Bragg grating?.
  - A periodic or almost periodic structure consisting of a variation of for example the refractive index along the length of a waveguide.



~ Bragg grating fundamentals ~

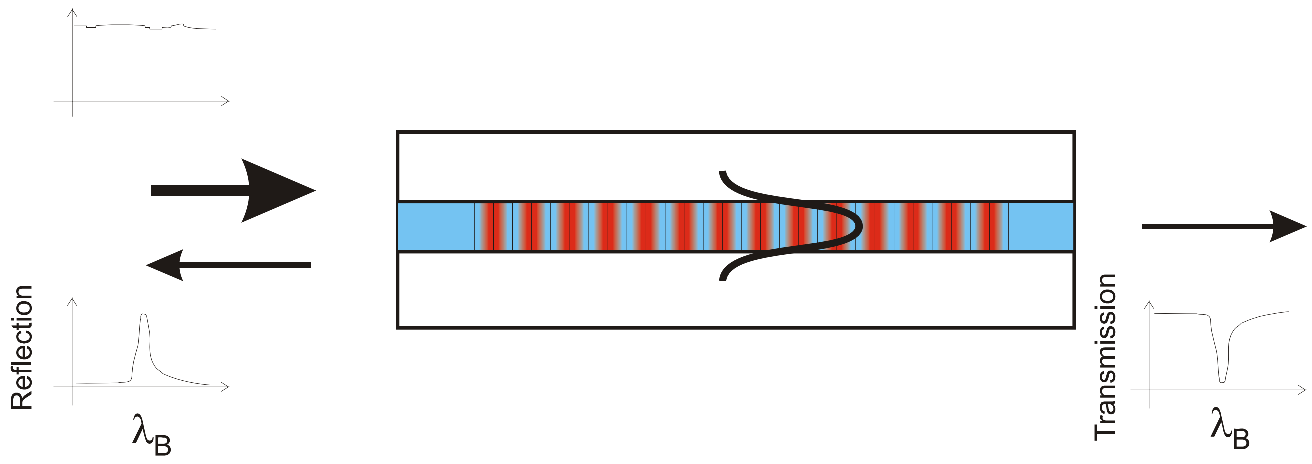
- What is a Bragg grating?.
  - A small reflection (Fresnel reflection) from each low-high (high-low) refractive index transition.

$$r = \left(\frac{n-(n+\delta n)}{n+(n+\delta n)}\right)^2 = \left(\frac{\delta n}{2n+\delta n}\right)^2 \approx \underline{10^{-9}}$$



~ Bragg grating fundamentals ~

- What does it do?.
  - Coupling of a forward propagating core-mode to a backward propagating core-mode.
  - Acts as a band-rejection filter passing all wavelengths that are not is resonance with the grating and reflecting wavelengths that satisfies the Bragg condition.



~ Bragg grating fundamentals ~

- Parameters related to a Bragg grating.
  - Strong overall reflection is achieved when each of the reflected contributions add in-phase (phase coherence/matching).

$$\beta = k \cdot n_{eff} = \frac{2\pi}{\lambda} \cdot n_{eff}$$ (Propagation constant)

$$\delta = \beta \cdot \Lambda$$ (phase of the propagating wave)

For each of the reflected contribution to add in phase

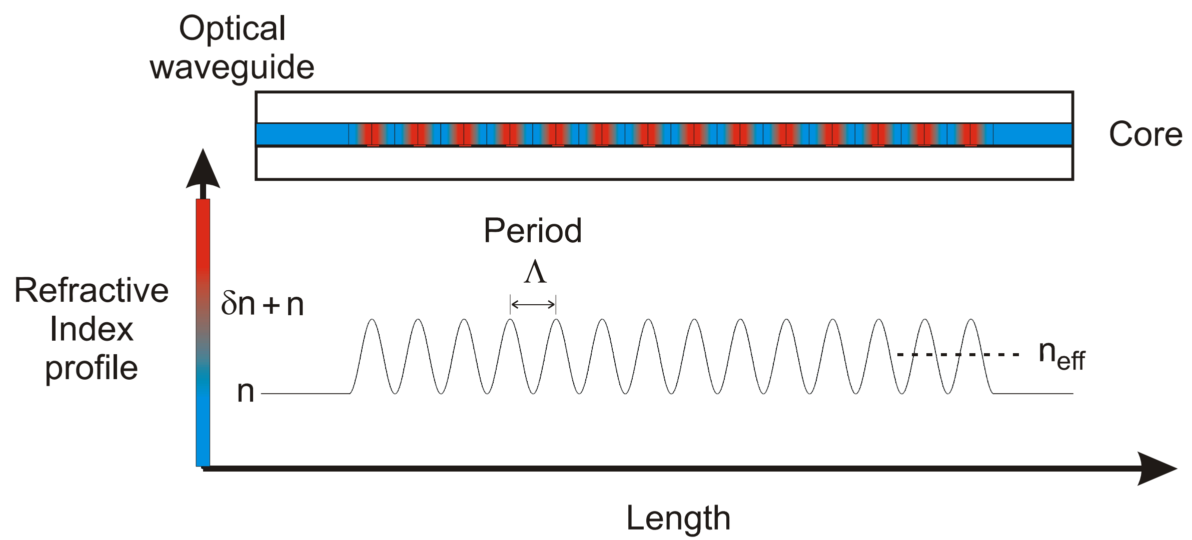
$$\delta = m \cdot 2\pi$$ (m positive integer)

$$\Downarrow$$

$$\underline{\lambda_B \cdot m = 2 \cdot n_{eff} \cdot \Lambda}$$ (Bragg condition)

~ Bragg grating fundamentals ~

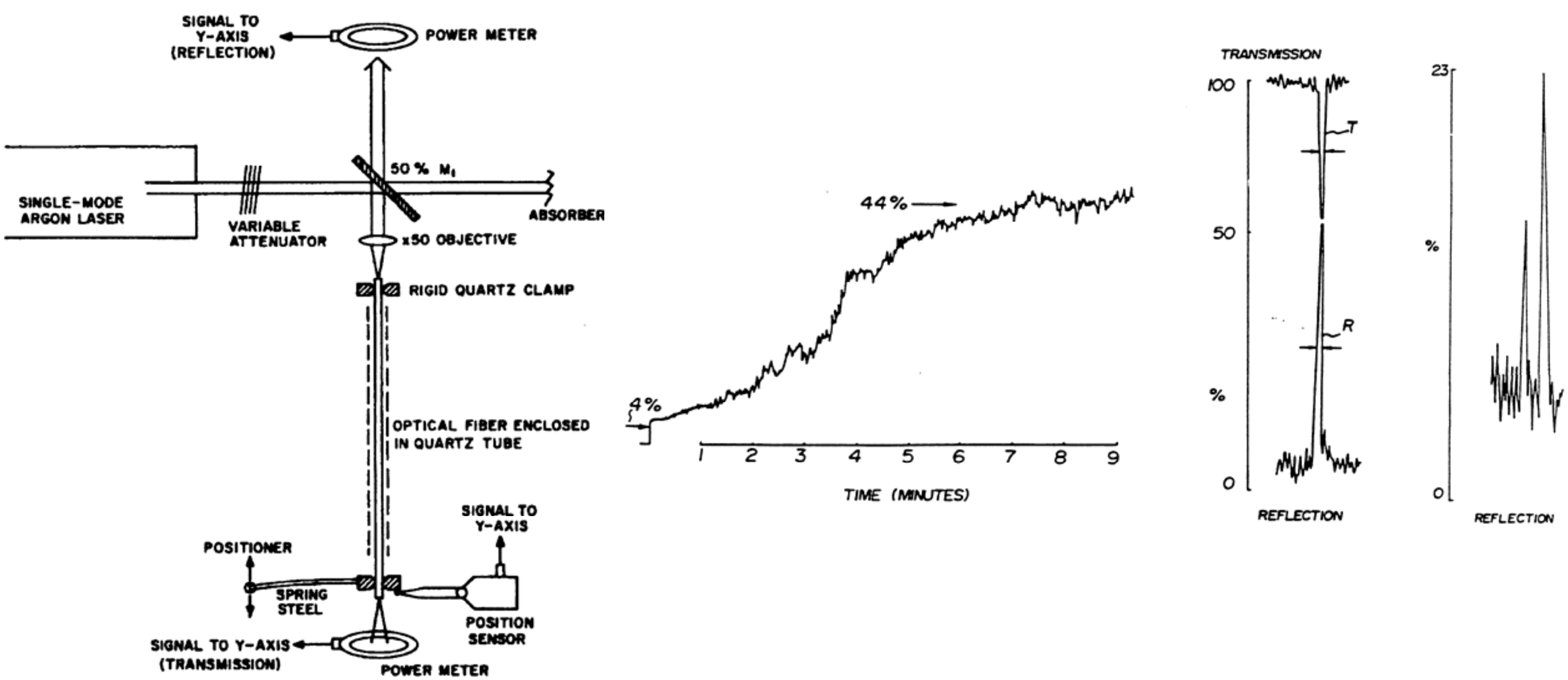
- Parameters related to a Bragg grating.
  - n_{eff} ~ 1.455 in silica.
  - "Short" period grating to operate in lowest order mode (m=1) with Bragg wavelength λ_B ~ 1550nm, Λ~500nm.
  - Typical index changes, $\delta n \sim 10^{-5} - 10^{-3}$.
  - Typical lengths, 1cm – 10cm, some types ~1m.



M. Ibsen, **UV-written Bragg gratings**, Lecture 4 POWAG 2004.

~ Bragg grating history ~

- ***1978***: First observation of photo-induced fibre Bragg grating.
  - Discovered by a coincidence.
  - Fibre was exposed to 514.5nm light.



K.O.Hill et al., *Appl. Phys. Lett.*, **32**, p. 647, 1978.

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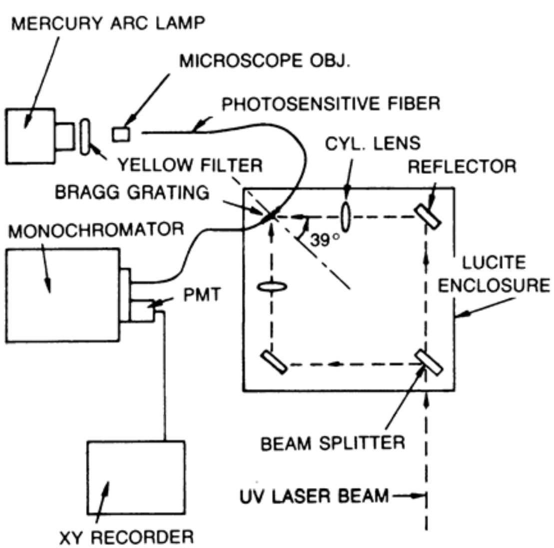
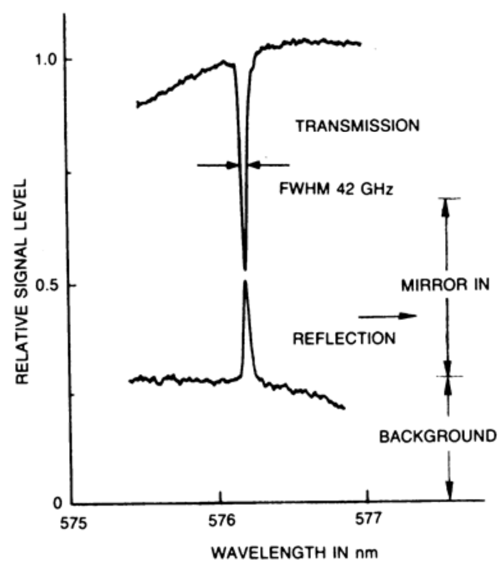
~ Bragg grating history ~

- ***1989***: First demonstration of Bragg grating inscription of a wavelength different to the writing-beam wavelength.
  - Initial grating demonstrations was believed to be a two-photon process (based on work done by *Lam and Garside* in 1980-81).
  - UV-light at 257nm was used.





$$\Lambda = \frac{\lambda_{write}}{2 \cdot \sin(\phi)}$$

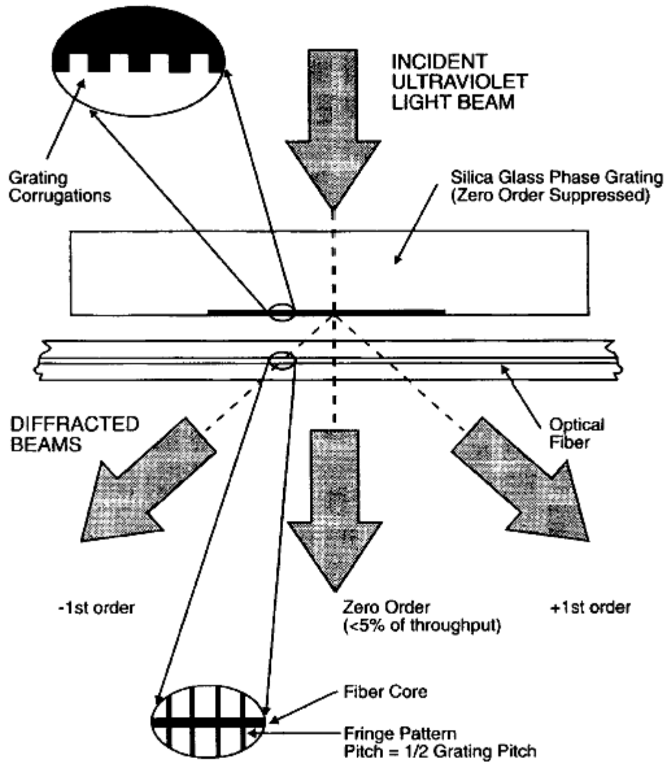
$$\Downarrow$$

$$\lambda_B = \frac{n_{eff} \cdot \lambda_{write}}{\sin(\phi)}$$

G.Meltz et al., *Optics Lett.*, **14**, p. 823, 1989.

~ Bragg grating history ~

- ***1993***: First demonstration of practical Bragg grating inscription.
  - Phase-masks makes for stable and repeatable grating inscription.



$$\Lambda_{fibre-core} = \Lambda_{mask}/2$$

K.O. Hill et al., *Appl. Phys. Lett.*, **62**, p. 1035, 1993.

~ Historical background ~

- ***1995***: Kenneth O. Hill is awarded the *Principal Manning Award* (Canadian innovative excellence).
- ***1996***: Kenneth O. Hill is awarded the *John Tyndall Award* from the IEEE/OSA for his pioneering contributions to fibre-optic technology.
- ***2002***: Kenneth O. Hill is together with B.K. Garside, G. Meltz and W. W. Morey awarded the *Rank Prize for Opto-electronics* for the invention and development of practical Fibre Bragg Gratings.

Kenneth O. Hill on *right*

~ Bragg grating design ~

- Parameters that can be altered or controlled in a Bragg grating.

$A(z)$ Refractive index amplitude modulation.

$\theta(z)$ Grating phase.

$n_{eff}(z)$ Effective refractive index.

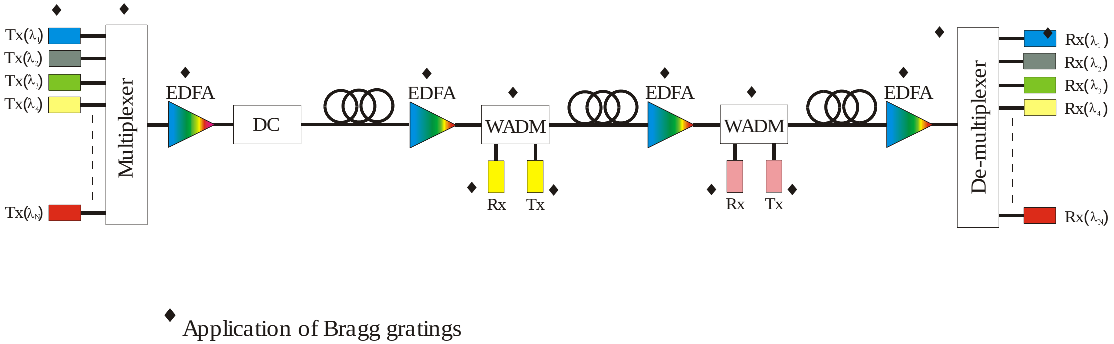
$\Lambda(z)$ Grating period/pitch.

$$E_{out}(\nu) = T(\nu)E_{in}(\nu)$$

$T(\nu)$ Grating transfer function

~ Grating applications ~

- Applications of Bragg gratings in systems.
  - Telecommunications systems.
    - Transmitter-sources/Source-stabilisation.
    - Multiplexing/de-multiplexing (add-drop filtering) at high bit-rates.
    - Gain-equalisation.
    - Dispersion-management.
    - Encryption.
    - Header-recognition.
  - Sensing systems.
    - Temperature and strain monitoring.

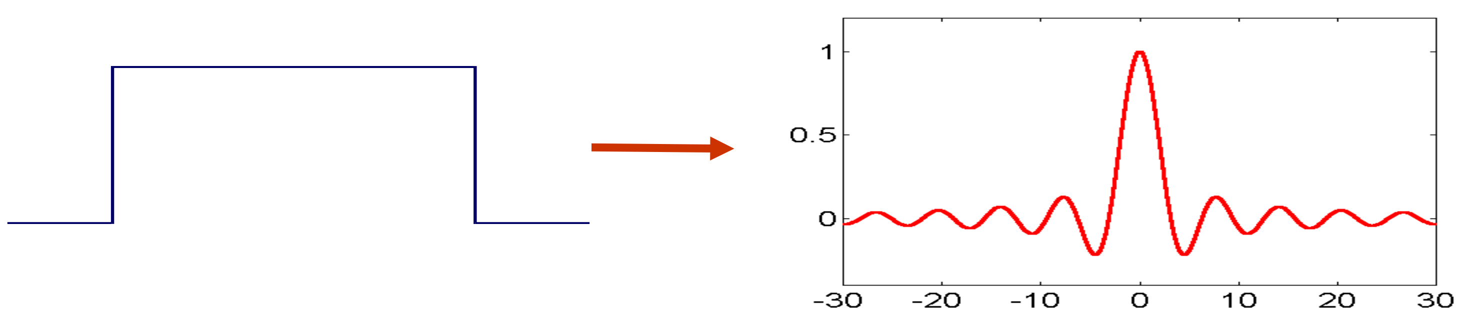


~ Bragg grating design ~

- *Fourier theory* can give a good first approximation to the spectral response of a Bragg grating.
  - Wave-vector response

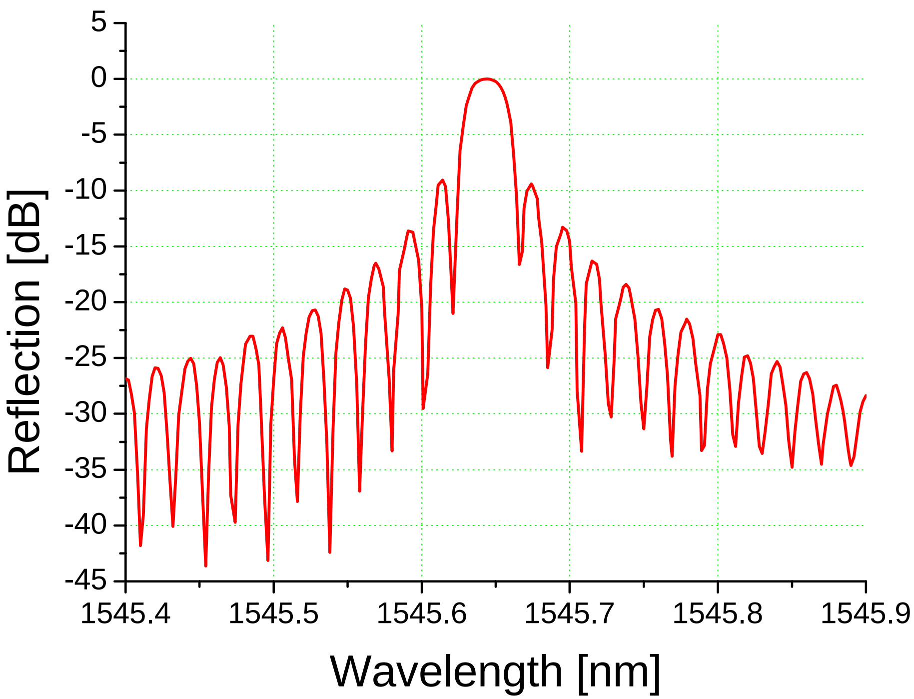
$$F(\kappa) = \frac{1}{2\pi} \int_{-\infty}^{\infty} A(z) e^{i\kappa z} dz$$

Coupling Constant | Reflection Coefficient



~ Bragg grating design ~

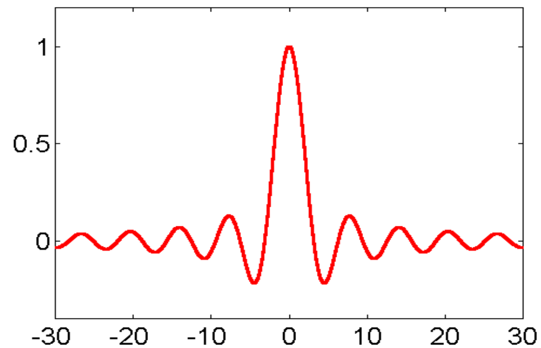
- Single-channel.
  - Uniform grating.

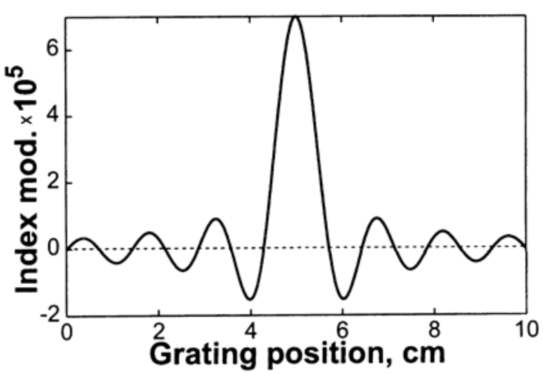


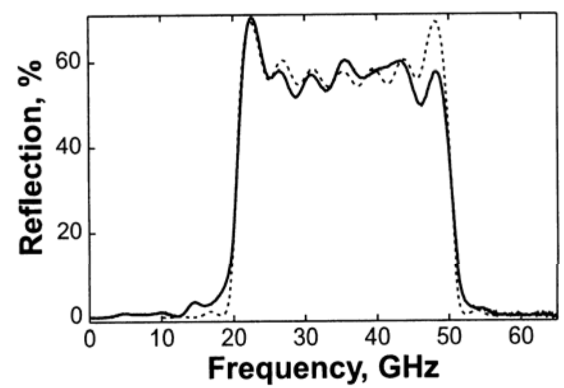
$A(z)$	Constant.
$\theta(z)$	Not controlled.
$n_{eff}(z)$	Constant.
$\Lambda(z)$	Constant.

~ Bragg grating design ~

- Single-channel design using Fourier theory.
  - Bragg grating with square spectral response (square filter).



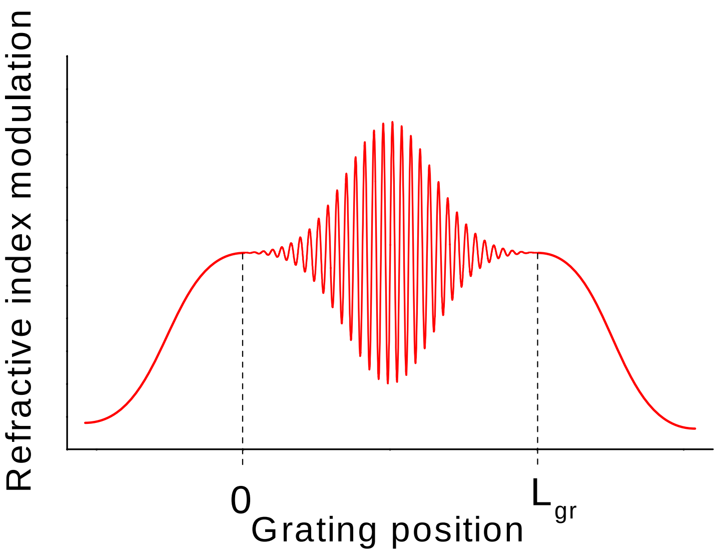


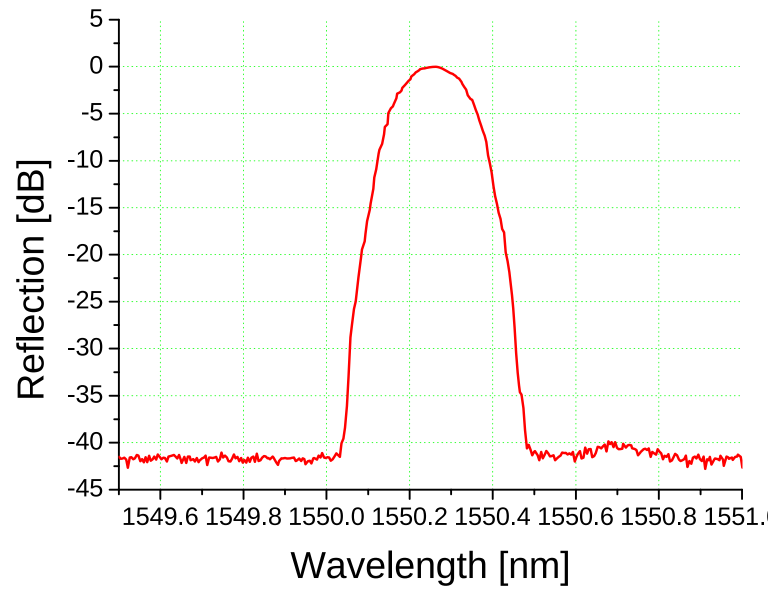


H.Storøy et al., *Optics Lett.*, **22**, p. 784, 1997.

~ Bragg grating design ~

- Single-channel.
  - Apodised grating.





$A(z)$ Tapered.

$\theta(z)$ Not controlled.

$n_{eff}(z)$ Constant.

$\Lambda(z)$ Constant.

~ Bragg grating design ~

- Fourier theory can only be used for the precise design of gratings when the reflectivity is low (<50%).
  - Grating strength

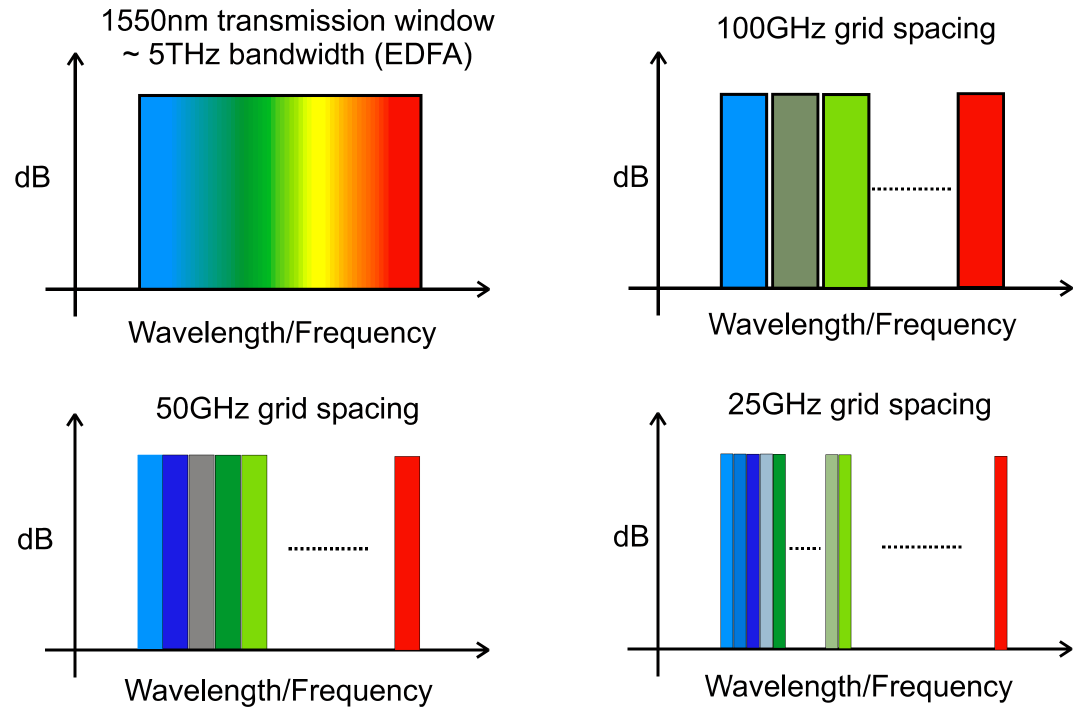
$$\kappa \cdot L_{gr} \leq 1$$

- When $\kappa \cdot L_{gr} \geq 1$ (higher reflectivity) Fourier theory can no longer provide an accurate design tool. Inverse-scattering (backward design) techniques become necessary.

- Layer-peeling inverse-scattering techniques can add functionality to a given design.
  - The grating response is inverted in the time-domain.
  - Based on causality.
  - Layer-by-layer building of the Bragg grating with full phase-control.
  - Directional design – asymmetric designs.

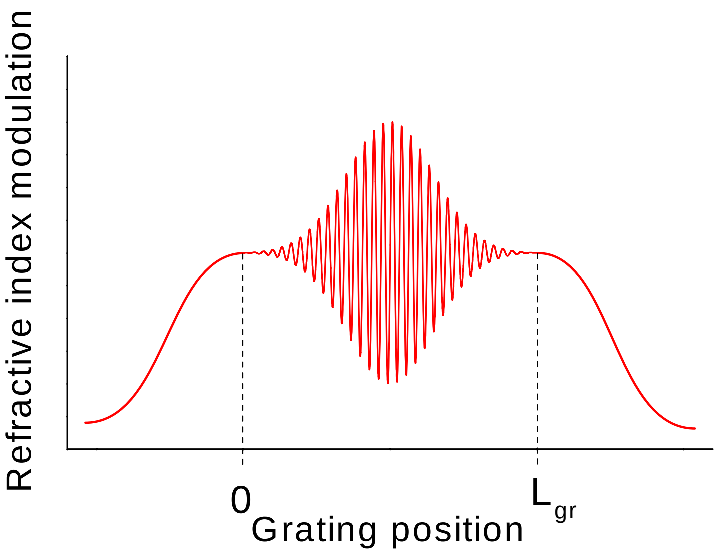
~ Application of Bragg gratings ~

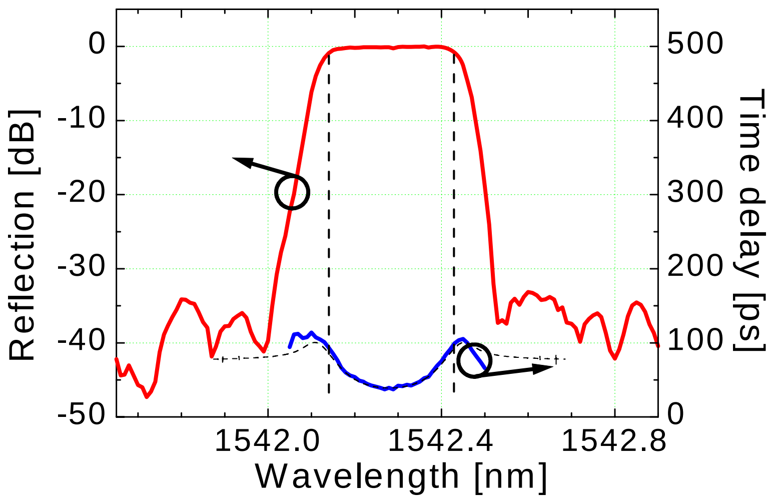
- Increase in data-traffic requires more bandwidth
  - 100GHz, 50GHz, 25GHz,…. DWDM grids become necessary.
  - *Keyword*: Maintenance of *channel integrity*.



~ Add-drop gratings ~

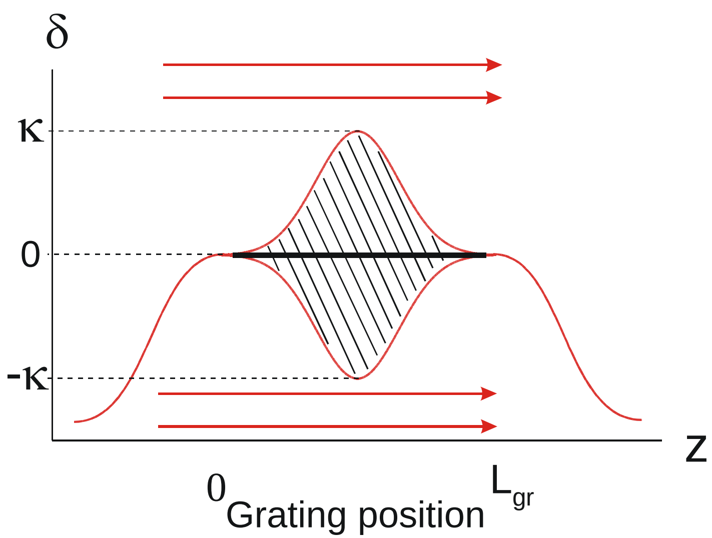
- Apodised Bragg gratings.
  - High bandwidth utilisation.
    - Uniform reflection in the stop-band (ΔR<0.5dB).
    - Large sidelobe suppression ($R_{sidelobes}$ <-30dB).
    - Sufficient "drop" function (>30dB).

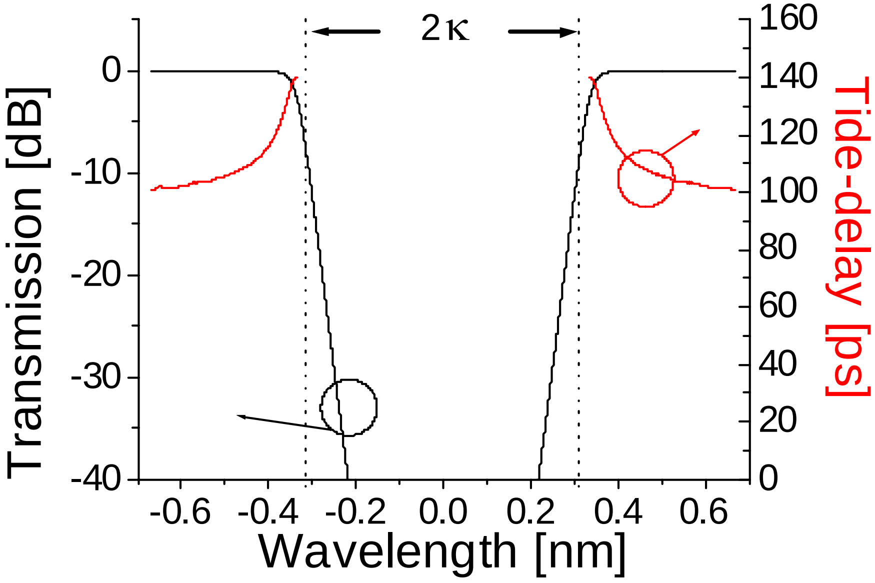




~ Dispersion from Bragg gratings ~

- *Out-of-band dispersion* from “standard” gratings.
  – Operating near a bandgap.

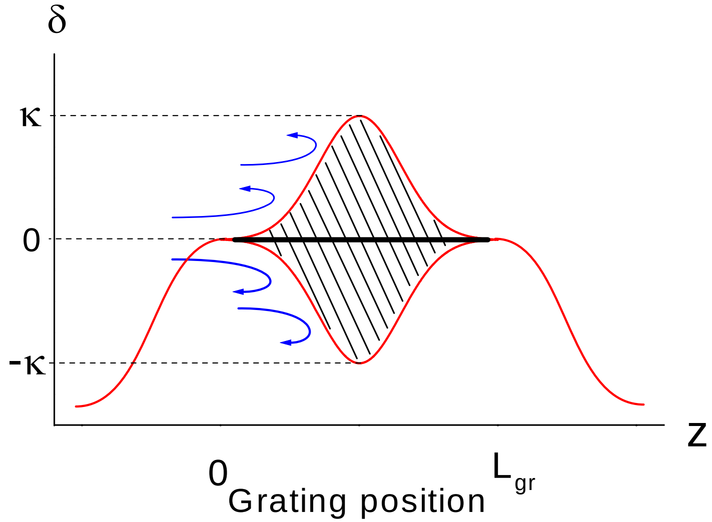


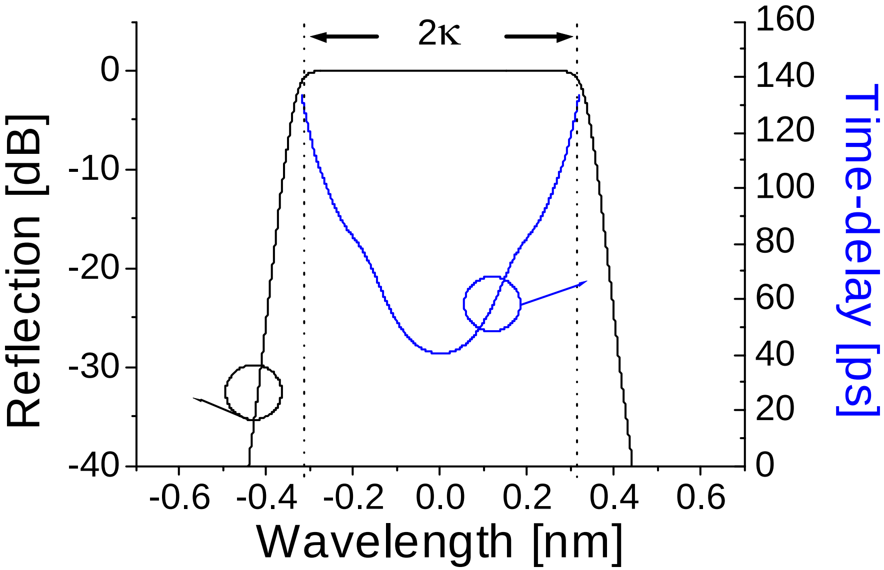


  – Affects adjacent channels and can impose a limitation to the number of channels passing the grating.
  – Proportional to grating-strength (κL).

~ Dispersion from Bragg gratings ~

- *In-band dispersion* from "standard" gratings.
  - Induced by the apodisation-process of the grating.
    - Different penetration into the grating as a function of detuning.





  - Affects channels to be dropped and added.
  - Proportional to grating-length (L), the longer the grating the higher the dispersion for constant κ.

~ Dispersion from Bragg gratings ~

- In-band dispersion.
  - Added term to the BWU.
    - 1) Reflection-bandwidth.
    - 2) Transmission-bandwidth.
    - 3) Dispersion-limited bandwidth.
  - Dispersion-limited bandwidth is bit-rate dependant.

  - Tolerable dispersion in systems
    - 2.5Gbit/s ~ 15000ps/nm (~1000km)
    - 10Gbit/s ~ 1000ps/nm (~60km)
    - 40Gbit/s ~ 70ps/nm (~4km)

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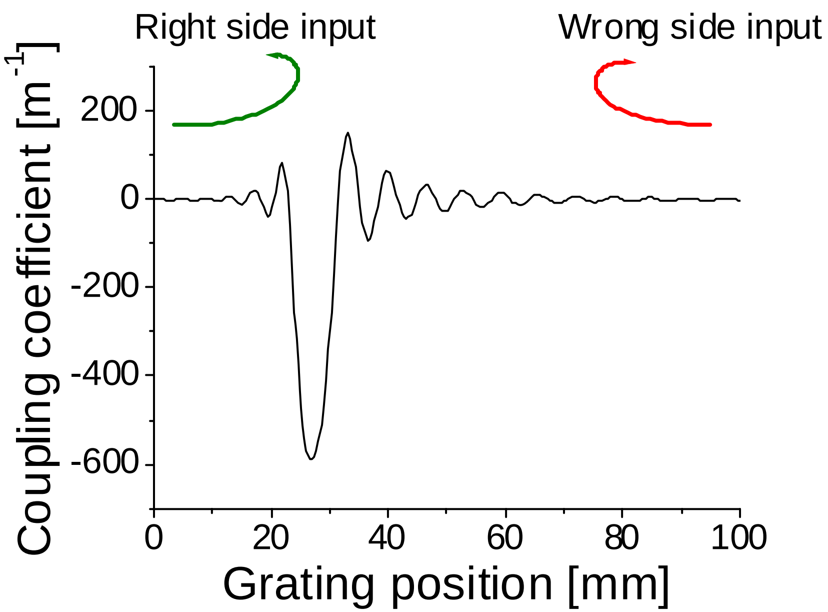
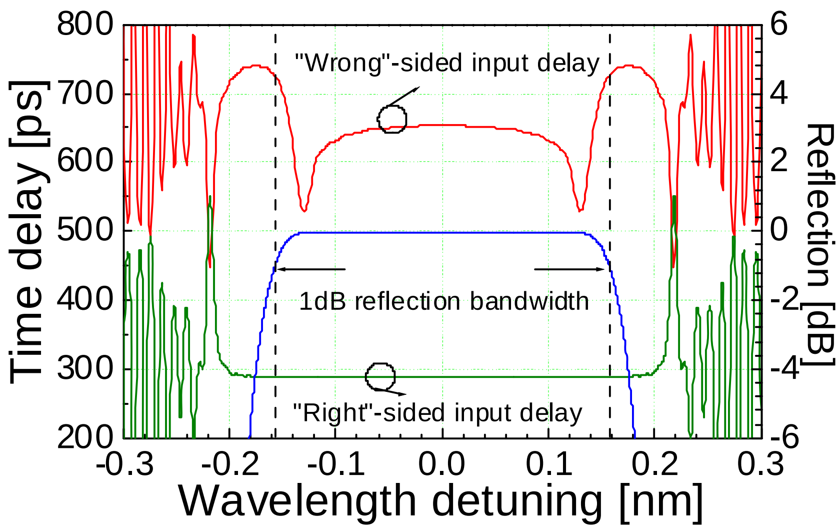
~ Dispersion-free gratings ~

- Index profile designed from layer-peeling inverse-scattering.
  - Directional design.



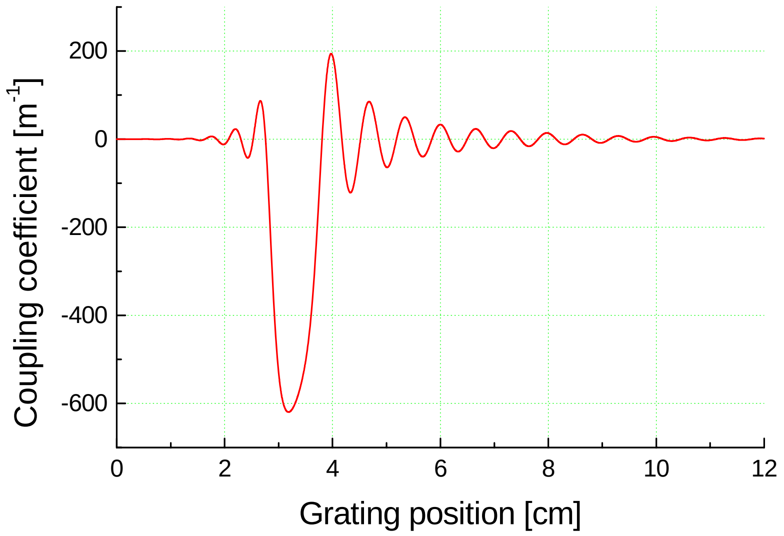


R.Feced et al., *J. Quantum Electron.*, **35**, p. 1105, 1999.

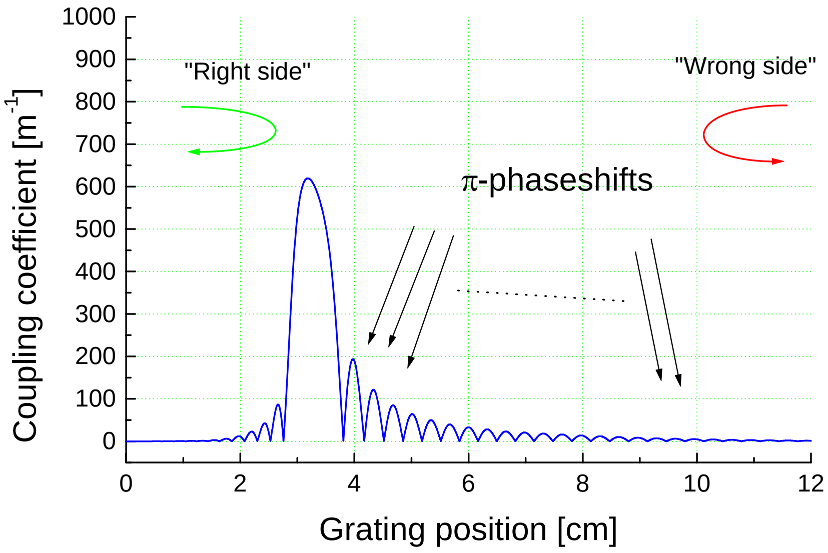
~ Dispersion-free gratings ~

- *Only positive index-modulation* is used.
  - When there is a change in sign of the index-modulation a discrete phase-shift of π is inserted.

Theoretical profile



Experimental profile



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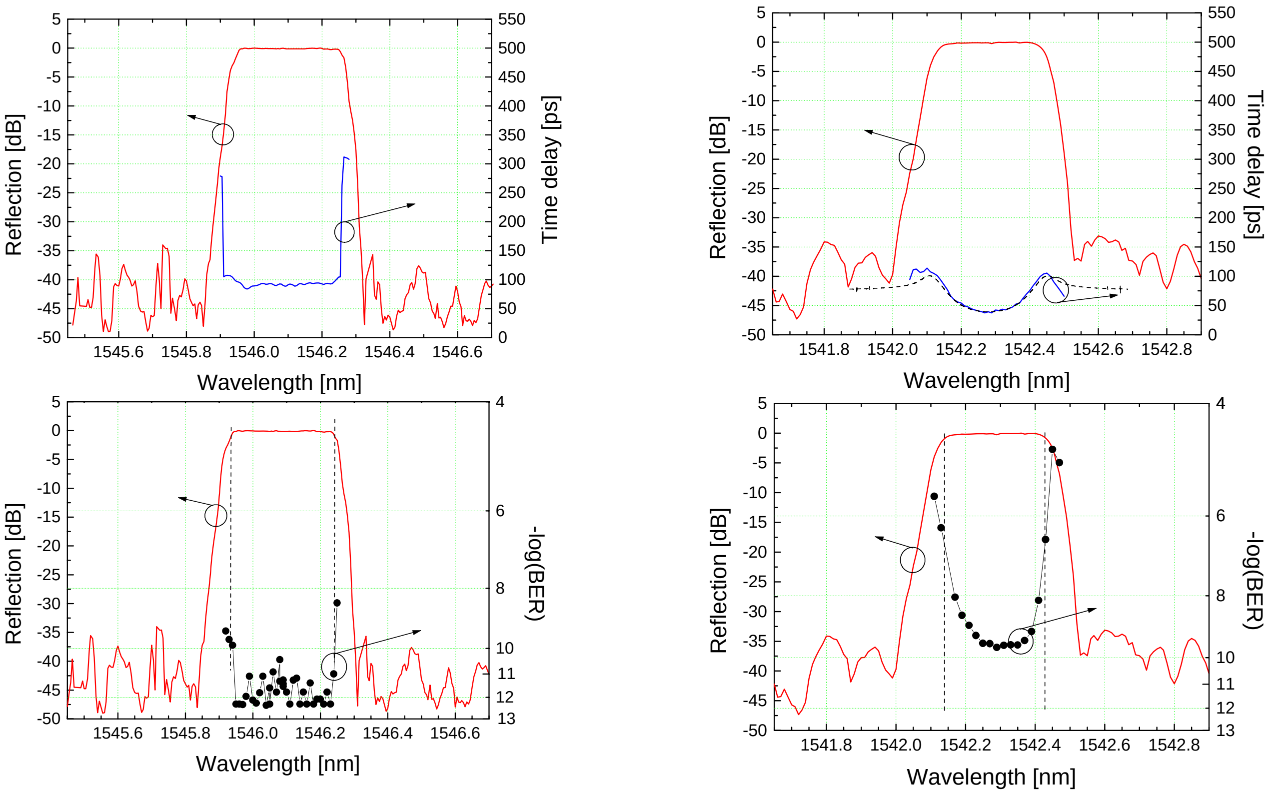
~ Dispersion-free gratings ~

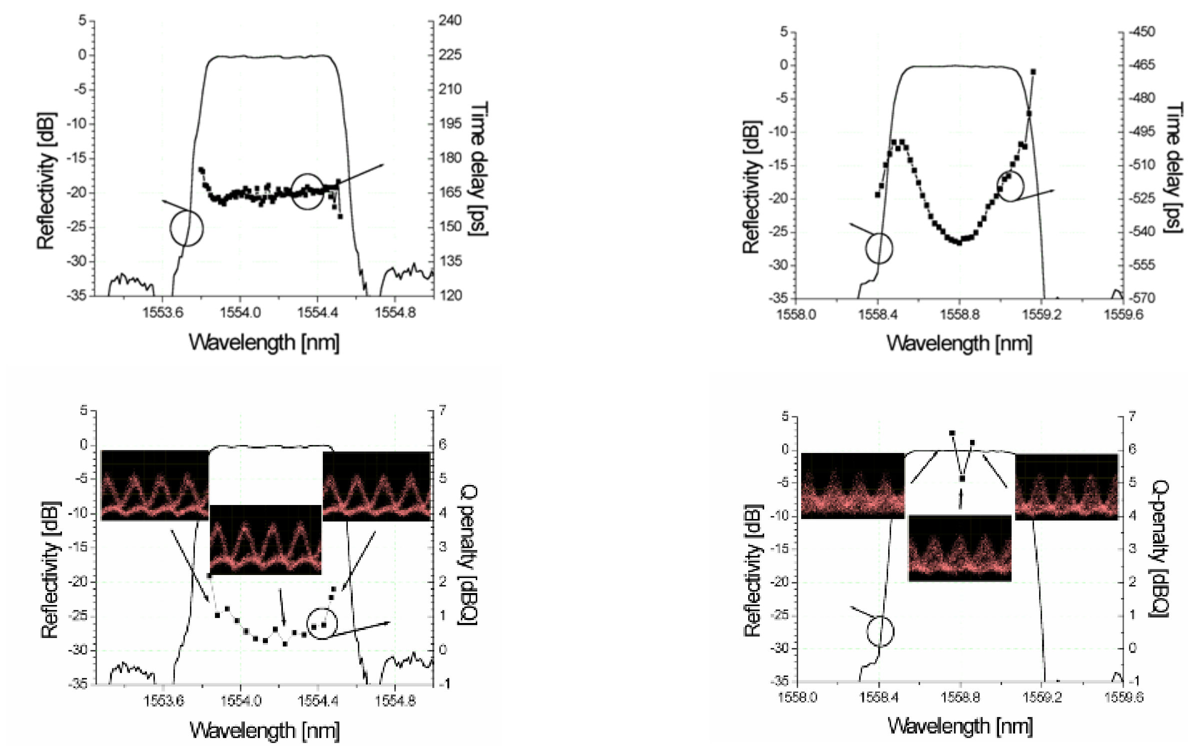
- Dispersion-free gratings vs standard apodised gratings in a 10Gbit/s NRZ system.



M.Ibsen et al., *OFC'2000*, PD21, 2000.

~ Dispersion-free gratings ~

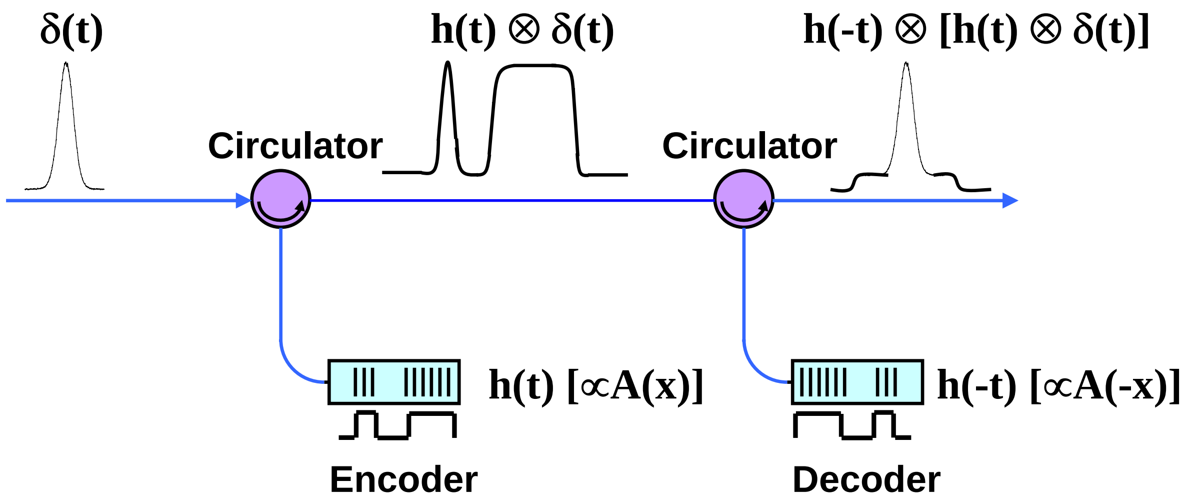
- Dispersion-free gratings vs standard apodised gratings in a *40Gbit/s* RZ system (100GHz grid).



M.Ibsen et al., *ECOC'2001*, Th.B.2.1, 2001.

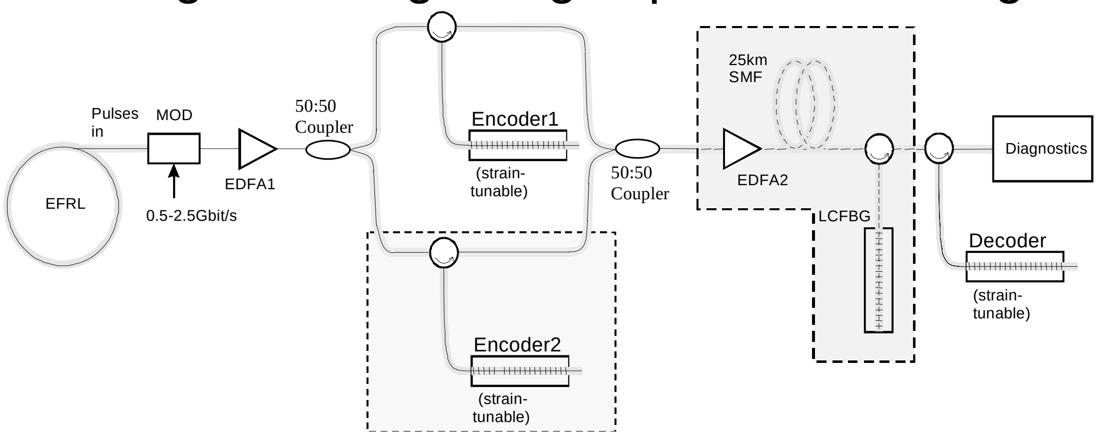
~ OCDMA applications ~

- Pulse encoding/decoding using superstructured gratings.
  - Multiple users having same carrier frequency but a unique code/key.
  - *Principle*: A short pulse is spread in time in accordance with the refractive index profile of an encoding grating. A correctly decoded pulse is detected as the autocorrelation function of the code.

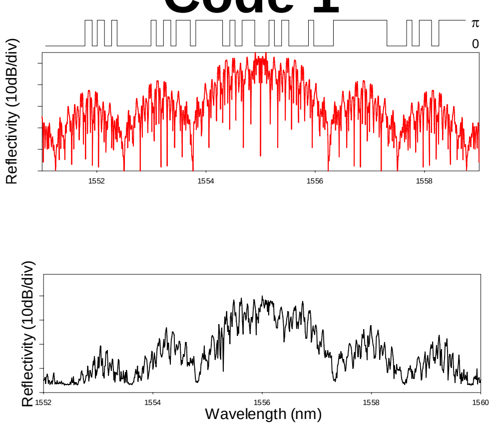


~ OCDMA applications ~

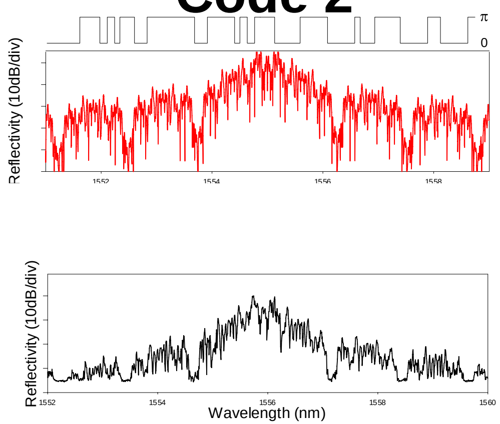
- Pulse encoding/decoding using super-structured gratings.

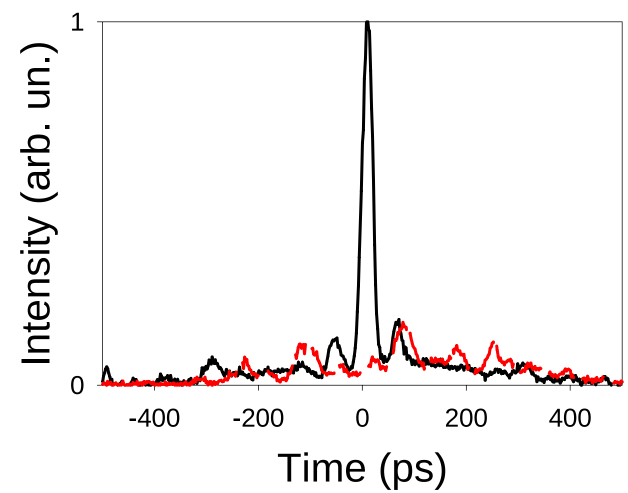


Code 1



Code 2





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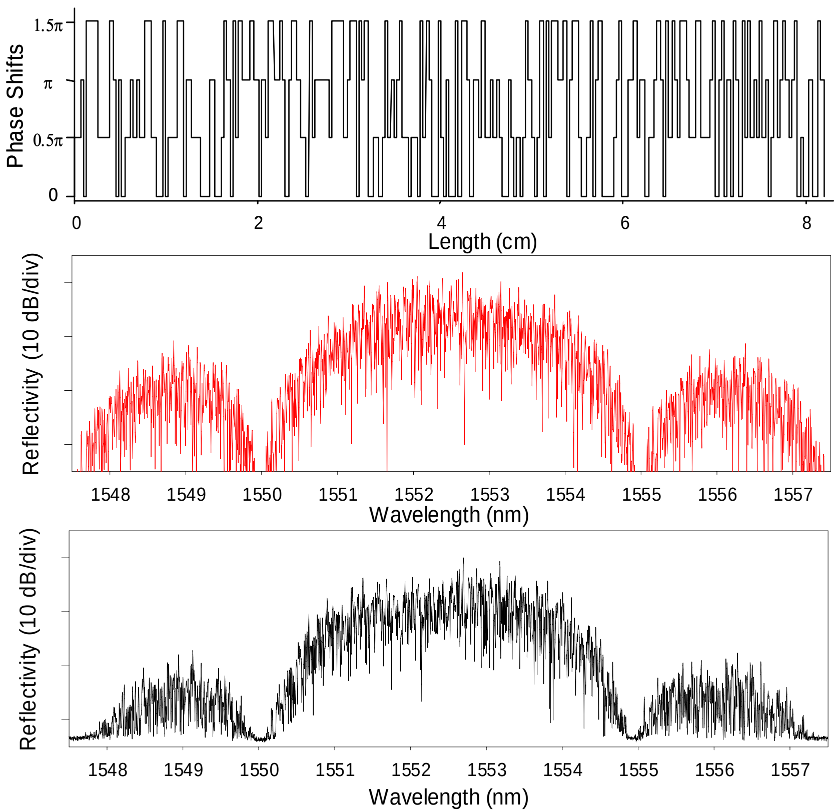
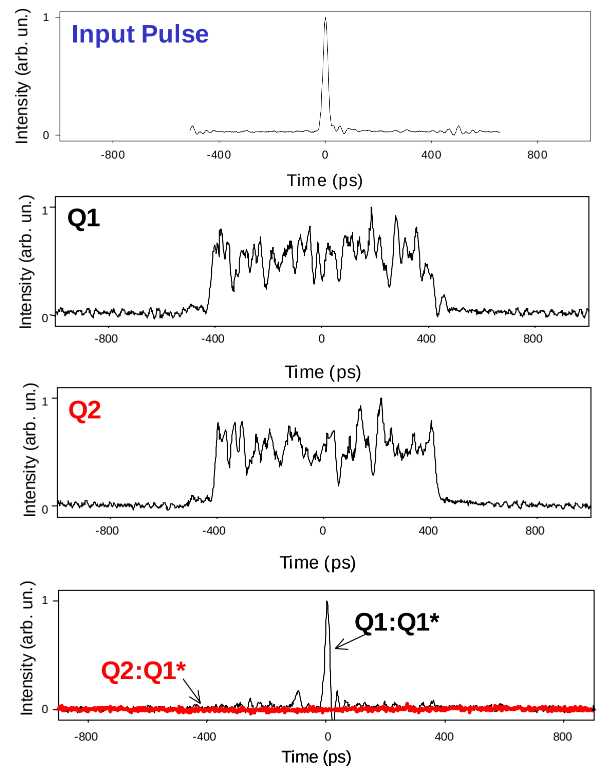
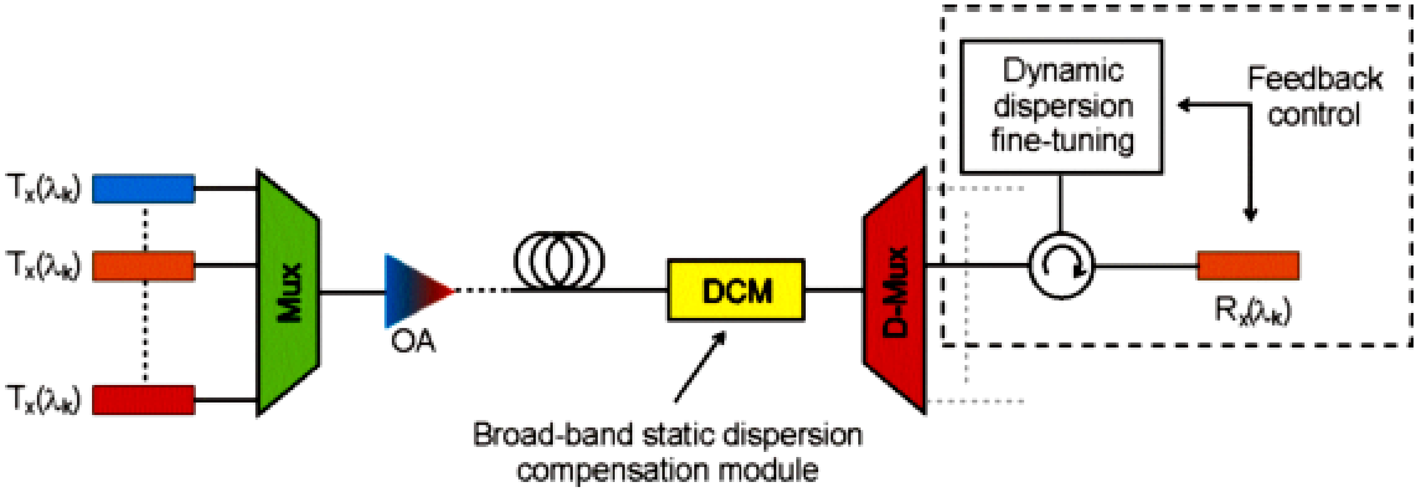




M. Ibsen, **UV-written Bragg gratings**, Lecture 4 POWAG 2004.

~ Dispersion management ~

- Channel-by-channel dispersion optimisation.



~ Dispersion-slope compensation ~

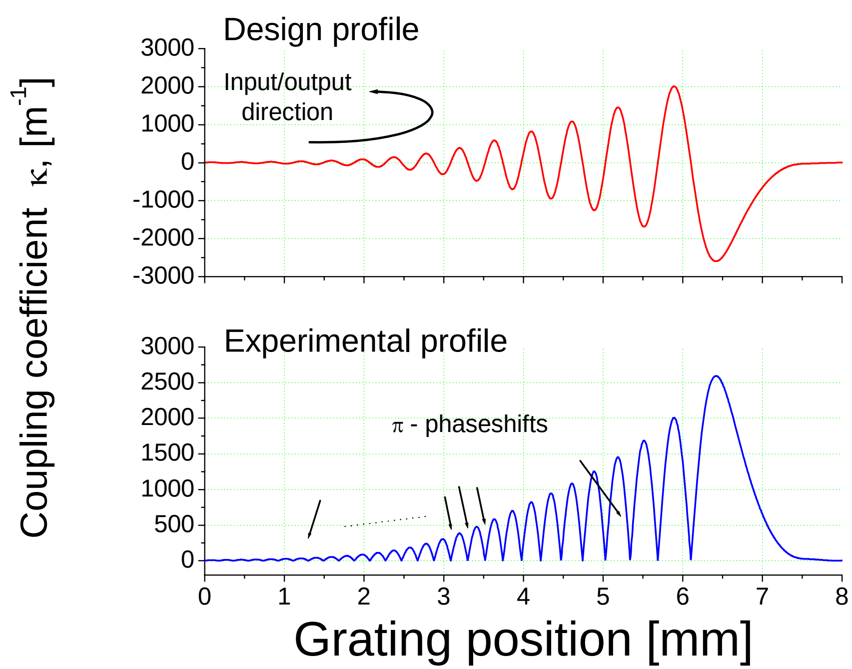
- Broadband Bragg gratings for pure third-order dispersion compensation.

- *BWU*=0.66
  - *-1dB bw=3nm*.
  - *-30dB bw=4.5nm*.

- *R*=75%.

$$\boxed{\frac{\partial D}{\partial \lambda} = -20 ps/nm^2.}$$

  - Uniform grating pitch!!.
- *Only* positive index-modulation is used.



M.Ibsen and R. Feced, OFC*'2002*, PD paper FA7, 2002.

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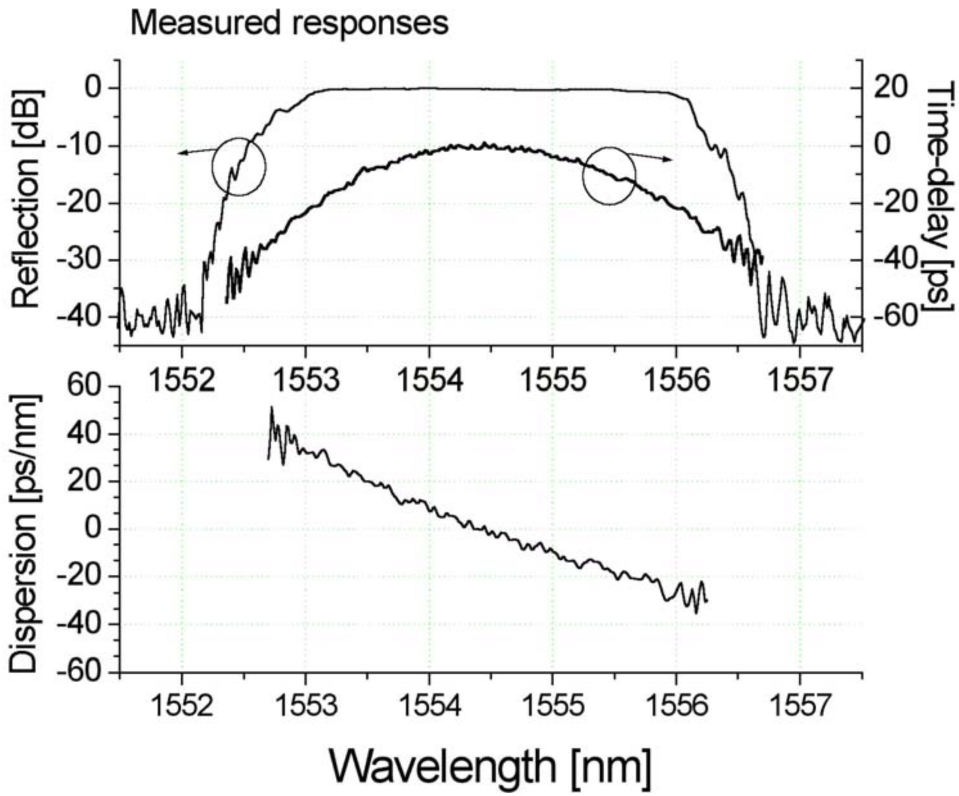

M.Ibsen and R. Feced, OFC*'2002*, PD paper FA7, 2002.

~ Bragg grating trends ~

- There has been a growing demand for devices which can be tuned or re-configured.
  - Full C-band coverage of filters and possibly between bands, L-band to C-band forexample.
  - Tunable transmitter lasers.
  - Dynamic dispersion equalisers.
  - Completely re-configurable devices.

- Multiple functionally from Bragg gratings.

~ Tunable grating devices ~

- Electrically re-configurable OCDMA encoder/decoder.