REDUCTION OF FOUR-WAVE MIXING CROSSTALK USING A NOVEL HYBRID WDM/TDM TECHNIQUE

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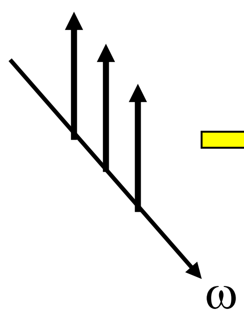
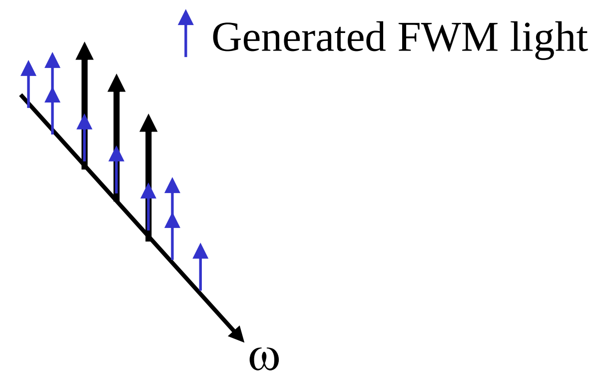
Four-wave mixing (FWM)

Four-wave mixing is a serious cause of system impairment in multi-channel transmission systems.





$$f_F = f_i + f_j - f_k$$

f_F: generated FWM frequency.

f_i, f_j, f_k: signal frequencies.

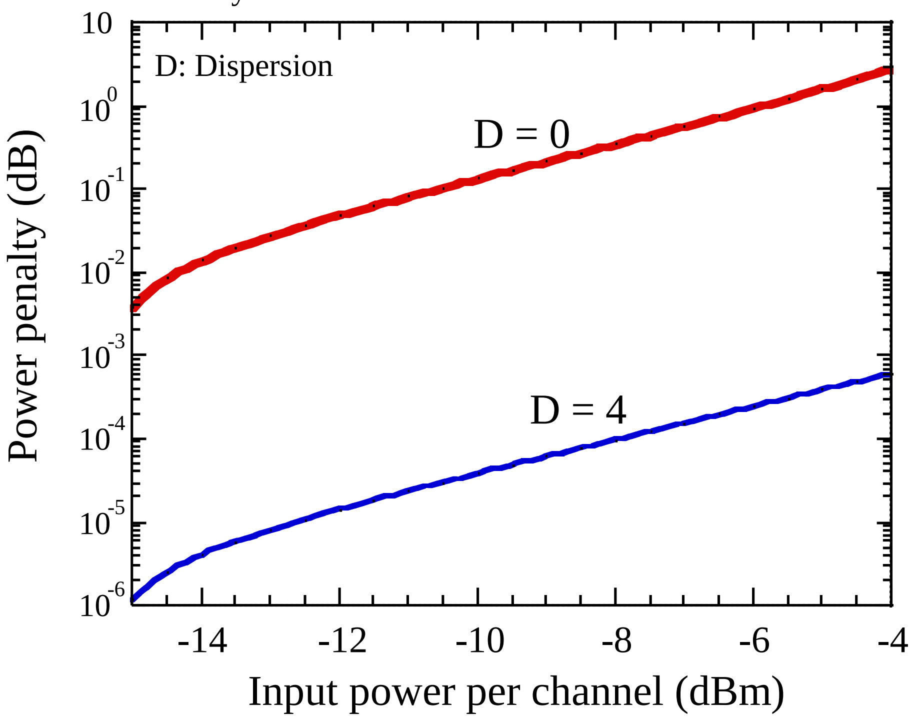
FWM efficiency strongly depends on phase matching condition.

$$\Delta\beta = \beta_F + \beta_k - \beta_i - \beta_j$$

β: Propagation constant

Power penalty caused by FWM effect

12-channel systems with a channel spacing of 100 GHz.
Penalty on the 7th channel is calculated.



Curves are derived using Gaussian approximation.
(K. Inoue et al, J.L.T, vol. 12, pp 1423 - 1438, 1994)

<u>Basic parameters used in the calculations.</u>
Fiber loss: 0.22 dB/km
Dispersion slope: 0.07 ps/nm^2/km
Propagation distance: 50 km

→ *Transmission degradation is most severe near zero-dispersion wavelength.*

FWM crosstalk reduction techniques

- Use of non-zero dispersion-shifted fibers.
  → Create enough phase mismatch between each channels for suppressing the FWM.
- Use of unequally spaced channels.
  → Generated FWM frequencies do not fall at the signal channel wavelengths.
- Bit-phase arranged RZ signals.
  → Shifting the bit phases of specific RZ signals by half-bit against the other signals to reduce interaction between channels.
- Use of optical fibers with large effective area.
  → Reduce optical power density.

Hybrid WDM/TDM approach for FWM crosstalk reduction

- Each channel in a group is multiplexed in time domain. → TDM

  The generated FWM lights are less likely to overlap in time domain with the signal of the same frequencies.

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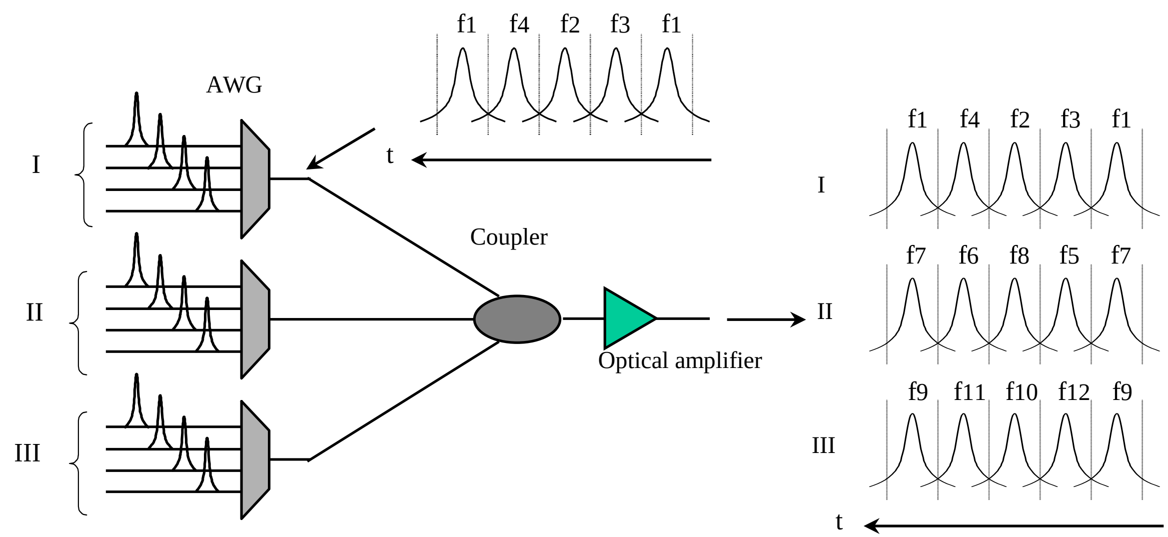
- Time slots of each group are adjusted to be identical. → WDM

  The frequencies of channels occupying the same time slot is unequally spaced in frequency domain. As a result, the generated FWM will not fall at the signal frequencies.



Channels are equally spaced in frequency domain.

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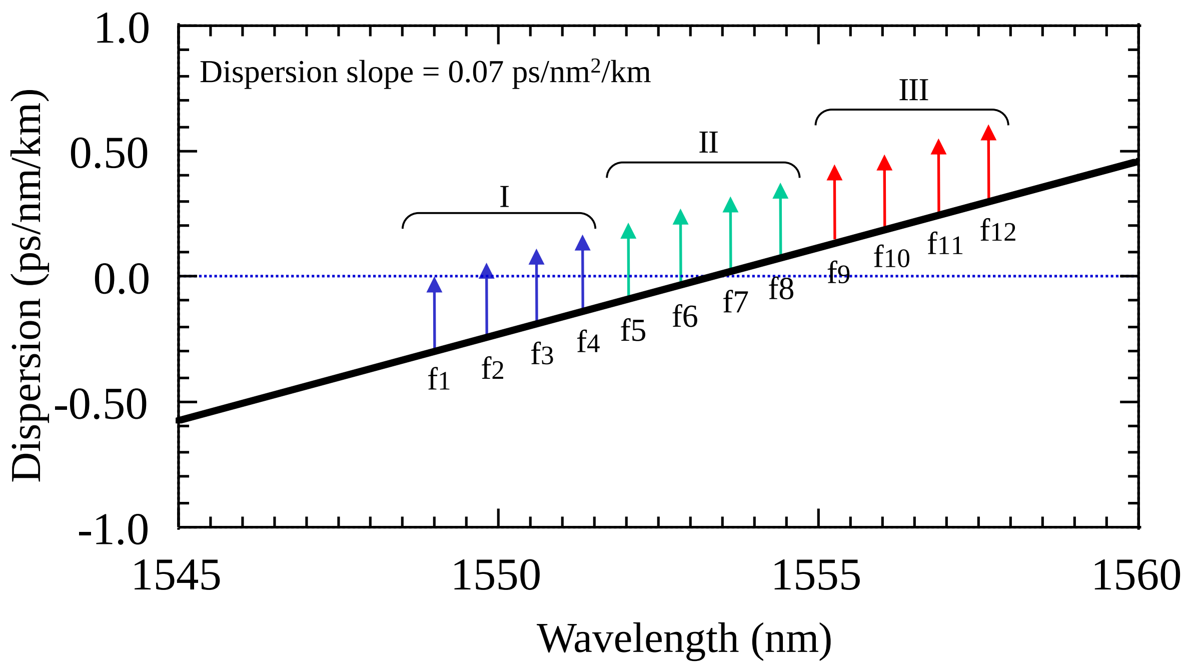
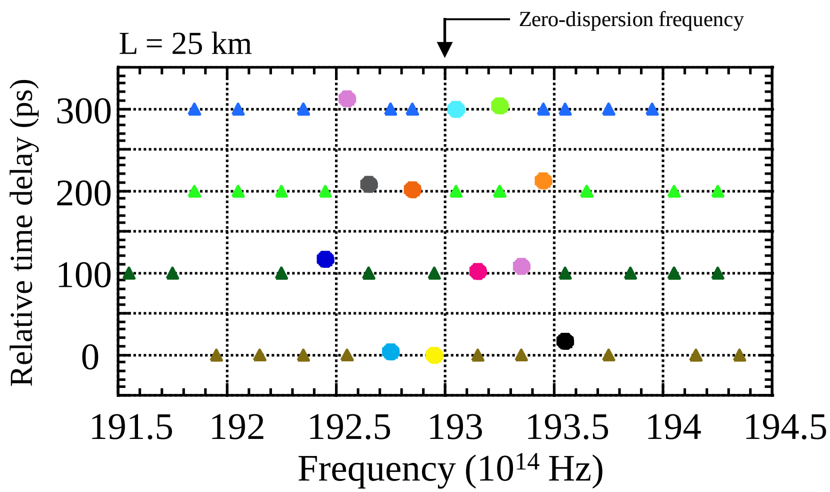
AWGs can be used for demultiplexing.

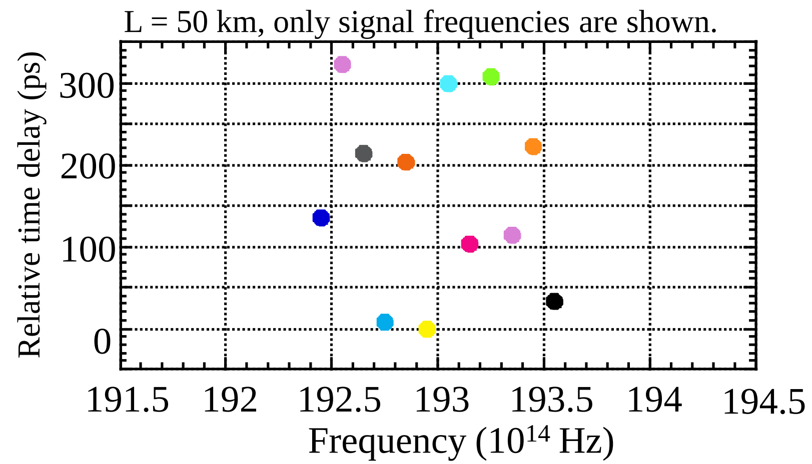
Channel arrangement for 12-channel systems

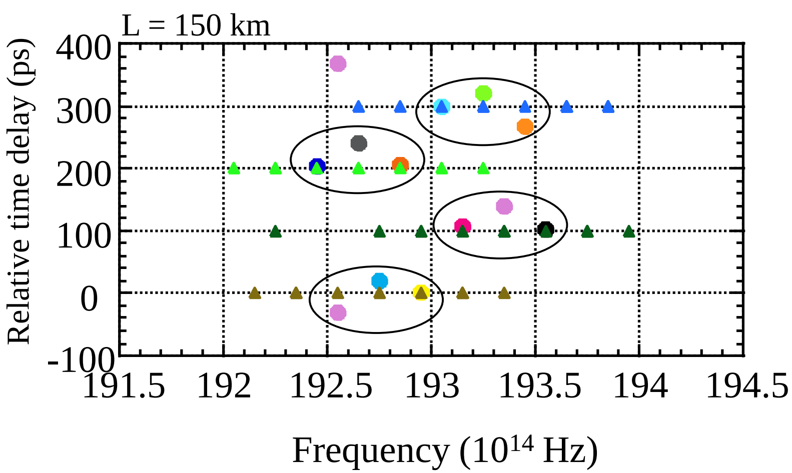


Channel group	TDM sequence of WDM channels
I	f1 → f3 → f2 → f4
II	f7 → f5 → f8 → f6
III	f9 → f12 → f10 → f11

Relative time delay of channels







Filled circles denote the position of signal pulse peaks for each frequency.

Triangle symbols denote the generated FWM. The marks do not represent the peak position of the FWM lights

Evaluated systems by simulations

- 4-channel 2.5 Gb/s per channel systems (10 Gb/s) with/without employing the hybrid WDM/TDM technique.

  - 100 GHz spacing
  - 50 GHz spacing

- 12-channel 2.5 Gb/s per channel systems (30 Gb/s) with/without employing the hybrid WDM/TDM technique.

  - 100 GHz spacing
  - EDFA's output power of 1 mW and 3 mW.

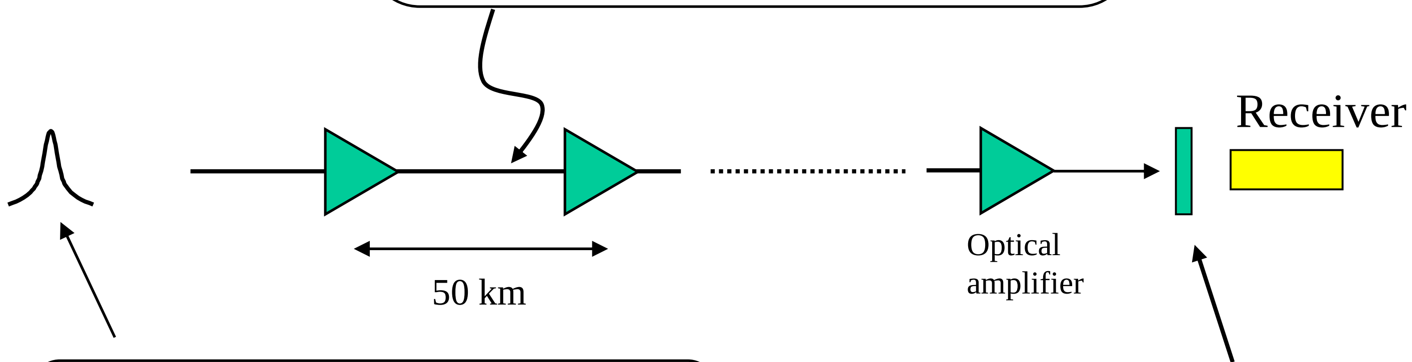
- Simulation scheme
  - Solving the nonlinear Schrödinger equation using the *split-step Fourier method.*
  - Polarization-related phenomena, such as *fiber birefringence* and *polarization-mode dispersion* were taken into account.

Simulations are performed using OptSim (Optical Communication Systems Simulator) developed by ARTIS.

Reference web page : http://www.artis.it/OPTSIM/index.html

Simulation parameters

Fiber loss	:	0.22 dB/km
Fiber dispersion slope	:	0.07 ps/nm^2/km
Fiber nonlinearity γ	:	1.3 w^{-1}km^{-1}
PMD coefficient	:	0.1 ps/km$^{1/2}$
Fiber beat length	:	10 m



<u>Pulse width (FWHM)</u>

Employing the technique : 100 ps
Without employing the technique: 200 ps

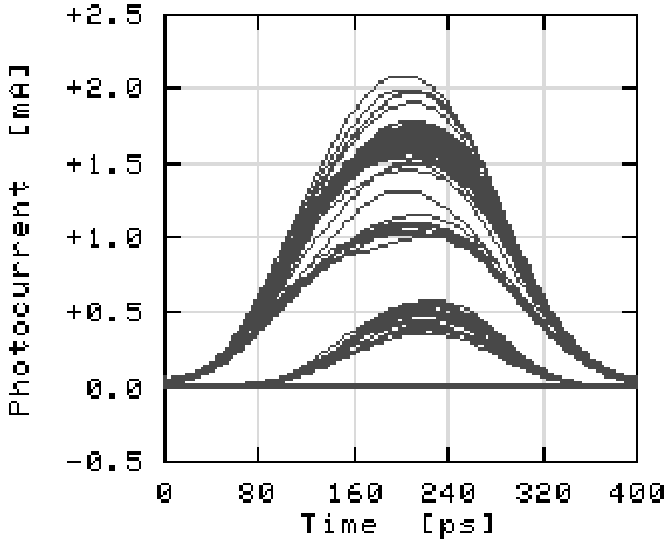
<u>Receiver optical filter bandwidth(3dB)</u>

100 GHz spacing: 40 GHz
50 GHz spacing: 30 GHz

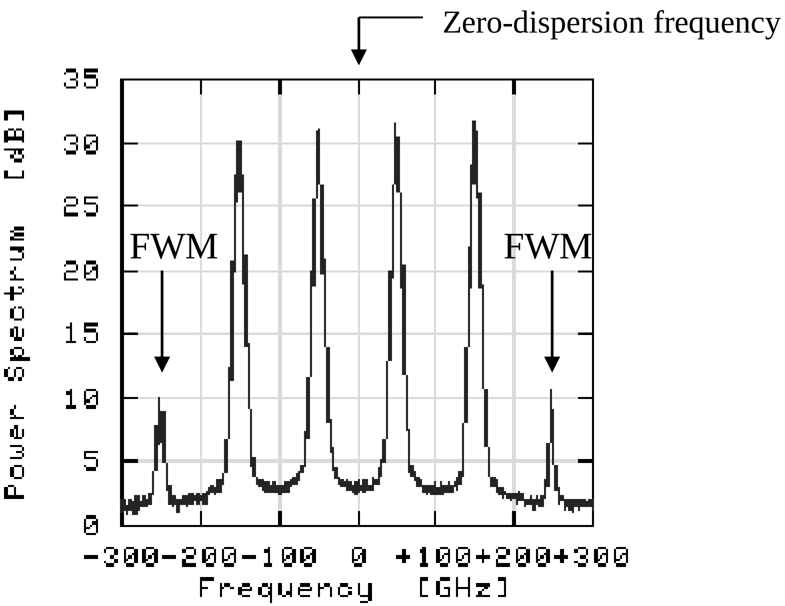
Results of 4-channel 2.5 Gb/s system

Without employing the WDM/TDM technique.

100 GHz spacing (200 km)



Eye diagram



Optical Spectrum

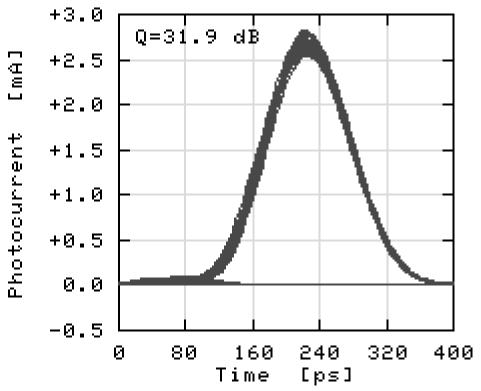
EDFA's output power : 2 mW
Pulse width (FWHM) : 200 ps

Results of 4-channel 2.5 Gb/s systems

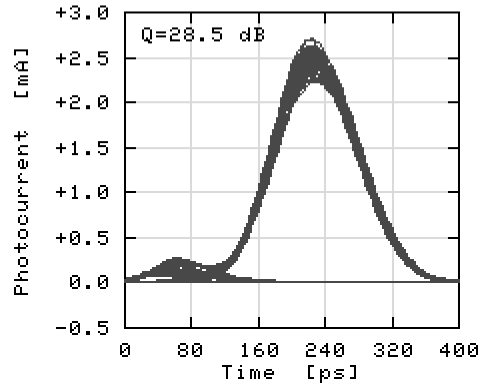
Eye diagrams

Employing the WDM/TDM technique.

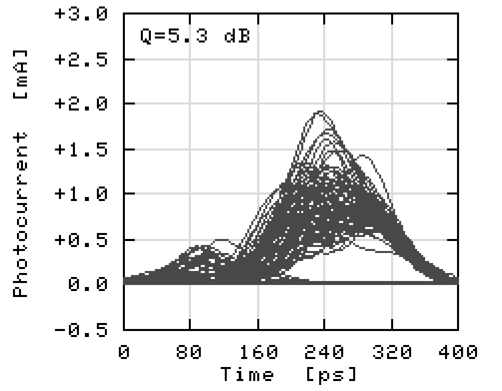
100 GHz spacing (1000, 2000, 4000km)



1000 km



2000 km



4000 km

Eye diagrams are of 3rd (f3) channel.

EDFA's output power : 2 mW

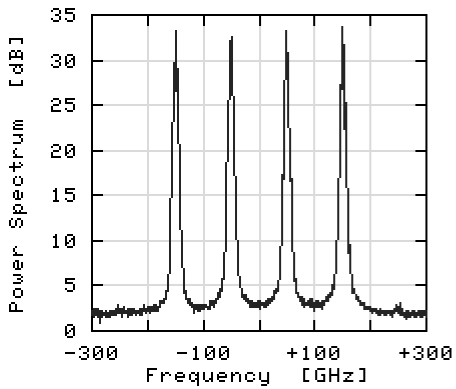
Pulse width (FWHM) : 100 ps

Results of 4-channel 2.5 Gb/s systems

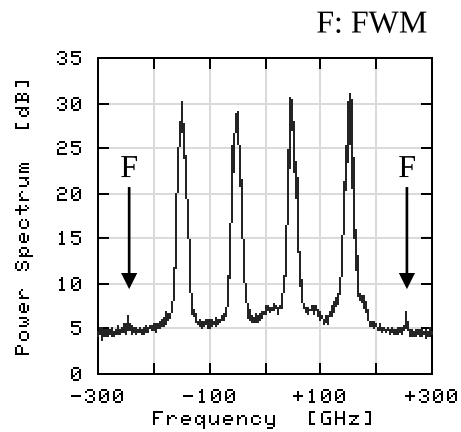
Optical Spectra

Employing the WDM/TDM technique.

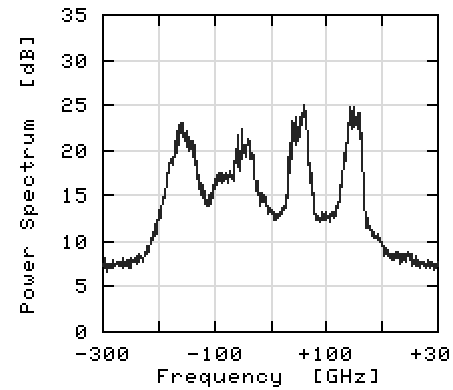
100 GHz spacing (1000, 2000, 4000km)



1000 km



2000 km



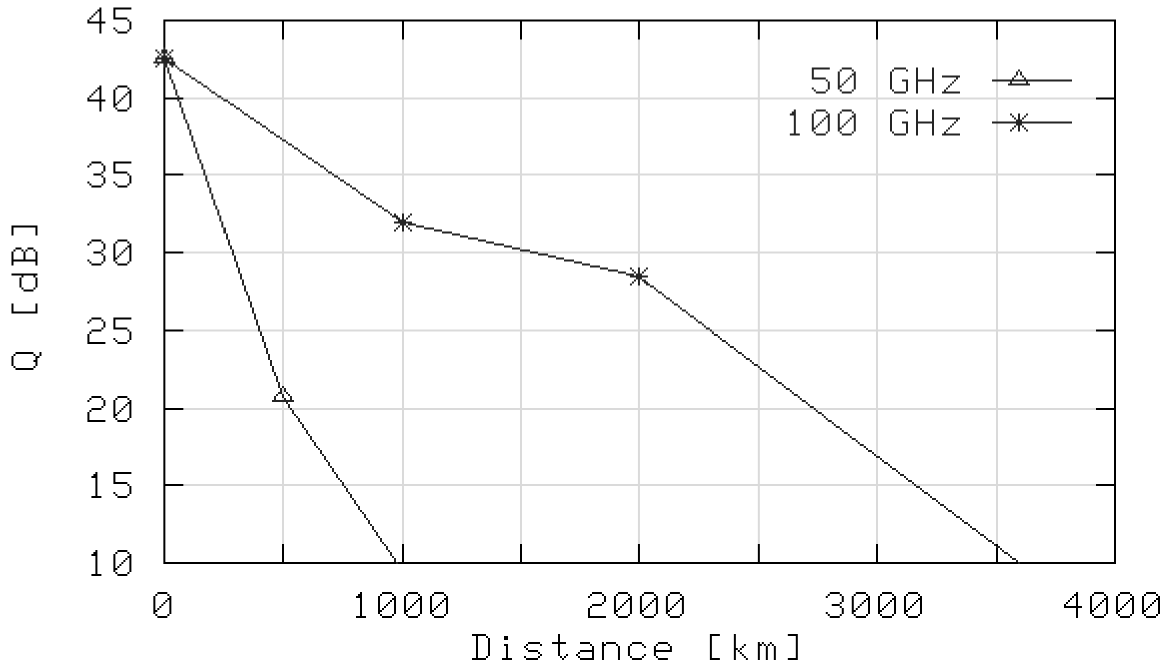
4000 km

EDFA’s output power : 2 mW
Pulse width (FWHM) : 100 ps

Q-factors as a function of propagation distance

<u>2.5 Gb/s 4-channel system</u>

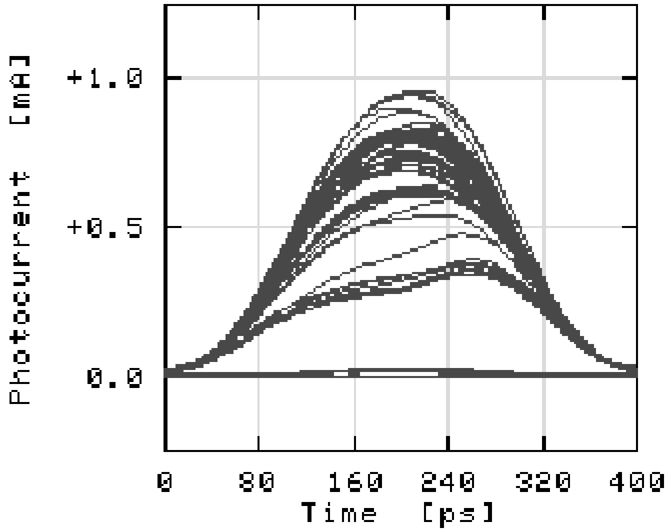
100 GHz and 50 GHz spacing



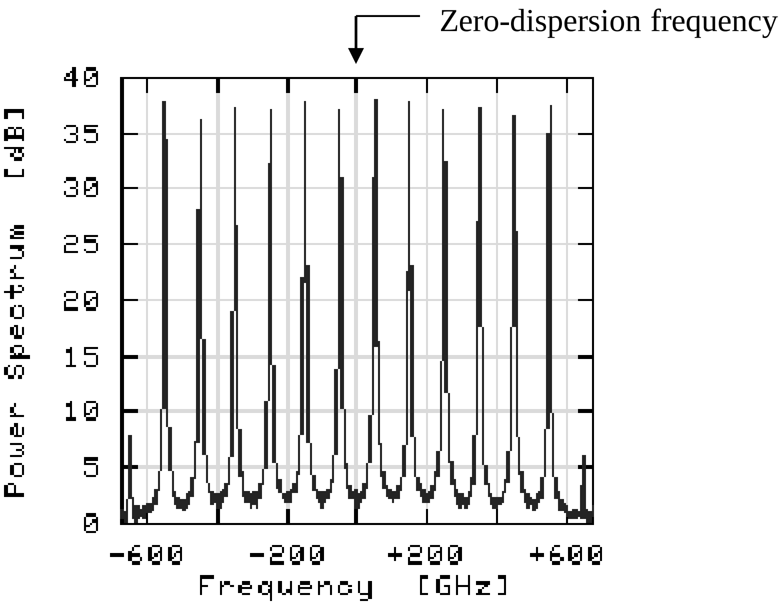
Results of 12-channel 2.5 Gb/s system

Without employing the WDM/TDM technique.

100 GHz spacing (200 km)



Eye diagram of 7th (f7) channel



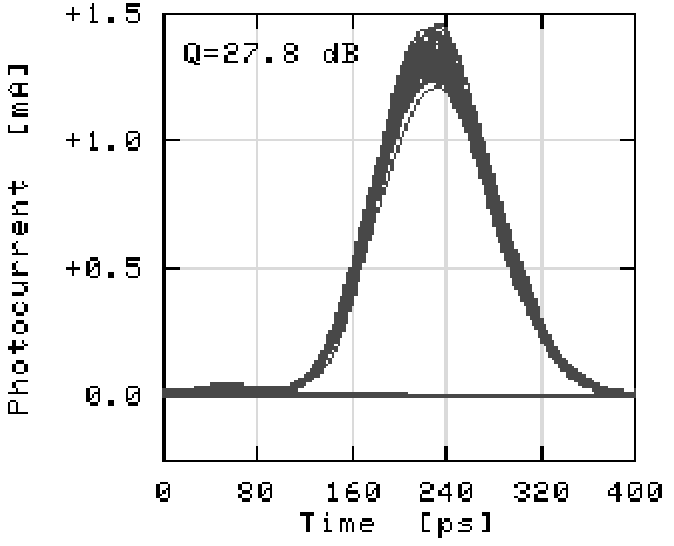
Optical Spectrum

EDFA's output power : 3 mW
Pulse width (FWHM) : 100 ps

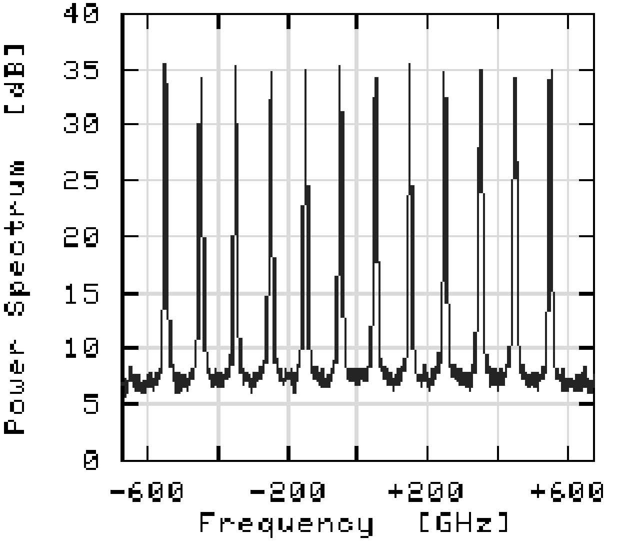
Results of 12-channel 2.5 Gb/s system

Employing the WDM/TDM technique.

100 GHz spacing (1000 km)



Eye diagram of 7th (f7) channel

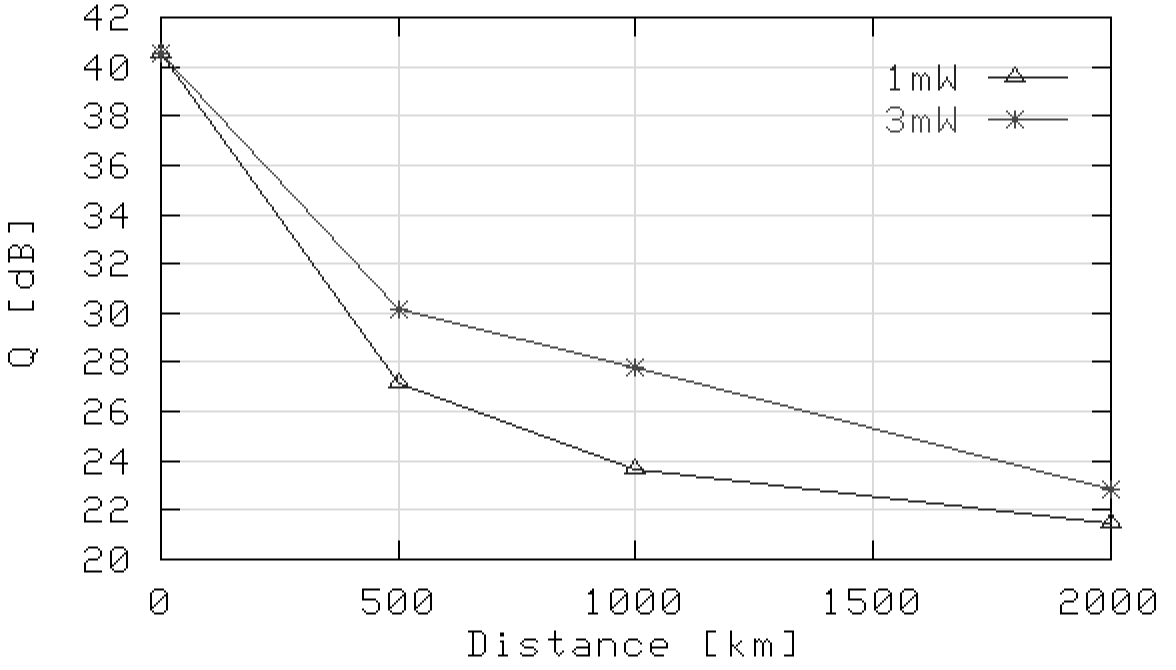


Optical Spectrum

EDFA's output power : 3 mW
Pulse width (FWHM) : 100 ps

Q-factors as a function of propagation distance

2.5 Gb/s 12-channel system
100 GHz spacing



Pulse width (FWHM) : 100 ps

Summary

- Hybrid WDM/TDM technique is proposed to reduce the transmission impairment due to FWM in systems operating close to zero-dispersion wavelength.

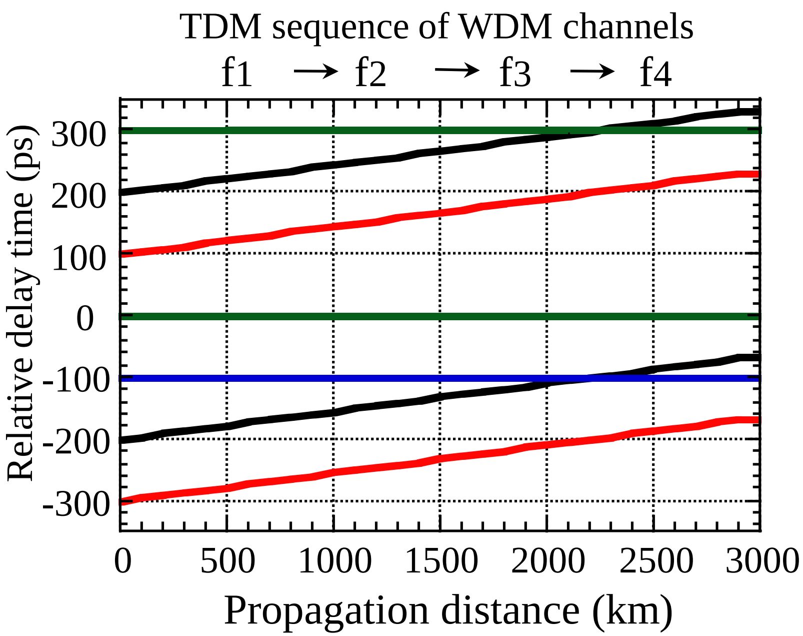
- Effectiveness of the technique is confirmed by simulations for dispersion-shifted fibers.

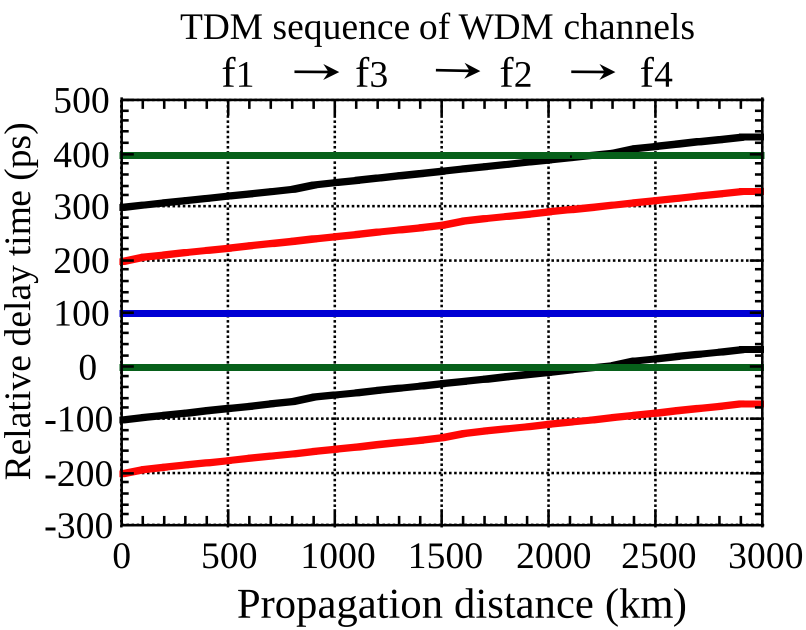
  According to our simulation results, by employing the proposed technique;

  - 2.5 Gb/s 4-channel (total capacity of 10 Gb/s, 100 GHz spacing) system can be transmitted over 2000 km with a Q-factor of 28.5 dB.
  - 2.5 Gb/s 12-channel (total capacity of 30 Gb/s, 100 GHz spacing) system can be transmitted over 1000 km with a Q-factor of 27.8 dB and over 2000 km with a Q-factor of 23 dB.

Relative time delay of channels

4-channel system: 100 GHz spacing.
Figures show the traces of the pulse peaks of each channel.





f1 (193.15×10^{14} Hz) | f3 (192.95×10^{14} Hz)
f2 (193.05×10^{14} Hz) | f4 (192.85×10^{14} Hz)

Zero-dispersion frequency: 193×10^{14} Hz