Simulation and Experimental Study of SCM/WDM Optical Systems

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May 23, 2001

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Outline

- Introduction to SCM technology
  - Demand for more bandwidth
  - TDM,WDM strategies
  - SCM and WDM combination
- Numerical simulation model
  - Goals and general requirements
  - Description of the simulation model
    - Transmitter
    - Optical fiber nonlinear model
    - Receiver

Outline

- Simulation results
  - BPSK, 4-subcarrier each with 2.5Gb/s datarate, self-coherent detection
  - QPSK, 2-subcarrier each with 2x2.5Gb/s datarate, self-coherent detection
  - ASK, 4-subcarriers each with 2.5Gb/s datarate, direct detection using narrowband optical filter
  - Traditional NRZ modulated OC192 system
- Experiment
- Conclusions and future work

Introduction: Demand for more Bandwidth

- Faster Internet access
- High speed data transmission
- Video Conferencing
- High resolution image transmission
- Other new services

- More fiber everywhere
- Higher data-rate each wavelength----------TDM
- More wavelengths in the fiber--------------- WDM

Introduction: TDM,WDM strategies

- TDM strategy
  - Simple modulation format: IMDD binary system
  - Short bit length, more bits in unit time
  - Electrical TDM and optical TDM, soliton
  - Grooming may be a big problem
  - Difficult in transmission through fiber: chromatic dispersion, PMD, fiber nonlinearity
  - Does not scale well beyond OC192

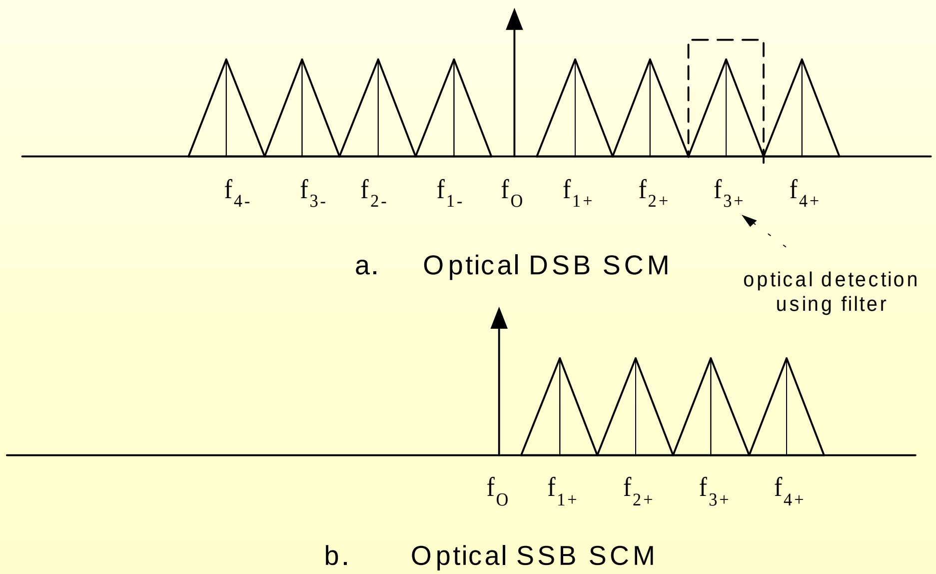
Introduction: TDM,WDM strategies

- WDM strategy
  - Multiple wavelengths in a single fiber
  - Better utilization of optical fiber transmission window
  - Lower bitrate & lower power per wavelength
  - From CWDM to DWDM: increase bandwidth efficiency

    example:2.5Gb/s per-channel data rate and 50GHz channel spacing, the bandwidth efficiency is 0.05 bit/Hz.
  - Technical difficulties: lightwave sources, optical filters, dispersion management, nonliear crosstalk, ….

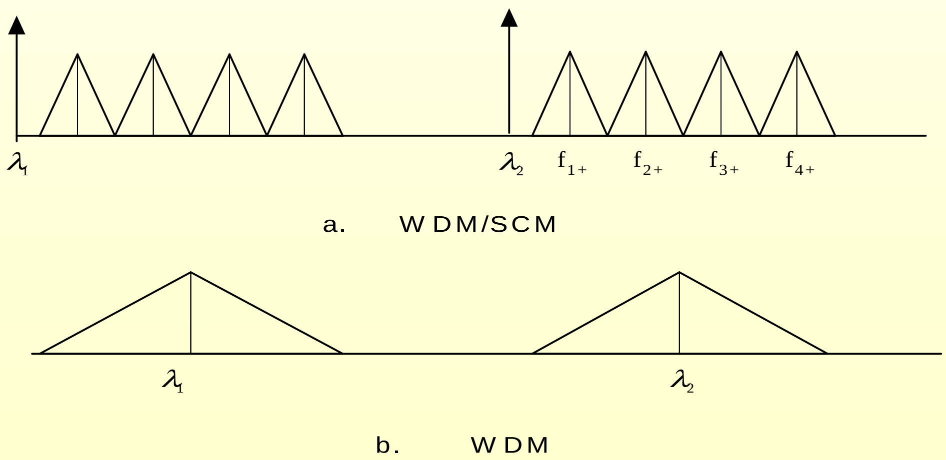
Introduction: SCM/WDM and OSSB

- SCM leverages mature microwave technology
- Two-step modulation: RF modulation at sub-carriers, optical modulation at wavelengths.
- OSSB is preferred: less dispersion penalty, higher bandwidth efficiency

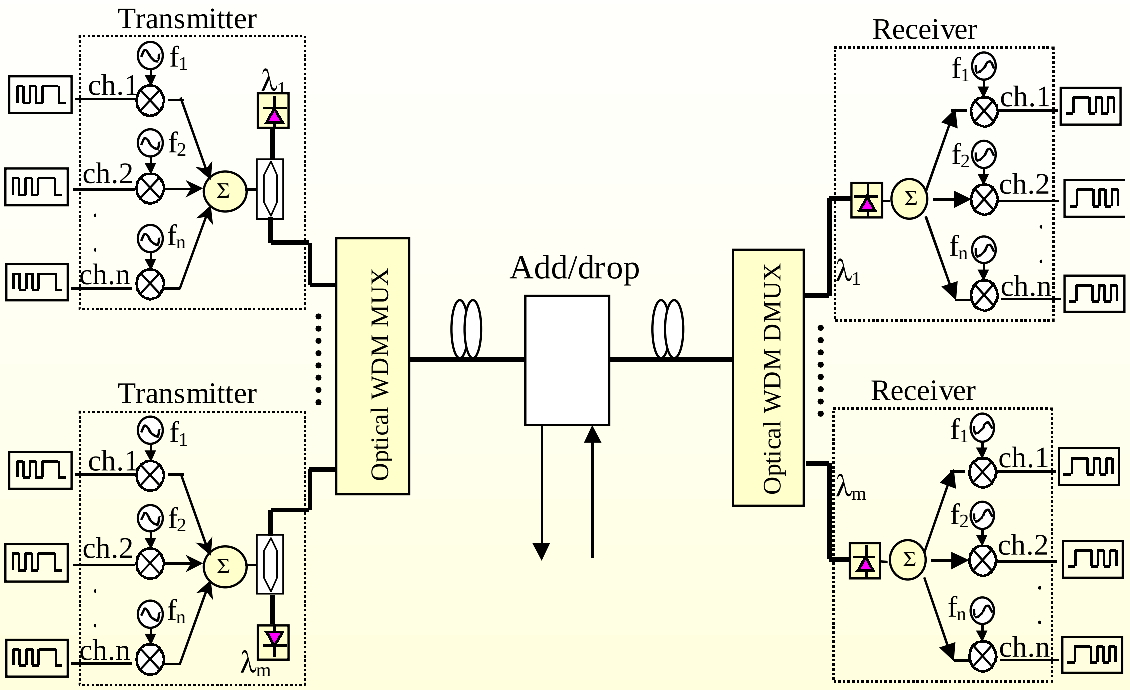


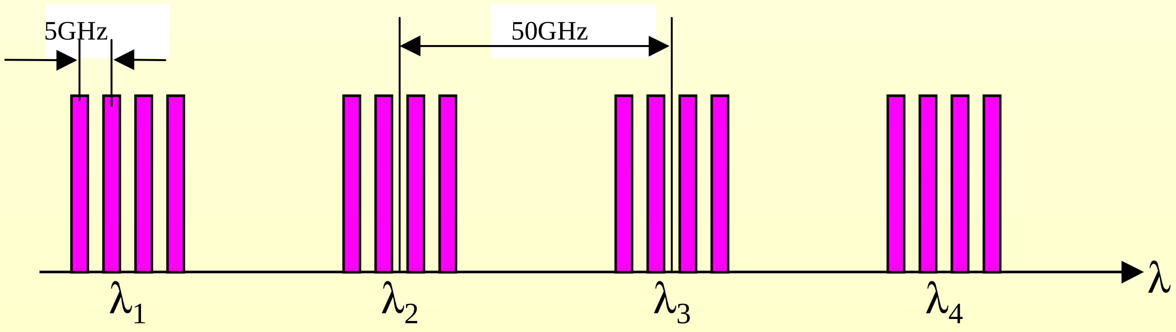
Introduction: SCM/WDM and OSSB

- SCM/WDM combination
  - Large number of channels, low channel speed, easy grooming and scaling, lower dispersion penalty
  - Advanced modulation format, phase modulation possible
  - Nonliearity-introduced distortion



An exemplary setup of SCM/WDM system

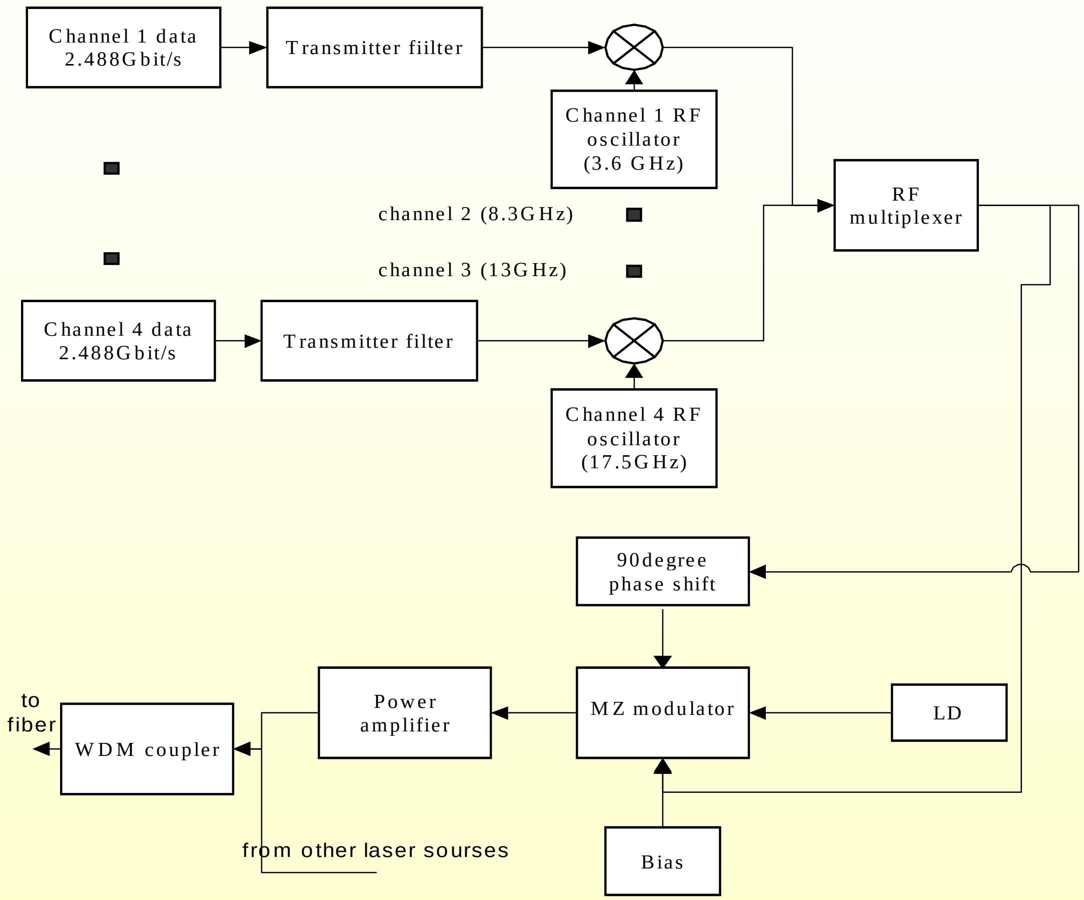




Numerical model for SCM/WDM systems

- Goals and general requirements
  - To be able to handle different types of multi-wavelength SCM/WDM systems
  - Include both dispersion and fiber nonlinearity
  - To be able to handle a variety of modulation formats, OSSB, ASK, BPSK, QPSK and binary IMDD
  - Combine waveform distortion and noise: *sensitivity*

Transmitter simulation model



SCM Transmitter Block Diagram

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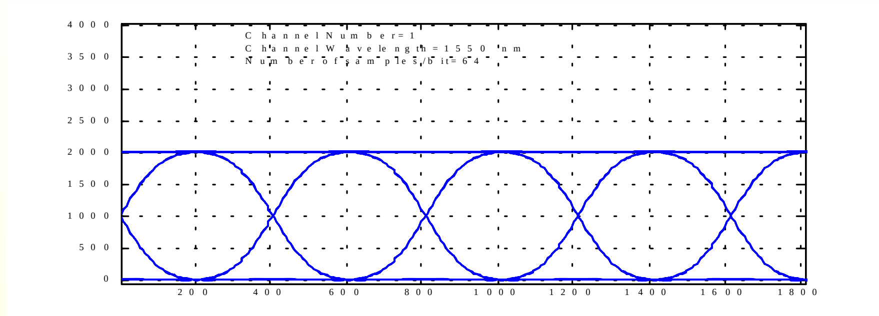
Baseband signal generation

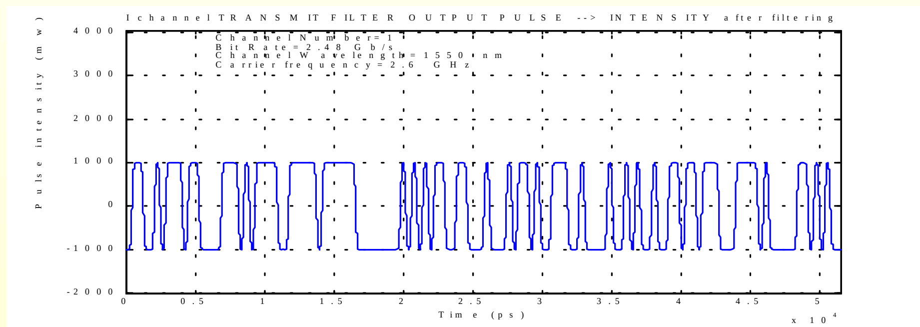
- 2^7-1 PRBS
- Random relative delay between different sub-carriers and wavelengths
- 6-order Butterworth filter for band-limiting
- 64 to 256 samples per bit depending on the required simulation bandwidth

Baseband signal generation

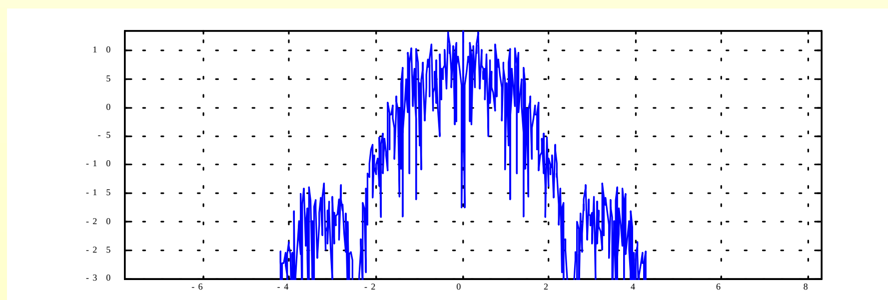
- Signal eyediagram



- Signal waveform



- Baseband Spectrum



Sub-carrier generation

$$s(t) = A_c \sum_{-\infty}^{\infty} x_n f(t - nT_s)\cos(\omega_c t) - A_c \sum_{-\infty}^{\infty} y_n f(t - nT_s)\sin(\omega_c t)$$

A_c peak signal value

x_n and y_n information bits (0, 1 or -1)

$f(t)$ normalized baseband bit shape function

ω_c subcarrier frequency

ASK:	BPSK:	QPSK:
$x_n = 1$ or 0	$x_n = 1$ or -1	$x_n = 1$ or -1
$y_n = 0$	$y_n = 0$	$y_n = 1$ or -1

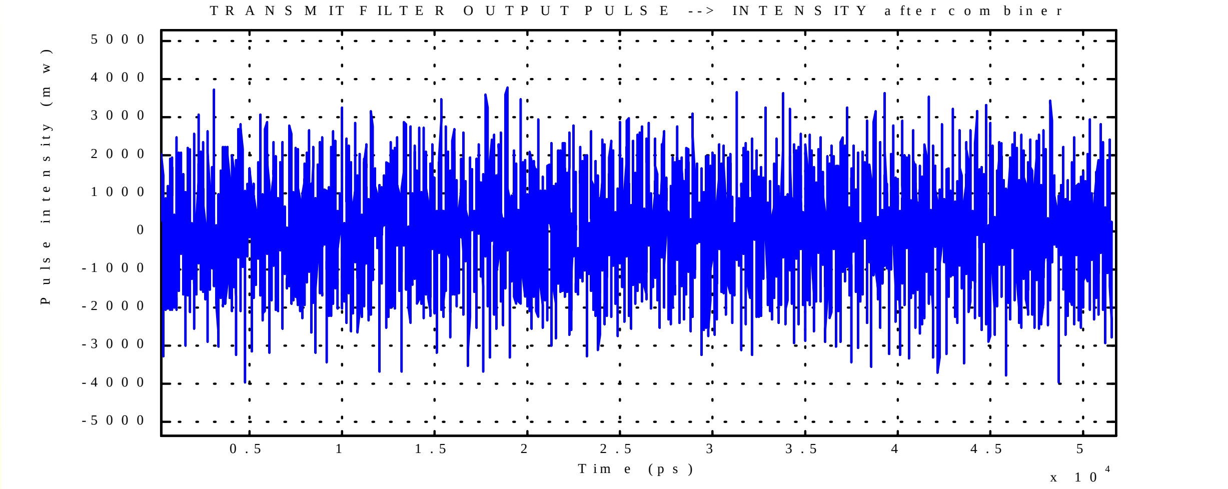
If *f*(t) represents a rectangular bit shape, the PSD of the complex envelope of MPSK is

$$P(f) = A_c^{\,2} T_S \left(\frac{\sin(\pi f T_S)}{\pi f T_S}\right),$$ where T_S is the symbol time.

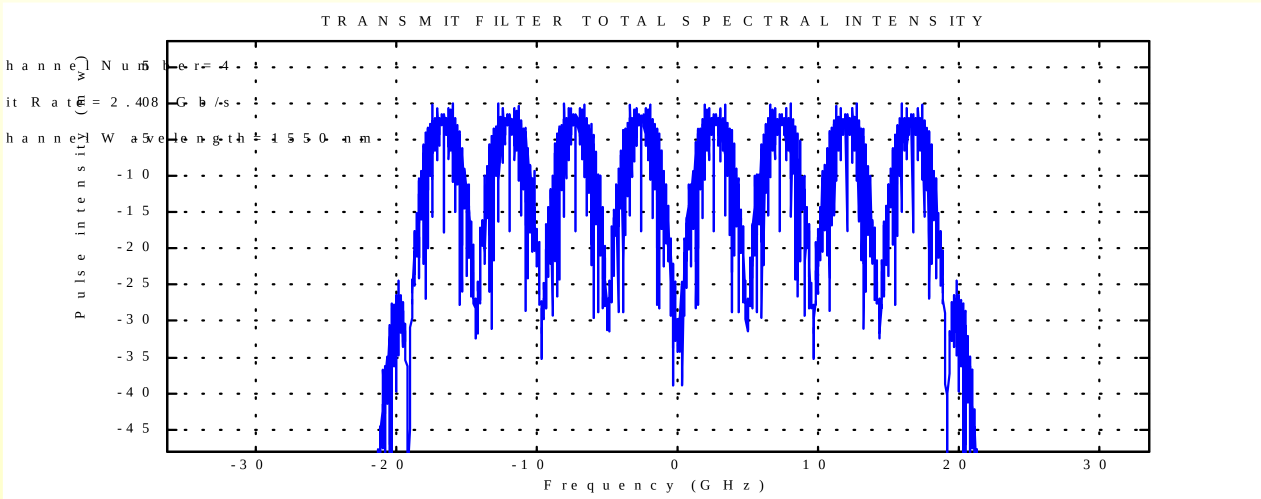
The 3dB bandwidth of BPSK and QPSK are both 0.88R if they have the same symbol rate R. Each symbol in QPSK represents 2 bits, so the spectrum efficiency is doubled.

4-subcarrier BPSK composite signal

Waveform



Spectrum



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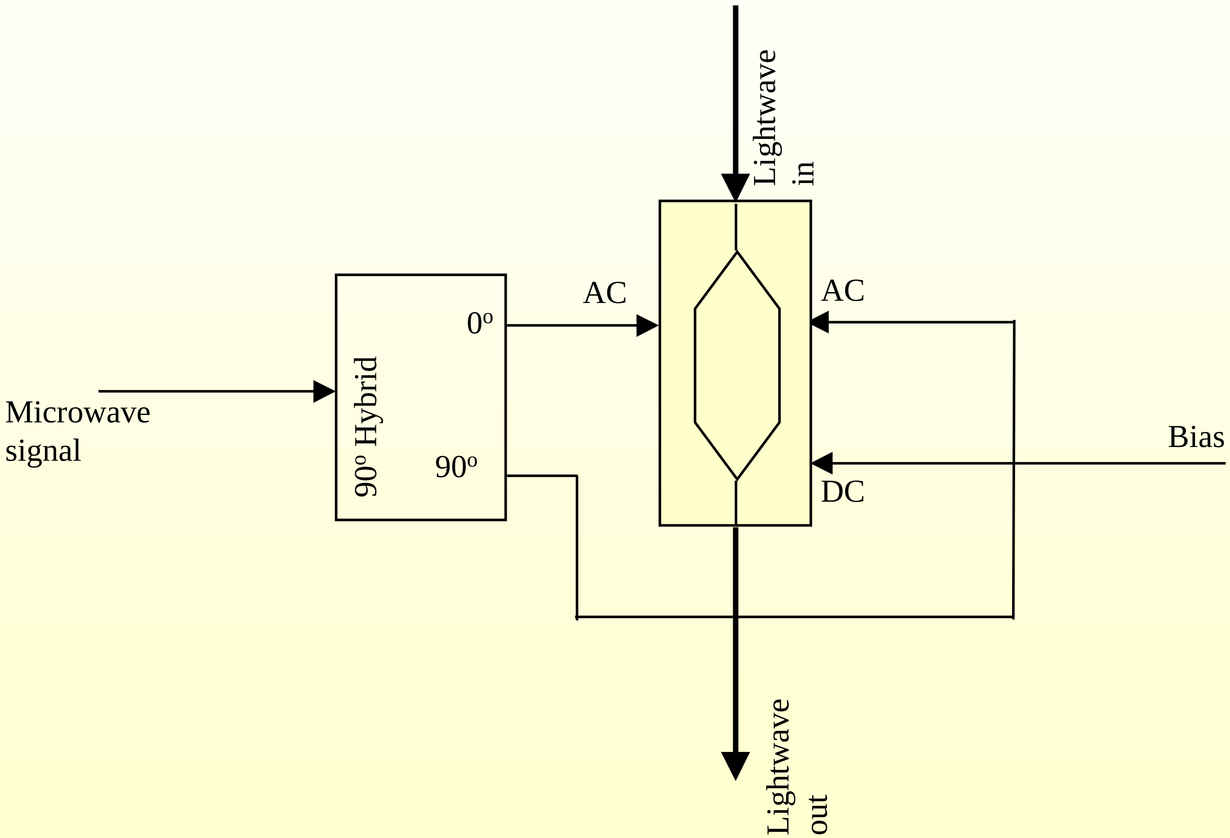
Dual-drive MZ modulator and OSSB signal generation

Implementation



Dual-drive MZ modulator and OSSB signal generation
Theory

Modulator output $E_o(t) = \frac{A}{2}\{\cos[\omega_o t + \phi_1(t)] - \cos[\omega_o t + \phi_2(t)]\}$

ϕ_1, ϕ_2 phase delay of the two arms

Set $\phi_1(t) = \gamma\pi + \beta\pi \cos \Omega t$ and $\phi_2(t) = \beta\pi \cos(\Omega t + \theta)$,

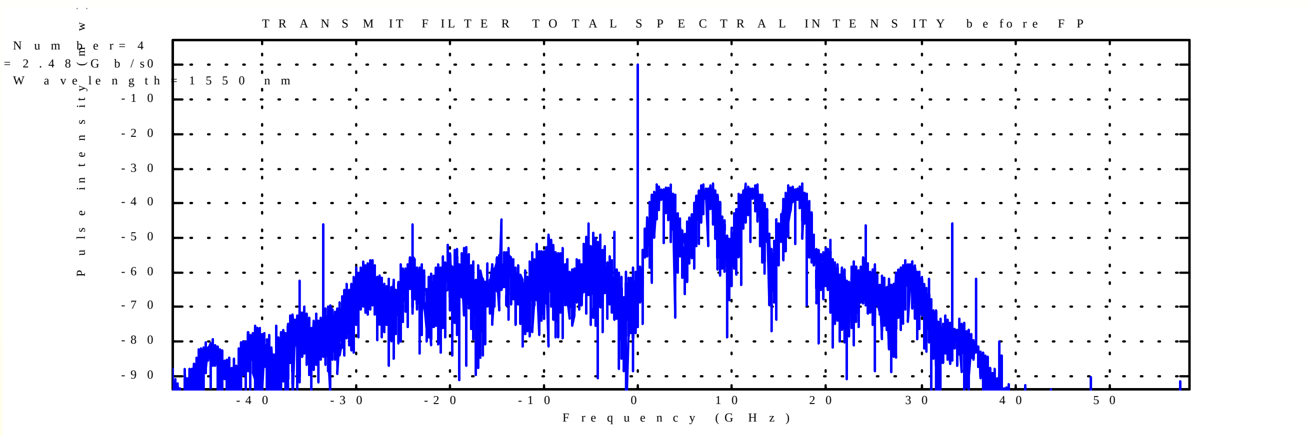
$\gamma = \frac{V_{dc}}{V_\pi}$ DC bias of one arm,

$\beta = \frac{|V_{ac}|}{V_\pi}$ optical modulation index.

When $\gamma = \frac{1}{2}$, and $\theta = \frac{\pi}{2}$,

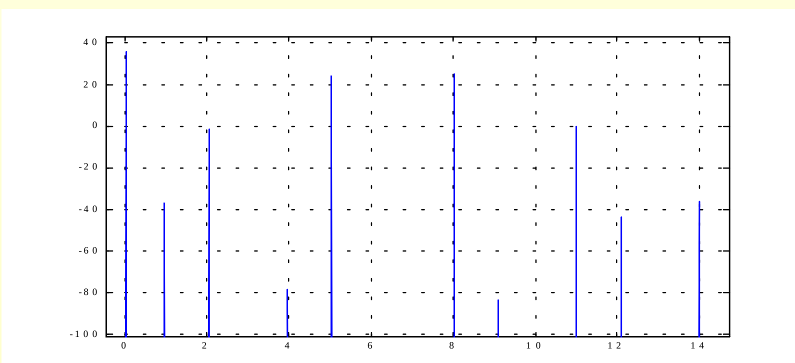
$$E_o(t) = -\frac{E_i}{2}\{J_0(\beta\pi)[\sin(\omega_o t) + \cos(\omega_o t)] + 2J_1(\beta\pi)\cos(\omega_o - \Omega)t + 2J_2(\beta\pi)......$$

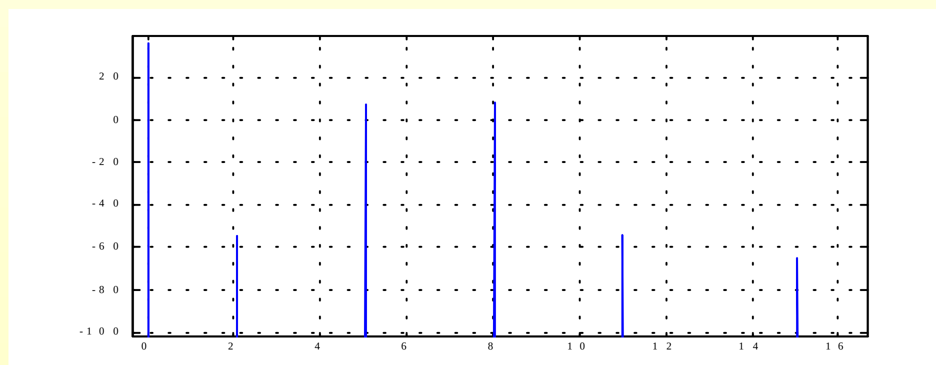
OSSB Spectrum



Nonlinear distortion of unlinearized modulator

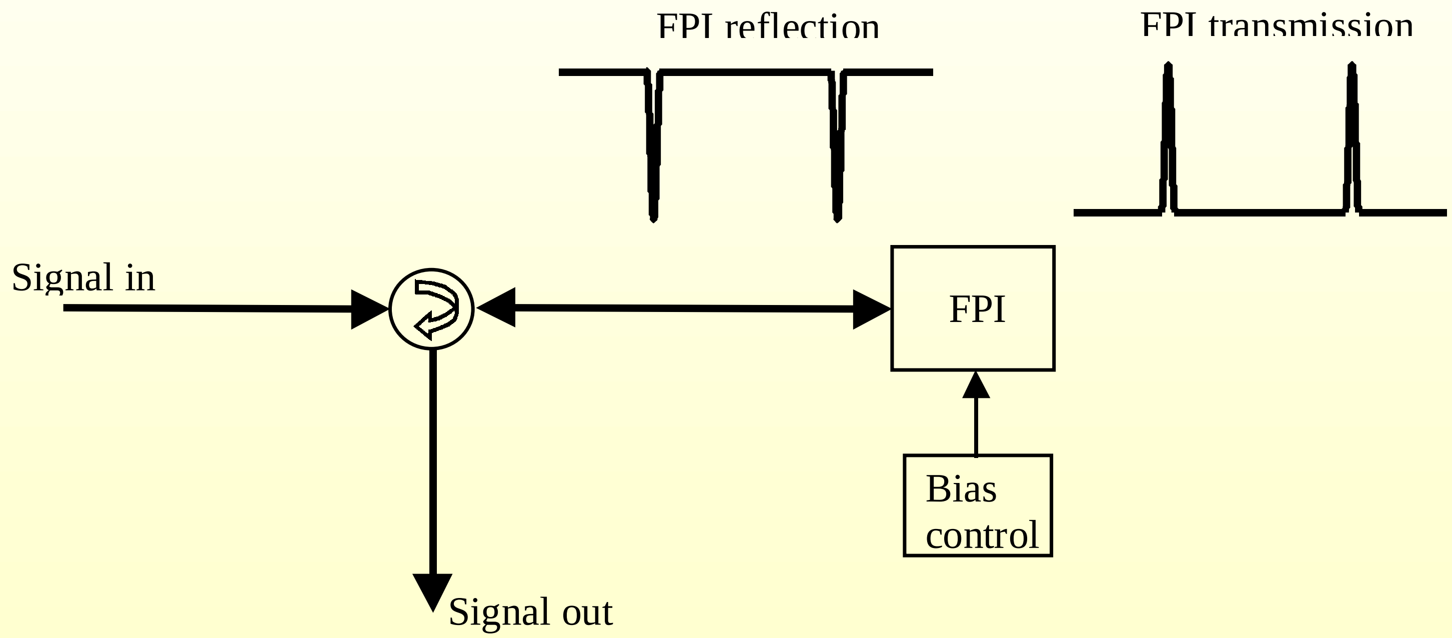
- Generate CTB but no CSO
- CTB is proportional to the square of modulation index





Carrier suppression

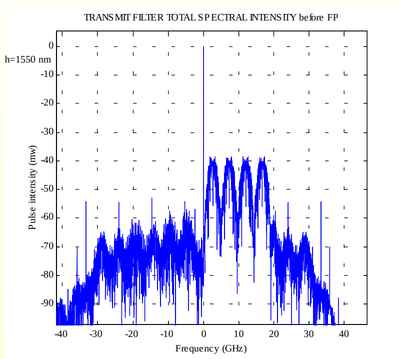
- Increase modulation efficiency
- Reduce modulator-induced nonlinearity

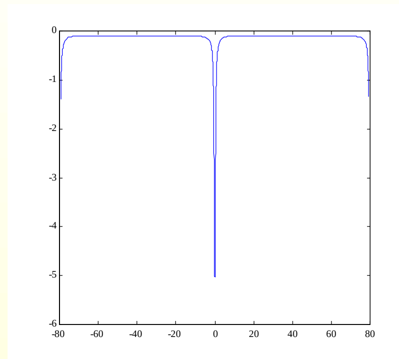


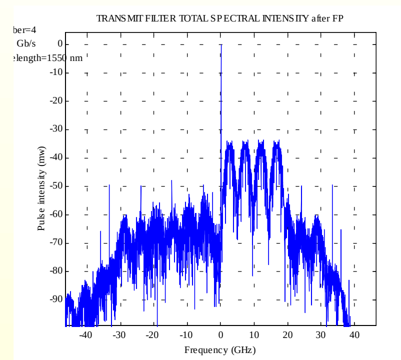
Carrier suppression

Before carrier suppression | FP filter | After carrier suppression

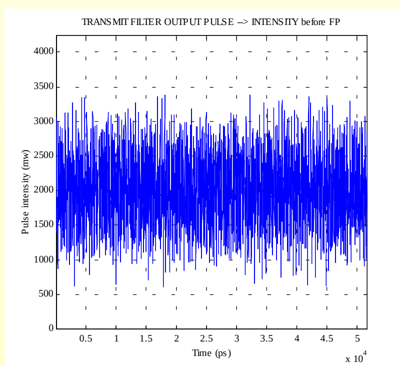
amplitude

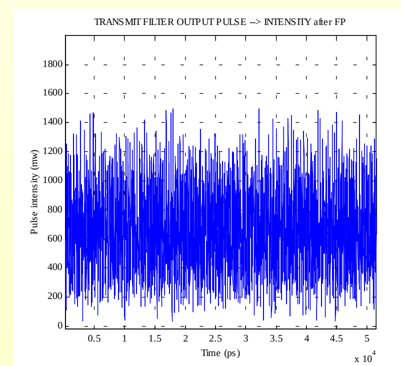




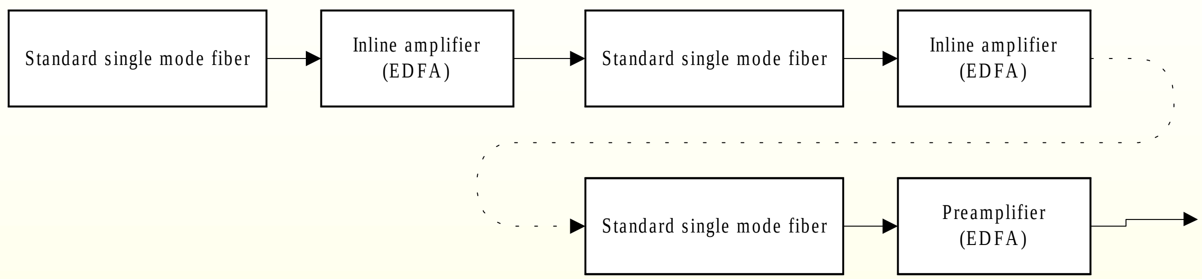


waveform

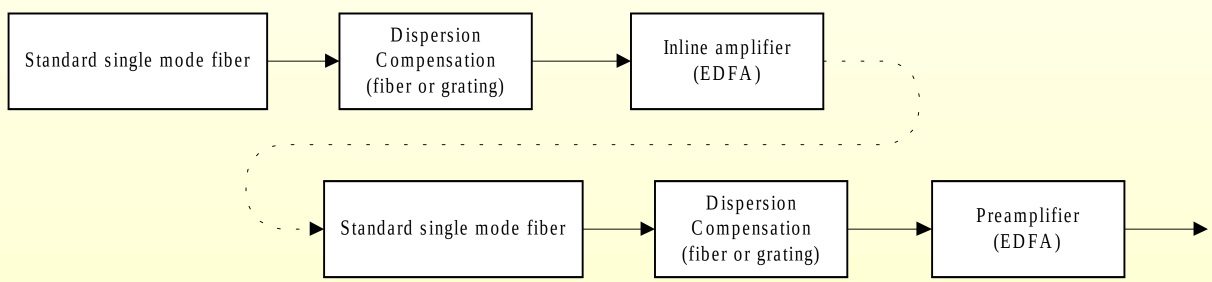




Optical fiber simulation model



Fiber path without dispersion compensation

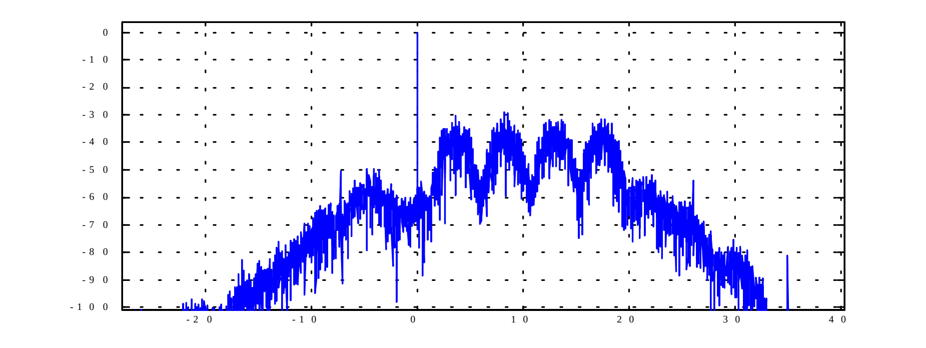


Fiber path with dispersion compensation

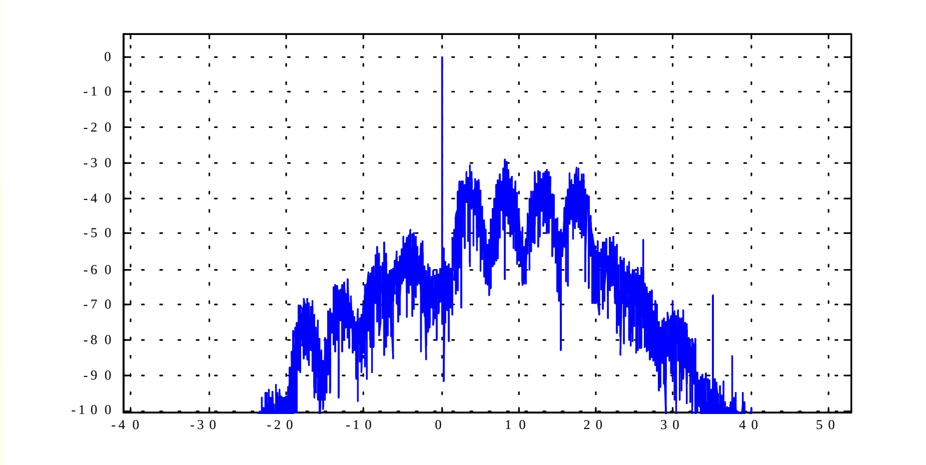
Optical fiber simulation model

- Span length ranges from 40 to 80 km. 3 dB loss margin reserved for each span (If the dispersion compensation is implemented, the additional loss is 6dB)
- Attenuation of each span is compensated by optical amplification.
- Neglect nonlinearity of Dispersion Compensator
- SMF parameter: α=0.25 dB/km, n_2=2.36e-20, Aeff = 71um^2 , D= 18 ps/nm/km. Dispersion slope 0.093 ps/nm^2/km. PMD coefficient 0.1 or 0.5ps/sqrt(km) .
- Solve Nonlinear Schrodinger Equations, neglect SRS and SBS.
- Using Split-step Fourier method.

Optical fiber simulation model



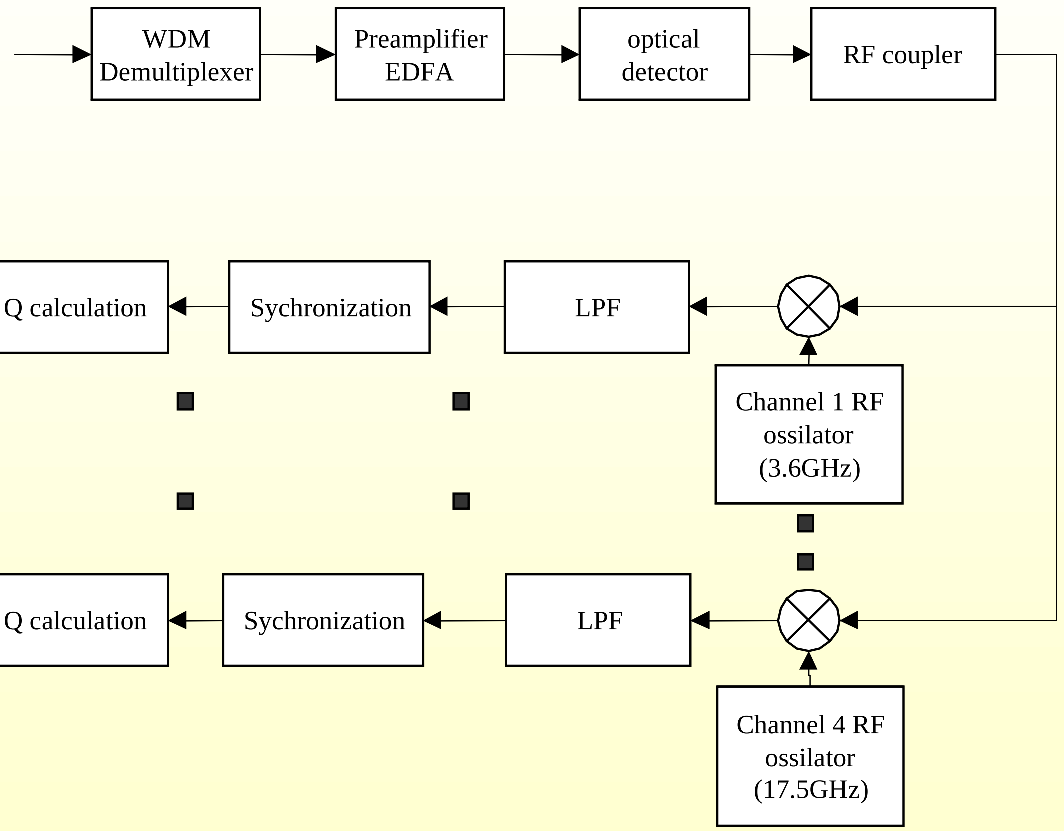
(a) spectrum before the optical fiber



(b) optical spectrum after 80 km fiber transmission

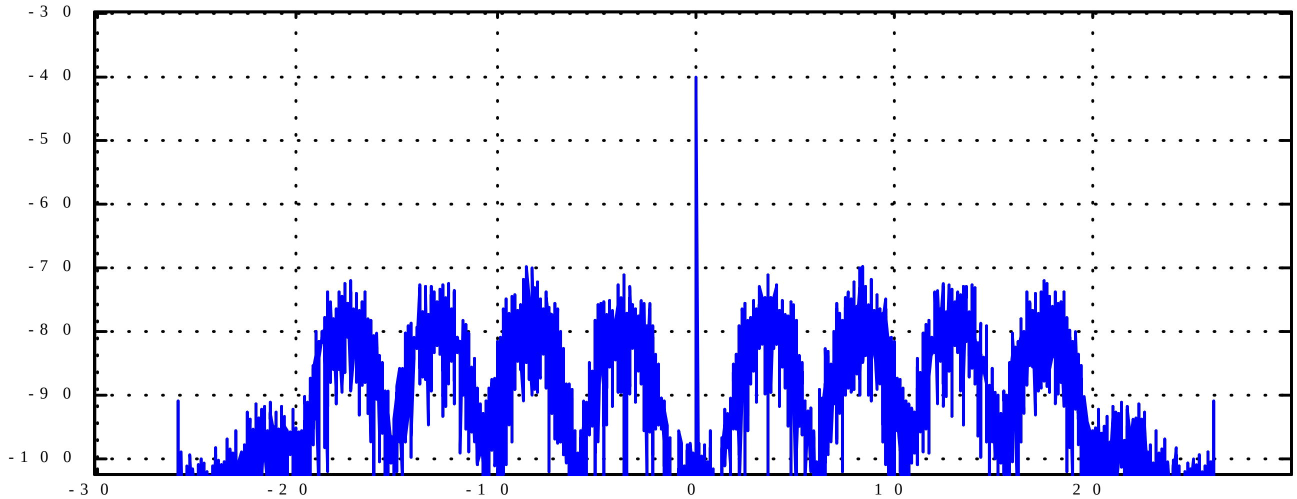
Figure 2.12 optical spectrum before and after 80 km fiber transmission, optical power is 3dBm

Simulation model for receiver



Simulation model for receiver

- WDM demultiplexer: 6th-order Butterworth filter, 30GHz bandwidth.
- EDFA preamplifier: fixed output 1dBm total
- Analytic formula to calculate ASE noise
- Photo-detection: square-law operation + low-pass filter.



Simulation model for receiver

- High pass filter: reduce DC component after O/E conversion
- Carrier recovery: Mth Power loop for MPSK carrier recovery

Input: $s(t) = A\cos(2\pi f_c t + \theta_k + \theta)$, for $kT_S \le t \le (k+1)T_S$, T_S symbol time

$$\theta_k = 0, \frac{2\pi}{M}, 2\frac{2\pi}{M}, 3\frac{2\pi}{M}, \ldots\ldots, (M-1)\frac{2\pi}{M}$$

θ : phase delay due to the transmission and transmitter bias

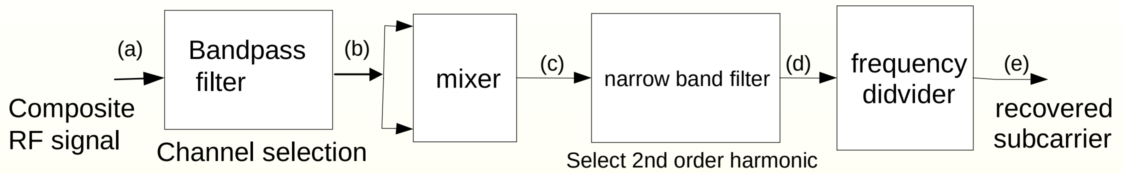
$s^M(t) = A^M \cos(2\pi M f_c t + M\theta) +$ higher order harmonics

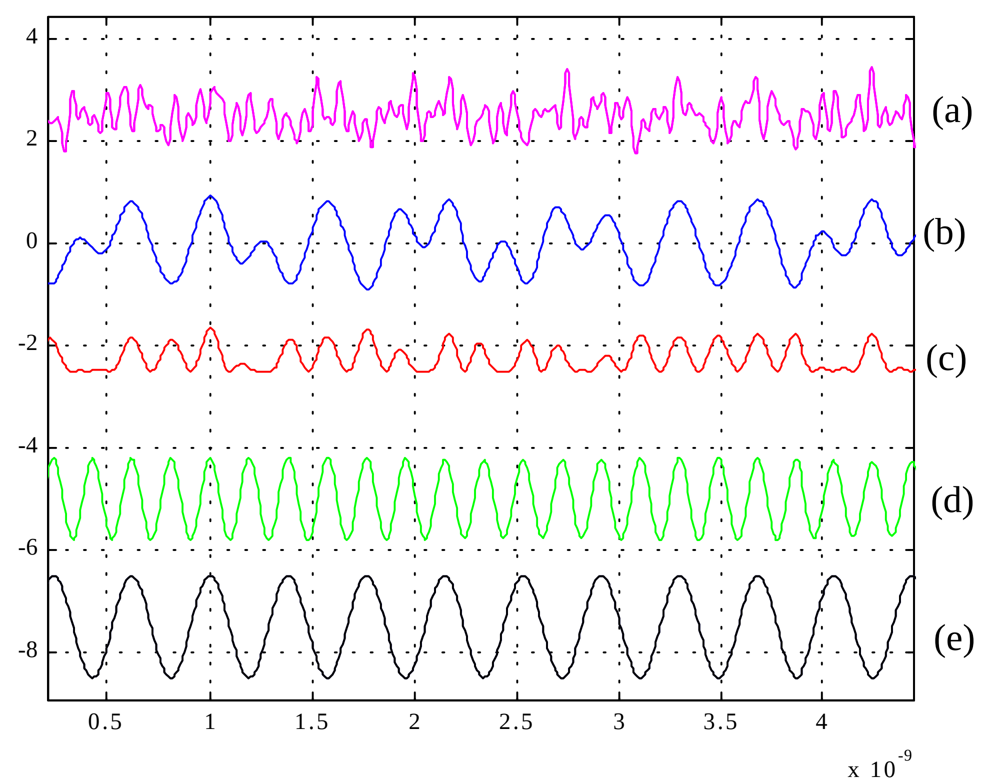
Select the first term using a bandpass filter, divide the frequency by M

$$C(t) = K\cos(2\pi f_c t + \theta)$$

2nd power loop for BPSK carrier recovery

An example

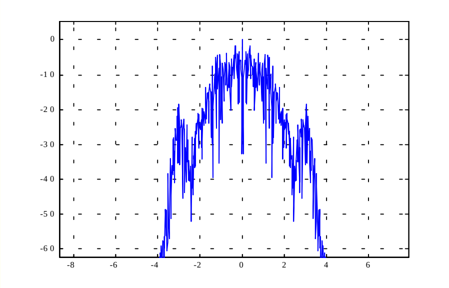




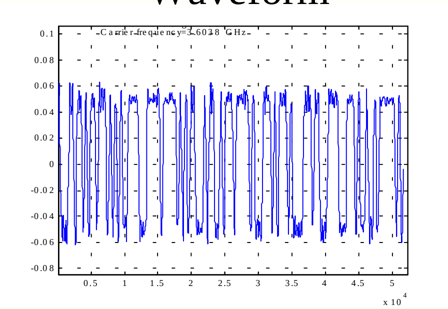
Demodulation

Mixer output

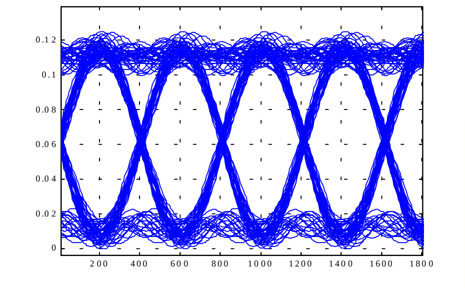
Spectrum



Waveform

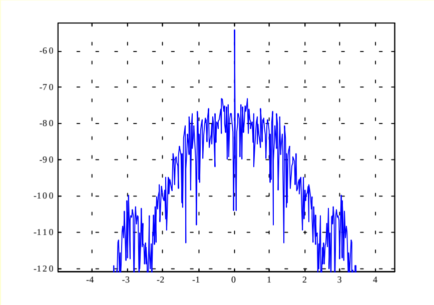


Eyediagram

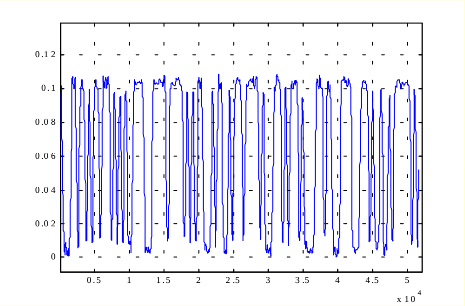


Baseband filter output

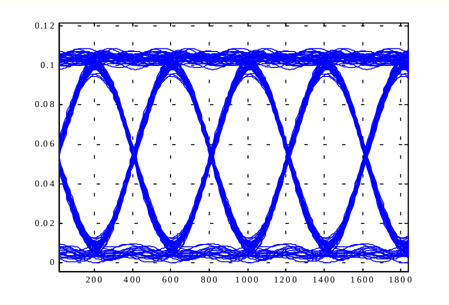
Spectrum



Waveform



Eyediagram



PMD-induced polarization walk-off

between carrier and sub-carriers

PMD definition: $\Delta\tau = \dfrac{\Delta\theta}{\Delta\omega}$

$\Delta\tau$ DGD in seconds,

$\Delta\theta$ relative wave vector rotation in radians

$\Delta\omega$ optical frequency change that produced the rotation, in radians/seconds

Consequence:

Decrease the beating efficiency between carrier and sub-carriers by cos($\Delta\theta$)

PMD-induced waveform distortion

- In a Gaussian pulse IMDD system, the limitation from PMD is estimated by

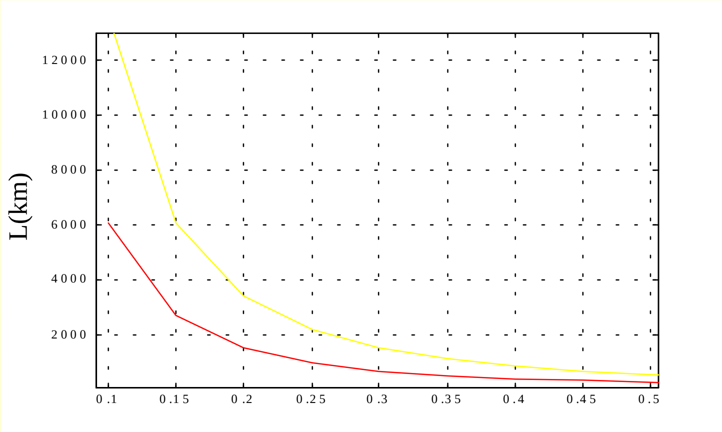
$$B^2 L \approx \frac{0.020}{(DGD)^2}$$

B: data rate, *L*: maximum transmission distance

- For SCM system, assume the pulse width is the period of the sinusoid sub-carriers at 12GHz or 18GHz
- With DGD of $0.5 ps/\sqrt{km}$

  L = 240km and 550km for 12GHz and 18GHz sub-carriers
- With DGD of $0.1 ps/\sqrt{km}$

  L = 6000km and 13000km for 12GHz and 18GHz sub-carriers



DGD (ps/sqrt(km))

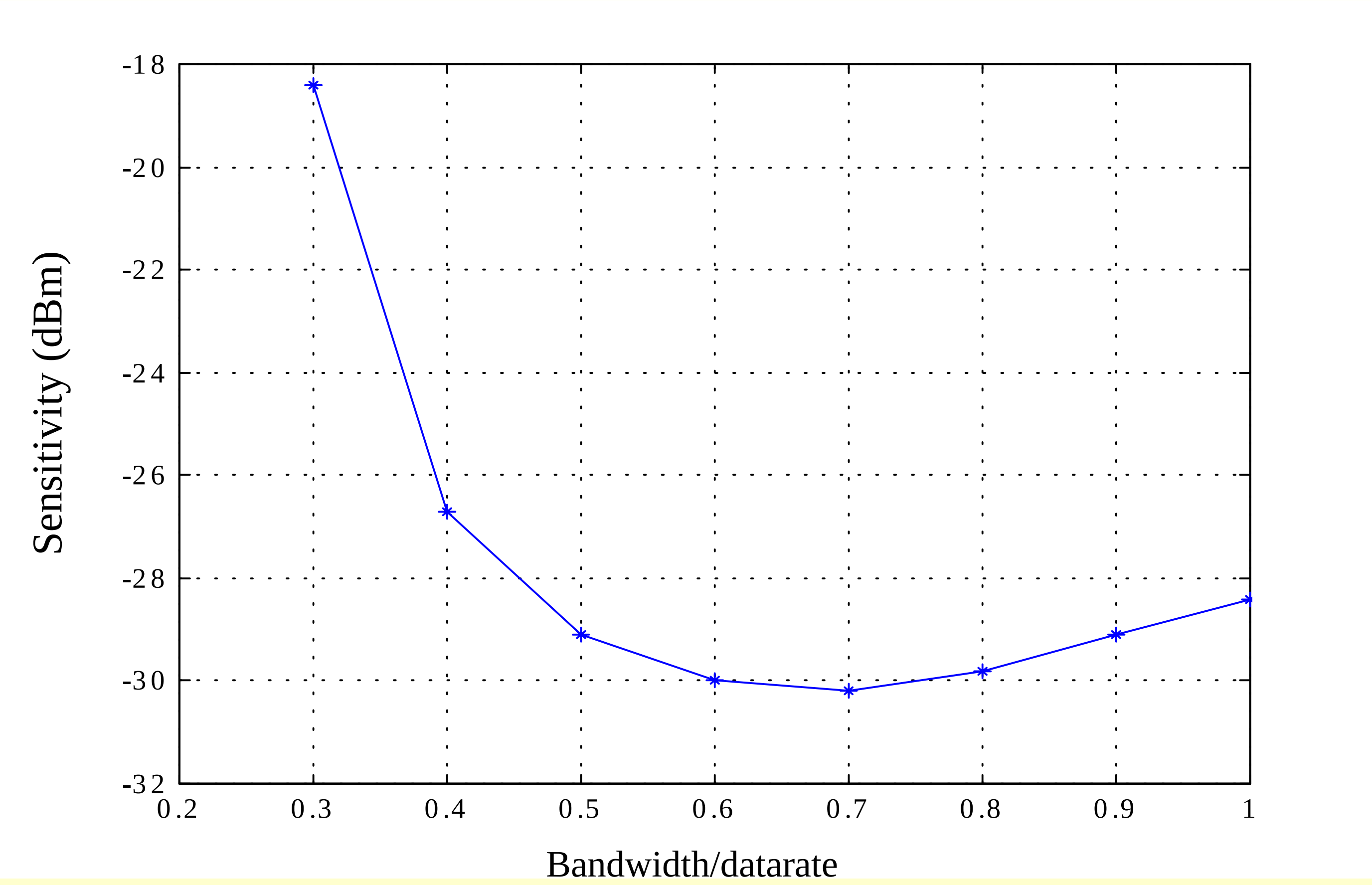
Analytic estimation of receiver sensitivity

- Approximations:
  - All noises considered additive with Gaussian statistics
  - Signal-ASE beat noise dominant
  - 5dB EDFA noise figure
  - Neglect waveform distortion
  - Linear approximation for MZ modulator
- Calculated receiver sensitivity
  - -31dBm for 4-subcarrier BPSK, 10Gb/s total capacity
  - -34dBm for 2-subcarrier QPSK , 10Gb/s total capacity
  - -46dBm for single channel IMDD OC48, 2.5Gb/s capacity
  - -40dBm for single channel IMDD OC192, 10Gb/s capacity

4-subcarrier BPSK, self-coherent detection

(2.5Gb/s per sub-carrier,10Gb/s total capacity)

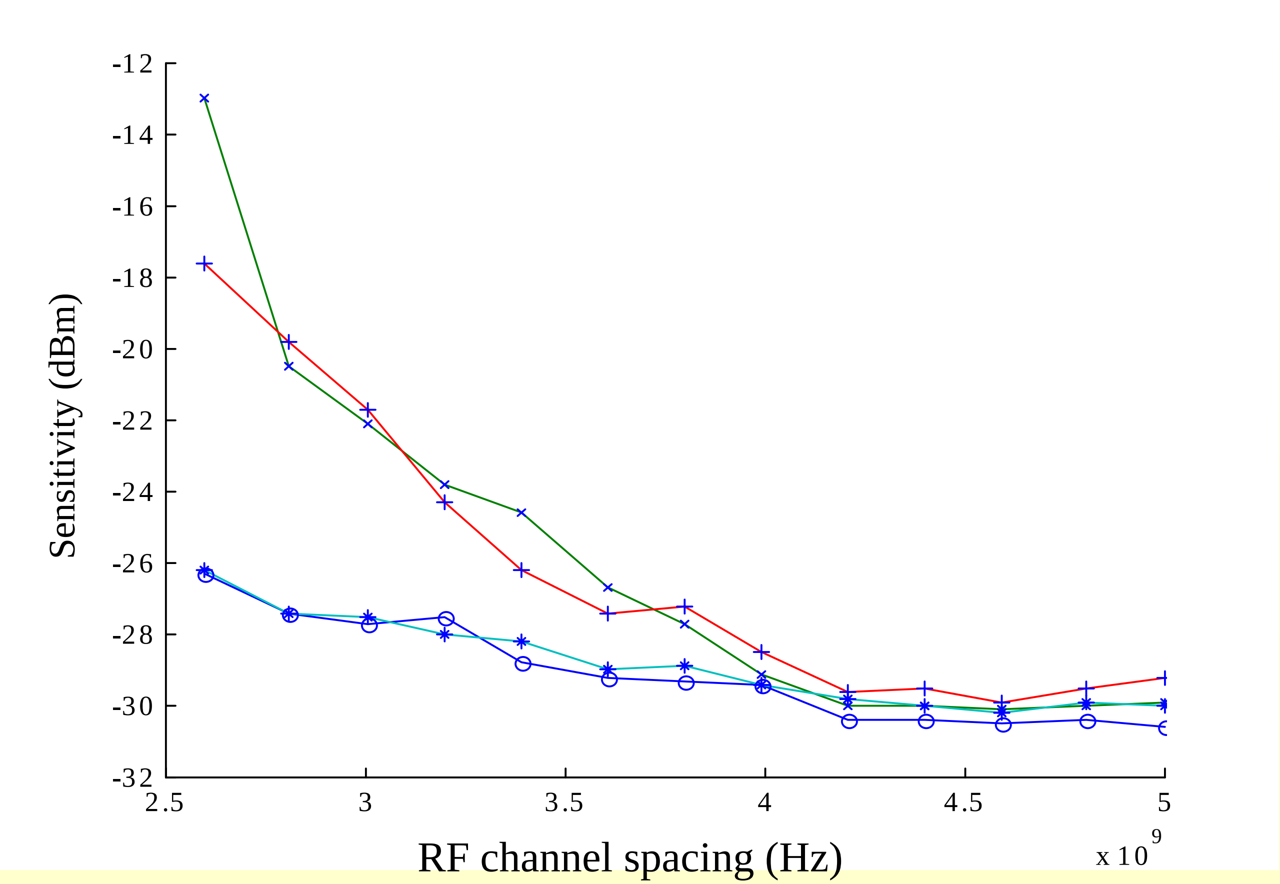
Optimal receiver bandwidth 0.7 ξ datarate



4-subcarrier BPSK, self-coherent detection

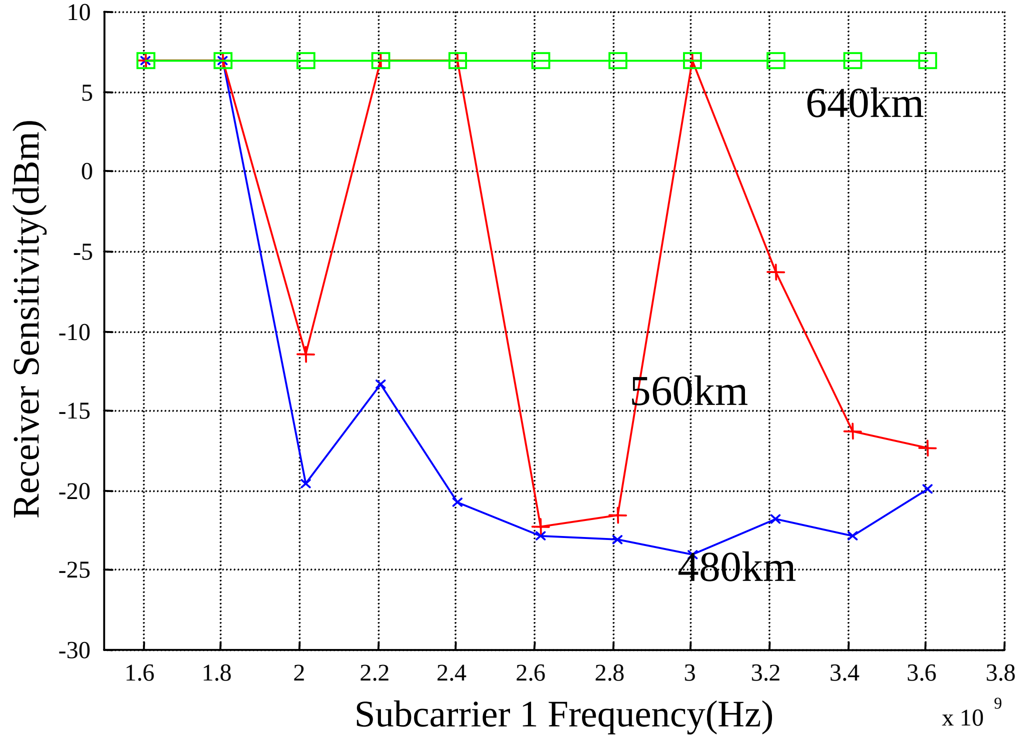
(2.5Gb/s per sub-carrier,10Gb/s total capacity)

RF channel spacing should be larger than 4.2 GHz



4-subcarrier BPSK, self-coherent detection
(2.5Gb/s per sub-carrier,10Gb/s total capacity)

Lowest frequency sub-carrier should be larger than 2.6 GHz



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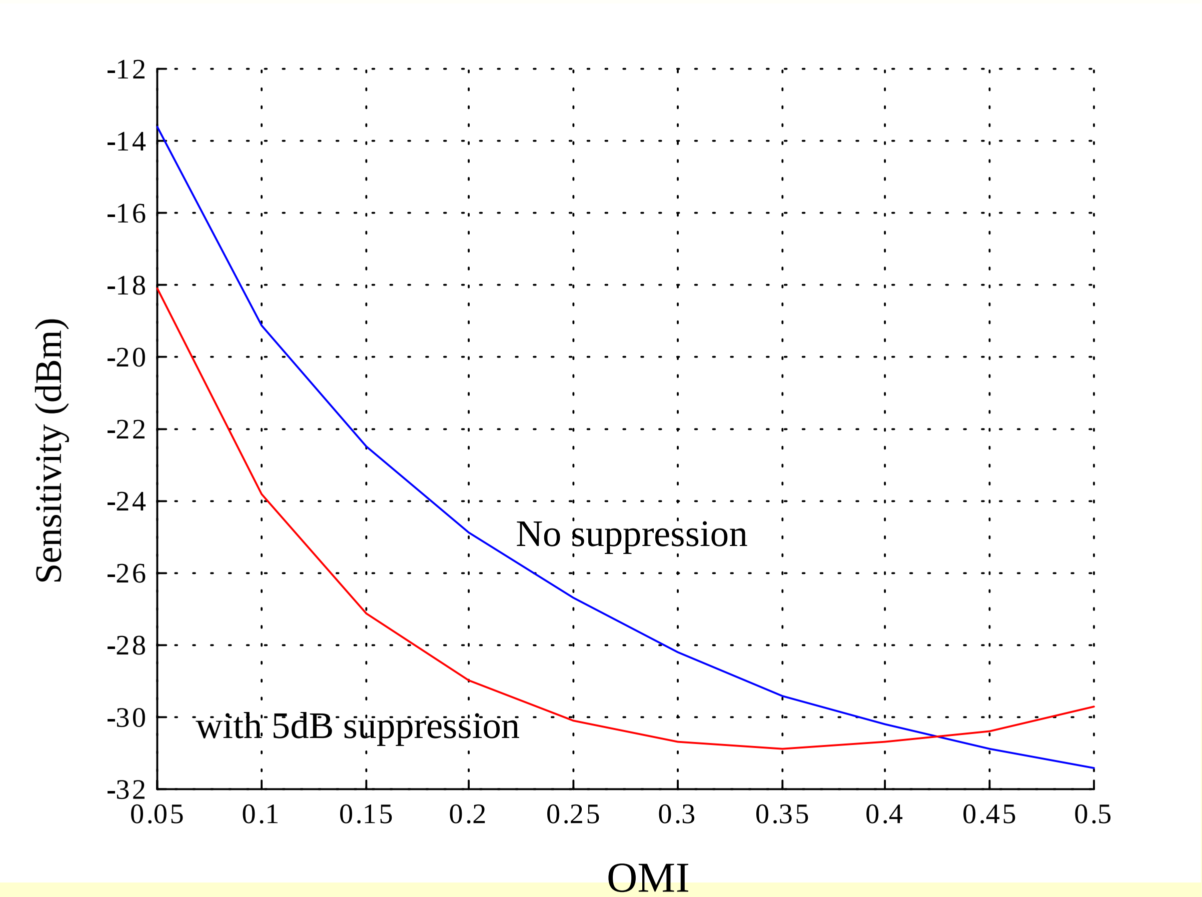
4-subcarrier BPSK, self-coherent detection
(2.5Gb/s per sub-carrier,10Gb/s total capacity)

Carrier suppression can improve the sensitivity on a roughly dB-per-dB base



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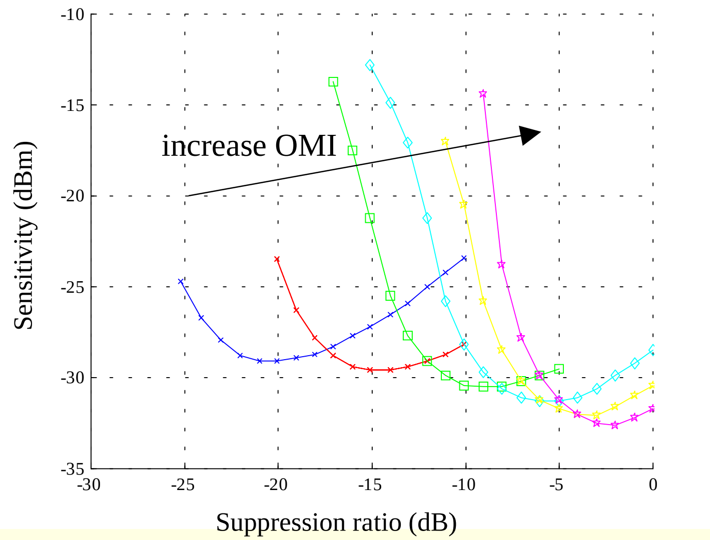
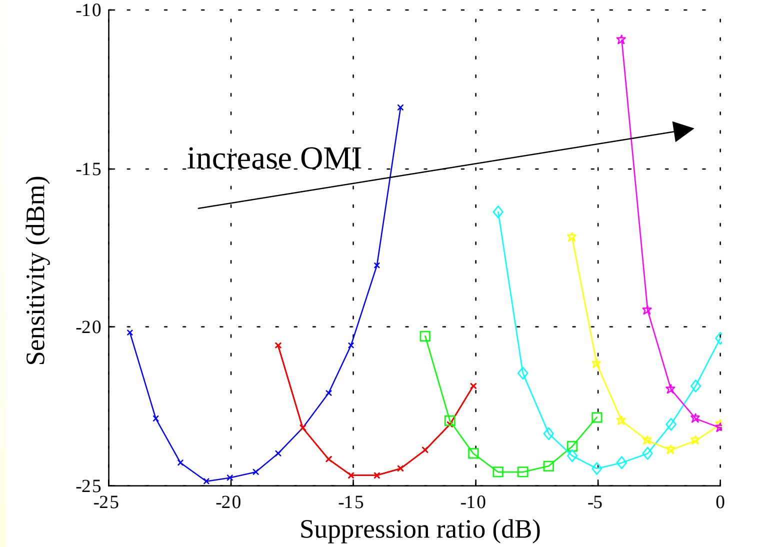
4-subcarrier BPSK, self-coherent detection

(2.5Gb/s per sub-carrier,10Gb/s total capacity)

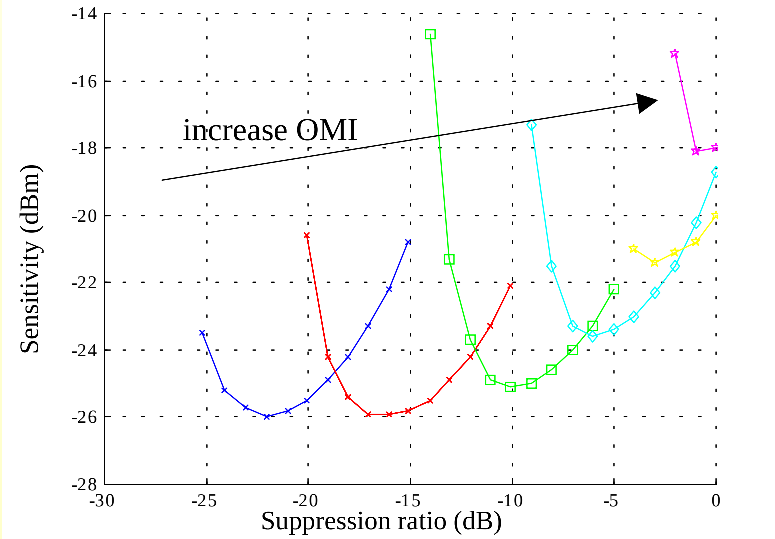
0 km



500 km



420 km



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4 BPSK subcarrier SCM system results

PMD $\frac{ps}{\sqrt{km}}$	DC	OMI	OP dBm	RFMI	Freq1	L: 1 wavelength	L: 4 wavelength
0.1ps	Yes	0.3	5	0.9 0.9 1.15 1.35	2.6	920	450
0.1ps	yes	0.4	5	0.9 0.9 1.15 1.35	2.6	680	300
0.1ps	yes	0.3	3	0.9 0.9 1.15 1.35	2.6	640	350
0.1ps	yes	0.4	3	0.9 0.9 1.15 1.35	2.6	520	400
0.1ps	yes	0.3	0	0.9 0.9 1.15 1.35	2.6		350
0.1ps	yes	0.4	0	0.9 0.9 1.15 1.35	2.6		250
0.1ps	yes	0.3	-3	0.9 0.9 1.15 1.35	2.6		250
0.1ps	yes	0.4	-3	0.9 0.9 1.15 1.35	2.6		200
0.1ps	no	0.3	5	1.12 1.05 1.05 0.9	2.6	600	200
0.1ps	no	0.4	5	1.12 1.05 1.05 0.9	2.6	600	200
0.1ps	no	0.3	3	1.12 1.05 1.05 0.9	2.6	560	250
0.1ps	no	0.4	3	1.12 1.05 1.05 0.9	2.6	400	250
0.1ps	no	0.3	0	1.12 1.05 1.05 0.9	2.6		350
0.1ps	no	0.4	0	1.12 1.05 1.05 0.9	2.6		350
0.1ps	no	0.3	-3	1.12 1.05 1.05 0.9	2.6		350
0.1ps	no	0.4	-3	1.12 1.05 1.05 0.9	2.6		250

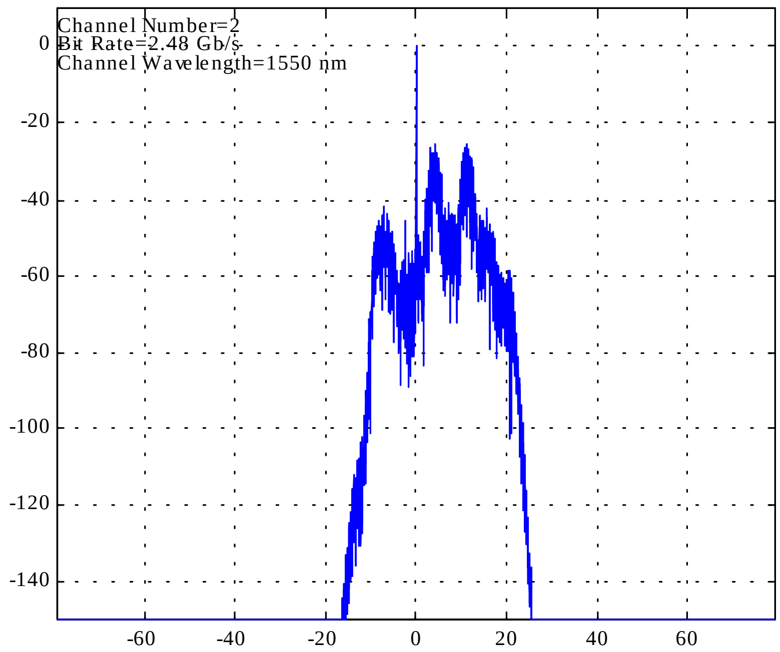
4 BPSK subcarrier SCM system results

PMD $\frac{ps}{\sqrt{km}}$	DC	OMI	OP dBm	RFMI	Freq1	L: 1 wavelength	L: 4 wavelength
0.5ps	yes	0.3	5	0.9 0.9 1.15 1.35	2.6	440	350
0.5ps	yes	0.4	5	0.9 0.9 1.15 1.35	2.6	360	350
0.5ps	yes	0.3	3	0.9 0.9 1.15 1.35	2.6	360	350
0.5ps	yes	0.4	3	0.9 0.9 1.15 1.35	2.6	280	350
0.5ps	yes	0.3	0	0.9 0.9 1.15 1.35	2.6		250
0.5ps	yes	0.4	0	0.9 0.9 1.15 1.35	2.6		250
0.5ps	yes	0.3	-3	0.9 0.9 1.15 1.35	2.6		250
0.5ps	yes	0.4	-3	0.9 0.9 1.15 1.35	2.6		150
0.5ps	no	0.3	5	1.12 1.05 1.05 0.9	2.6	500	200
0.5ps	no	0.4	5	1.12 1.05 1.05 0.9	2.6	440	200
0.5ps	No	0.3	3	1.12 1.05 1.05 0.9	2.6	440	250
0.5ps	No	0.4	3	1.12 1.05 1.05 0.9	2.6	360	250
0.5ps	No	0.3	0	1.12 1.05 1.05 0.9	2.6		300
0.5ps	No	0.4	0	1.12 1.05 1.05 0.9	2.6		250
0.5ps	No	0.3	-3	1.12 1.05 1.05 0.9	2.6		250
0.5ps	No	0.4	-3	1.12 1.05 1.05 0.9	2.6		200

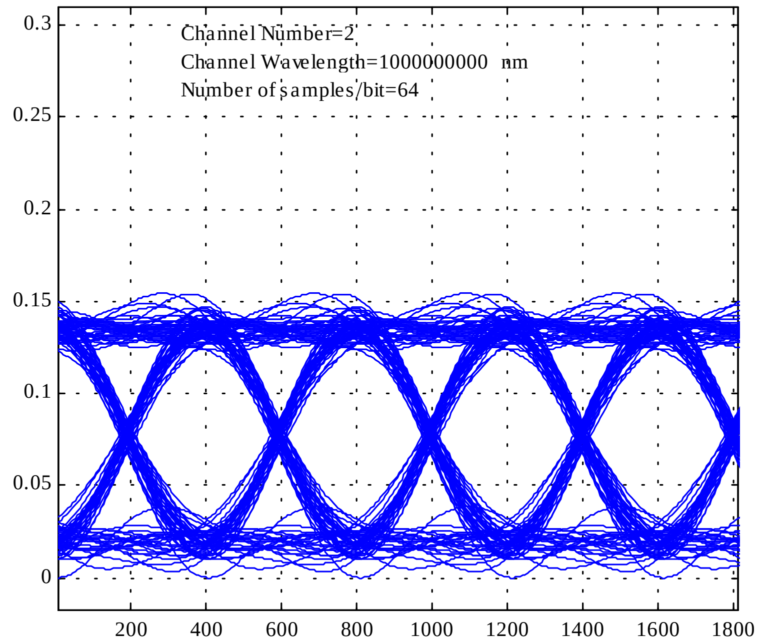
2-subcarrier QPSK, self-coherent detection

(5Gb/s per sub-carrier,10Gb/s total capacity)

Optical spectrum



Eye diagram



2-subcarrier QPSK, self-coherent detection
(5Gb/s per sub-carrier,10Gb/s total capacity)

PMD	DC	OMI	OP(dBm)	RFMI	Freq1	L	
0.1ps	Yes	0.3	5	1 1	4	1100	
0.1ps	Yes	0.4	5	1 1	4	950	
0.1ps	Yes	0.3	3	1 1	4	1200	
0.1ps	Yes	0.4	3	1 1	4	900	
0.1ps	Yes	0.3	0	1 1	4	750	
0.1ps	Yes	0.4	0	1 1	4	550	
0.1ps	Yes	0.3	-3	1 1	4	500	
0.1ps	Yes	0.4	-3	1 1	4	350	
0.1ps	No	0.3	5	1 1	4	400	
0.1ps	No	0.4	5	1 1	4	400	
0.1ps	No	0.3	3	1 1	4	450	
0.1ps	No	0.4	3	1 1	4	450	
0.1ps	No	0.3	0	1 1	4	250	
0.1ps	No	0.4	0	1 1	4	250	
0.1ps	No	0.3	-3	1 1	4	250	
0.1ps	No	0.4	-3	1 1	4	250	

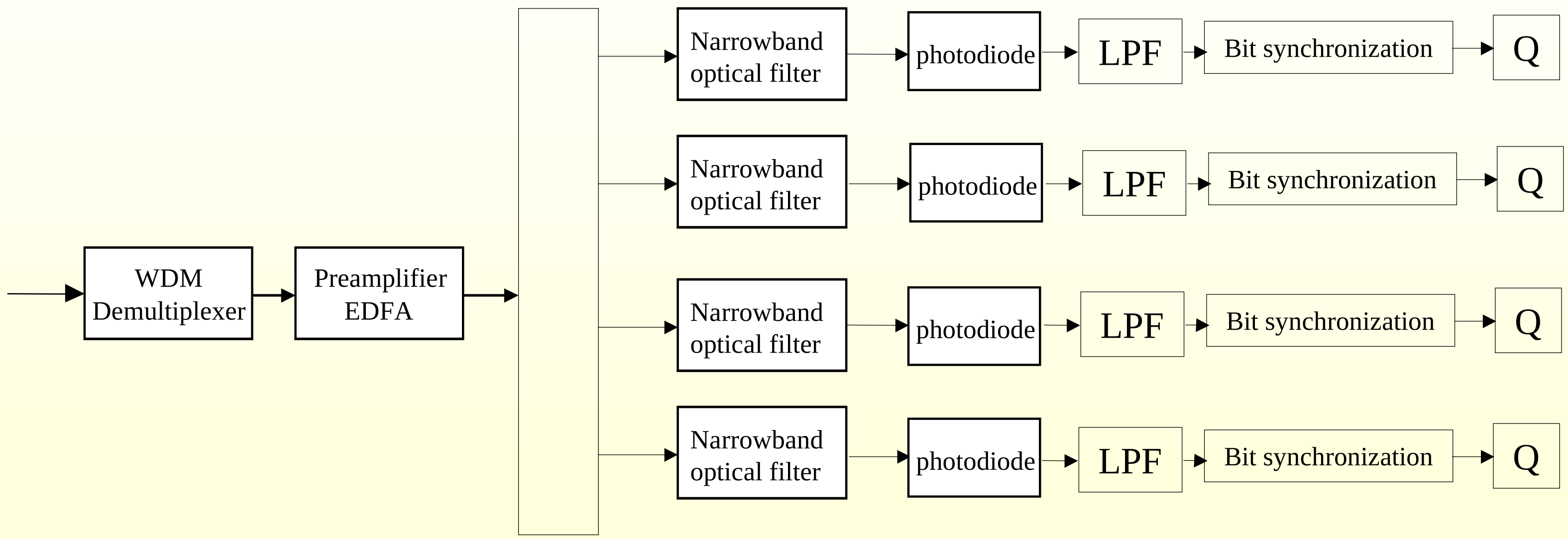
2-subcarrier QPSK, self-coherent detection

(5Gb/s per sub-carrier,10Gb/s total capacity)

PMD	DC	OMI	OP(dBm)	RFMI	Freq1	L	
0.5ps	Yes	0.3	5	1 1	4	750	
0.5ps	Yes	0.4	5	1 1	4	650	
0.5ps	yes	0.3	3	1 1	4	700	
0.5ps	yes	0.4	3	1 1	4	500	
0.5ps	yes	0.3	0	1 1	4	500	
0.5ps	yes	0.4	0	1 1	4	350	
0.5ps	yes	0.3	-3	1 1	4	350	
0.5ps	yes	0.4	-3	1 1	4	250	
0.5ps	no	0.3	5	1 1	4	400	
0.5ps	no	0.4	5	1 1	4	400	
0.5ps	no	0.3	3	1 1	4	450	
0.5ps	no	0.4	3	1 1	4	450	
0.5ps	no	0.3	0	1 1	4	250	
0.5ps	no	0.4	0	1 1	4	250	
0.5ps	no	0.3	-3	1 1	4	250	
0.5ps	no	0.4	-3	1 1	4	250	

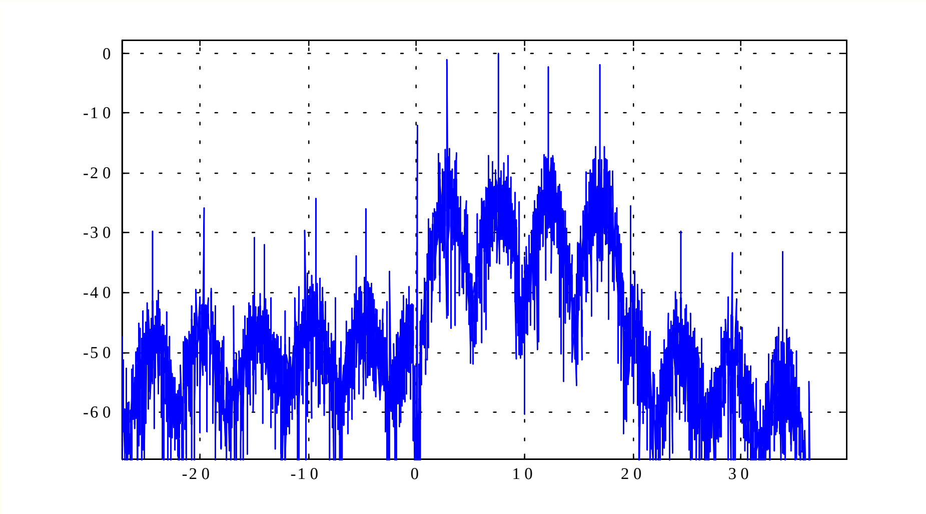
SCM system, direct-detection

Using narrow-band optical filters

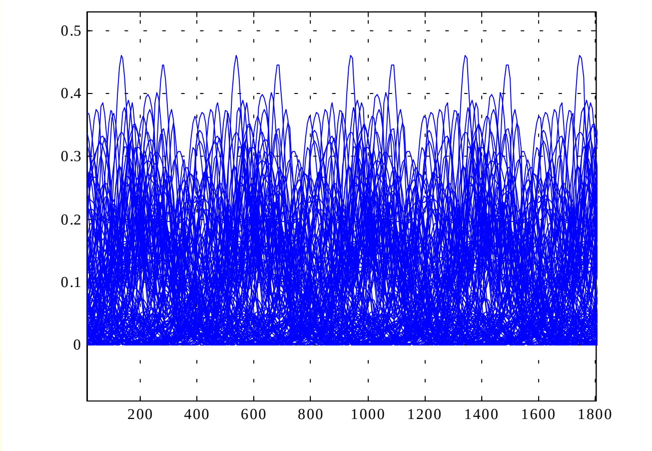


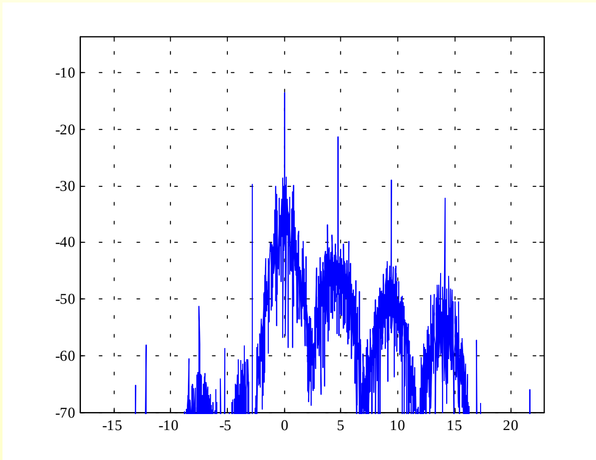
SCM system, direct-detection

Using narrow-band optical filters

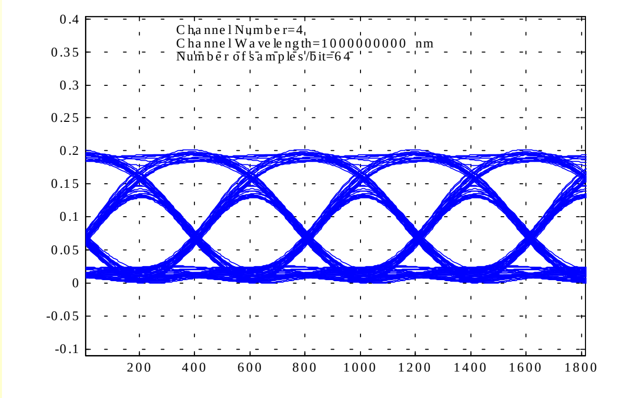


Before baseband filter



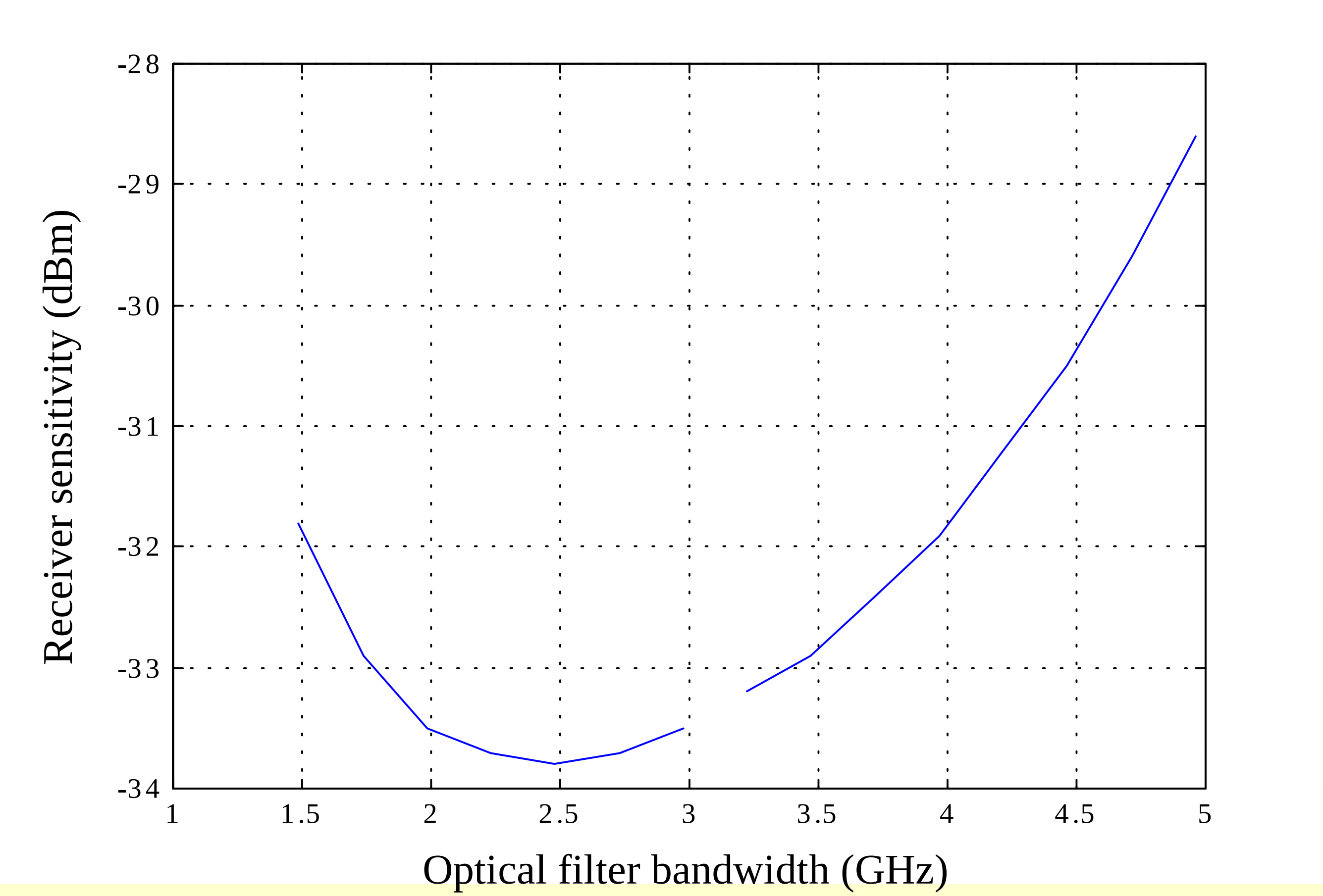


after baseband filter



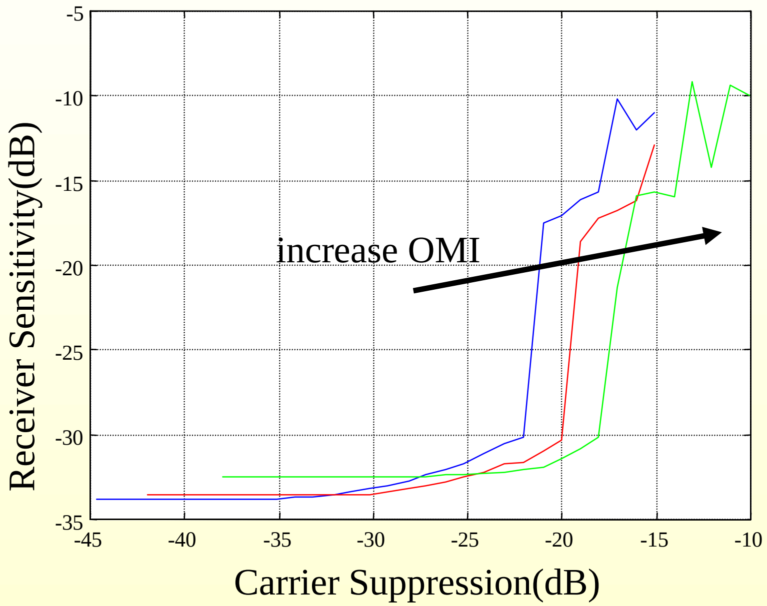
After narrowband
optical filter

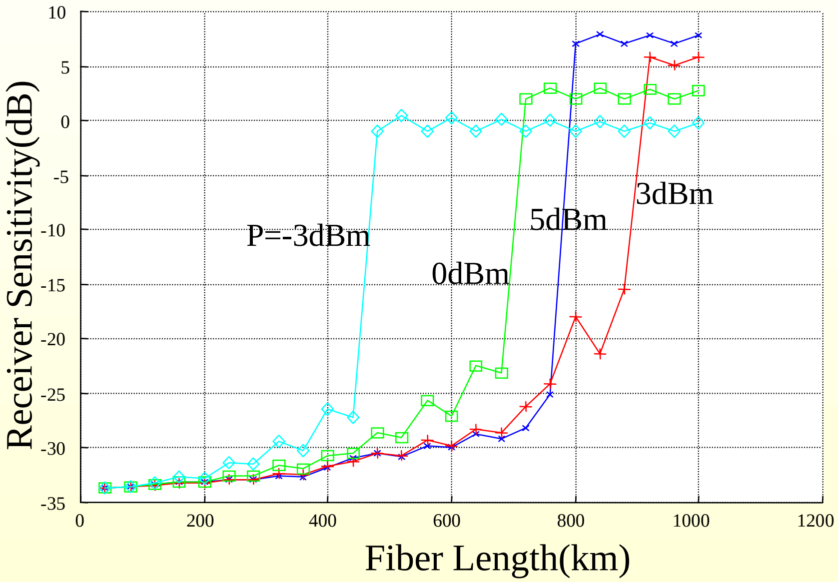
Impact of optical filter bandwidth



SCM system, direct-detection

Using narrow-band optical filters





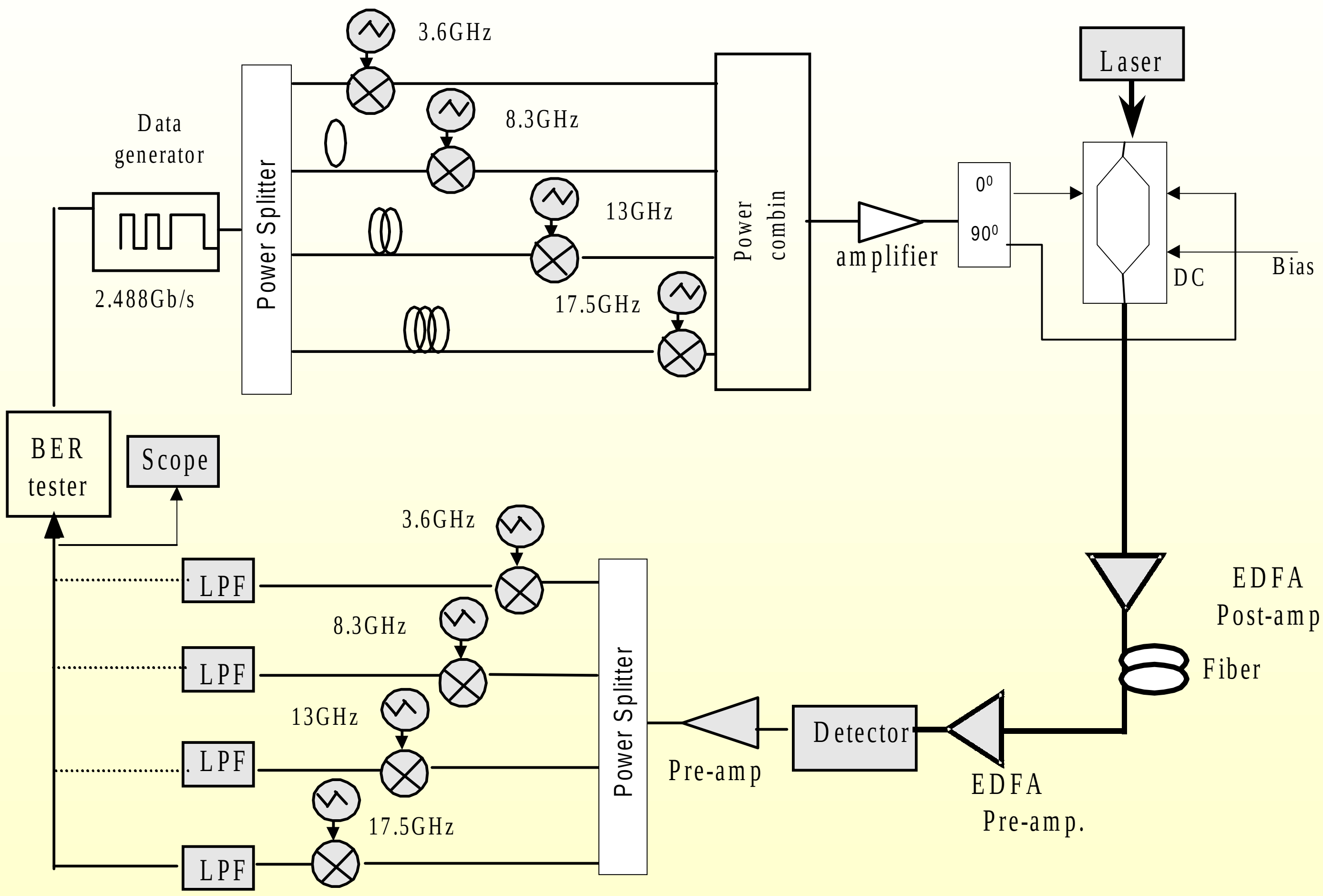
Maximum transmission distance
direct-detected SCM system

DC	OMI	OP	RFMI	L
Yes	0.3	3	1 1 1 1	50
Yes	0.3	0	1 1 1 1	200
Yes	0.3	-3	1 1 1 1	250
Yes	0.3	-6	1 1 1 1	250
No	0.3	3	1 1 1 1	250
No	0.3	0	1 1 1 1	550
no	0.3	-3	1 1 1 1	500
No	0.3	-6	1 1 1 1	350

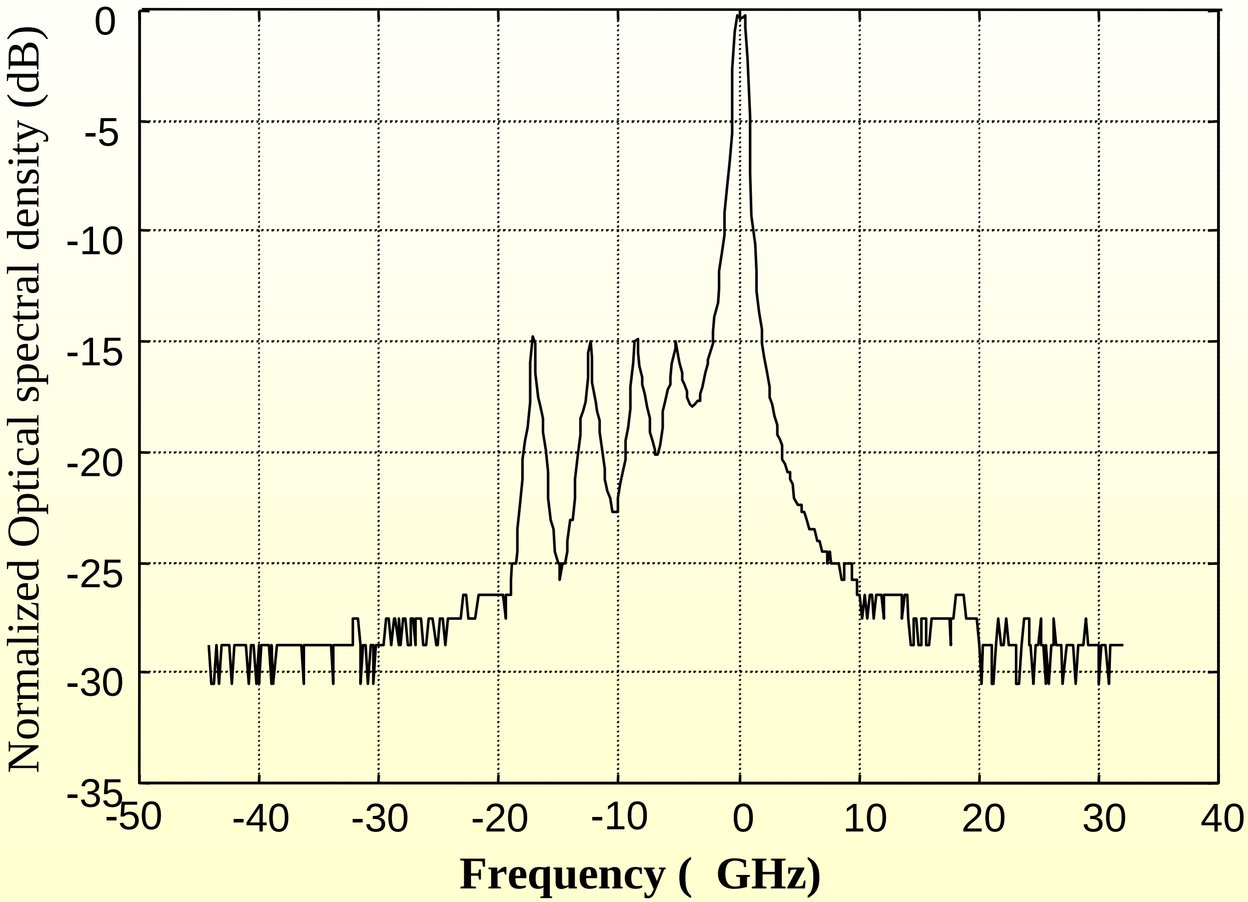
OC192 TDM system using NRZ modulation

DC	OMI	OP (dBm)	Length (km)
Yes	0.5	3	950
Yes	0.5	0	1100
Yes	0.5	-3	800
Yes	0.5	-6	500
No	0.5	3	100
No	0.5	0	100
No	0.5	-3	100
No	0.5	-6	100

Experiments for one wavelength four subcarriers BPSK SCM system

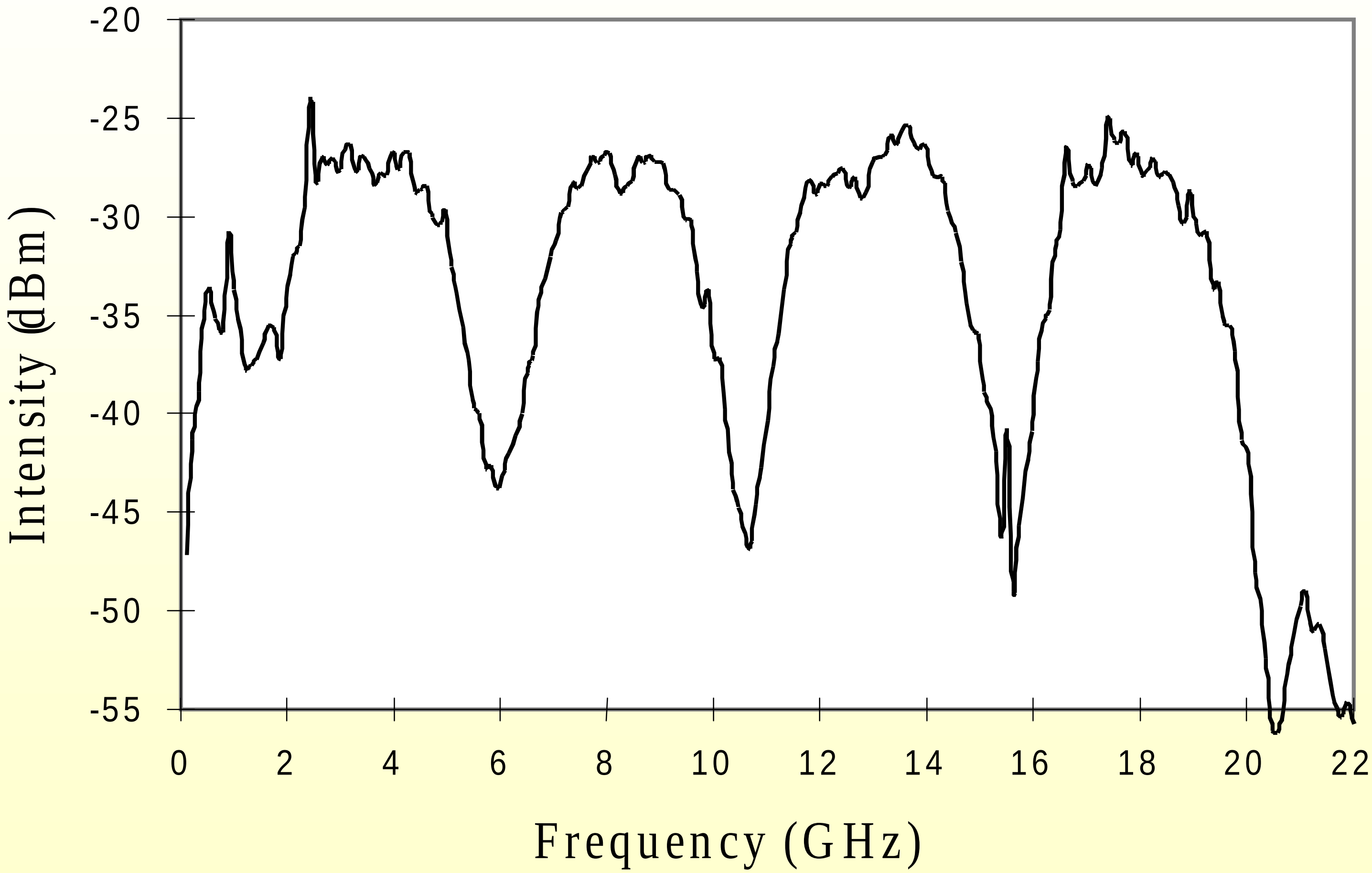


OSSB



Normalized Optical spectral density (dB)
0
-5
-10
-15
-20
-25
-30
-35
-50
-40
-30
-20
-10
0
10
20
30
40
Frequency (GHz)

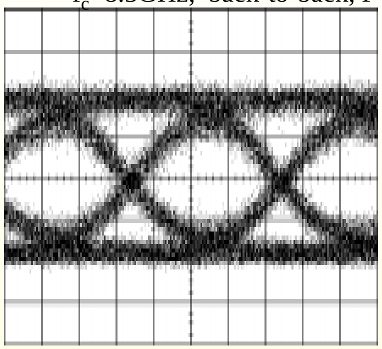
Detected composite signal RF spectrum



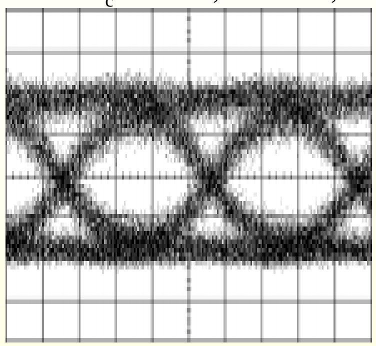
Measured eye diagrams

back-to-back and over 75km SMF

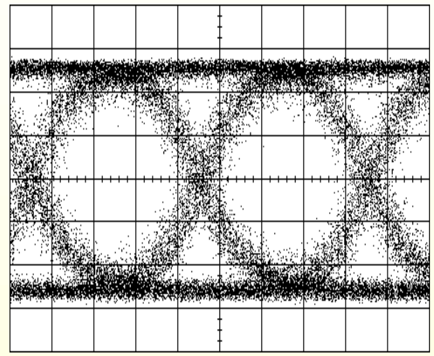
f_c=8.3GHz, back-to-back, P=-23.5 dBm



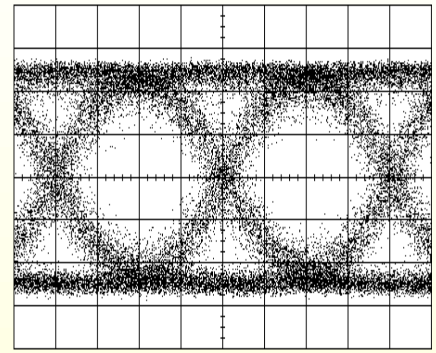
f_c=8.3GHz, over fiber, P =-23 dBm



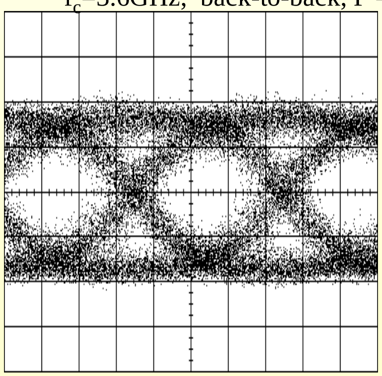
f_c=13GHz, back-to-back, P =-27.6 dBm



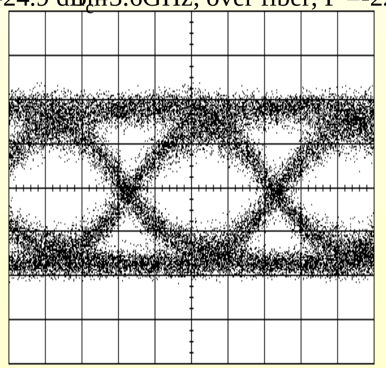
f_c=13GHz, over fiber, P =-24 dBm



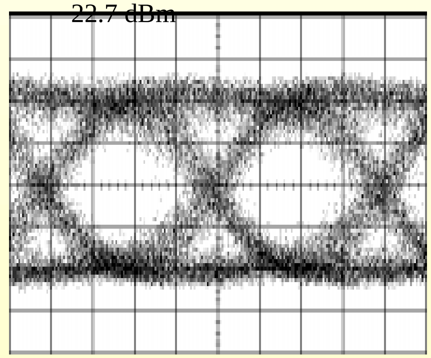
f_c=3.6GHz, back-to-back, P =-24.9 dBm



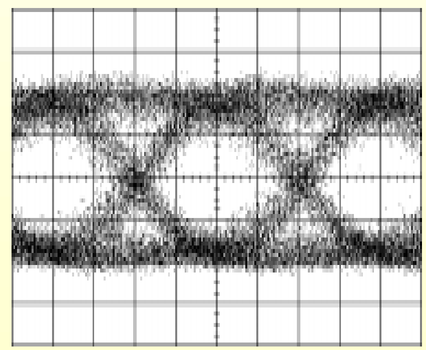
f_c=3.6GHz, over fiber, P =-22.6 dBm



f_c=17.5GHz, back-to-back, P =-22.7 dBm

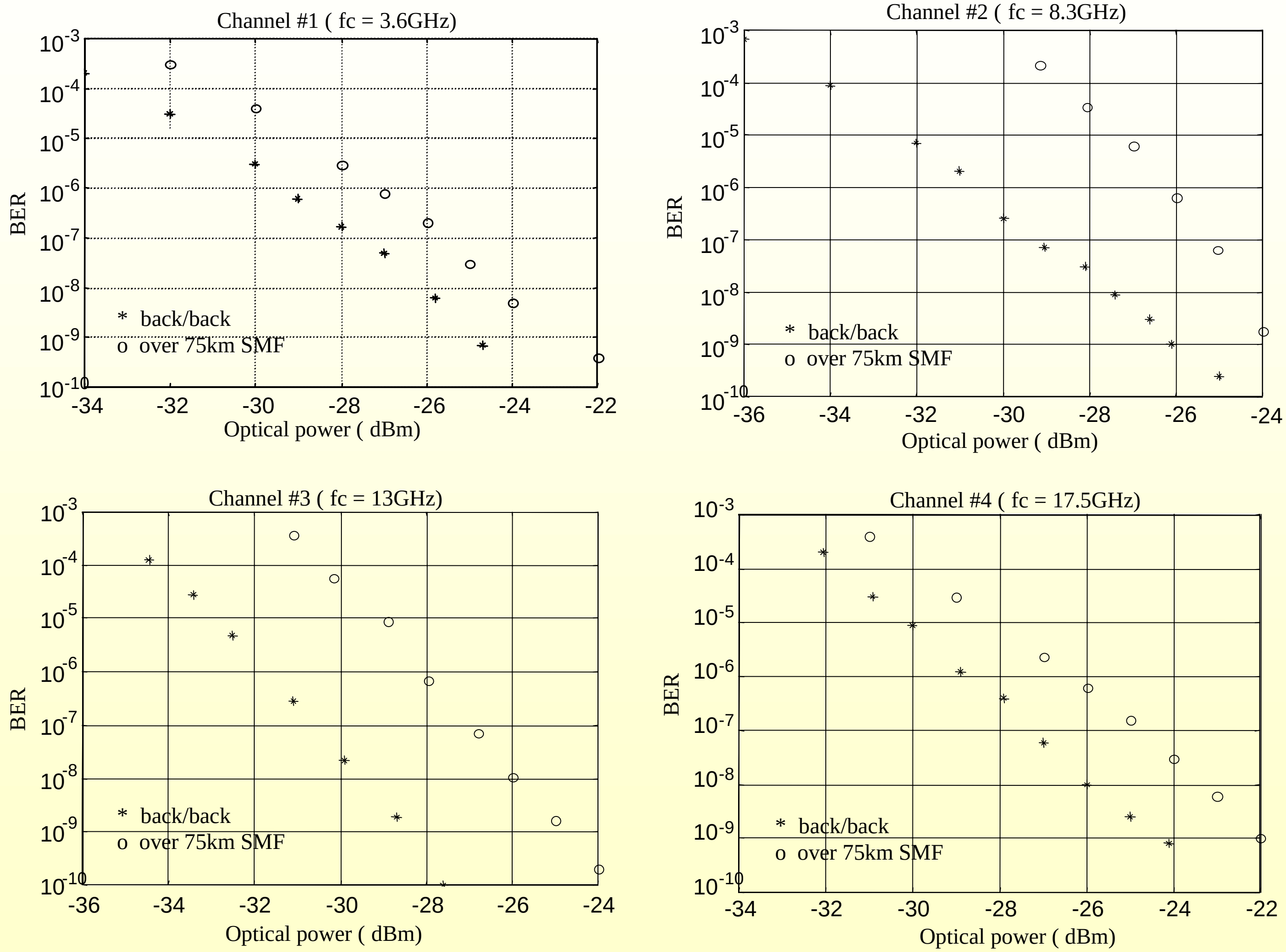


f_c=17.5GHz, over fiber, P =-21.5 dBm



Measured BER

back-to-back (stars) and over 75km SMF (circles)



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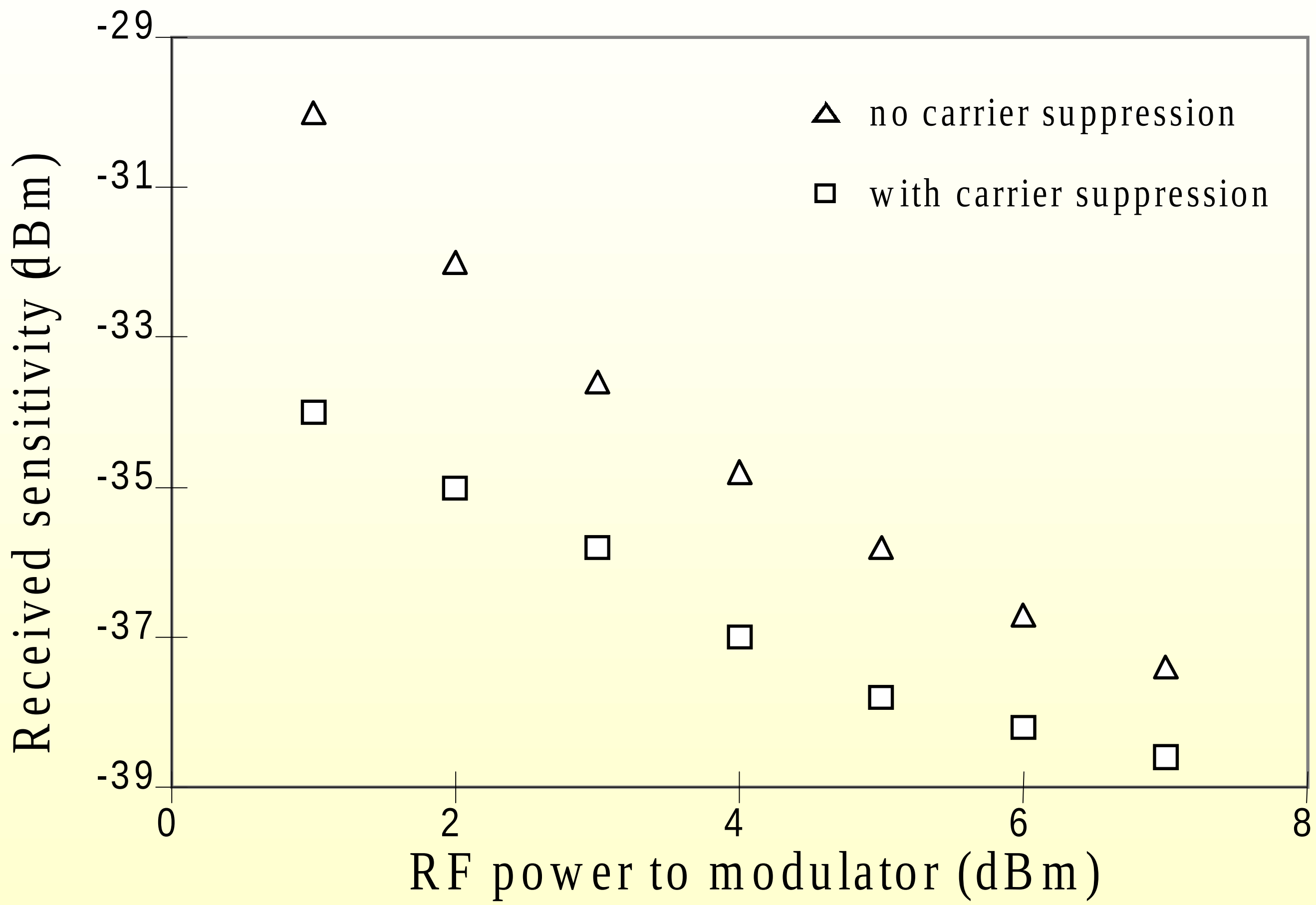
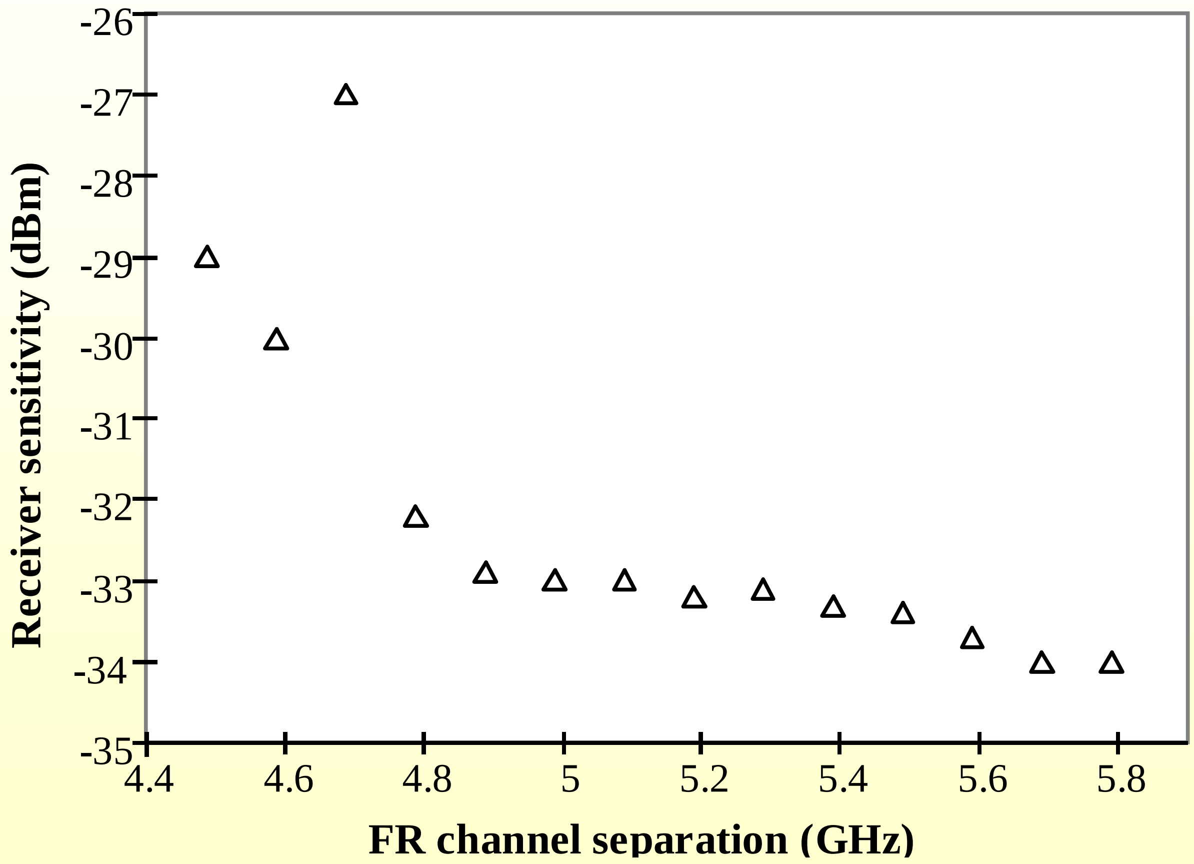
Effects of carrier suppresion



Effect of channel spacing



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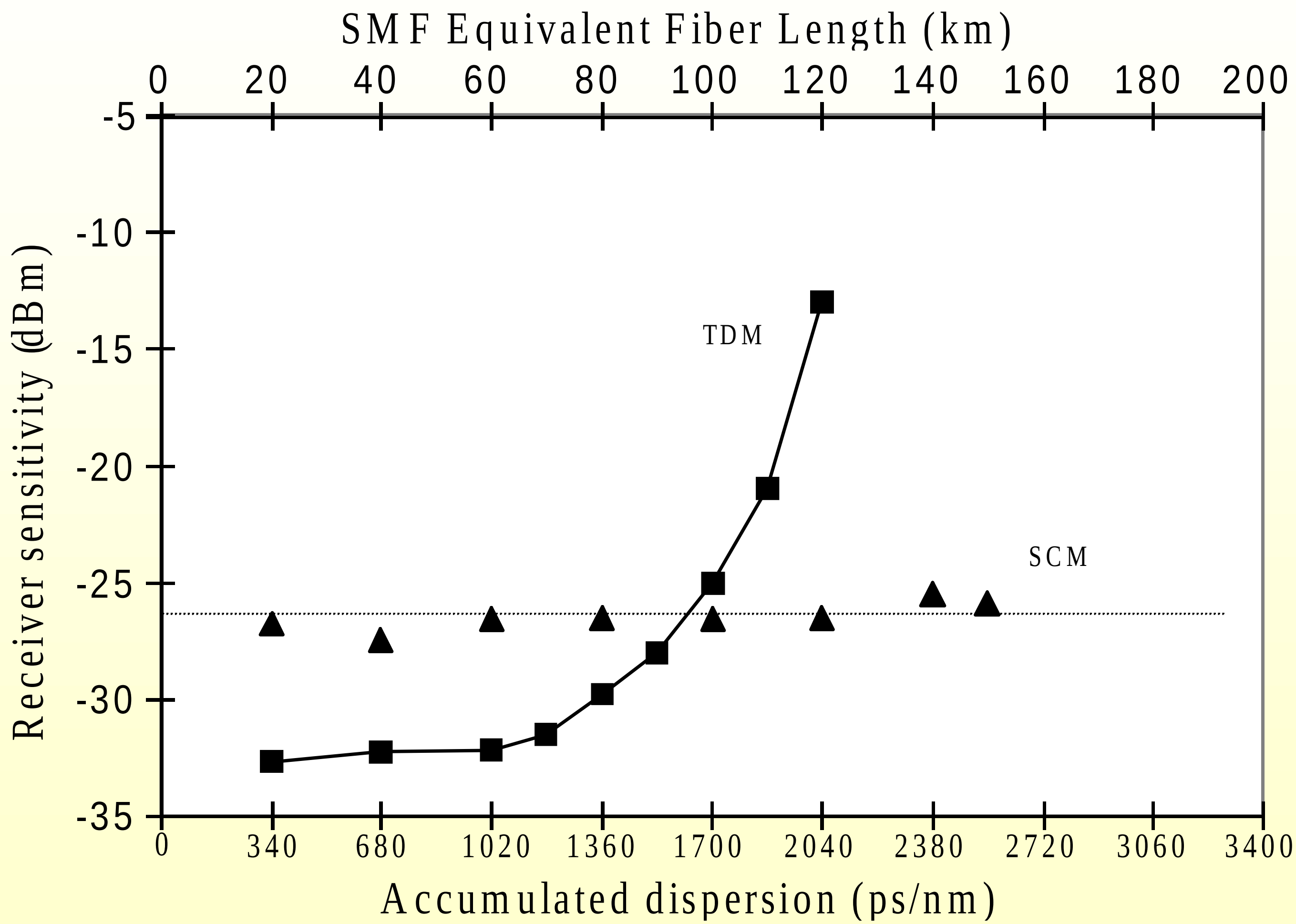
Comparison between SCM and TDM



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Conclusion remarks

- Built a simulator for SCM/WDM systems
- Simulated multi-wavelength SCM systems: 4-subcarrier BPSK, 2-subcarrier QPSK and 4-subcarrier ASK
- Optimized system parameters
- BPSK format is recommended for 300km to 350 km transmission without dispersion compensation.
- QPSK format is recommended for up to 750 km transmission with dispersion compensation and 450km without dispersion compensation.
- ASK system is not recommended because of the stringent requirement of optical filters.
- Experimentally measured the performance of single-wavelength 4-subcarrier BPSK system

Furture work

- Multi-wavelength SCM test bed
- Experimental investigation of QPSK and M-ary
- Impact of Raman amplification on SCM systems
- Single-sideband RF modulation
- Detailed PMD analysis

Questions ?

Thank You