IEEE Photonics Society Distinguished Lecturer

Developing flexible, reconfigurable, and spectrally efficient systems for optical networks

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CONNECT Networks of the Future
IEEE Photonics Society Transforming Science into Technology™
IPIC BRINGING PHOTONICS TO LIFE

Radio and Optical Communications Group in DCU

Ability to accurately characterize novel high speed devices, and sub-systems including:

- Initial simulation/modeling of the optical and optoelectronic devices
- Complete systems simulations to demonstrate device performance
- Detailed characterization of optical and optoelectronic devices
- Performance testing of novel devices & sub-systems in coherent & direct detection testbed (56Gbaud PAM4, 33Gbaud 64QAM, 100G OFDM, etc.)

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Examples of Current Projects

- ***Applications of tunable laser diode in optical networks***
- ***Generation, characterisation & optimisation of optical frequency combs***
- *Development of all-optical processing technologies for Tb/s systems*
- *Design of hybrid radio/fibre systems for broadband access and 5G networks*
- *Development of advanced optical signal characterization techniques*
- *Design, realization & characterization of new lasers for THz emission*
- *Characterizations of novel single mode lasers for access networks*
- *Implementation of novel modulation formats for optical systems*

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MOTIVATION

The Internet: enabled by photonics

Underpins ICT industry worldwide

- Employs ~7 million in EU
- Turnover €800Billion

The Internet is under strain

- 10x traffic every 5 years
- Energy consumption too high
- Need new technology solutions

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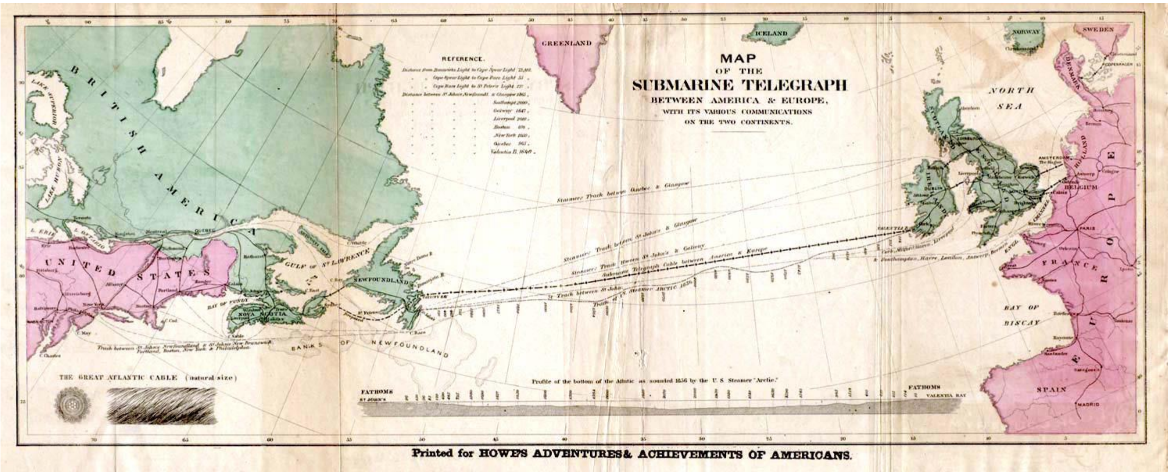
Communications Before Photonics ?



First transatlantic telegraph cable (August 16, 1858) reduced communication time between North America and Europe from ten days to several hours …

"***the world read closing quotations from Wall Street, learned the prices on the Brussels grain market and the fact that Congress had readmitted Tennessee into the Union …on same day***"

1927 - Transatlantic telephone service became radio-based

1956 – First transatlantic telephone cable, carrying 36 telephone calls

TWO KEY OPTICAL/PHOTONIC INVENTIONS

1988 – First transatlantic fibre optic cable, carrying 40,000 telephone calls or 280 Megabit/s

2018 – MAREA Fibre Optic Cable (Microsoft/Facebook), 160 Terabits/s

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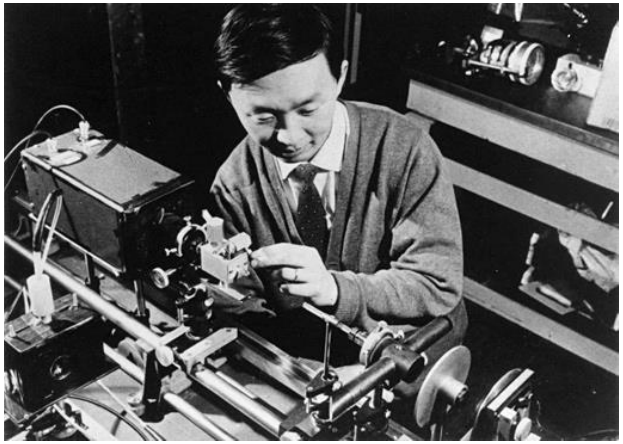
Key Inventions

LASER

Charles Townes **Theodore Maiman**

OPTICAL FIBRE

Charles Kao



The Nobel Prize in Physics 2009

"for groundbreaking achievements concerning the transmission of light in fibers for optical communication, which have revolutionized the way we work, study, interact, and live our daily lives “ --- CHARLES K. KAO

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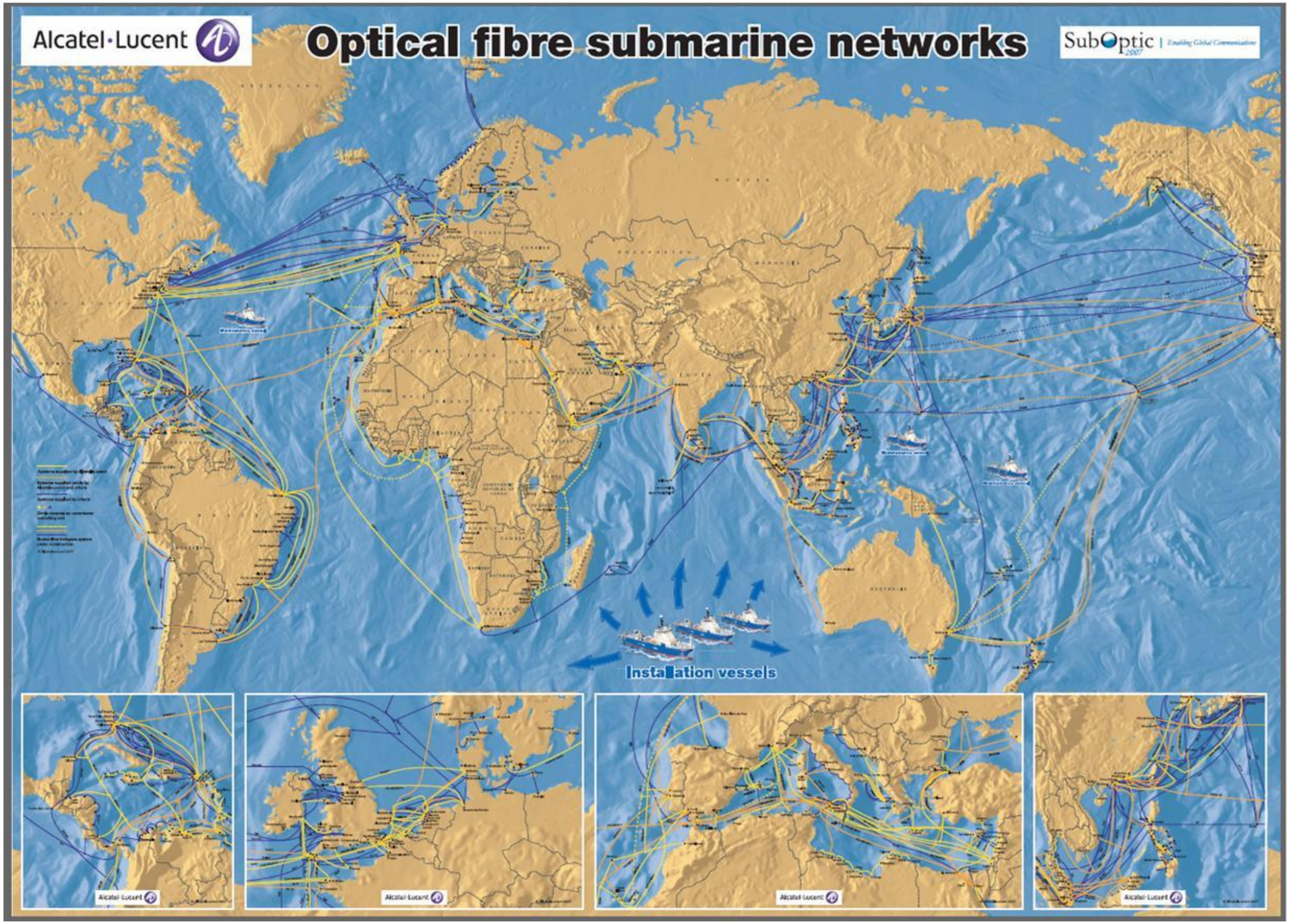
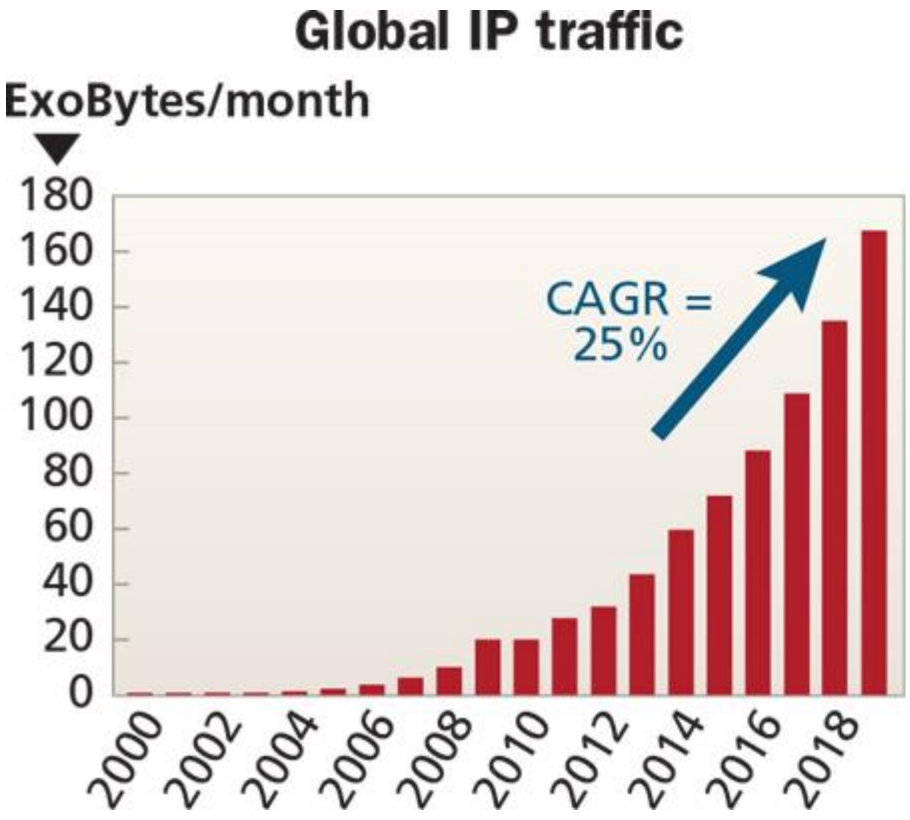
Optical Fibres: Backbone of the Internet

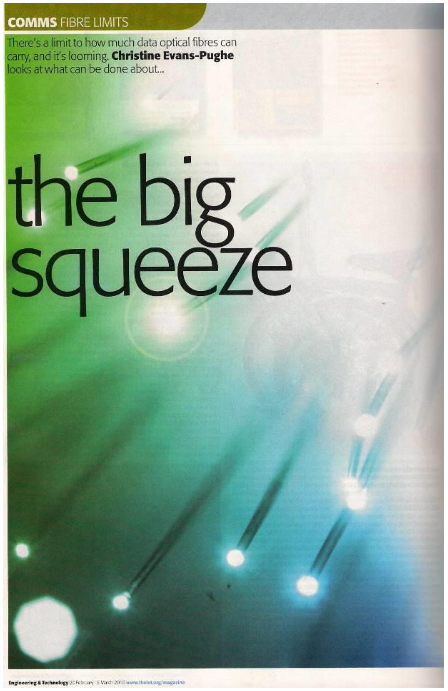


Continual Traffic Growth

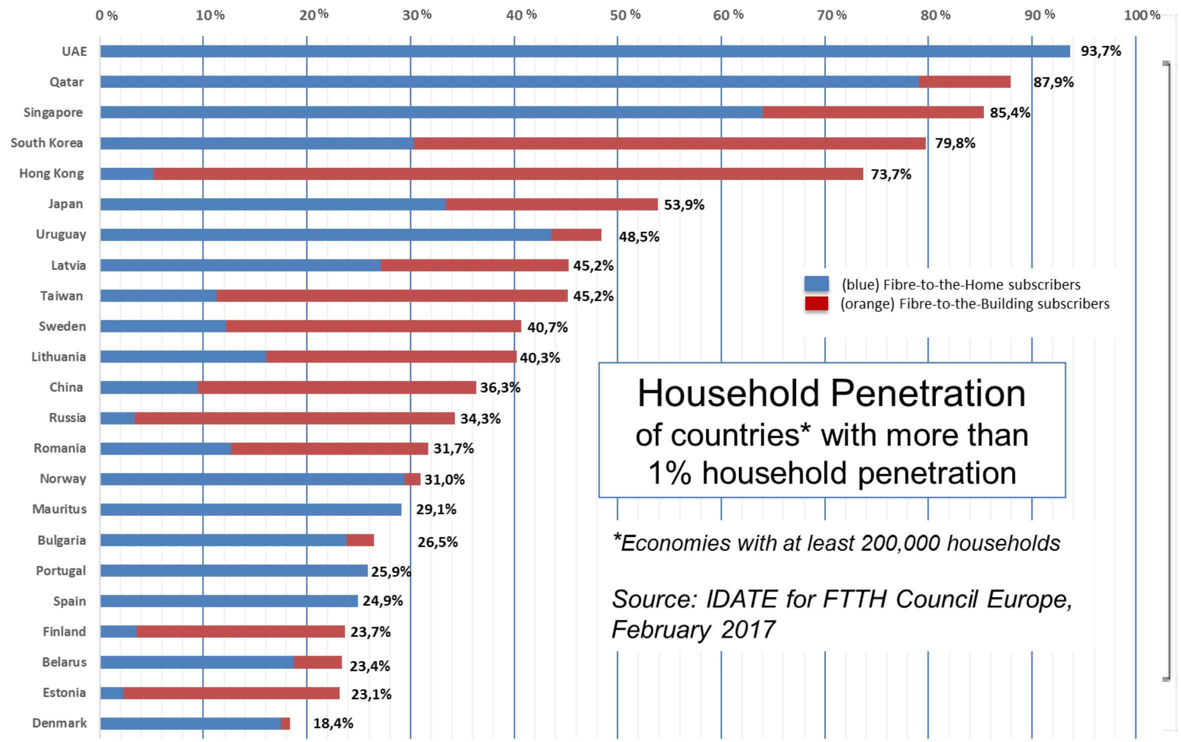


https://visual.ly/community/infographic/how/internet-real-time

Is Communication/Bandwidth important ?



Growth in available download speeds



IRELAND (2017)

~ 13000 FTTP connections
~ 1.5 Million Fixed Broadband connections
~ 1% !!

FRANCE: 15%

- ***Growth in access rates driving requirement for higher speed core optical networks***
- ***Core networks are based on Wavelength Division Multiplexing technology***
  - ***Only scalable broadband access solution is Fibre To The Home***

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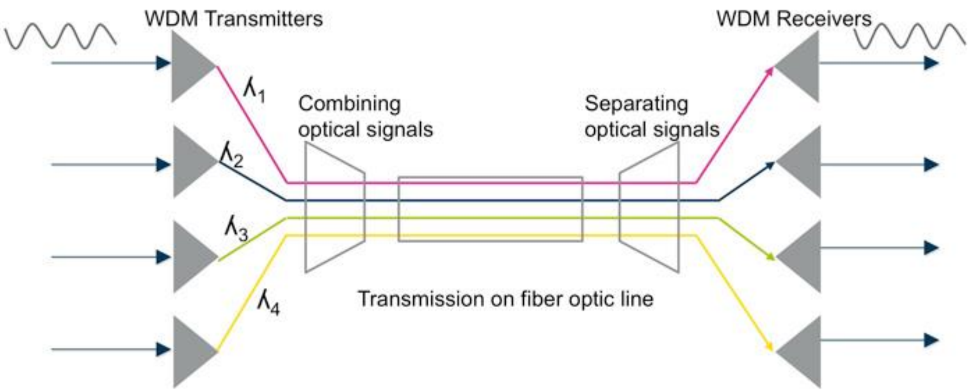
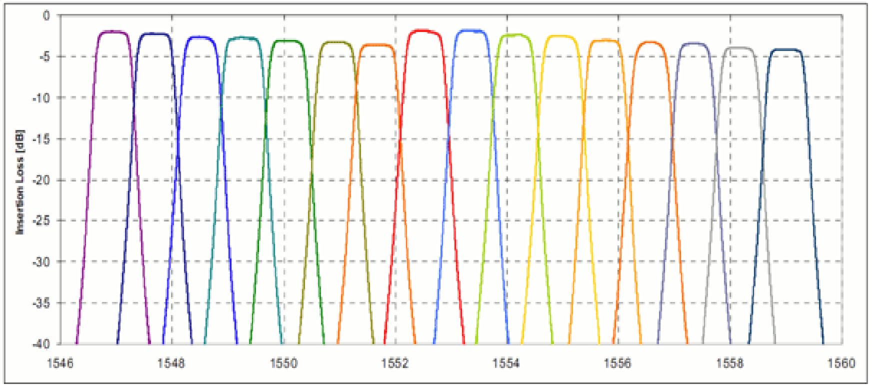
Wavelength Division Multiplexing (WDM)





- ***Sending multiple wavelength channels (colours) down single fibre***
- ***Initially using basic ON/OFF signalling ("1" Light on, "0" Light Off)***
- ***Current Systems use both phase and amplitude modulation***

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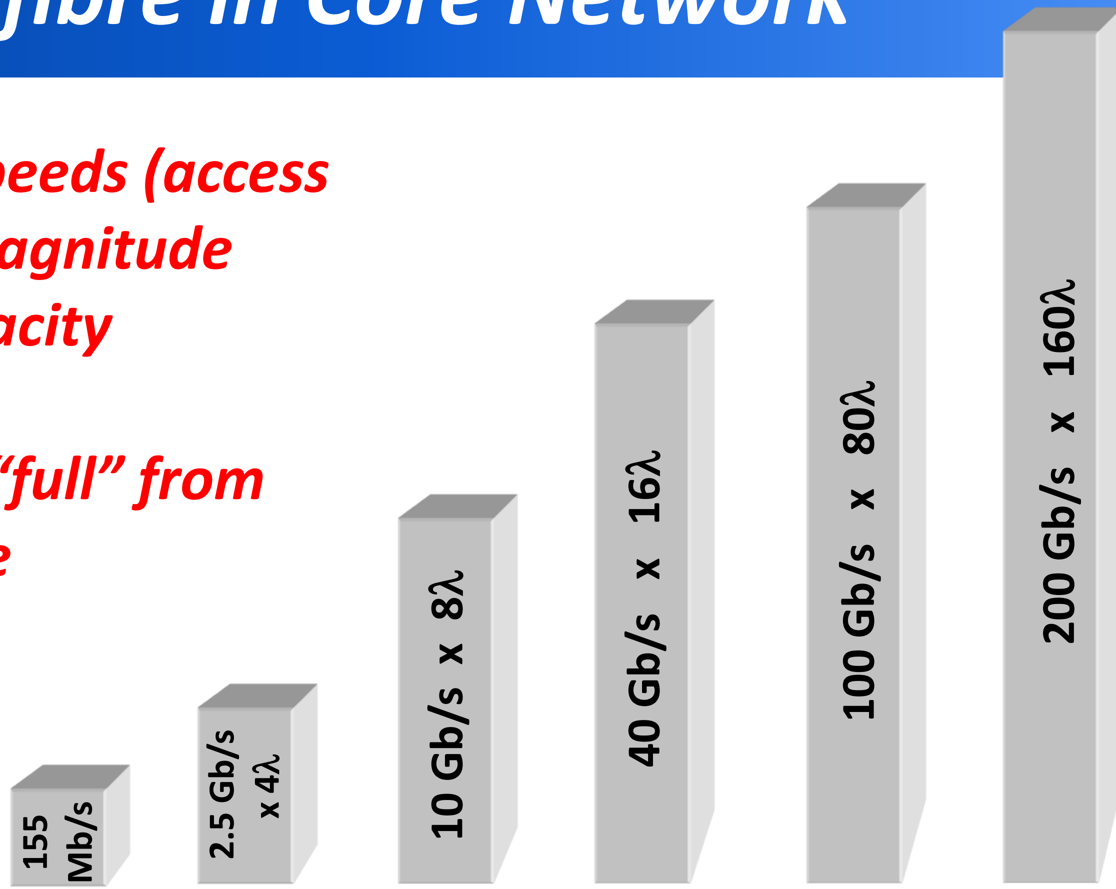
Evolution of WDM systems: Data Rate per fibre in Core Network

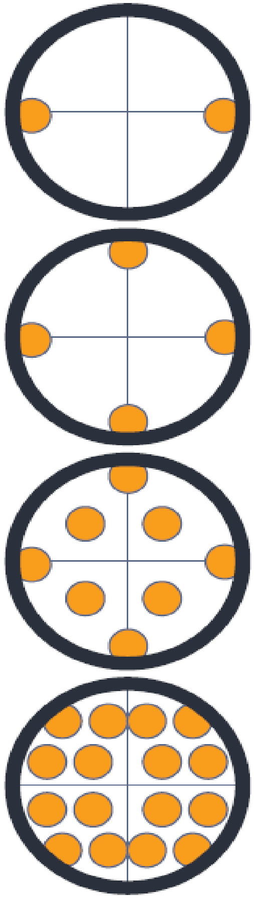
Average download speeds (access links) are orders of magnitude slower than core capacity

Fibres are becoming "full" from a spectral perspective



	~1980s	~1990	~2000	~2007	~2012	~2020
Spectral Efficiency (bits/sec/Hz)	~0.0001	~0.001	~0.01	~0.1	~1	~4
Time to send one film	~2 mins	~1 sec	~0.1 sec	~10 ms	~1 ms	~0.2 ms

Advanced modulation formats for spectral efficient WDM links



	+ Coherent Detection	Dual Polarisation at 25 Gbaud
BPSK	1 bit per symbol	- 50 Gbit/s
QPSK	2 bits per symbol	- 100 Gbit/s
8QAM	3 bits per symbol	- 150 Gbit/s
16QAM	4 bit per symbol	- 200 Gbit/s

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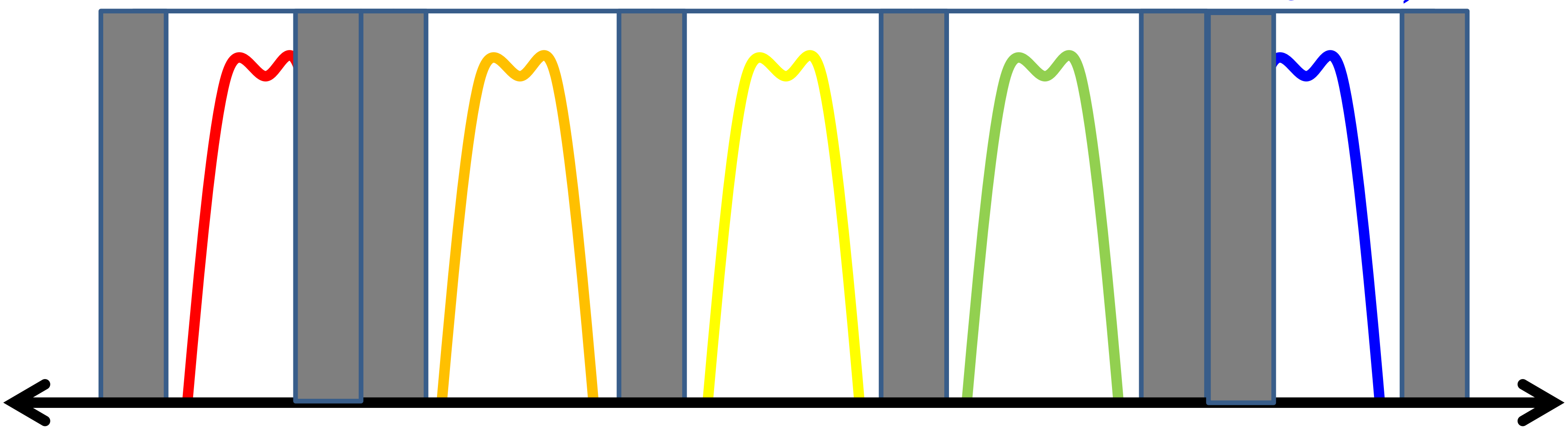
Evolution of static WDM systems - towards superchannels

Remove guard bands
50 GHz spacing

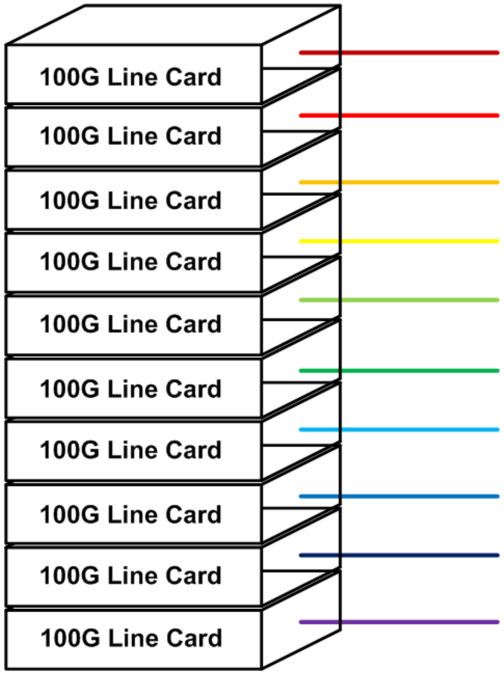
100 Gb/s (200 Gb/s With DP-16 QAM)



Available Frequency

Separate Channels
Superchannels

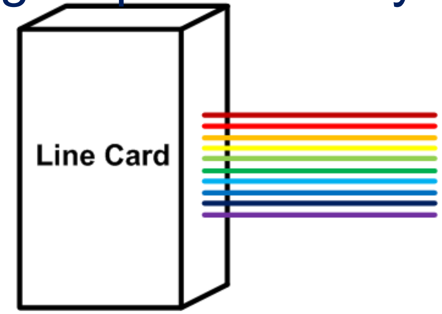
What is a super-channel?



- Bulky
- Power hungry
- Does not scale operationally

All carriers are provisioned in a single operational cycle…

Practical to build



A super-channel implements multiple carriers - ideally in a single line card…

Superchannel is seen as a single unit of capacity by the services that use it !!!

Difference between superchannel and conventional WDM is channel separation

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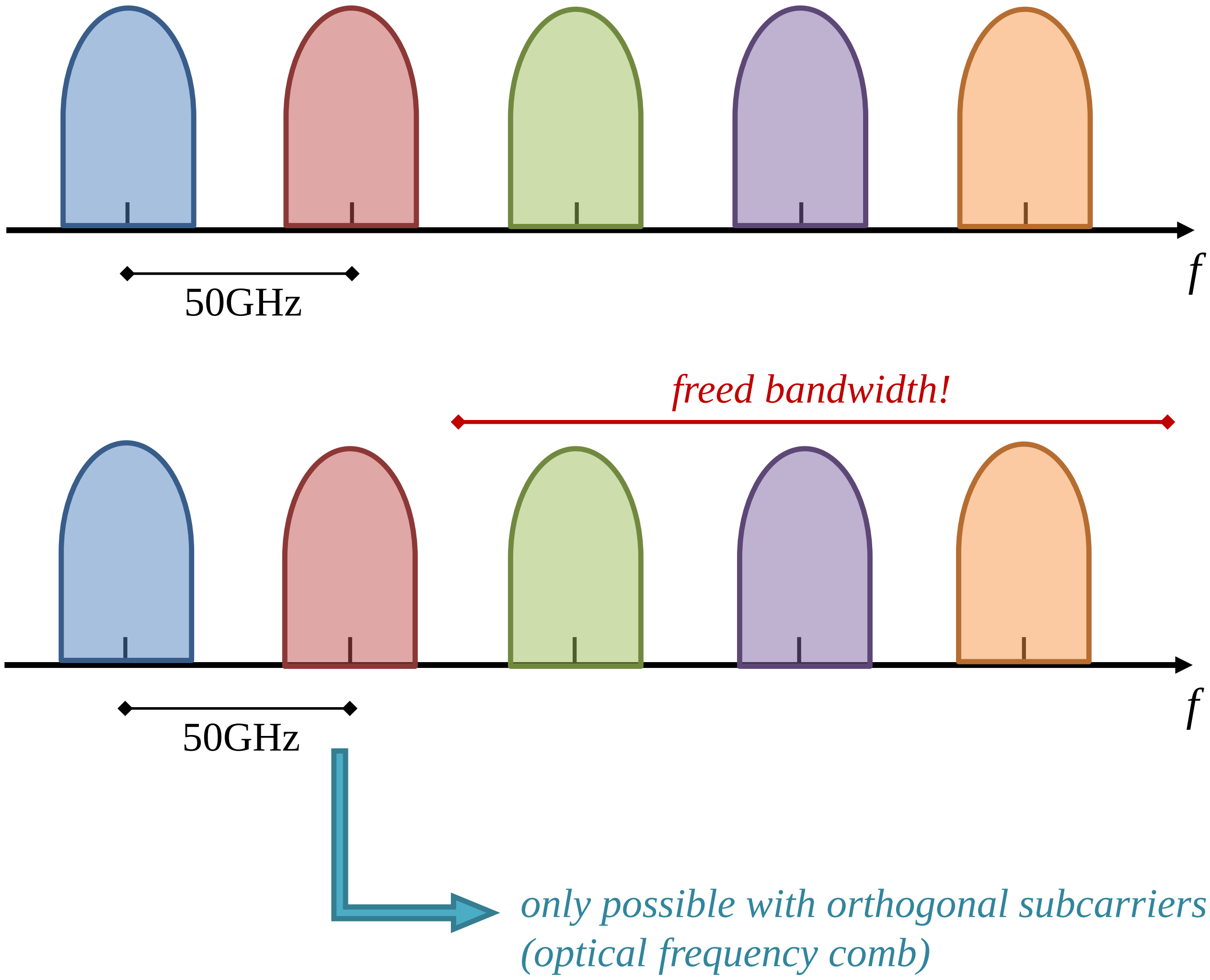
The *superchannel* approach
Coherent WDM / All-Optical OFDM / Nyquist



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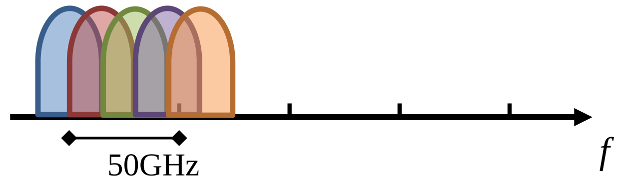
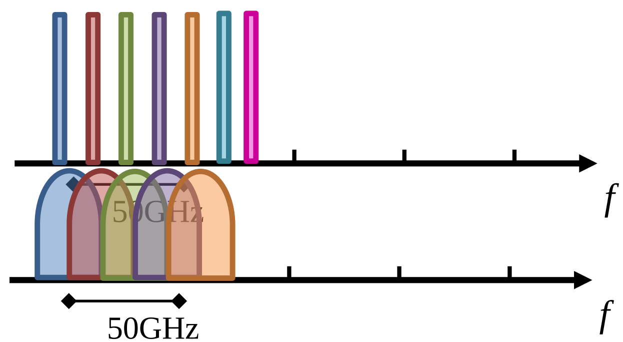
Superchannel developments at DCU

Studying superchannel flexibility in terms of:

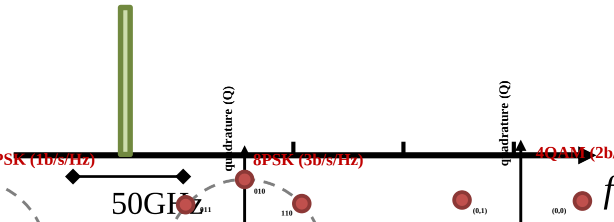


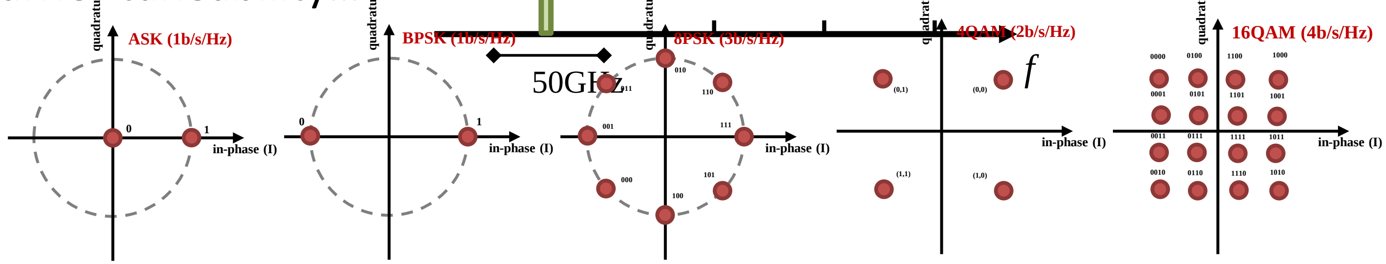
comb generation…

data rates &
modulation formats
Coherent/Direct Detection



& centre carrier tuneability…





Generation of Optical Frequency Combs

3 main techniques

- **Strongly driven electro-optic modulators to impose sidebands on signal from a single-frequency continuous-wave laser**
- **Mode-locked laser to generate broadband frequency combs (*spectrum of a periodic pulse train from MLL consists of discrete lines with an constant spacing equal to pulse repetition frequency*)**
- **Gain-switching of laser diode**

Generation of a frequency comb requires that periodicity applies not only to the pulse envelopes, but to the whole electric field of the pulses, including their optical phase

→ ***Coherence between the pulses is required.***

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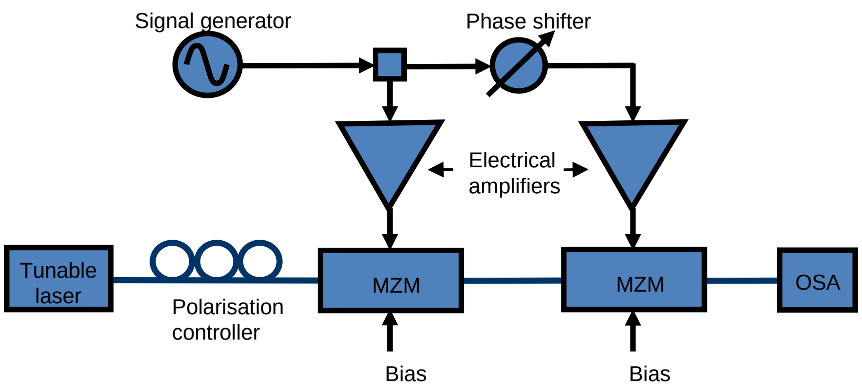
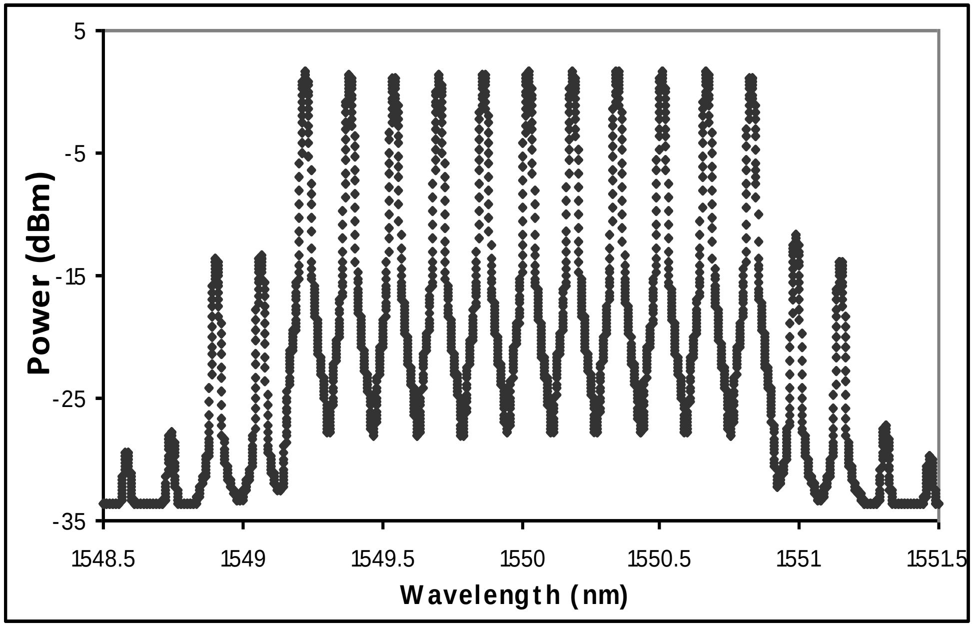
Generation of Optical Frequency Combs -- External Modulators

- **Modulation of CW signal using two cascaded MZMs**
- **Only requires a single laser source**





- **11 lines generated**
- **Constant 20 *GHz* spacing set by the RF signal generator**
- **200 *GHz* bandwidth**
- **Flatness < 0.6 *dB***
- **Side Mode Suppression Ratio > 13.5 *dB***

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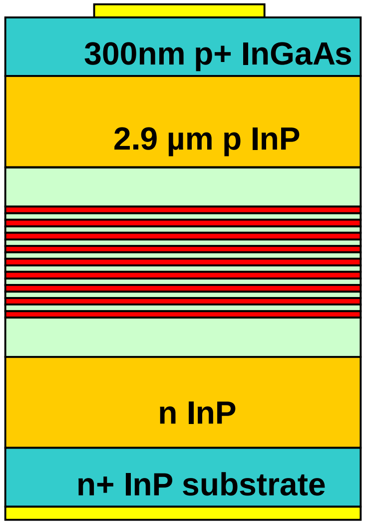
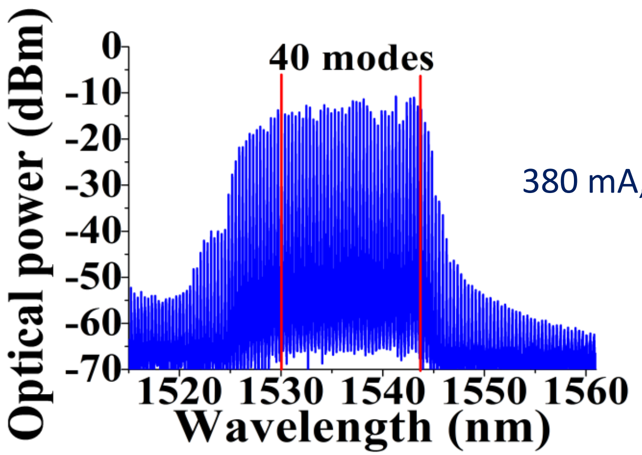
Quantum-Dash mode locked laser as comb source

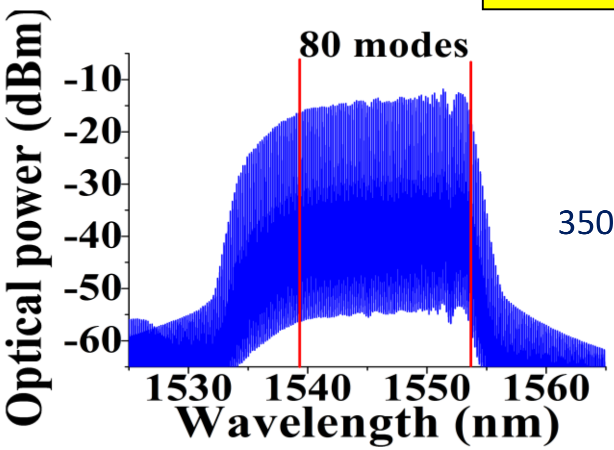
- Gas source molecular beam epitaxy (GSMBE) on an S-doped (001) InP substrate
- Active region composed of nine layers of InAs Q-Dashes separated by InGaAsP barriers
- Free Spectral Range (FSR) – 82.8 GHz, 44.7 GHz 22.7 GHz and 10GHz

- ***F. Lelarge et al., J. Selec. T. Quant. Electronics (2007)***
- ***R. Rosales et al., IEEE J. Selec. T. Quant. Electronics Vol. 17, 2011***



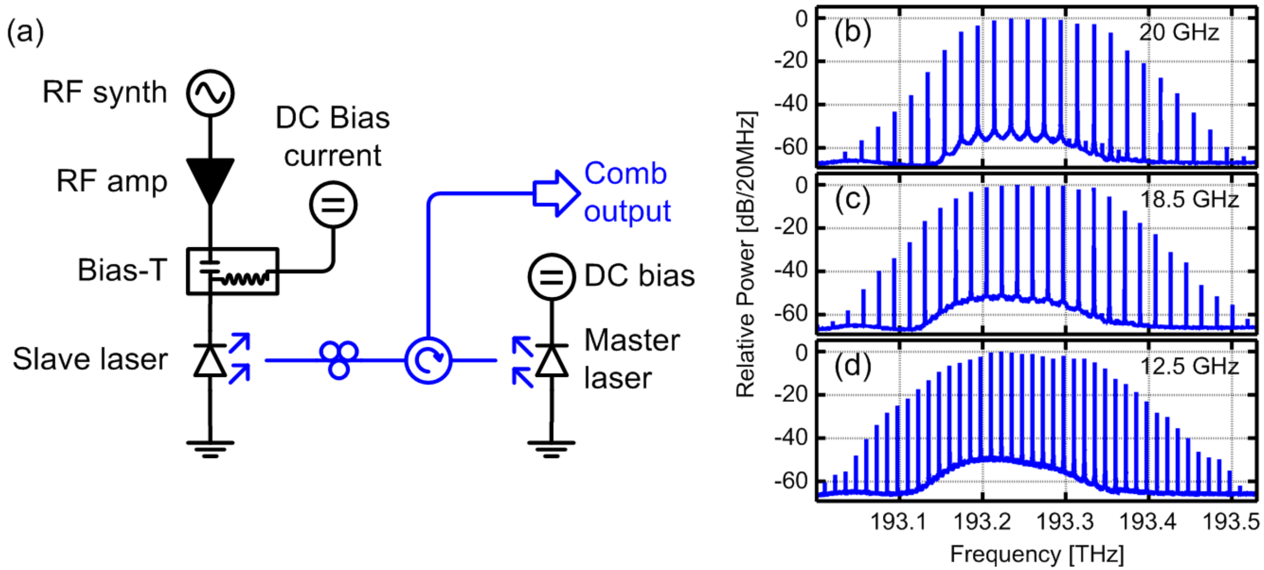


380 mA, 25ºC



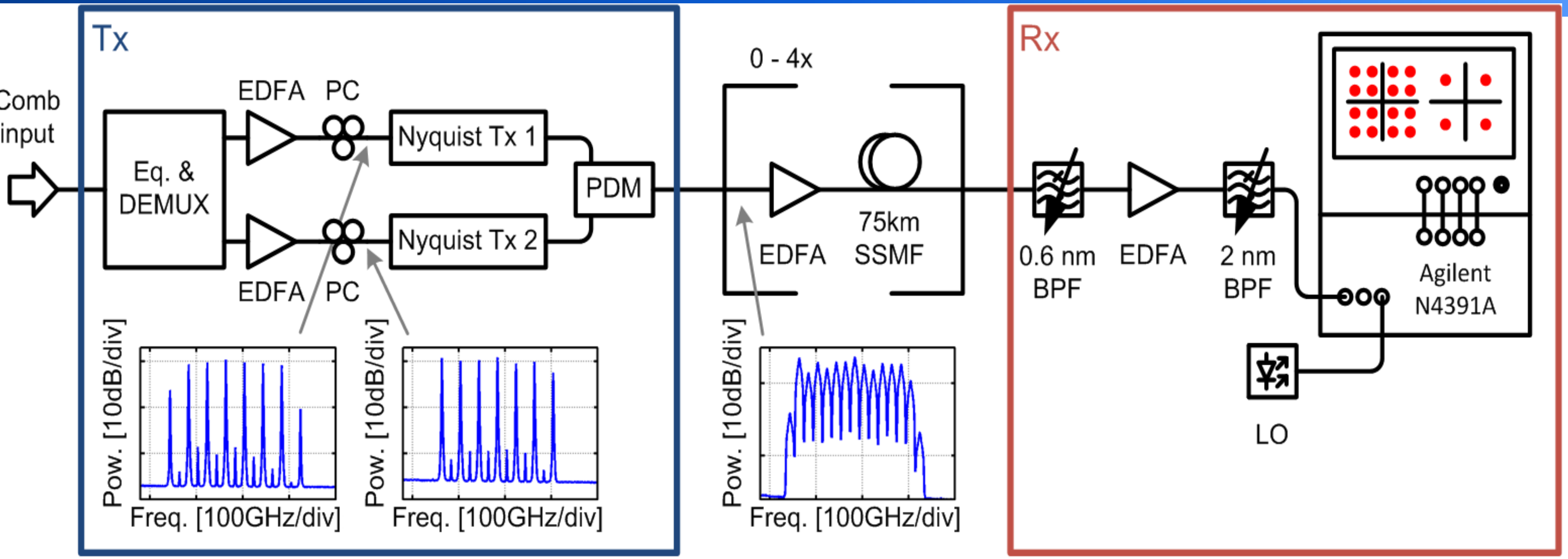
350 mA, 25ºC

Optical Comb source using gain-switched laser



- Direct modulation of high speed laser for comb generation
- Comb spacing variable using RF drive signal
- External injection reduces amplitude and phase noise on comb lines
    - Can achieve tunable comb source using FP slave laser
- Integrated version under development

Flexible Terabit/s WDM Super-Channel using gain switched comb source



Vidak Vujicic et al., 'Flexible Terabit/s Nyquist-WDM Superchannels with net SE > 7bit/s/Hz using a Gain-Switched Comb Source', Conference on Lasers and Electro-optics, (CLEO 2014), 2014.

Joerg Pfeifle et al., 'Flexible Terabit/s Nyquist-WDM Super-Channels using a Gain-Switched Comb Source', Optics Express vol. 23, pp. 724-738, 2015

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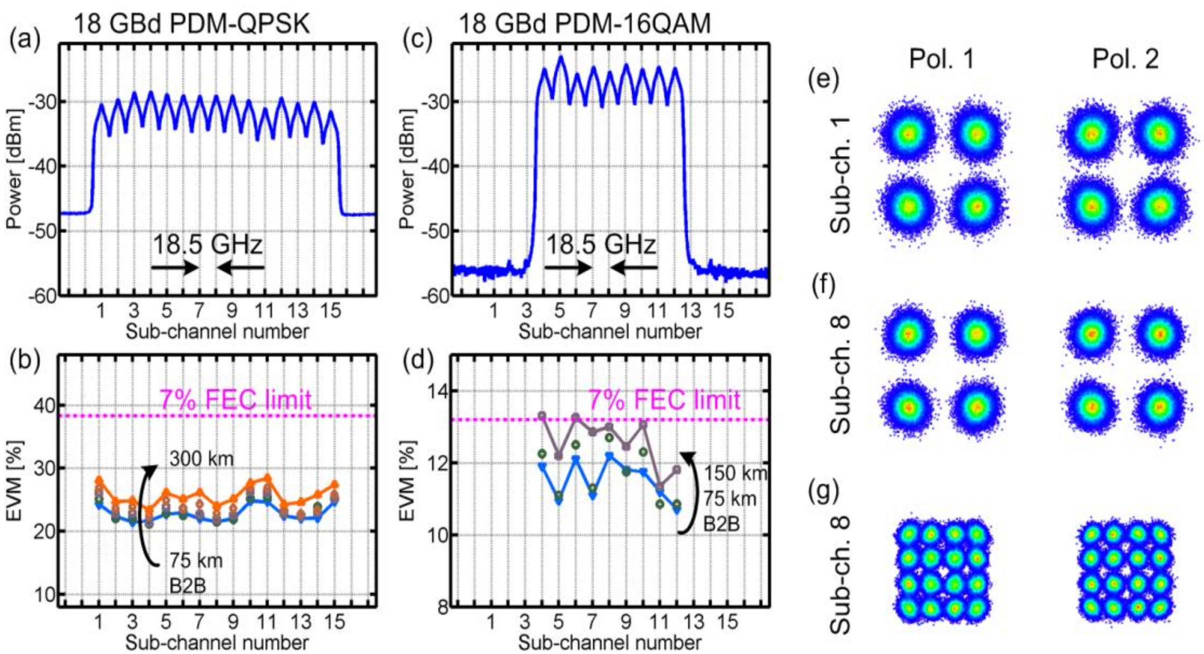
Performance of flexible comb source in Superchannel systems

- Aggregate bit rate 1.296 Tb/s
- Spectral efficiency 7.8 bit/s/Hz
- Among the highest globally reported values for spectral efficiency achieved for 16QAM in terabit/s super-channels
- Flexible subchannel spacing, modulation format, number of channels, ..



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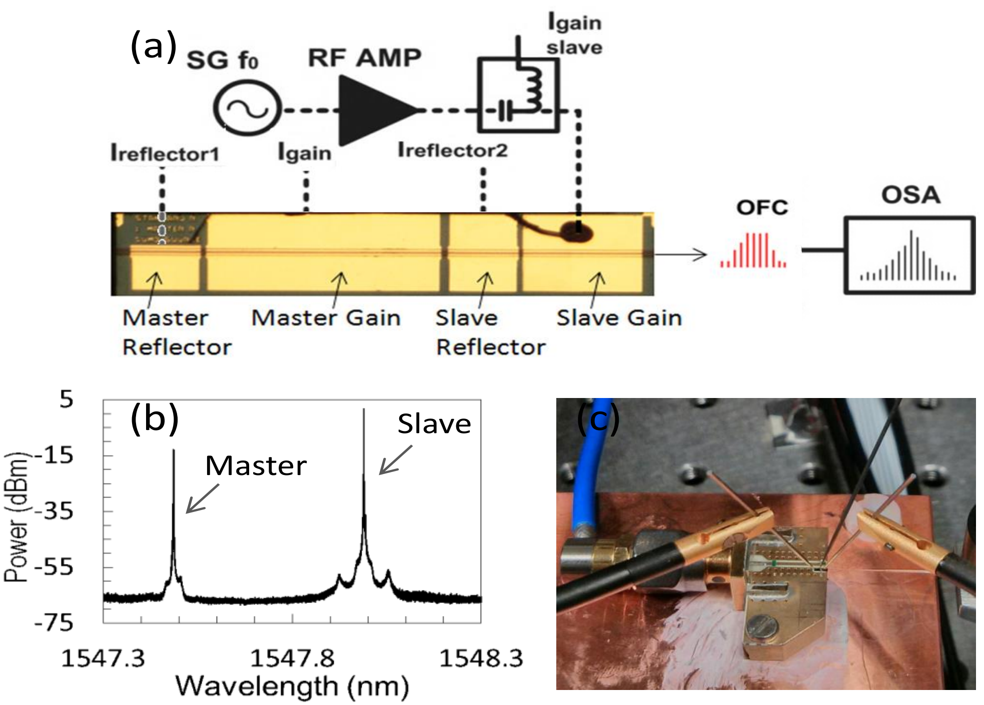
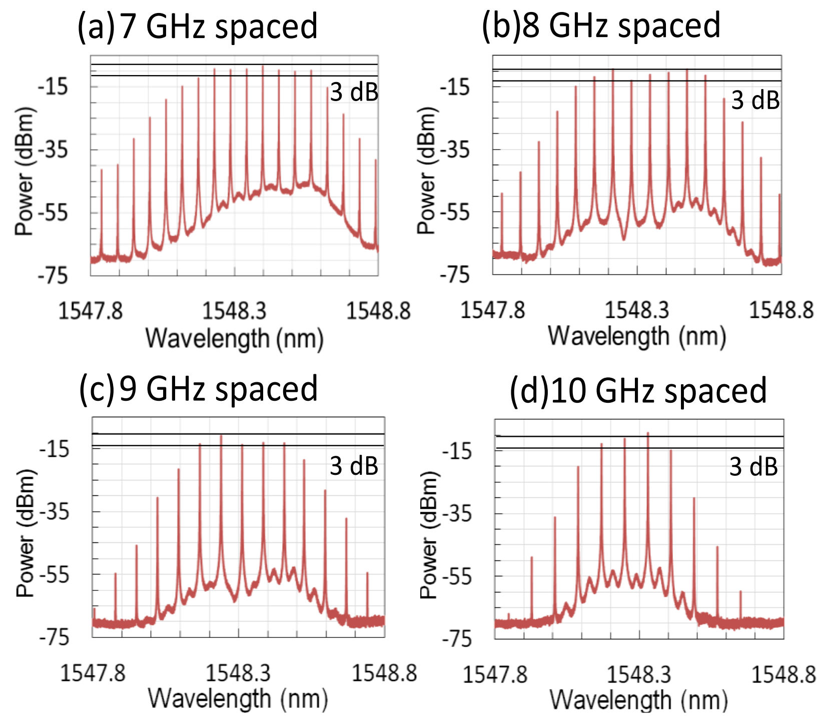
Integrated Gain Switched Comb Source



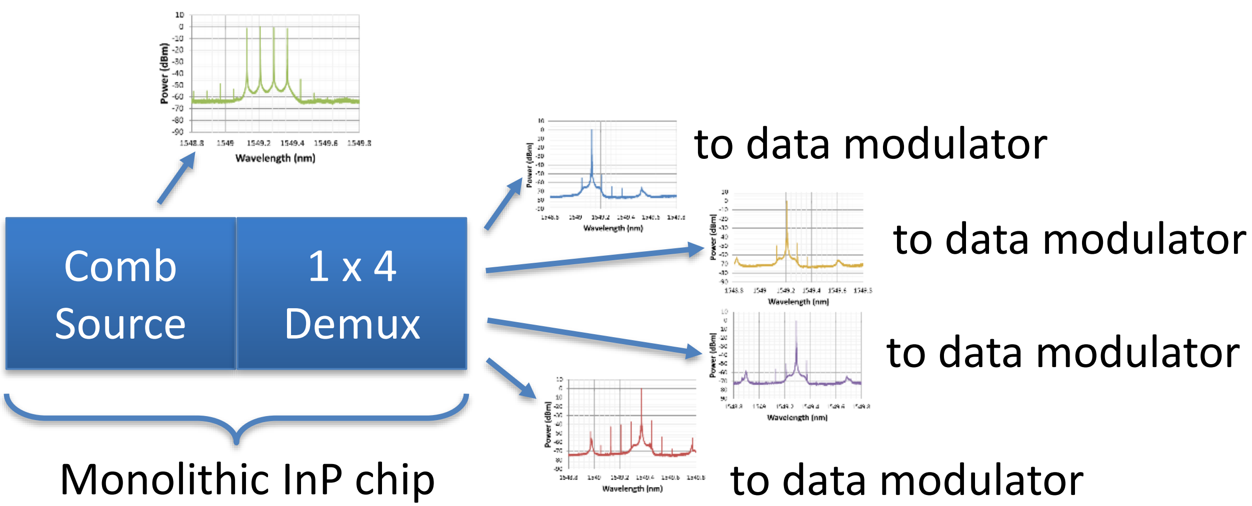
Integrated comb source with gain switched slave and master laser



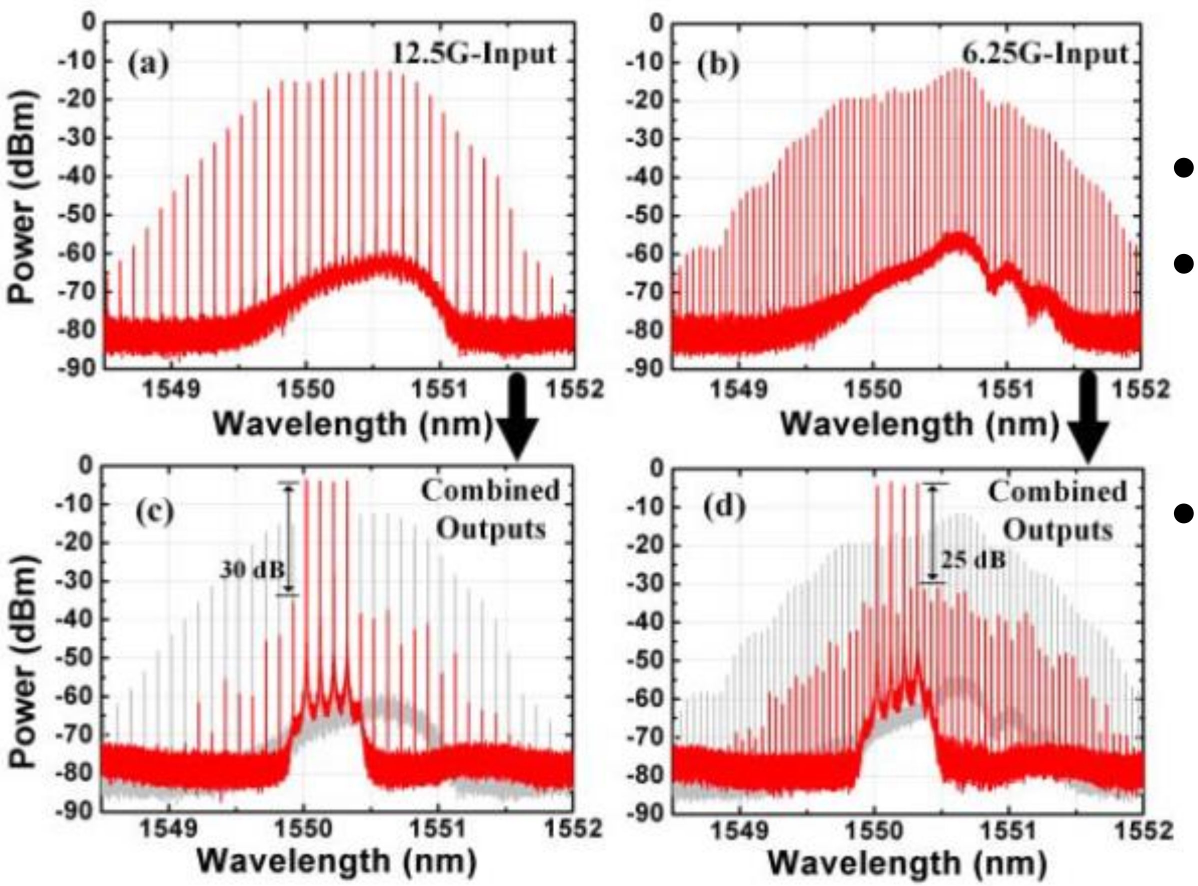
Tuneable comb spacing through RF drive
Move to 12.5 and 25 GHz in future devices

Photonic integrated comb source for superchannels

- Monolithically integrated comb source ***and demultiplexer***
- Multiple coherent wavelengths on individual outputs for modulation
- Reduced cost, footprint and power consumption with increased spectral efficiency and stability

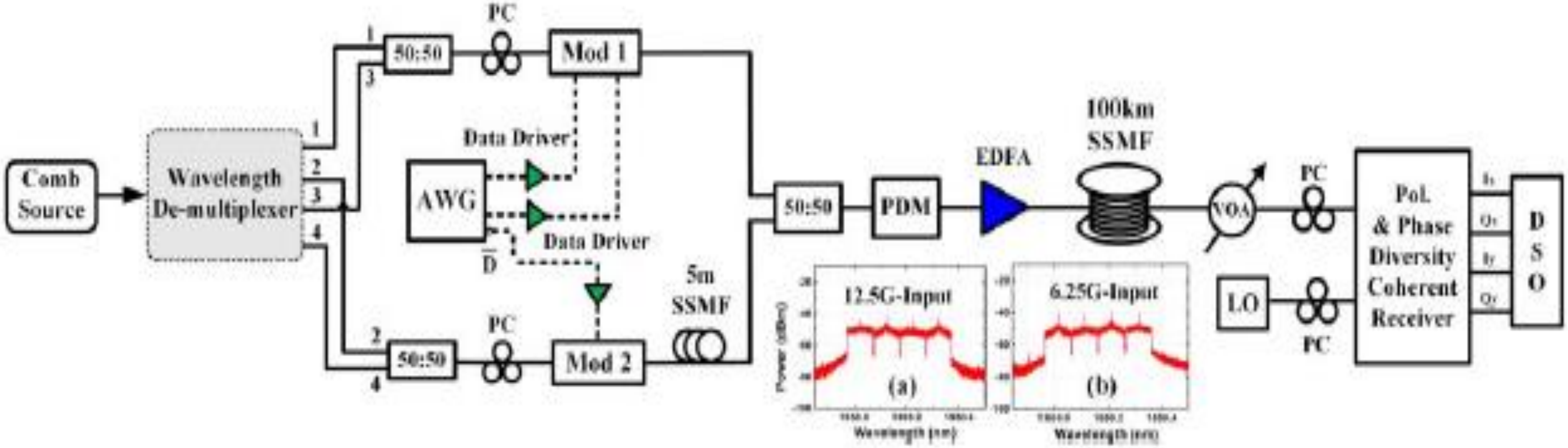


Integrated comb source and 4 channel demultiplexer



- ***FSR is variable***
- ***Multiple <u>coherent</u> wavelengths on individual outputs***
- ***Output combs lines equally spaced or variable spacing***

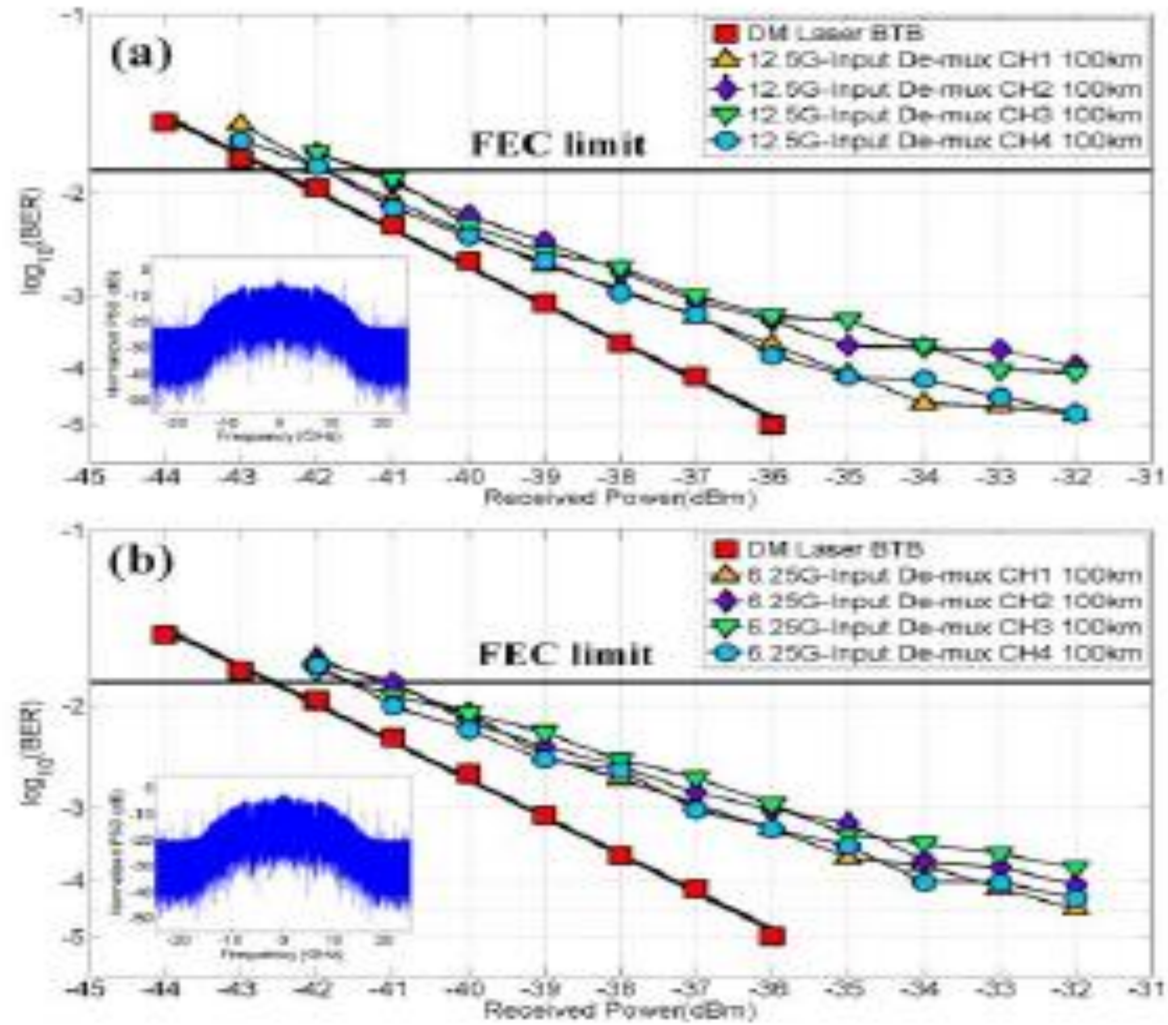
Integrated comb source and demux in Nyquist UDWDM



Experiential setup of Nyquist UDWDM system utilizing the 4 de-mux outputs

12 GBd Nyquist-quadratue phase shift keying (BPSK) used with 12.5 GHz FSR and 6GBd used with 6.25GHz FSR

Integrated comb source and demux in Nyquist UDWDM

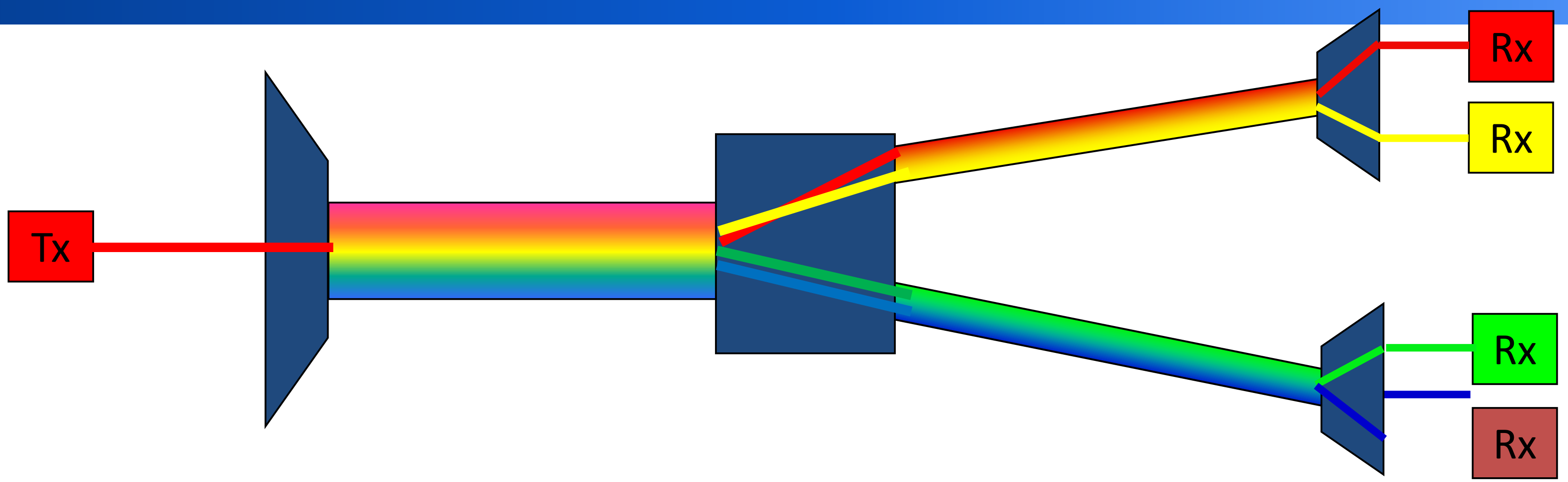


How to handle growth in demand for bandwidth

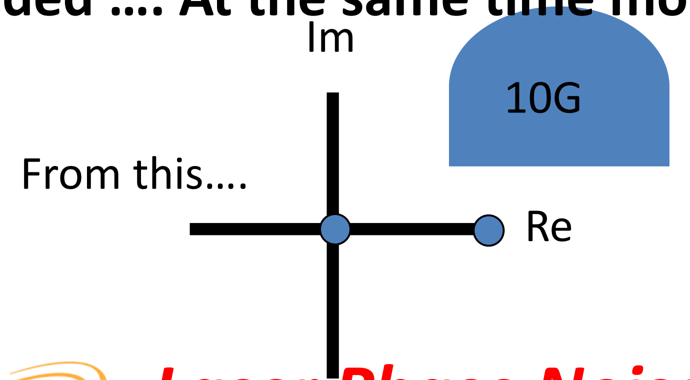
Better use of installed fibre in terms of spectral and temporal usage

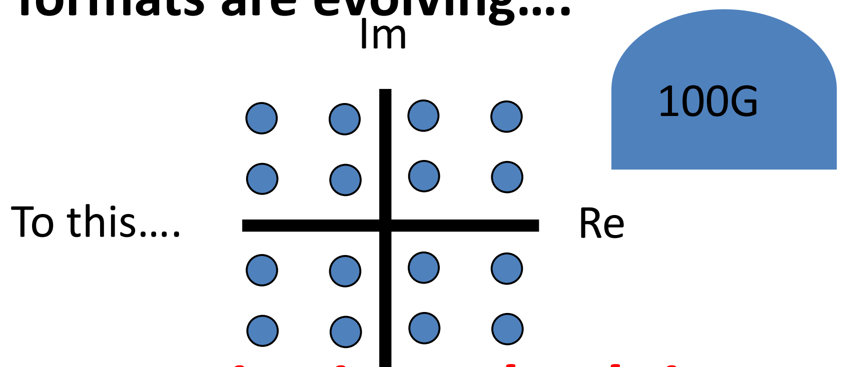
- ***Advanced modulation formats***
- ***Reconfigurable optical networks***
  - ***Better use of available fibre***

Developments in Optical Networks employing tuneable lasers



Fast reconfigurability allows bandwidth to be provisioned here/when it is needed …. At the same time modulation formats are evolving….



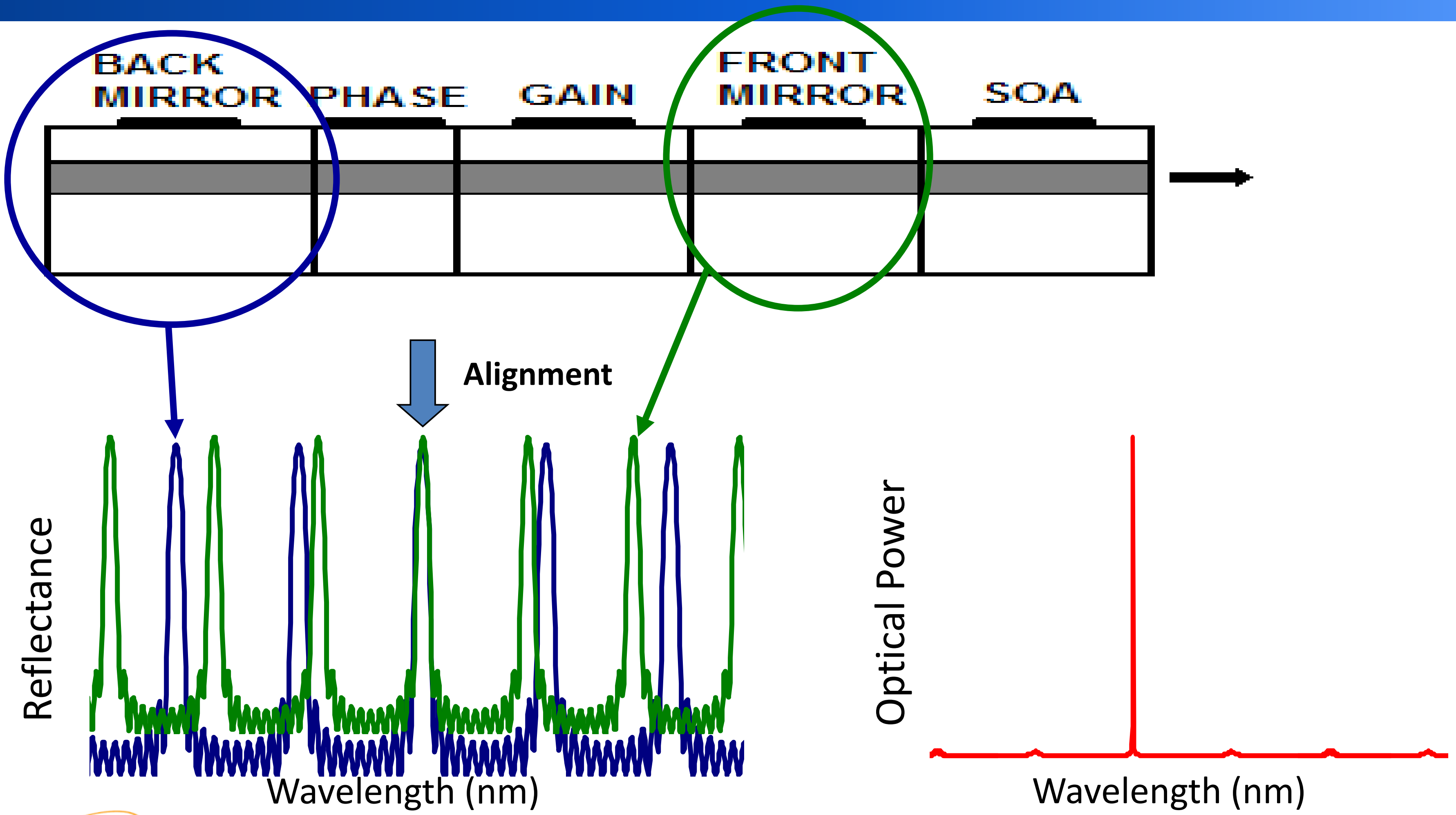


Laser Phase Noise becomes major issue both in static and switching environments

Key Technology for reconfigurable networks: Fast Switching Tuneable Lasers

	DFB Array	ECL MEMS	DBR-type (SG-DBR, DSDBR, MG-Y, SSG-DBR)	VCSEL
Company	NeoPhotonic, NTT.NEC	Luna Technology (iolon)	Lumentum, Oclaro, Finisar	Vertilas
Tunability (nm)	35	38	35 ~ 50	28
Switching time	1 ~ 10s	< 2ms	< 100ns	200μs ~ 1ms
SMSR (dB)	40 ~ 50	> 40	> 40	>30
Linewidth	100-200 kHz	< 2MHz	< 5MHz	>32MHz
Tuning Mechanism	Thermal	Mechanical	Electrical	Mechanical
Applications				
Sparing, Provisioning	✓	✓	✓	✓
Reconfigurability & restoration, protection		✓	✓	✓
OBS and OPS			✓	

Main type of tunable laser: DBR-type laser operation (SG-DBR)



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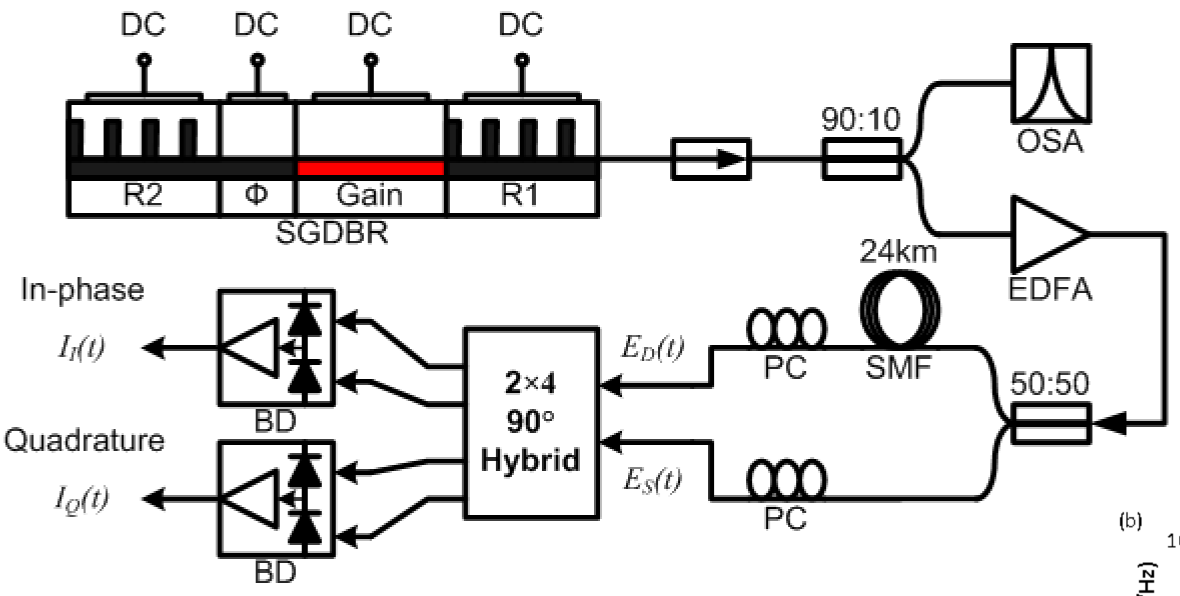
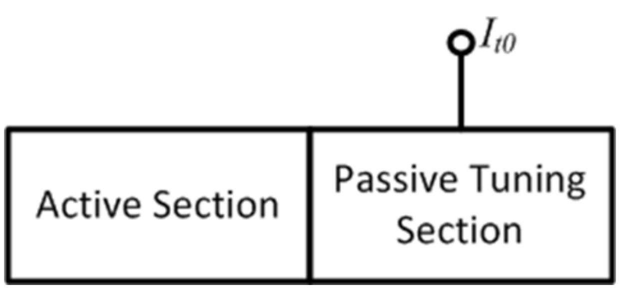
Phase noise characterization
Standard tunable laser; SGDBR device



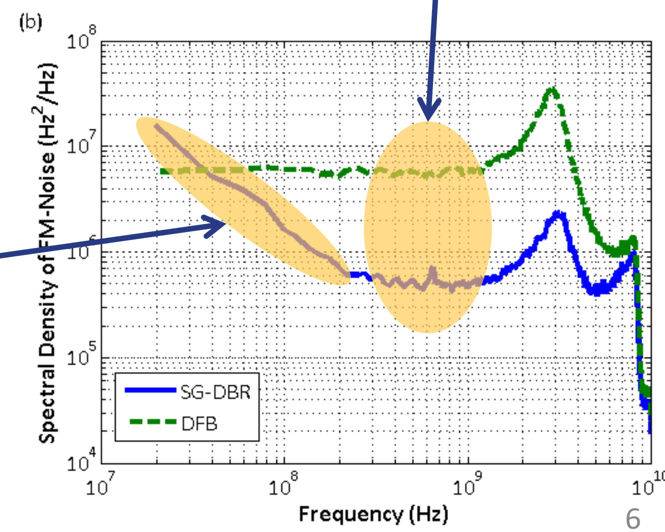
White Noise

$$\langle \Delta \emptyset^2 \rangle = \frac{R(1+\alpha^2)\tau}{2I} = 2\pi^2 S_0 \tau$$

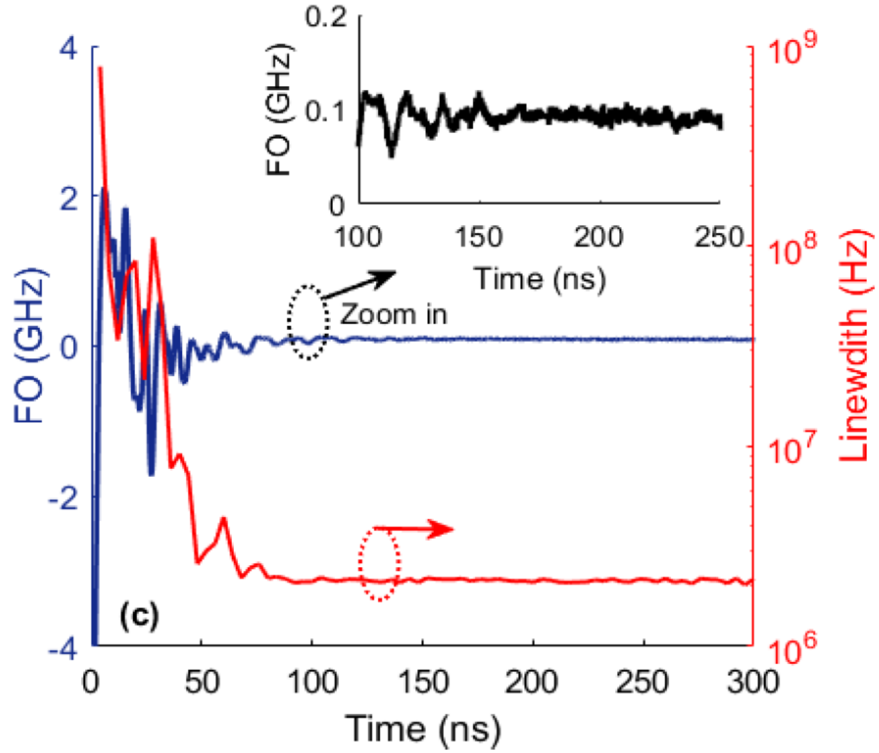


1/f Noise

$$S_F(f) = S_1/f$$



Phase noise and frequency variation of tunable laser after switch



- Excess phase noise (1/f noise) from SGDBR devices effects static coherent transmission systems
- FO and time varying FO after switch effects the waiting time after a switch when data can be sent
- Standard Mth power frequency offset estimation scheme would require ~200ns wait time
- Inefficient use of network resources
- Use double differential PSK

Walsh, Anthony John (2015) ***Optimising the efficiency of coherent optical packet switched networks.*** **PhD thesis, DORAS repository, Dublin City University.**

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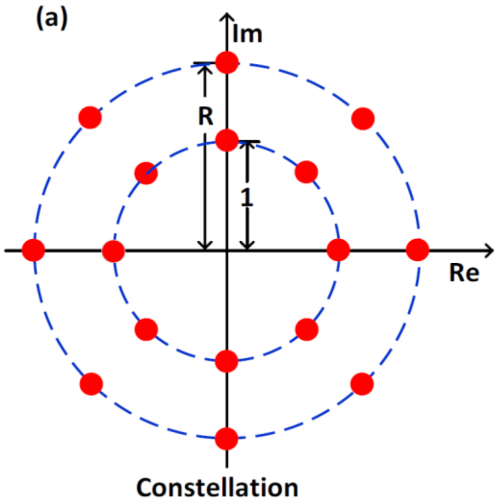
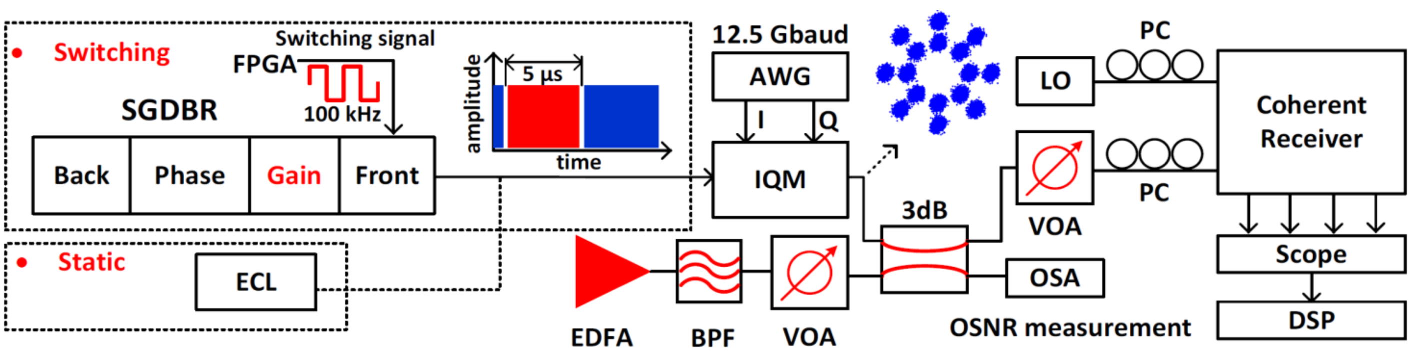
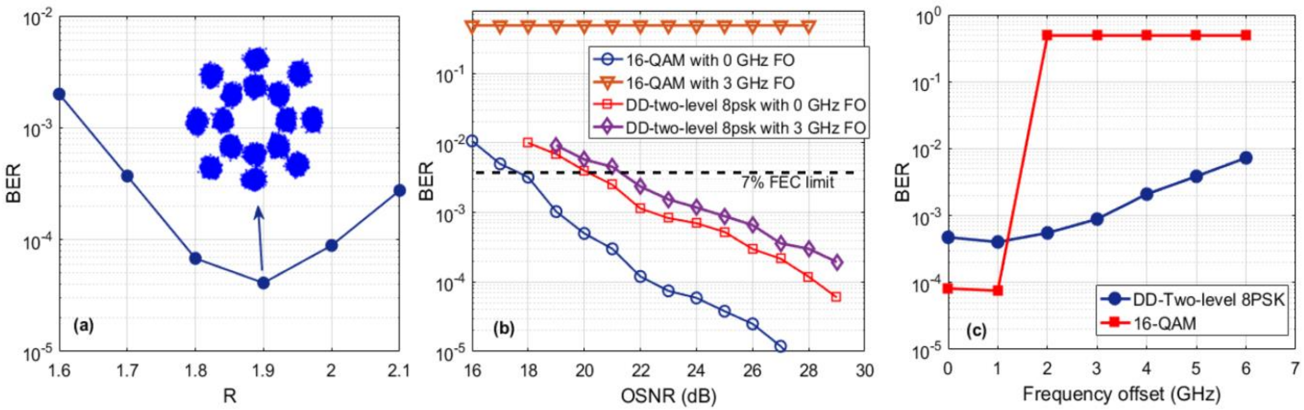
Move from DDQPSK to DD 2-level 8 PSK to increase efficiency (instead of standard 16 QAM)



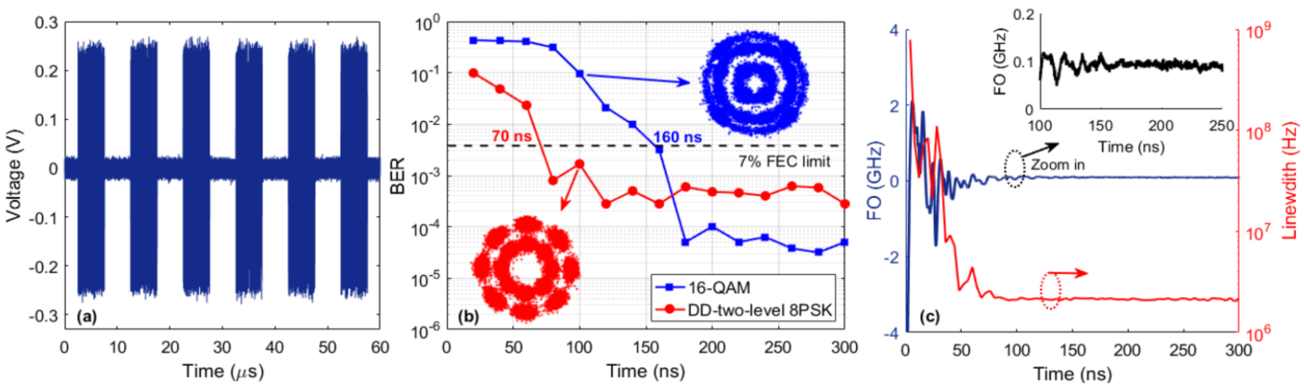
- 2 level 8 PSK constellation can be employed for double differential encoding/decoding
- DD encoding at transmitter
- DD decoding at receiver



Performance of DD 2 level 8PSK scheme at 12.5 Gbaud with SGDBR laser



- Optimise distance between inner & outer ring
- Performance in static case with different FO's presents advantage over standard DSP



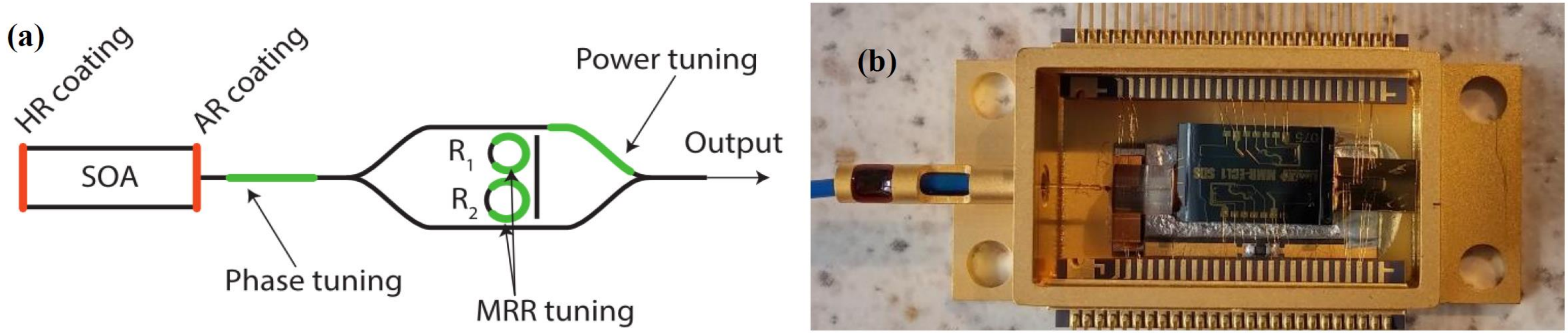
- Move to switching case
- Time to reach FEC limit reduced by 56% compared with standard DSP

FAN LIU, YI LIN, ANTHONY J. WALSH, YONGLIN YU AND LIAM P. BARRY, "Doubly differential star-16-QAM for fast wavelength switching coherent optical packet transceiver", Optics Express, Vol. 26, No. 7 | 2 Apr 2018

Low linewidth tuneable lasers for more spectrally efficient systems

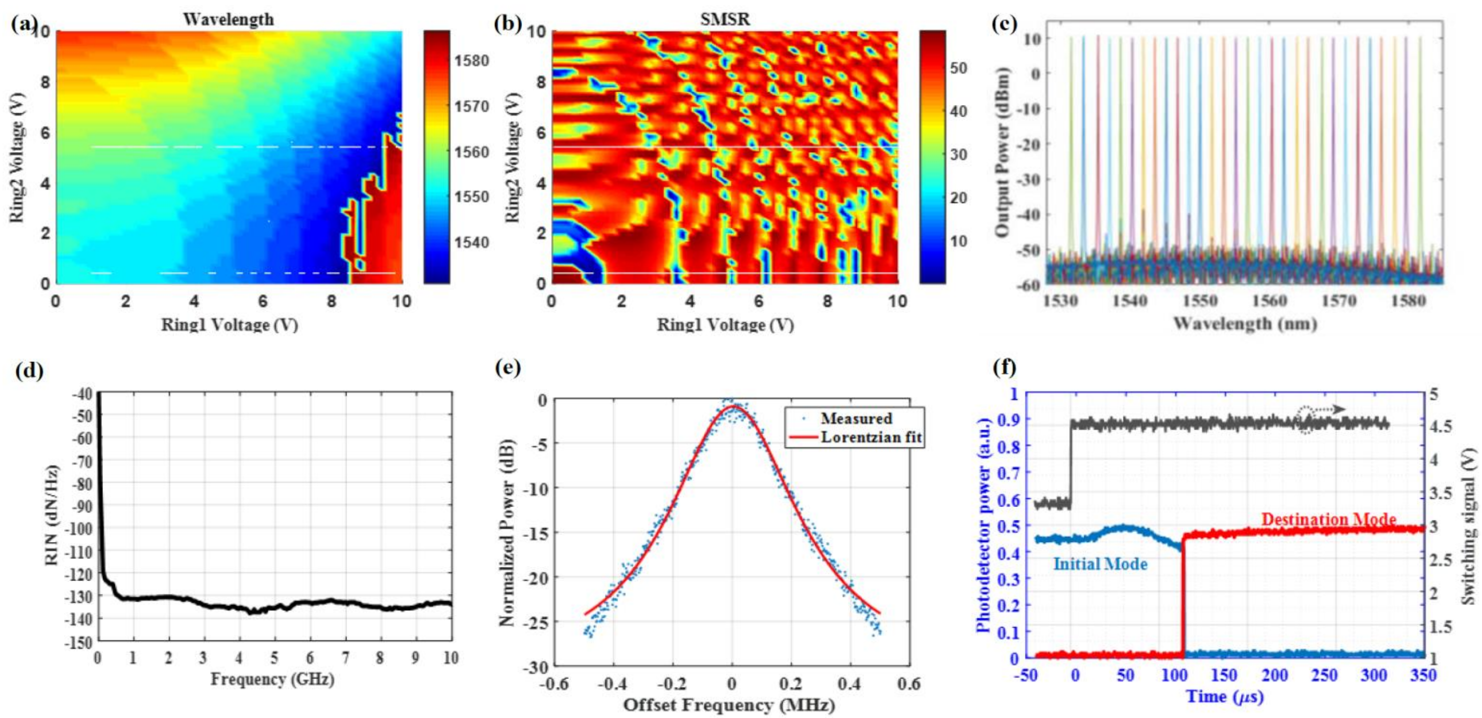
- Optical systems moving from QPSK to 16 QAM to xxQAM ?
- Laser phase noise can limit performance
- Standard SGDBR devices with linewidth ~ Several MHz (OK for QPSK at 28 Gbd)
- Using thermal tuning with SGDBR and advanced structure to achieve < 300 kHz

- Different tunable devices may be suitable for lower linewidth



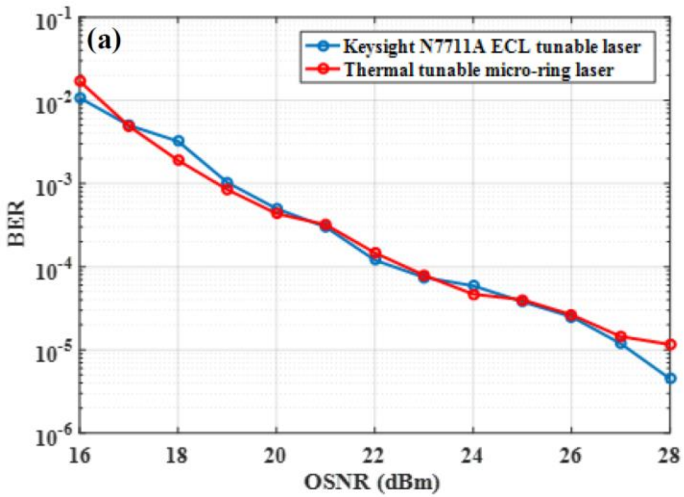
Y. Fan et al., "290 Hz intrinsic linewidth from an integrated optical chip-based widely tunable InP-Si_3N_4 hybrid laser", in Proc. Conference on Lasers and Electro-Optics, San Jose, USA, 2017

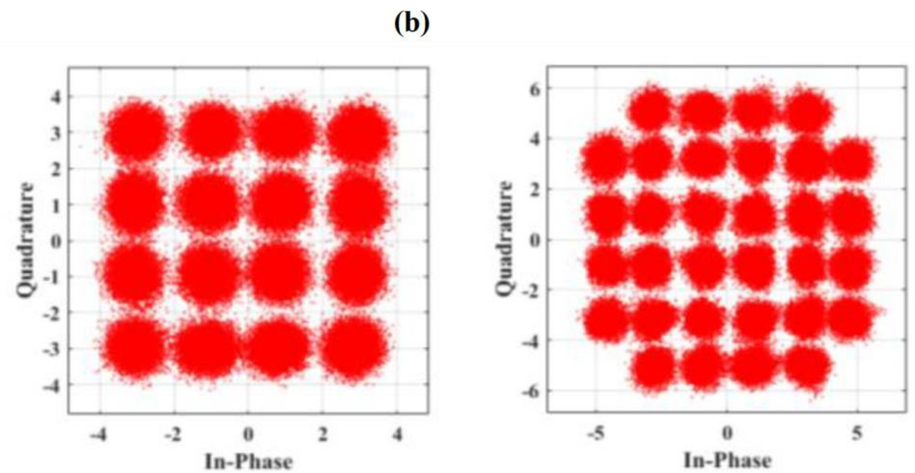
Characterisation of widely tunable InP-Si_3N_4 hybrid laser

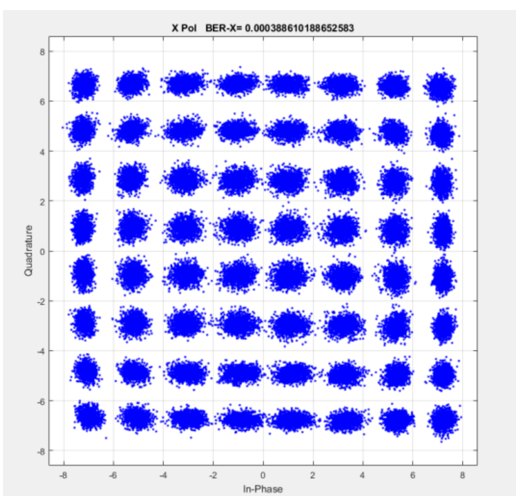


- Tunable over 60 nm using voltage (heating) of ring resonators
- SMSR in excess of 50 dB on all wavelengths
- RIN better than -130 dB/Hz
- Linewidth ~50kHz
- Switching time ~ microsecond

Performance of widely tunable InP-Si_3N_4 hybrid laser in coherent systems





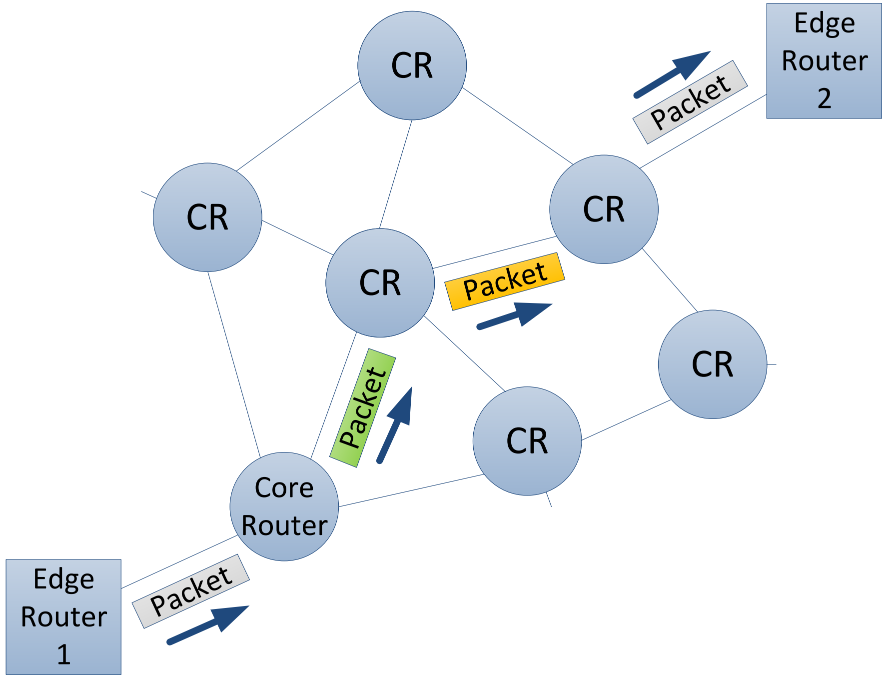


- Performance similar to ECL for 16QAM 12.5 Gbaud system
- Can also obtain clear constellations at 32 and 64 QAM demonstrating excellent phase noise

Wavelength conversion using fast tunable lasers for reconfigurable optical networks

Typical packet / burst switched network

- Route data through the Core Routers (CR)
- Overcome wavelength contention
- Avoid electronic processing in the CR
- Use spare wavelength channel capacity
- Maximum efficiency of network resources
- Packets have information encoded in amplitude and phase domain



Wavelength Conversion techniques

- **Wavelength Conversion**
- **Avoid electrical processing in the CR**
- **Requires optical nonlinearities (3rd order)**
  - **Cross- Gain and/or Cross Phase Modulation, Four-Wave Mixing**
  - **FWM is a coherent nonlinear process: amplitude and phase preserving**
- **Devices:**
  - **Semiconductor Optical Amplifiers (SOA), Optical Fiber, Nonlinear waveguides**
- **Flexibility**
  - **Tunability, Reconfiguration time**

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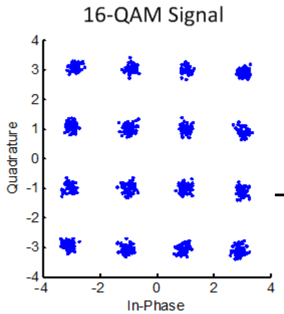
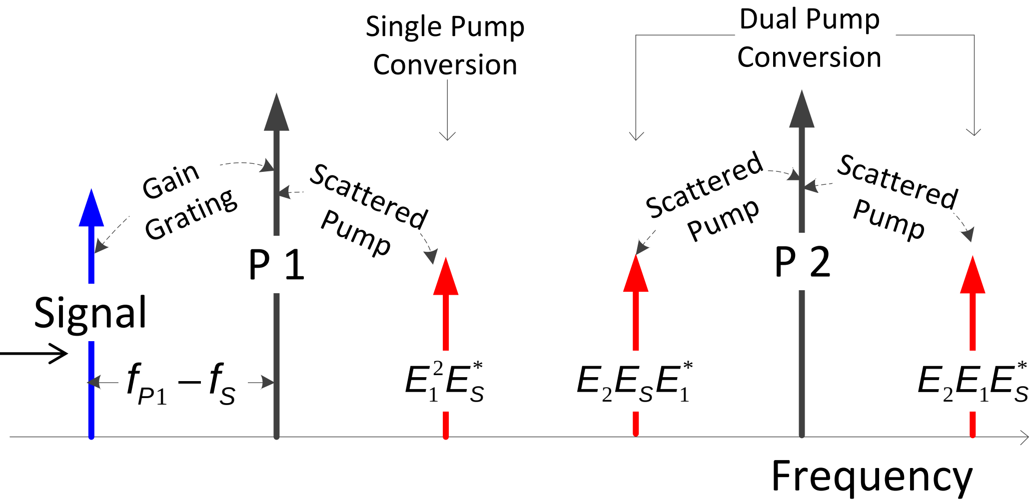
Wavelength Conversion using FWM

- **New wavelengths generated due to COHERENT scattering of optical waves from the creation of a gain and/or index grating arising from the 3rd order nonlinear optical process.**

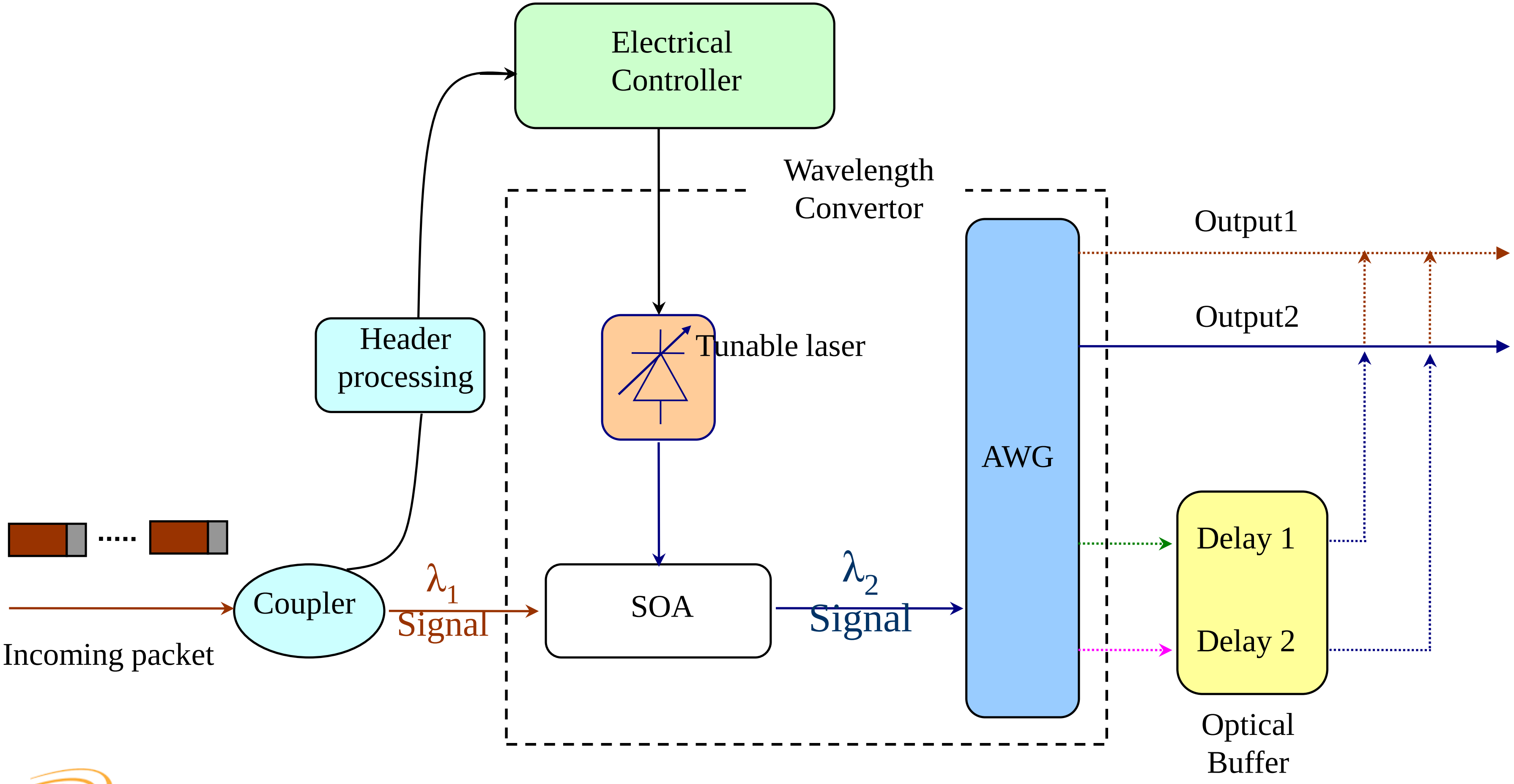
$$E_I \propto E_{P1}^{*} E_{P2} E_S \exp\left\{ j \left[\left(\omega_{P2} - \omega_{P1} + \omega_S \right) t \right] \right\}$$

- **Nondegenerate FWM – Pump P2 : anywhere within the system bandwidth!**

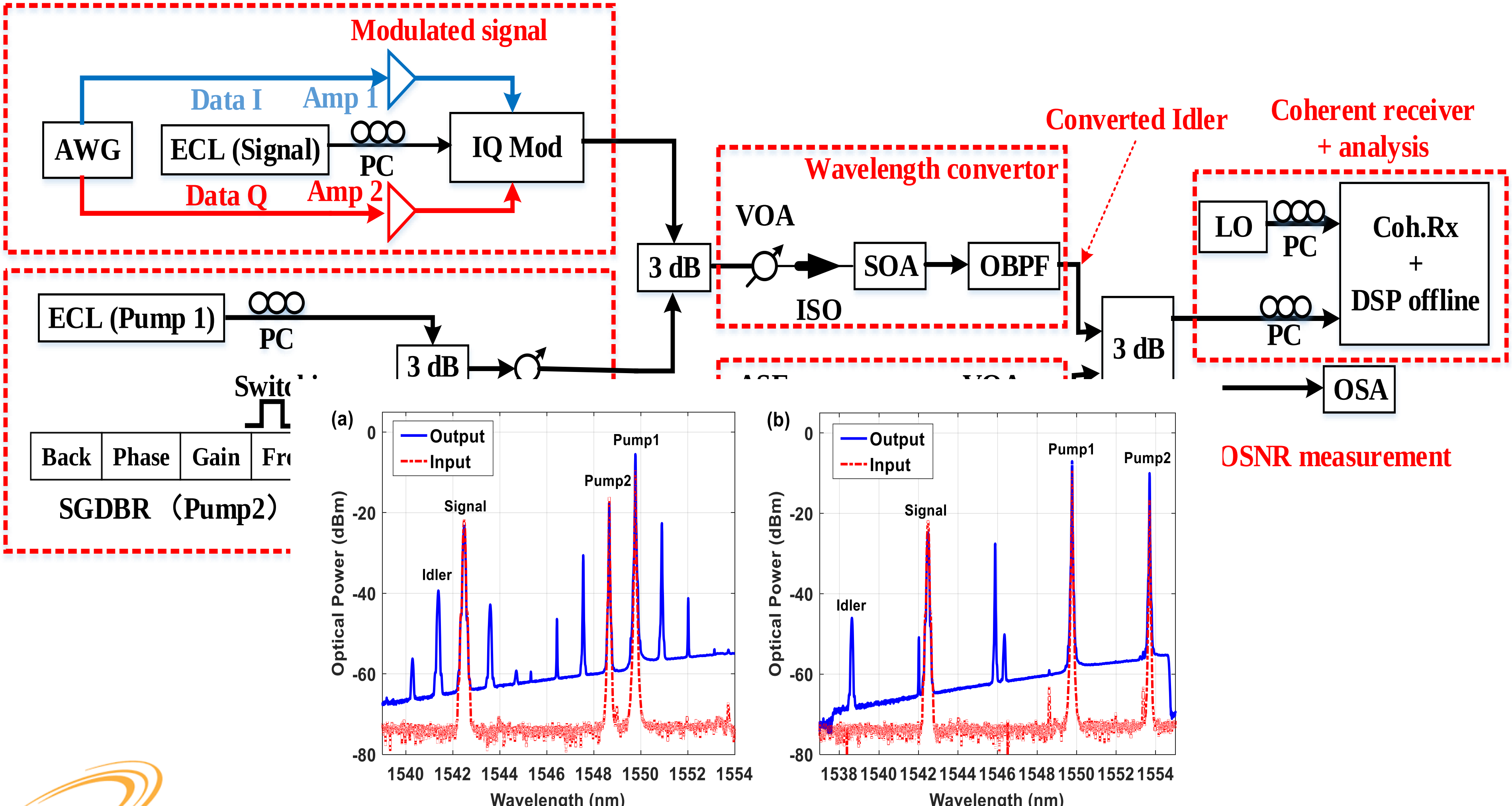




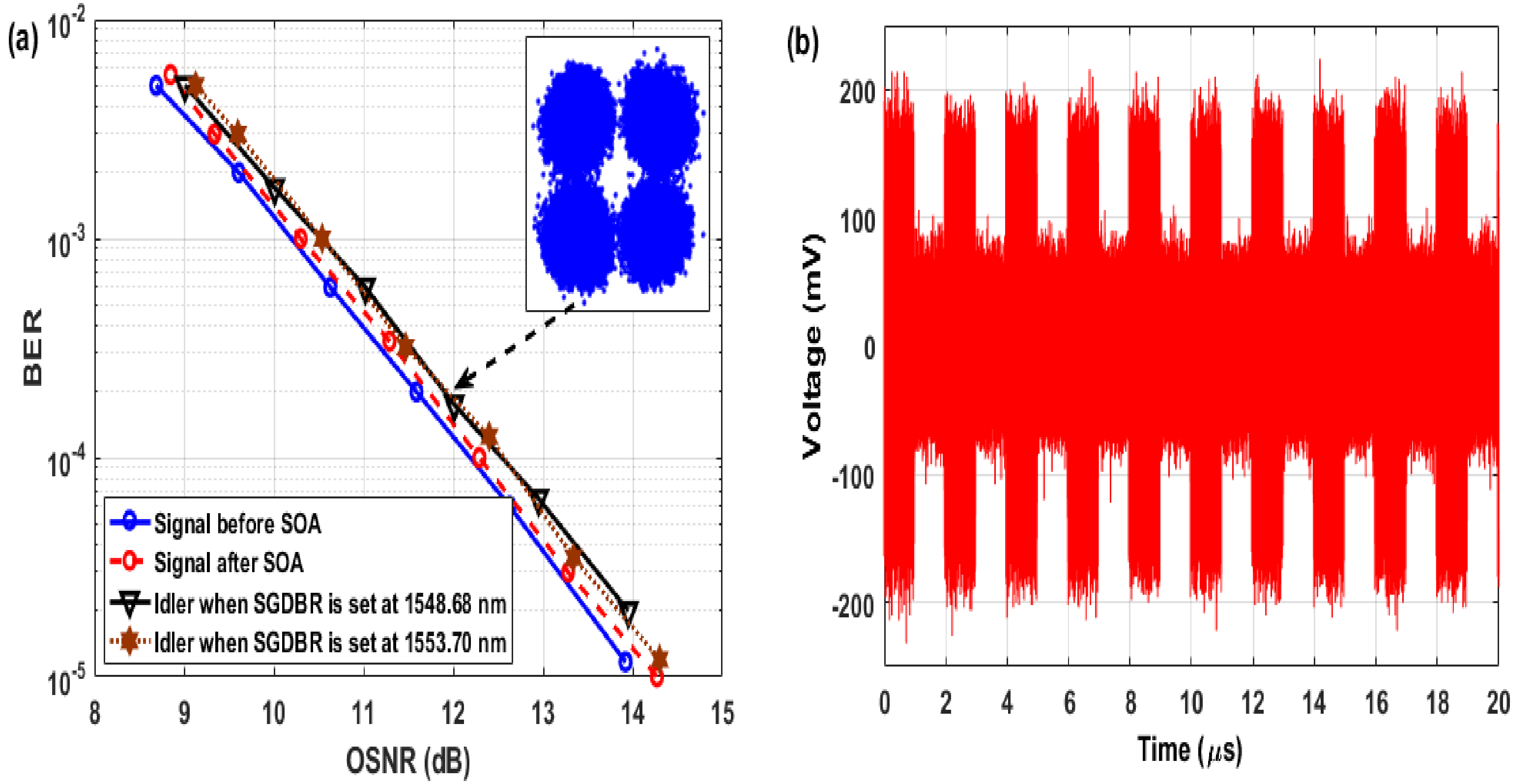
Wavelength Conversion using FWM



Experimental testbed

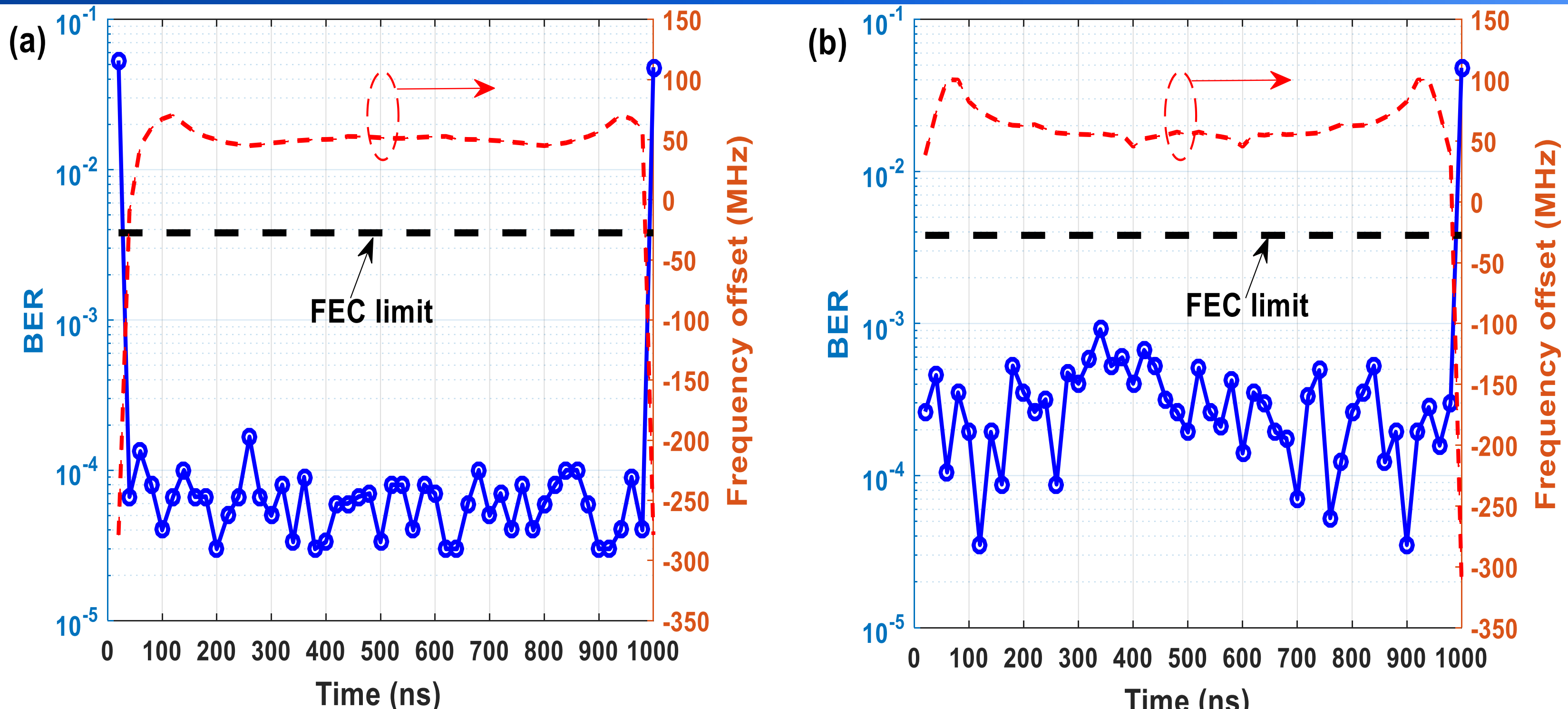


Experimental Results



BER as a function of OSNR for input signal, signal after SOA, and the wavelength converted signal12.5GBd QPSK signal

Experimental Results



- Time-resolved BER for the reconfigurable wavelength convertor as tunable SGDBR pump laser switches wavelength
- BER below FEC limit after ~20ns
- Average BER worse for one channel due to higher linewidth on SGDBR laser at this operating wavelength

Conclusions

- Continuing growth in demand placing strain on optical links
- Need enhanced efficiency in terms of spectral and temporal usage
- Optical Comb Sources can reduce power consumption & channel spacing
  - Develop superchannel systems based on direct/coherent detection
  - Electo-optic OFDM used with QD comb sources can achieve 4 Tb/s transmission
  - Use phase noise reduction to employ QD devices in coherent systems
  - Flexible comb sources based on gain-switched lasers to achieve Tb/s links
  - Integrated comb sources can reduce foot print
- Tunable lasers allow optical links to be reconfigured to meet demand
  - Employ advanced DSP to overcome FO issues after switching
  - Develop lower linewidth devices for higher order modulation formats
  - Integrate TL's with tuneable filters to develop novel switching fabrics

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Acknowledgments

Radio & Optical Communications Group, DCU

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