FPGA DSP *ASIC*

PIC

Monash Electro-Photonics Laboratory

Electro-Photonics

Arthur Lowery
Monash University
Clayton, VIC3800, Australia

Acknowledgements
Key to the success of the Electro-Photonic Laboratory has been the combined expertise of its research fellows and students. I also thank Monash University and the Australian Research Council for their generous support, especially through a Laureate Fellowship (FL130100041), and the CUDOS Centre of Excellence (CE10001018).

The Motivation……….

In optical communications research, a common justification for funding all-optical processing is that the electronics is too slow to support high data rates. While there can be some validity in this statement, it has often been used to dismiss the contribution that electronics could make to upgrading communications bandwidth. Conversely, photonic signal processing might be dismissed as being inflexible, compared with electronic digital signal processing (DSP).

The truth is that both electronic and photonic technologies are advancing rapidly. At any particular instant, there will be a different optimal mix of these technologies. This mix will also be influenced by non-technological factors —for example, digital signal processing for dispersion compensation eliminates the need for back-room engineering to plan the dispersion maps of long-haul links, so overcomes a labor shortage.

The aim of the *Electro-Photonics Laboratory* at Monash University, Australia, is to consider the best mix of optical and electronic technologies to produce an optimal solution for a particular problem. We've focused on the optical communications problem space, mainly because of familiarity and experience, though we also consider fundamental building blocks that are generally available in electronics, but are yet to have photonic equivalents.

This paper provides some examples of how we have brought together electronic and photonic technologies, developed sub-systems, and put together experimental demonstrations.

First Presented at APC, Wuhan, Nov. 2016

Are optical and electronic bandwidths incompatible?

Optical Bandwidth 10’s of THz

Electronic Bandwidth
< 100 GHz

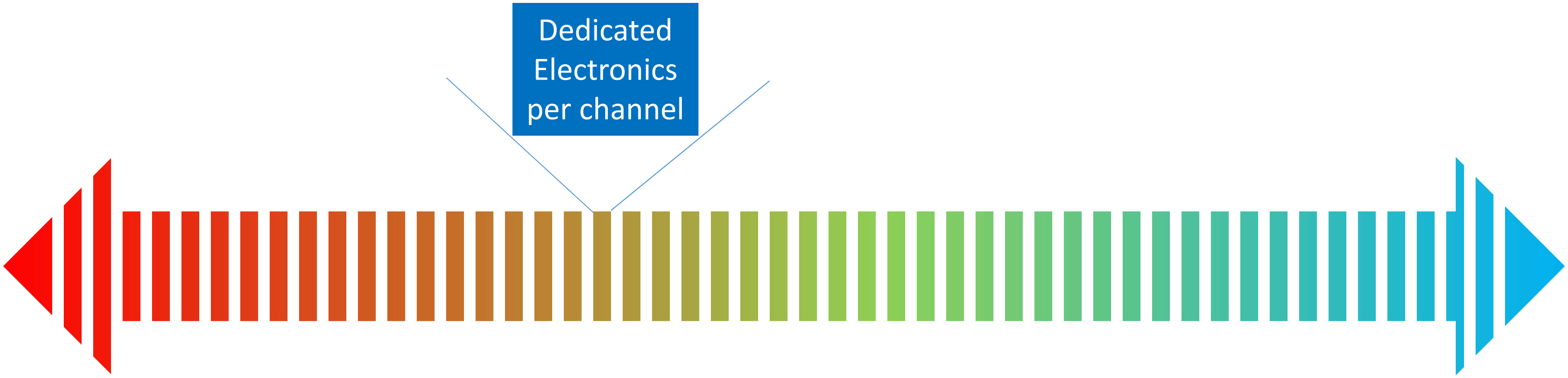
Bandwidth Compatibility

Optical Bandwidth 10’s of THz

Electronic Bandwidth
< 100 GHz

The “divide and conquer” approach of Wavelength Division Multiplexing has served us well.

The usual solution: divide the optical spectrum

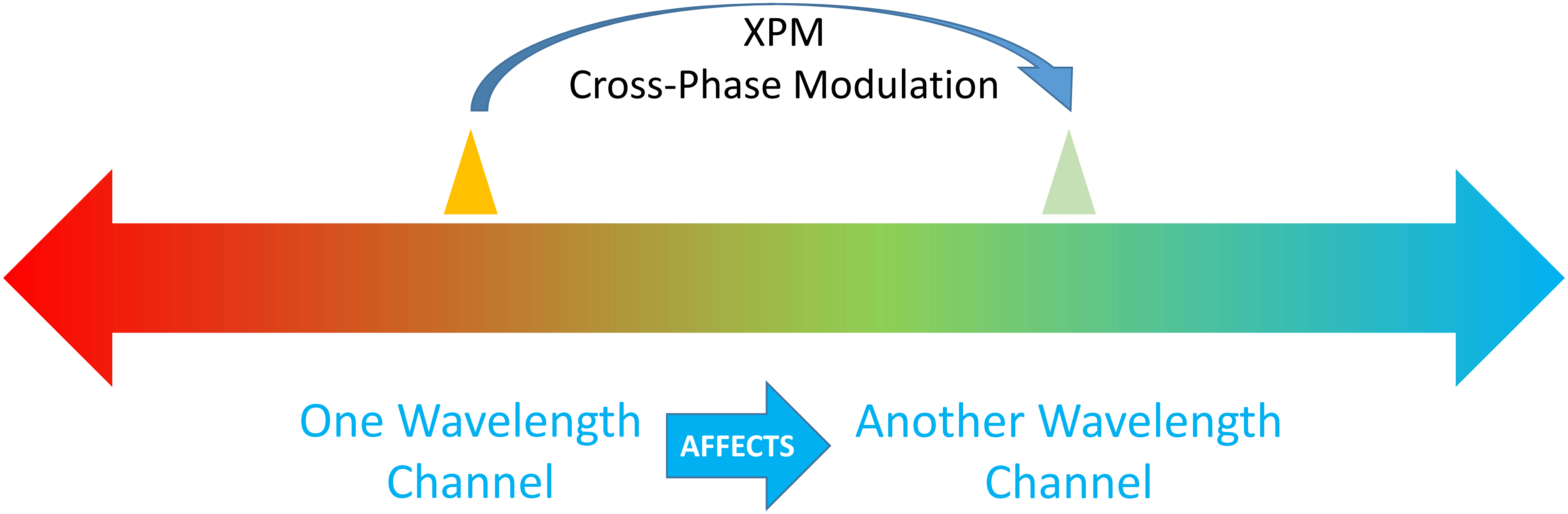


Dedicated Electronics per channel

The “divide and conquer” approach of Wavelength Division Multiplexing has served us well

- But should we think beyond division?

Cross-Phaase Modulation: Can Electronics solve this problem?



XPM

Cross-Phase Modulation

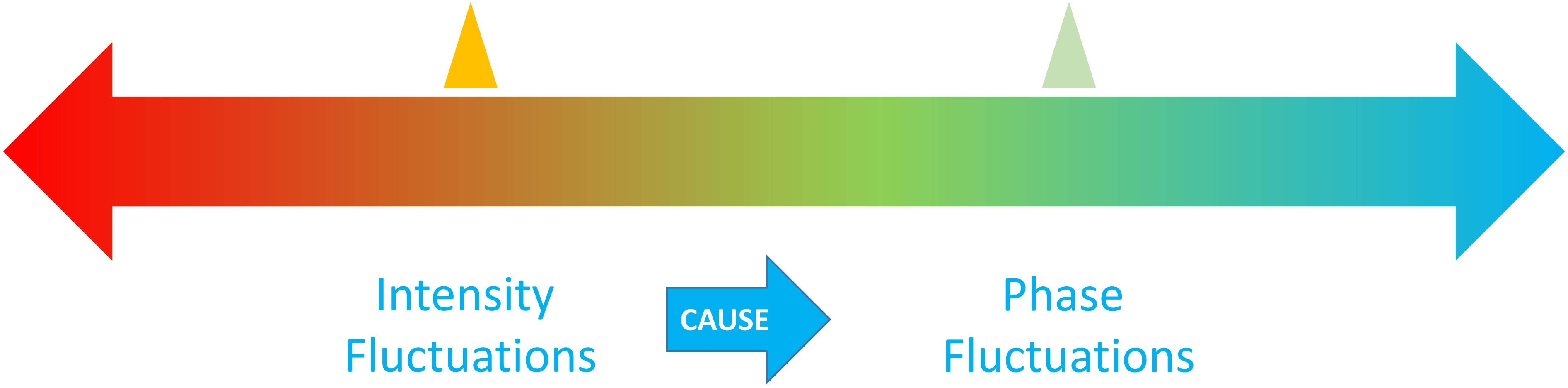
One Wavelength Channel

AFFECTS

Another Wavelength Channel

Seems impossible, as the effect is over several THz of bandwidth!

But should we be thinking differently?



Intensity Fluctuations

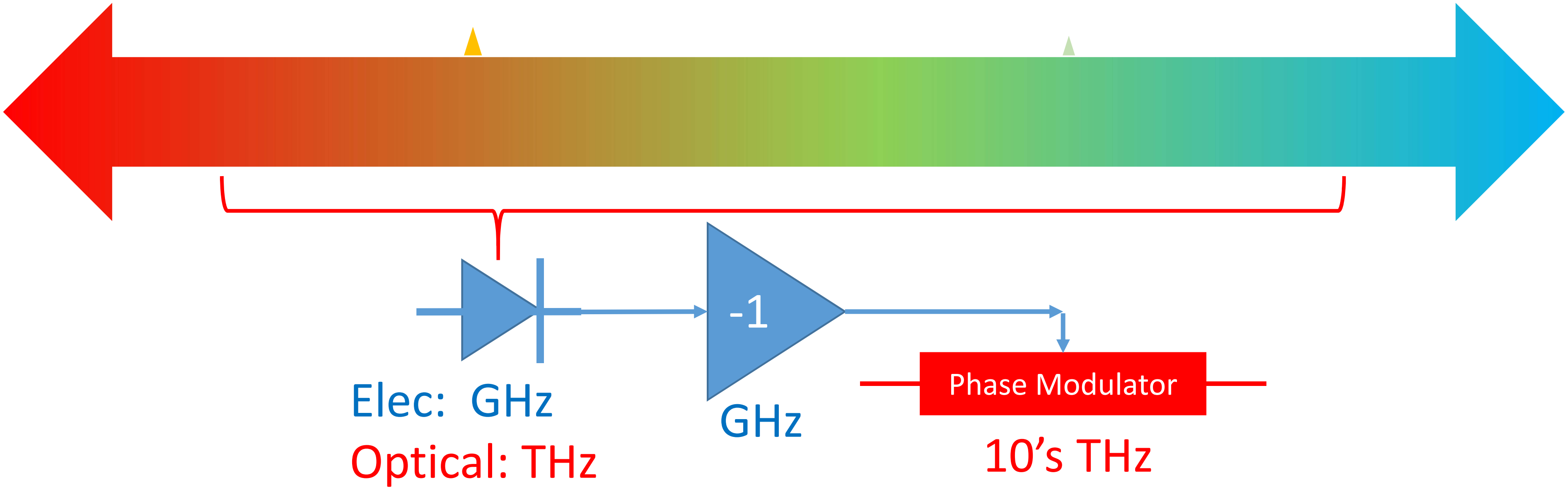
CAUSE

Phase Fluctuations

So the intensity fluctuations have a limited bandwidth!
Electronics might help!

A moment of realisation!

The electrical components are working to mitigate THz of optical interactions!



Elec: GHz
Optical: THz

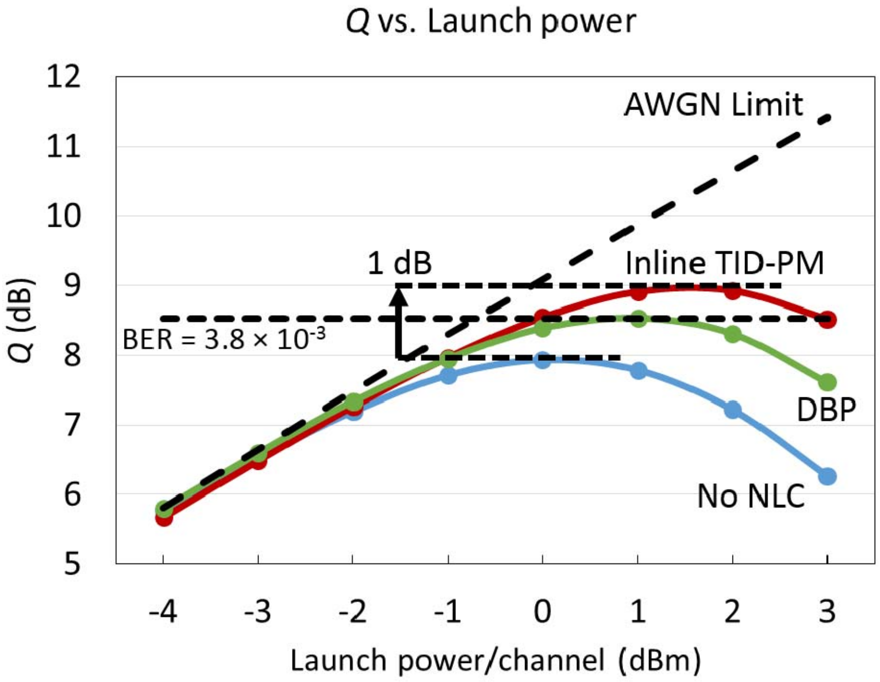
GHz

10’s THz

Our “Electro-Optic” approach is surprisingly simple: we detect the total intensity all (or groups) of wavelength channels in WDM systems with a single photodetector; we then undo the Kerr phase shift in all wavelengths with a single phase modulator [16]. The surprise is that the photodetector does not need terahertz of electrical bandwidth, indeed it only requires a few gigahertz of bandwidth. This is because walk-off in the fiber restricts the bandwidth of the XPM and FWM effects, so that only GHz frequencies cause significant XPM and SPM. This observation can also be used to increase the computational efficiency of DBP algorithms. We have recently been studying the use of multiple Kerr-nonlinearity compensators along the length of a system, and the effect of polarization on this technique [17].

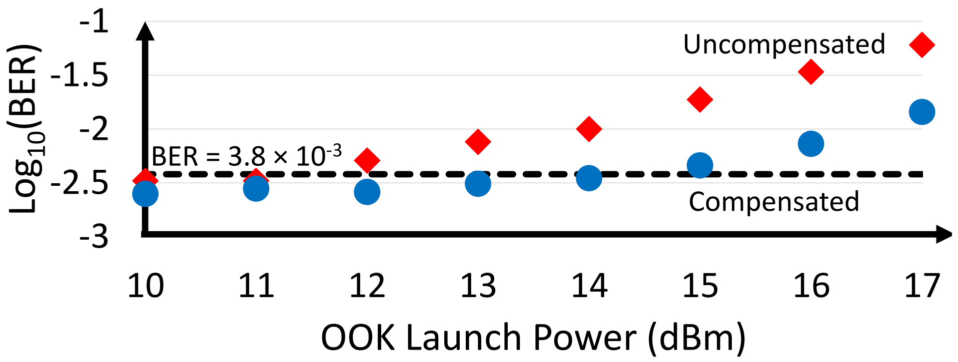
Wideband Nonlinearity Compensation

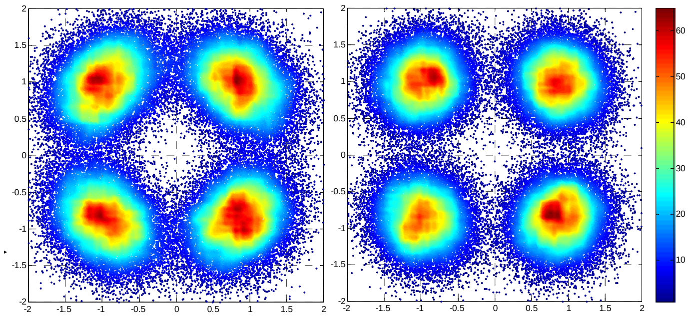
Simulated: Distributed along link



Ben Foo, Bill Corcoran, Chen Zhu, Arthur J Lowery "Distributed Nonlinearity Compensation of Dual-Polarization Signals Using Optoelectronics, " IEEE Photonics Technology Letters 28 (20), 2141-2144

Experimental OOK-> QPSK





Uncompensated Compensated
14 dBm OOK Launch Power

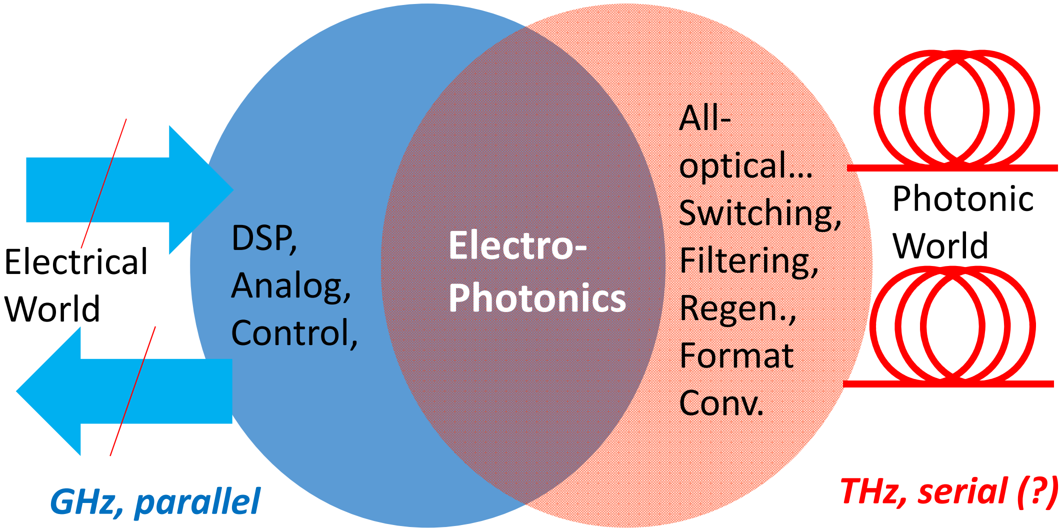
So What’s Possible in Electro-Photonics?

- All-optical signal generation (OFDM/NWDM)
  - Moving the signal shaping to the optical side
  - Requires parallelism/ integration of modulators
  - Photonic Integrated Circuits

- Digital Signal Processing
  - for dispersion, PMD and nonlinearity compensation
  - But also for adaptive filtering and crosstalk mitigation
  - Can some of it be performed optically?

- ADCs/DACs to support DSP
  - possibility of electro-optical DACs (Green)

- Specialised circuits
  - Fast Optical Signals to Parallel Electrical Signals
  - Delay discriminators
  - Wadley Loops



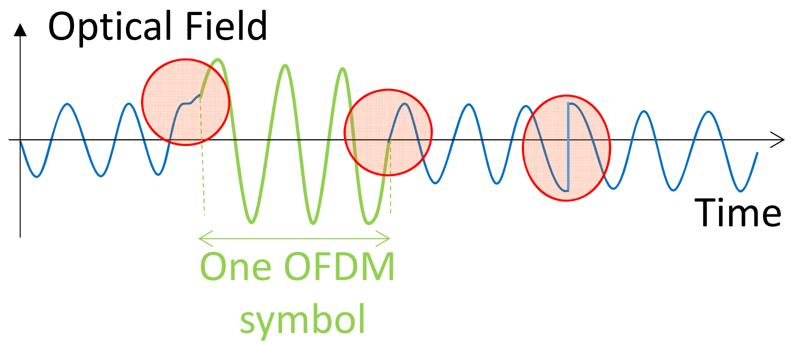
Example 1: Universal Transmitters

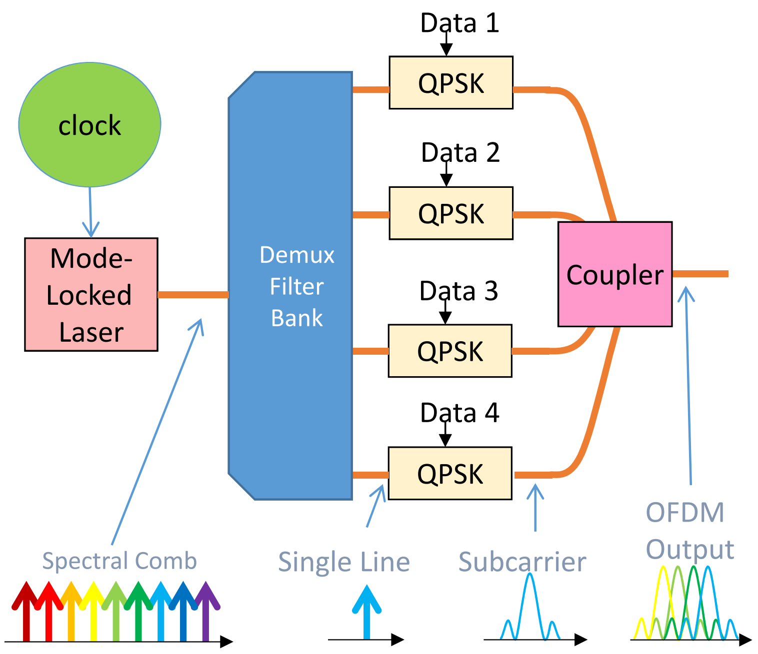
- Traditionally, the communications signals were shaped by the electrical circuitry
  - Root-Raised Cosine
  - OFDM using Fast Fourier Transforms
- *Though some OTDM systems used laser pulses as the shape*
- Such systems rely on fast modulators
  - Especially OFDM… let’s have a look….

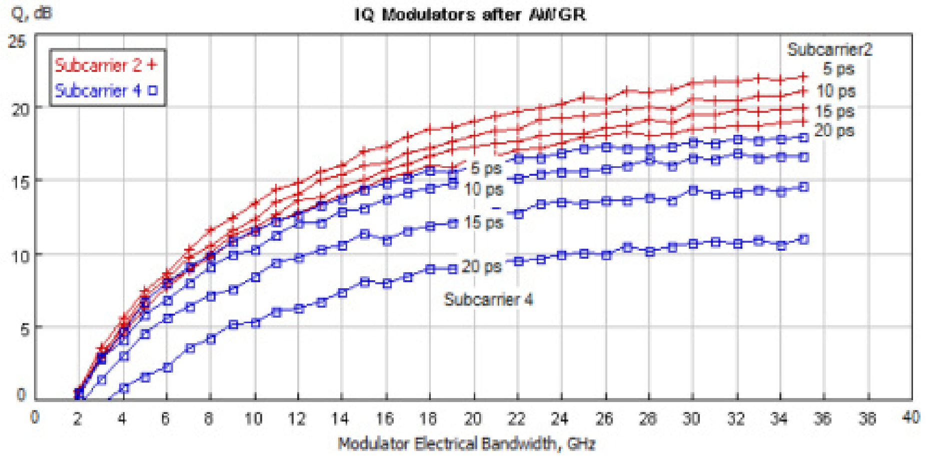
SUMMARY: We have also developed ‘universal’ transmitters in which an optical processor shapes optical pulses to define their spectra and central wavelength [6]. Our preferred approach is to modulate pulses from a mode-locked laser with one or more modulators; the advantage is that the modulator need only be in the correct state when the pulse passes through it. Thus, for example, ringing and slow transitions of the electrical drive waveforms may not matter. The shaping can be achieved by a Waveshaper™ for example, and interestingly, the modulation forms a ‘white’ spectrum, so the modulated signal can be assigned to any (or multiple) wavelengths, and not just the frequencies of the mode-locked lasers comb spectrum [7]. The shaping can also simultaneously different modulation formats, such as Nyquist-WDM, Optical Time-Division Multiplexing and Optical OFDM. This is very useful for loading the C-band with a variety of test channels, for example, but could also be used for format conversion.

Traditional Filter (CW) then Modulate

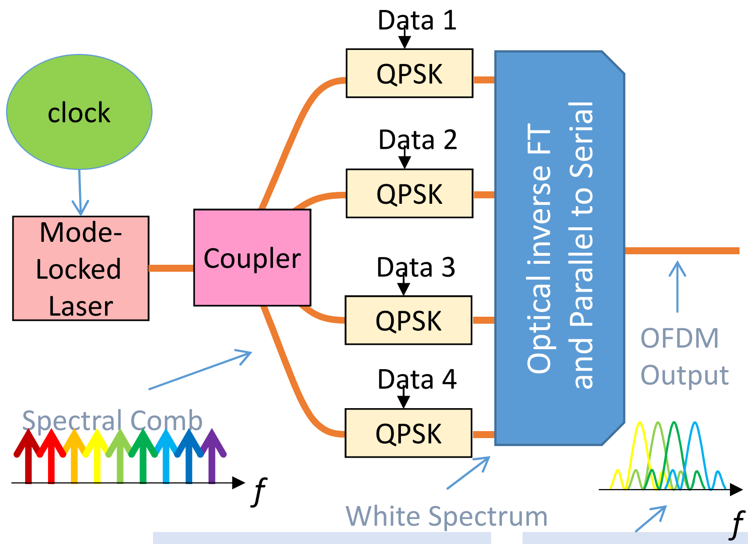
- Slow transitions cause inter-(sub) carrier interference
- 4 × 10 Gsymbols/ Second system







Modulate-then-Shape Increases Bandwidth



clock

Mode-Locked Laser

Coupler

Data 1

QPSK

Data 2

QPSK

Data 3

QPSK

Data 4

QPSK

Optical inverse FT and Parallel to Serial

OFDM Output

Spectral Comb

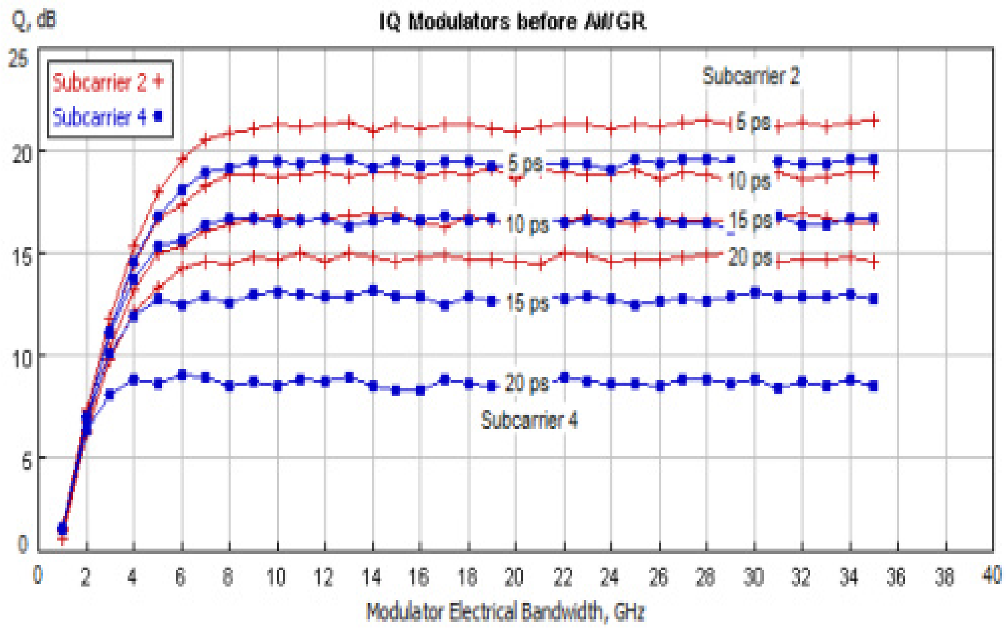
f

White Spectrum

f

The modulator turns each line into sinc; the result is a flat-top spectrum

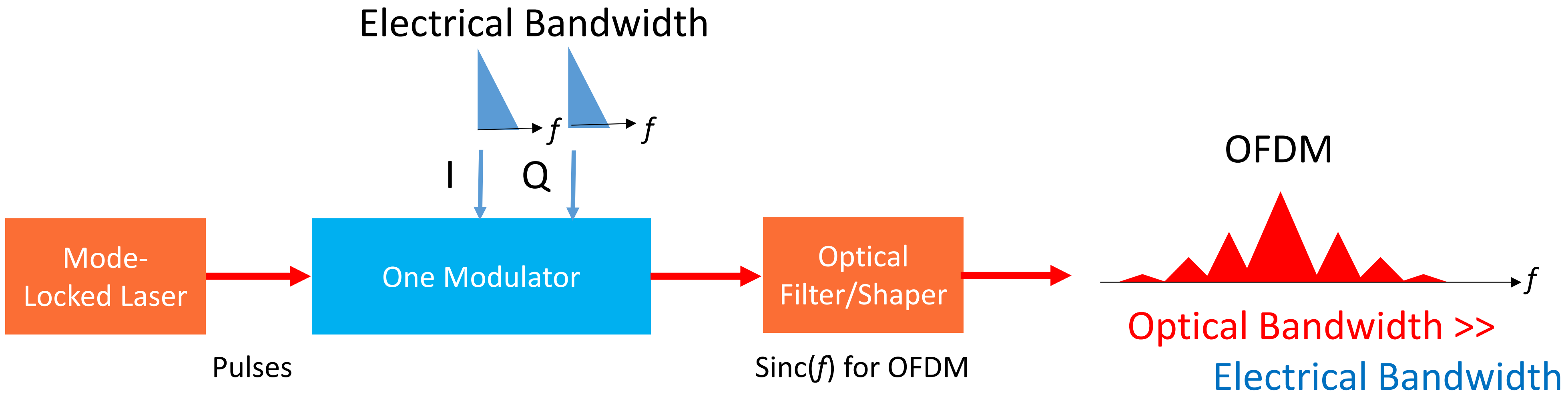
The FT creates a subcarrier from each input



- Note how, in this case, low-bandwidth modulators provide good signal quality.

1. K. Lee, C. T. D. Thai, and J.-K. K. Rhee, Opt. Express **16**(6), 4023–4028 (2008)
2. Y-K. Huang, D. Qian, R. E. Saperstein, P. N. Ji, N. Cvijetic, L. Xu, and T. Wang, OFC 2009, paper OTuM4.
3. A. .J. Lowery & L. B. Du, Opt. Exp., 19, 15696-15704 (2011)
4. J. Schröder, et al., J. Lightwave Technol., 32, (2014) pp. 752-759

Key: Modulate-then-Shape Increases Bandwidth



Electrical Bandwidth

I

Q

OFDM

Mode-Locked Laser

One Modulator

Optical Filter/Shaper

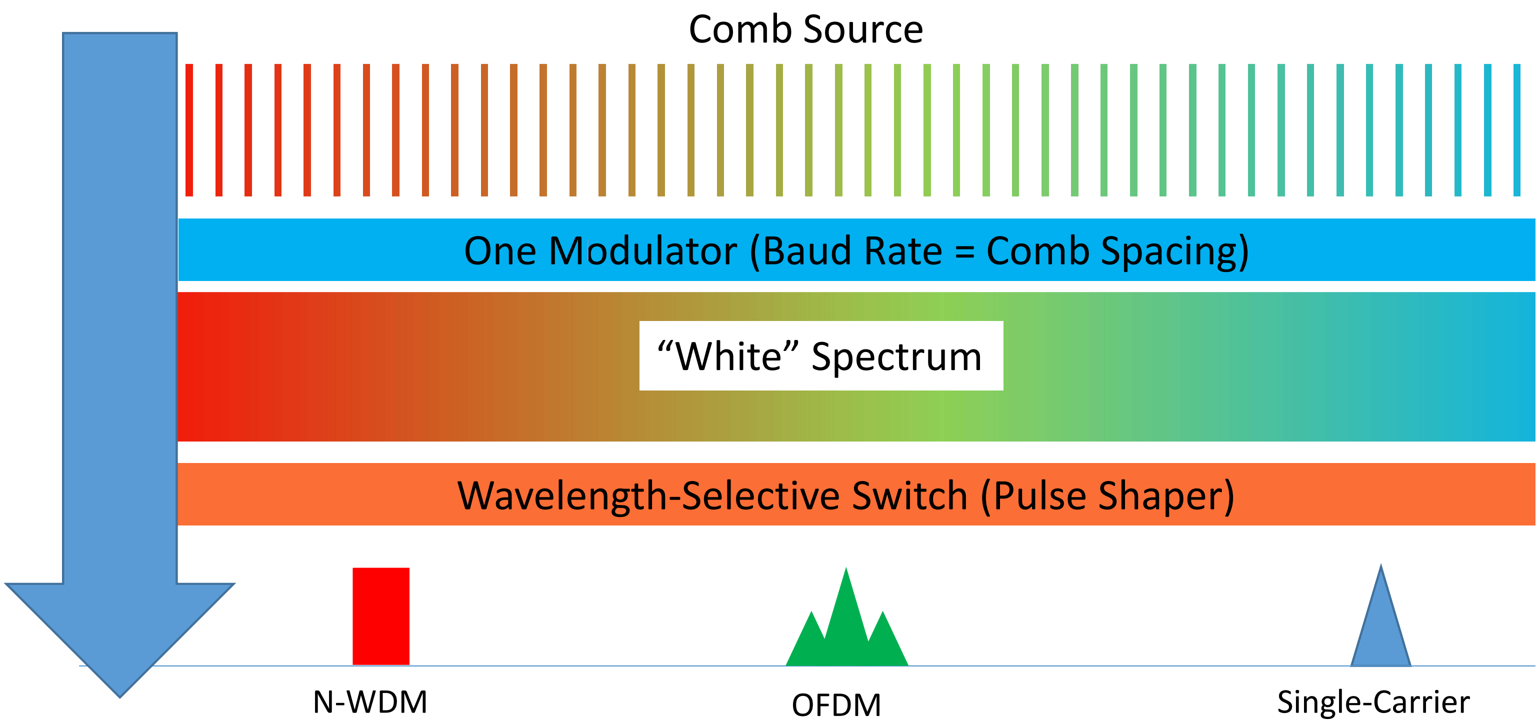
Pulses

Sinc(*f*) for OFDM

Optical Bandwidth >>
Electrical Bandwidth

The key advantage shown here is that the bandwidth of the modulated optical signal bandwidth exceeds the bandwidth of the electrical drive signals.

Universal Transmitters: Frequency Domain



Comb Source

One Modulator (Baud Rate = Comb Spacing)

“White” Spectrum

Wavelength-Selective Switch (Pulse Shaper)

N-WDM

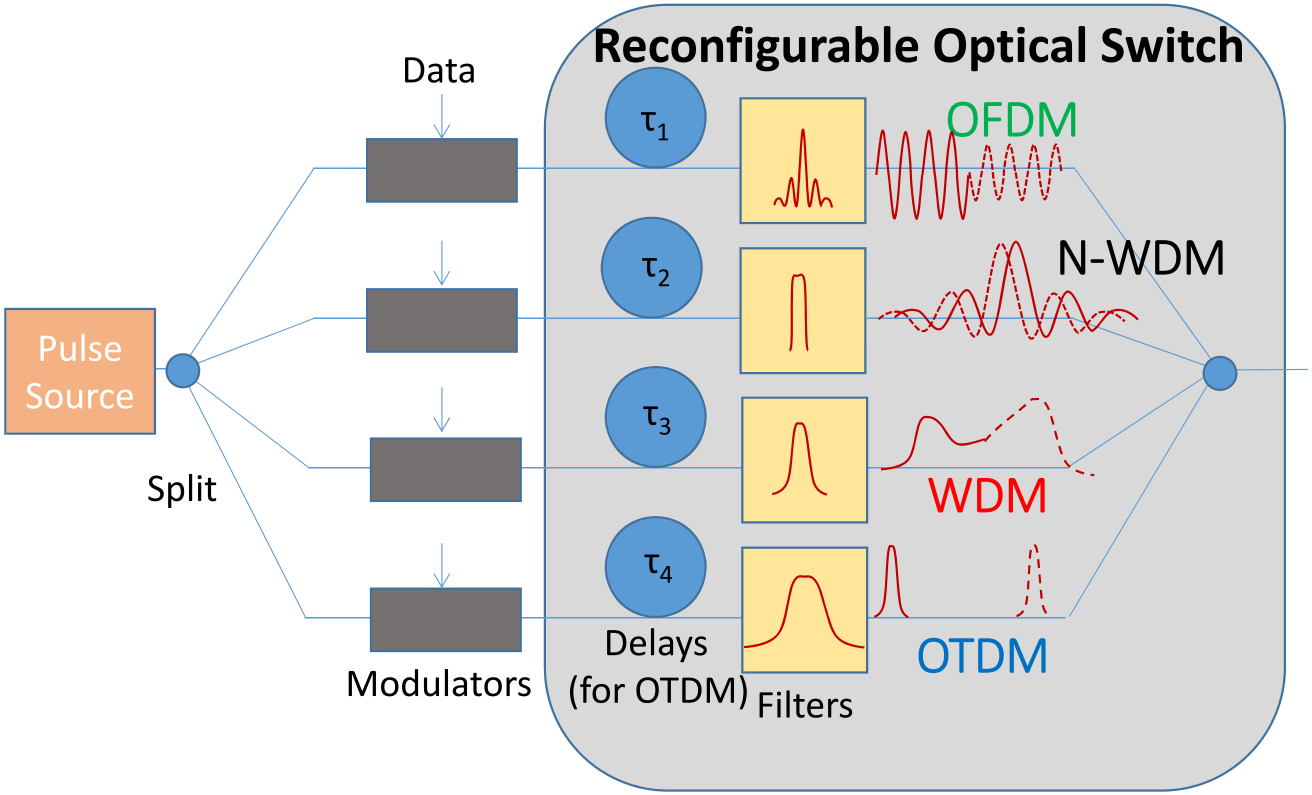
OFDM

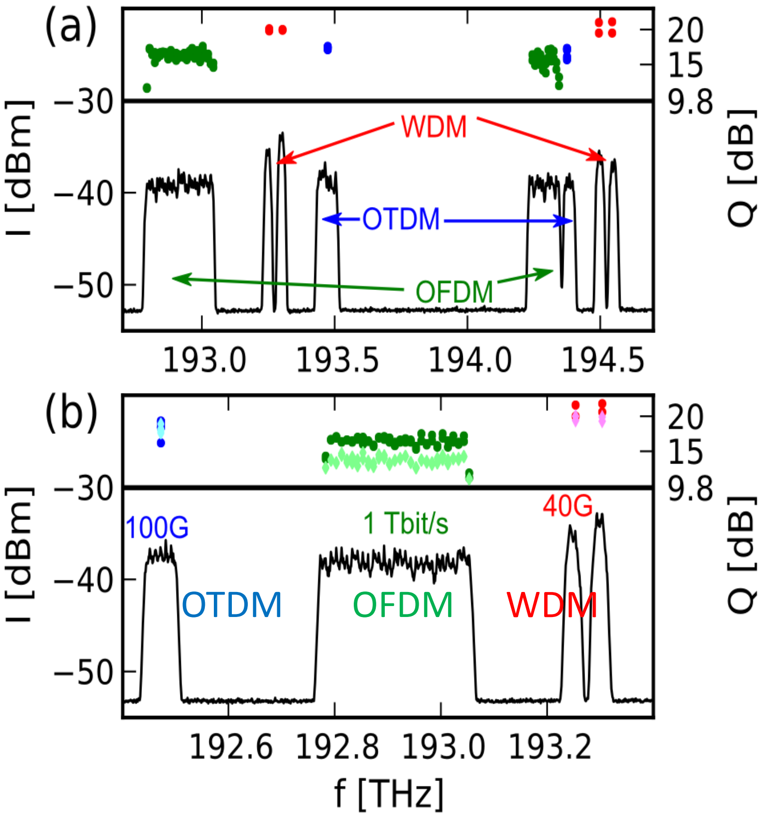
Single-Carrier

How can a single system provide different modulation formats at any wavelength, even between the comb lines?

For the answer, see: A. J. Lowery, J. Schröder, and L. B. Du, "Flexible all-optical frequency allocation of OFDM subcarriers," *Opt. Express,* vol. 22, pp. 1045-1057, 2014/01/13 2014.

Signal Shaping: Universal Transmitters

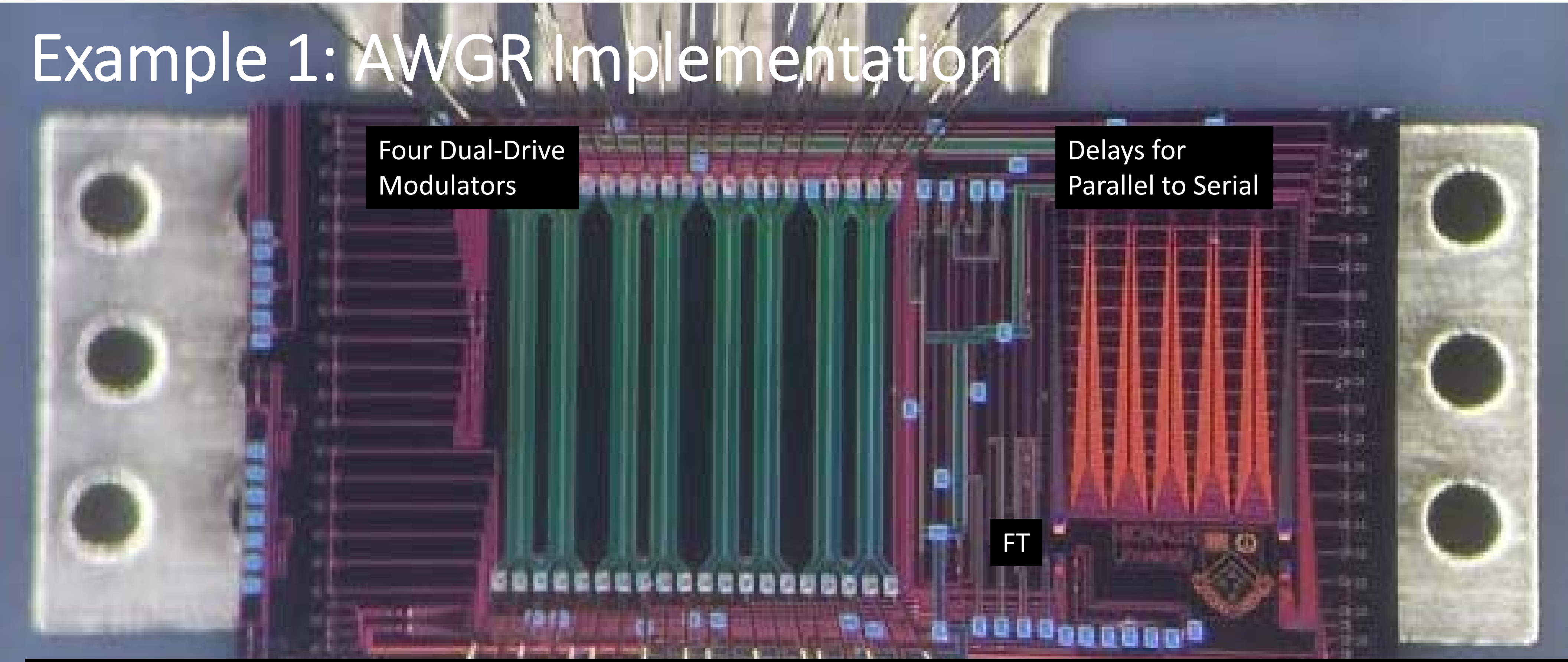




Jochen Schröder, *et al.*, "An optical FPGA: Reconfigurable simultaneous multi-output spectral pulse-shaping for linear optical processing," Opt. Express 21, 690-697 (2013)

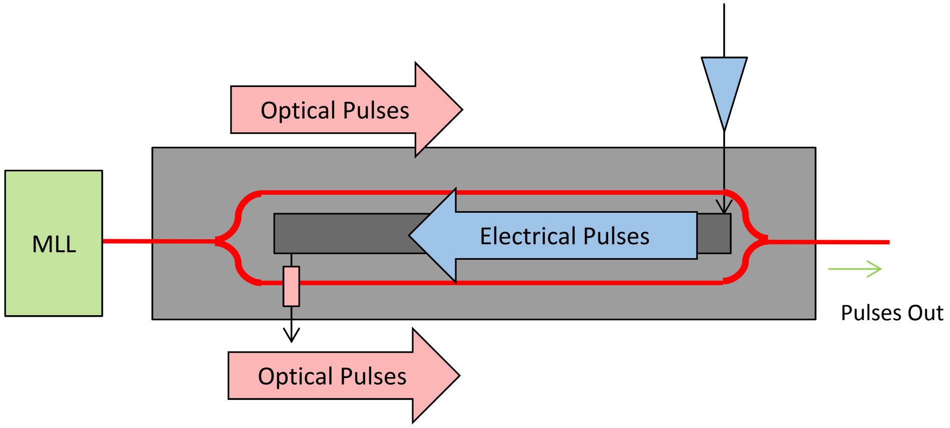
J. B. Schroeder, L. B. Du, M. M. Morshed, B. Eggleton, and A. J. Lowery, "Colorless Flexible Signal Generator for Elastic Networks and Rapid Prototyping," in Optical Fiber Communication Conference 2013, paper JW2A.44.

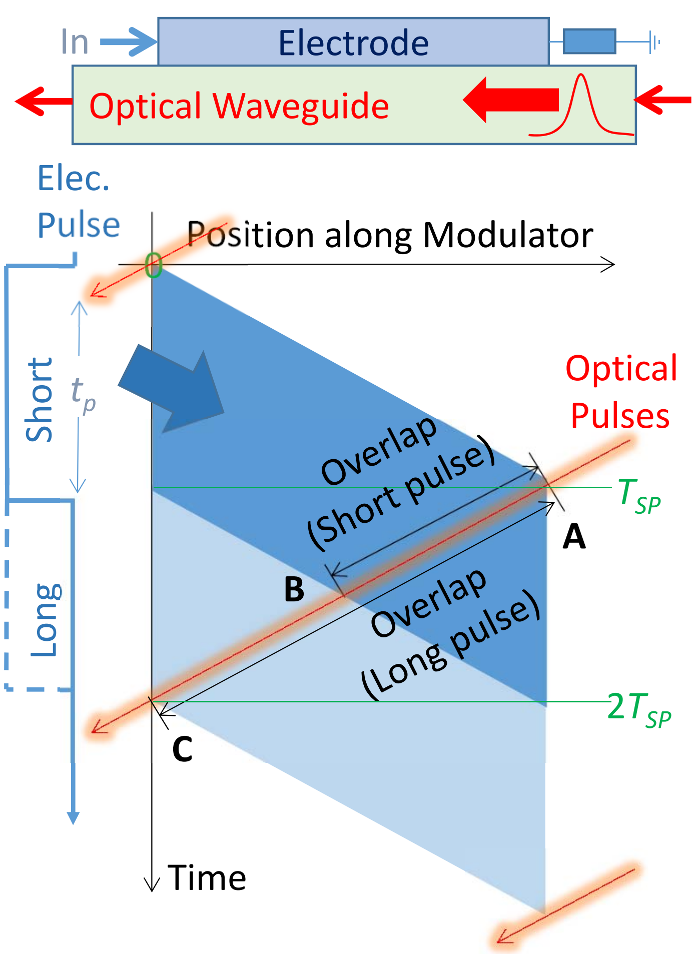
Example 1: AWGR Implementation



Whist the Waveshaper provides flexibility, we have also demonstrated PICs for creating multi-wavelength transmitters. With some modifications, Arrayed Waveguide Grating Routers (AWGRs) can be used as (inverse/forward) optical Fourier transforms (with inbuilt parallel-serial/serial-parallel conversion), and so are the basis of all-optical OFDM transmitters and receivers. We have shown that Ring-Assisted Mach-Zehnder Interferometers (RAMZIs) produce near-Nyquist pulses with very sharp roll-offs, and can also be used to upgrade the spectral efficiencies of wavelength-selective switches (ROADMs).

Example 2: Low-Bandwidth DAC Modulator

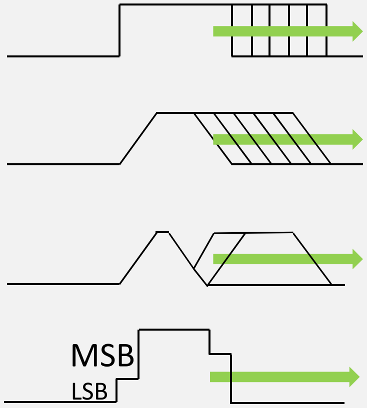




We are working on designs of optical modulators that do not require DACs. One simple method is to use a counter-propagating modulator [4]. Here the optical signal is fed into the opposite end of a LiNbO$_3$ modulator to the electrical signal. The result is that the optical phase change is a finite-duration integral of the electrical waveform. This means that a pulse-width-modulated electrical waveform is converted to an analog phase change, which can then be converted to an optical intensity variation using a Mach-Zehnder interferometer (MZI). The electrical waveform need not be very 'clean' as long as its voltage-time area is reasonably precise.

Low-Bandwidth DAC Modulator

The electronics only has to produce a pulse with a known area – it can be bandwidth limited, jittery, stepped……….

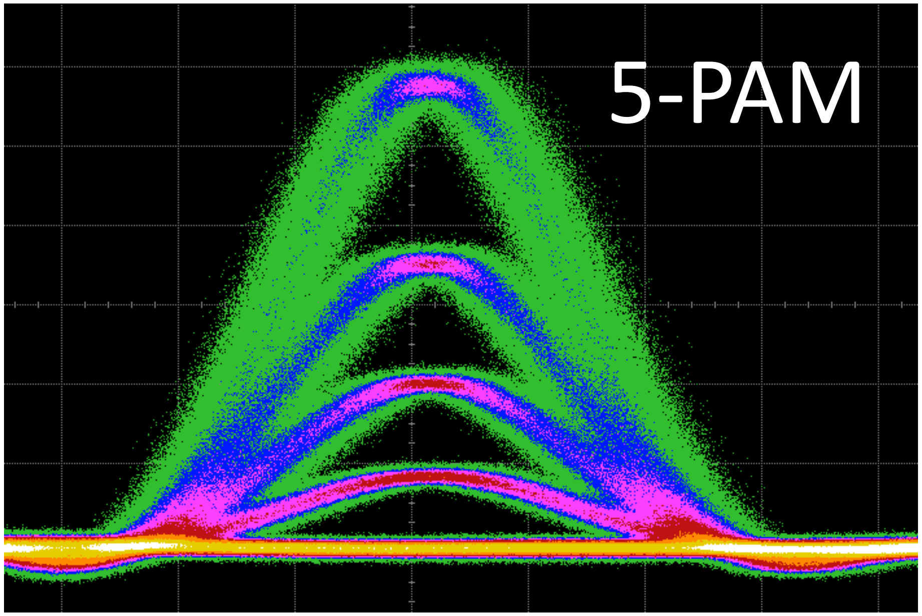


Pulse Width Modulated (PWM)

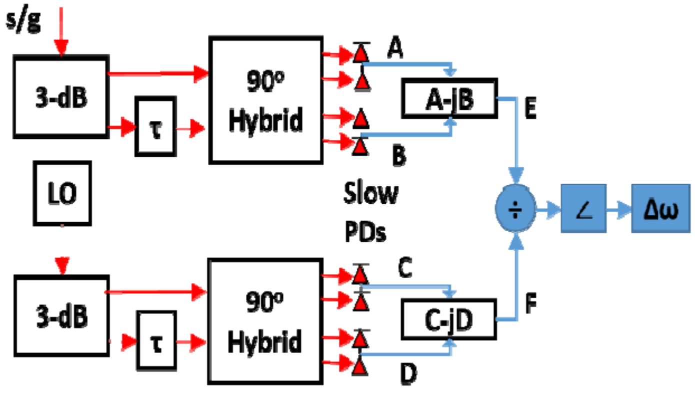
BW limited PWM

BW Limited Pulse Density Modulated

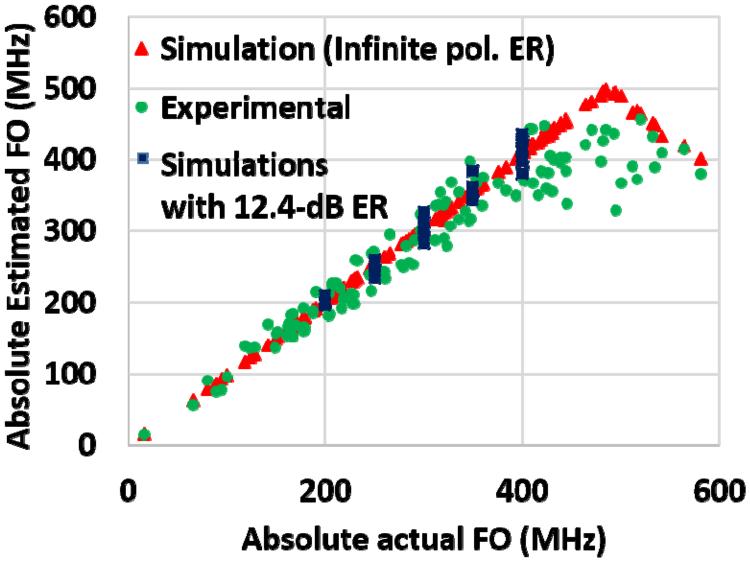
Unsynchronised DAC



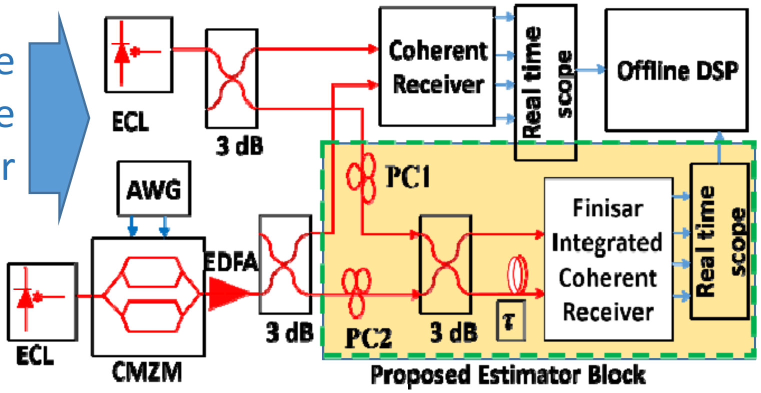
Example 3: Carrier-Offset Estimation



The idea is to estimate the carrier offset using autocorrelations of both the signal and the Local Oscillator



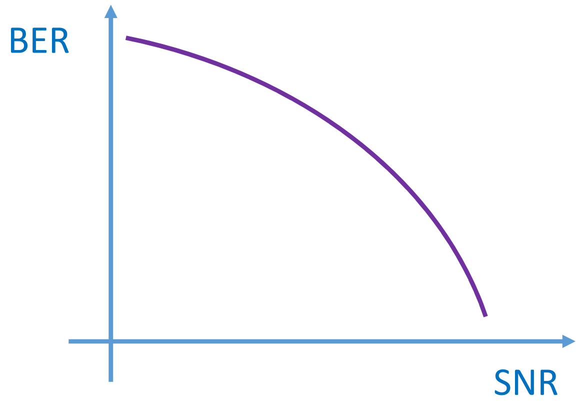
Both correlations can be achieved with a single Coherent Receiver



Jokhakar Jignesh *et al.* "Electro-Optic Frequency Offset Estimator for Optical OFDM," European Conference on Optical Communications (ECOC 2016), held from September 18th to 22nd, 2016 in Düsseldorf, Germany

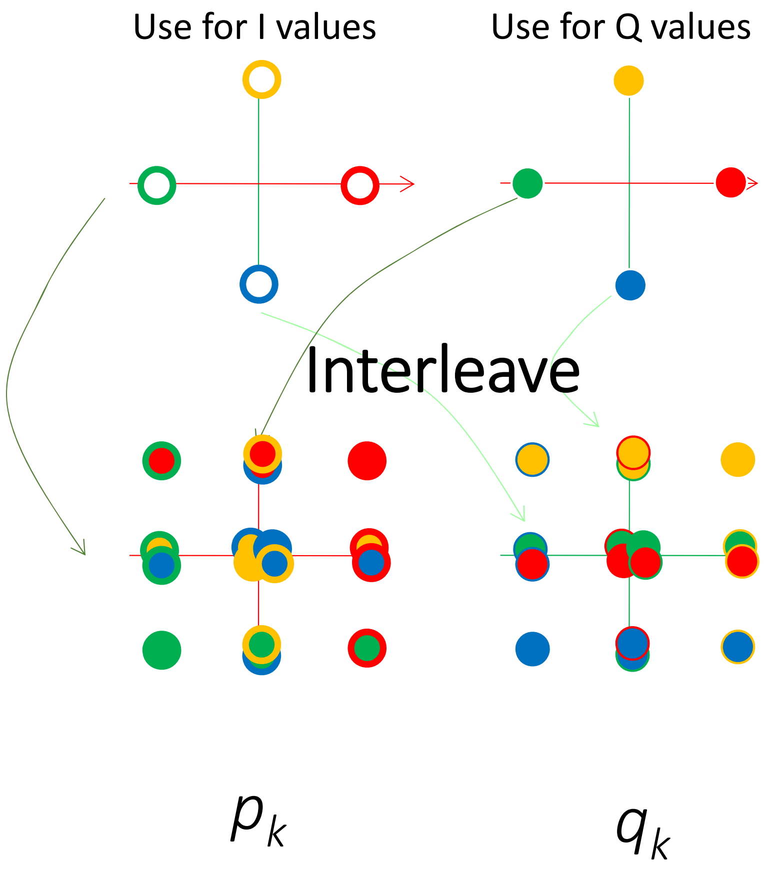
Example 4: Pairwise coding – dBQ for Free

- General Idea: Good Channel + Bad Channel produces far more errors than a two moderately-bad channels
- Coding method – interleaving and scaling
- Applications
  - DDO-OFDM
  - PDL
  - ROADMs



Our interest has been in pairwise coding, where data is interleaved across ‘good’ and ‘bad’ channels to provide a better overall BER than simply adding the BERs of the two independent channels. We first considered good and bad channels in direct-detection optical-OFDM systems [21]. A more common application is across good and bad polarizations in polarization-multiplexed systems with polarization-dependent loss [22], or for side and edge subcarriers passing through ROADMs [23].

Pairwise coding: Relies on interleaving…



p_k

q_k

For a detailed explanation, see:

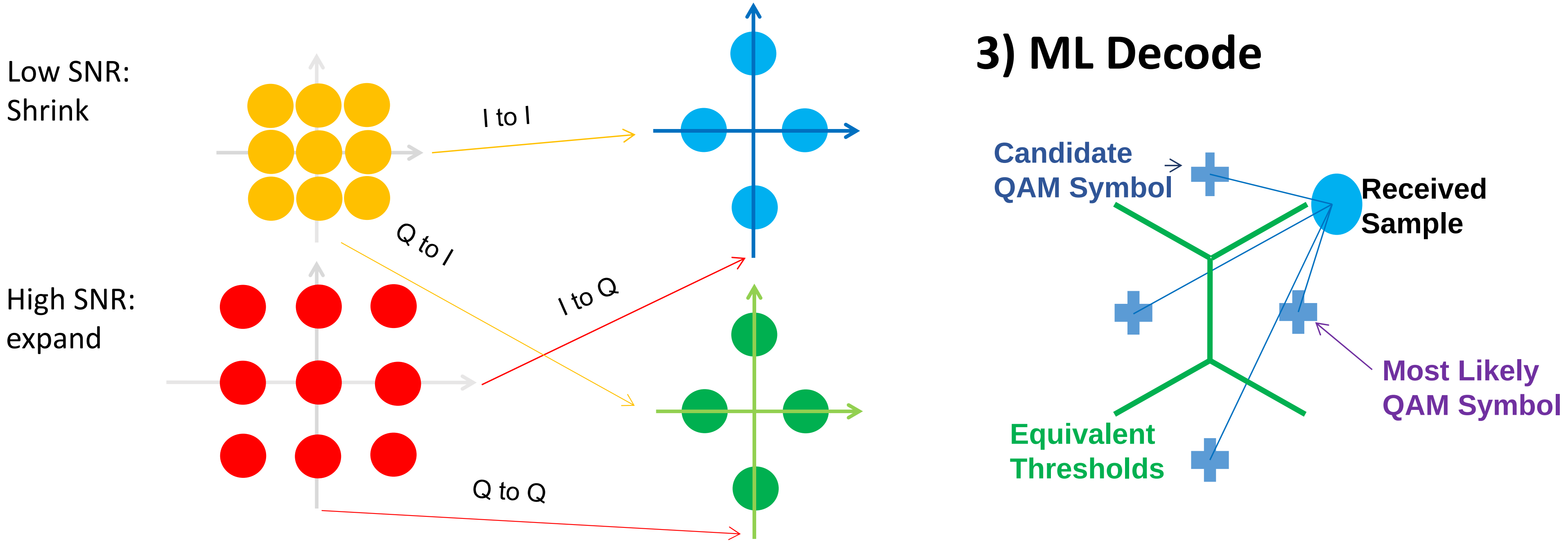
Yi Hong, A. J. Lowery, and Emanuele Viterbo, "Sensitivity improvement and carrier power reduction in direct-detection optical OFDM systems by subcarrier pairing," Opt. Express 20, 1635-1648 (2012)

Pairwise decoding: Receiver

1) Scale (spots to same size)

2) Deinterleave

3) ML Decode



Pairwise coding: Applications Examples

- Polarization Dependent Loss (PDL)

  Pair X and Y polarizations: only one is bad at a time

Chen Zhu, Binhuang Song, Bill Corcoran, Leimeng Zhuang, and Arthur James Lowery, "Improved polarization dependent loss tolerance for polarization multiplexed coherent optical systems by polarization pairwise coding", Opt. Express 23(21), 27434-27447 (2015)

- ROADMs and Superchannels

  The Left and Right edges of a channel: only one will be bad due to frequency drift

Chen Zhu, Binhuang Song, Leimeng Zhuang, Bill Corcoran, and Arthur James Lowery, "Subband Pairwise Coding for Robust Nyquist-WDM Superchannel Transmission," J. Lightwave Technol. 34, 1746-1753 (2016)

Chen Zhu, Bill Corcoran, Leimeng Zhuang, and Arthur J. Lowery, "Doubling the ROADM Sites using Pairwise Coding for 4%-Guard-Band Superchannels," Optical Fiber Communications, OFC2016, Anaheim, CA, paper Th1D1

- Direct-Detection Optical-OFDM

  Pair low-frequency and high-frequency subcarriers: only some are affected by signal-signal beating noise

Yi Hong, A. J. Lowery, and Emanuele Viterbo, "Sensitivity improvement and carrier power reduction in direct-detection optical OFDM systems by subcarrier pairing," Opt. Express 20, 1635-1648 (2012)

Example 4: Electro-Photonic Curiosities

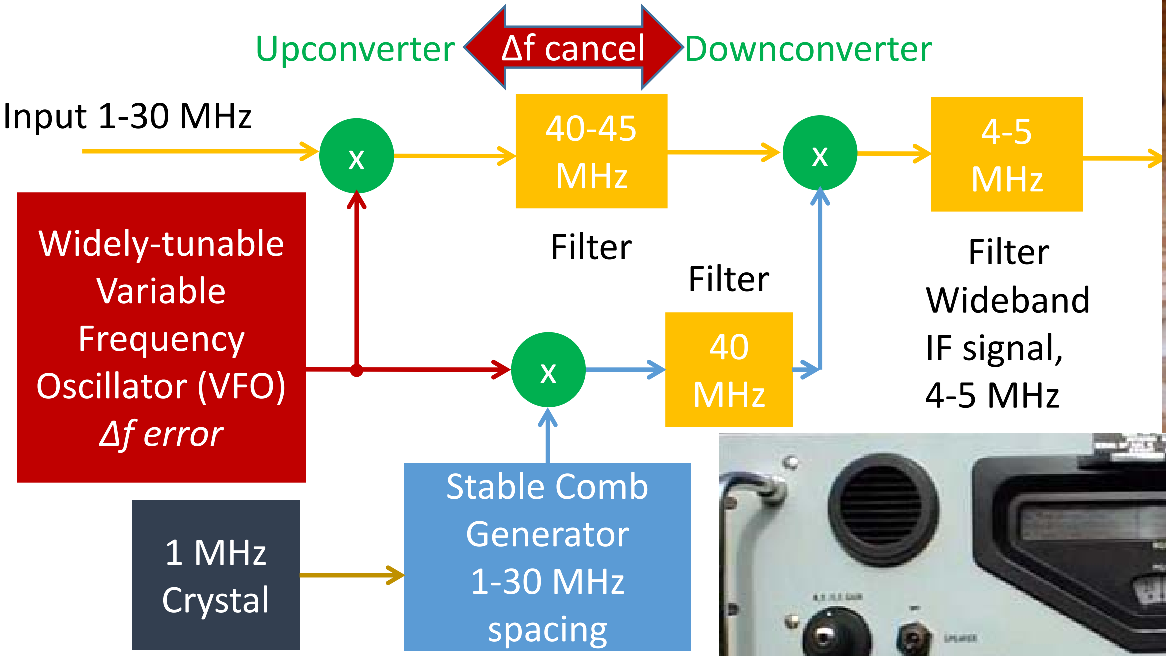
- Wadley Loop – rapidly *tunable* but *stable* comb-locked receiver

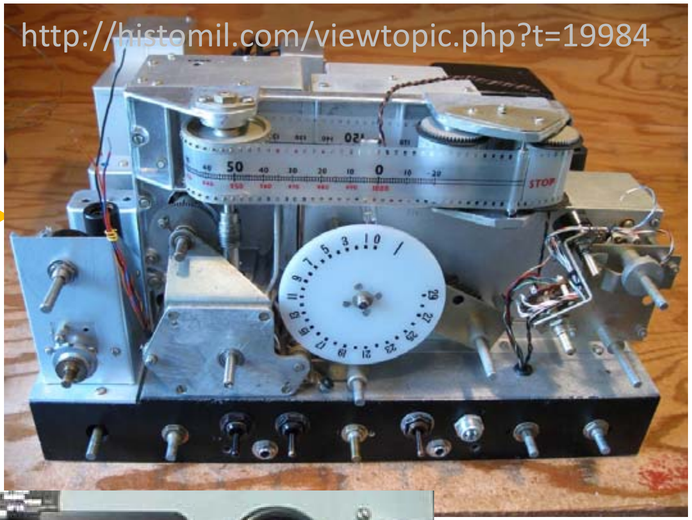
One problem with coherent optical systems is creating a compact tunable laser that also has a narrow linewidth and can be tuned rapidly, for a local oscillator. A similar situation occurred with radio receivers in the 1950's, where tuned-circuit local oscillators (LC oscillators) could not provide the stability to remain tuned on narrow-bandwidth military audio channels: the alternative was fixed crystals. The Wadley loop ingeniously solved this issue by combining the stability of a single crystal with the wide-tunability of an LC oscillator [18]. Recently we have demonstrated the same approach in an electro-optic system, where the stability of a mode-locked laser is combined with a widely-tunable laser, using multiple mixing processes [19]. This means that the variable-frequency outputs of multiple tunable lasers can be quantized to the comb-spectrum of a single mode-locked laser, which could be the master oscillator for a whole exchange, or indeed, network.

- Pulse Delay Measurement (SOA Pulse discriminator)
  - ps pulses, Precise optical timing accuracy – Low-Frequency Electronics

- Sagnac Loop (integrated SOA)
  - Demultiplexing of OTDM signals using a clock derived from the circuit above

Electro-Photonic Curiosities: RF Wadley Loop

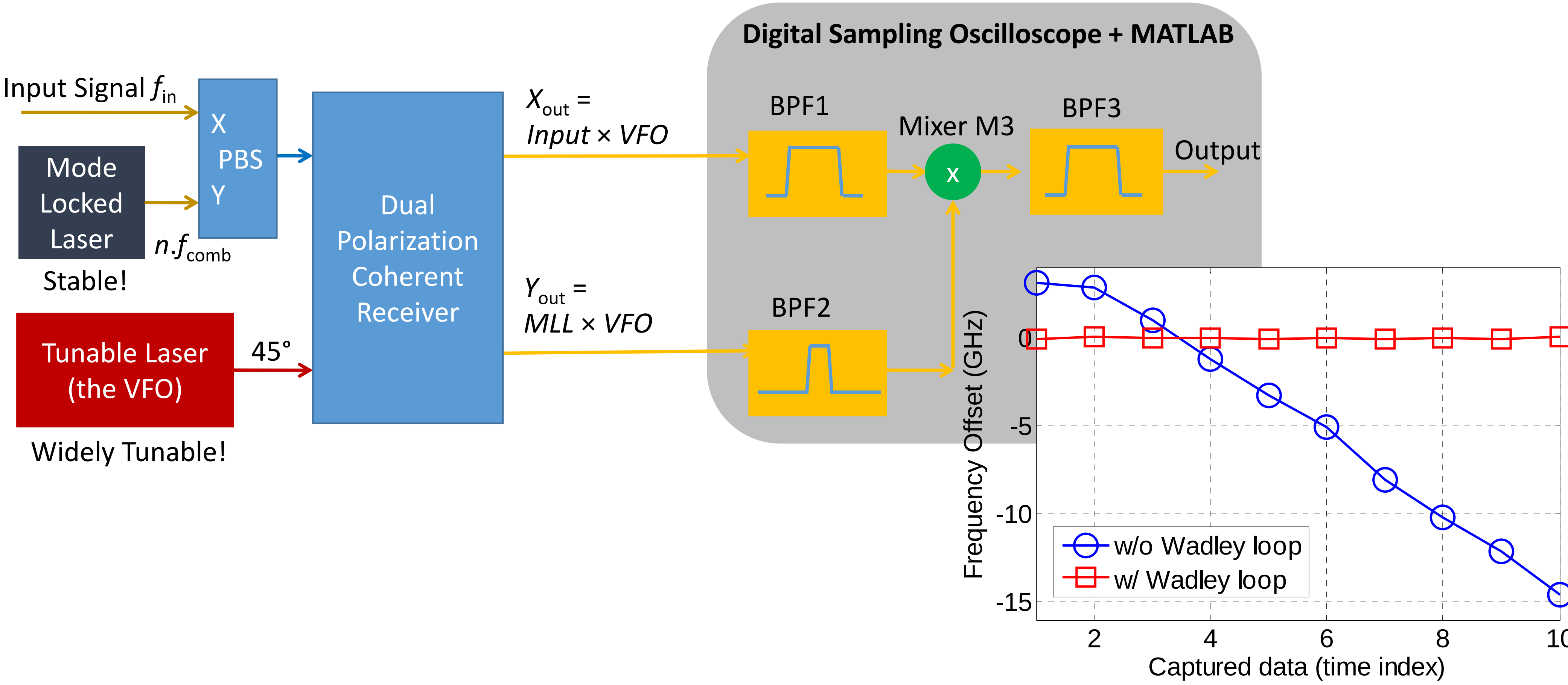



http://histomil.com/viewtopic.php?t=19984

http://armyradio.com/Racal-RA-17-HF-Communications-Receiver.html

Arthur J. Lowery, Bill Corcoran, and Chen Zhu, "Widely-tunable low-phase-noise coherent receiver using an optical Wadley loop," Opt. Express 23, 19891-19900 (2015)

Electro-Photonic Curiosities: Optical Wadley Loop



Input Signal f_{in}

Mode Locked Laser

$n.f_{comb}$

Stable!

Tunable Laser (the VFO)

45°

Widely Tunable!

X PBS Y

Dual Polarization Coherent Receiver

X_{out} = *Input × VFO*

Y_{out} = *MLL × VFO*

Digital Sampling Oscilloscope + MATLAB

BPF1

Mixer M3

x

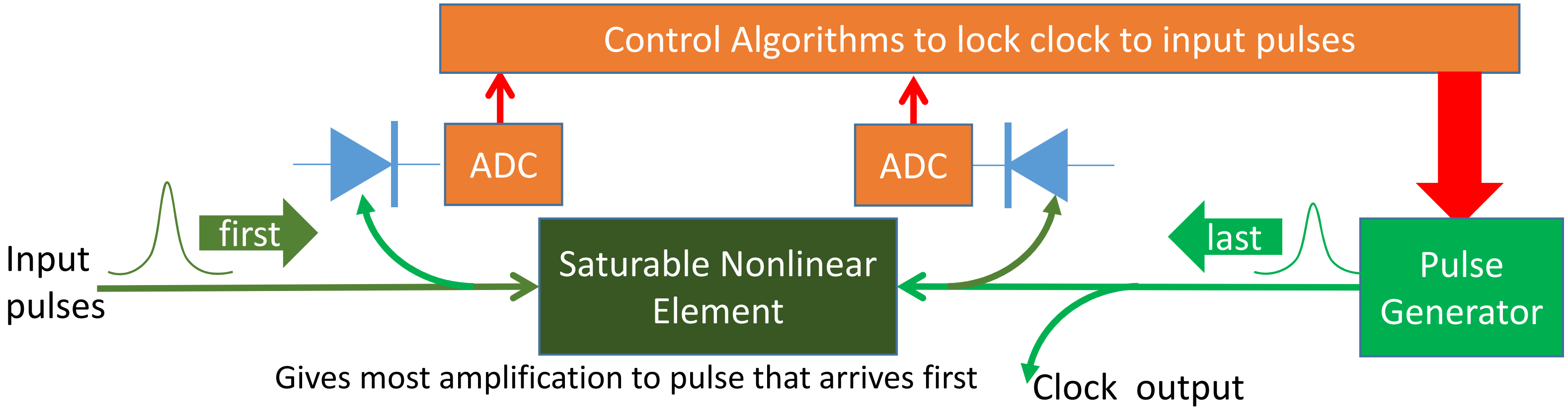
BPF3

Output

BPF2

Arthur J. Lowery, Bill Corcoran, and Chen Zhu, "Widely-tunable low-phase-noise coherent receiver using an optical Wadley loop," Opt. Express 23, 19891-19900 (2015)

Electro-Photonic Curiosities: Delay Discriminator



Control Algorithms to lock clock to input pulses

ADC

ADC

Input pulses

first

Saturable Nonlinear Element

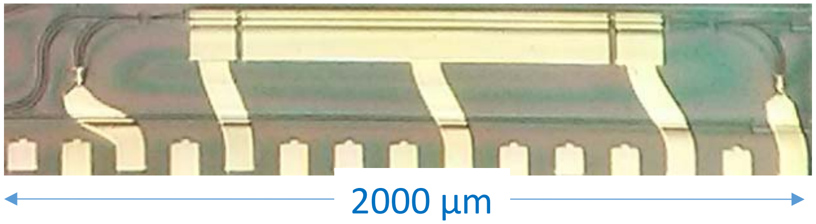
last

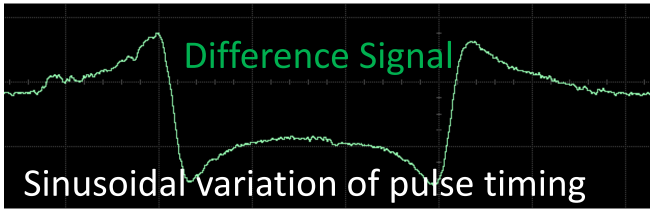
Pulse Generator

Gives most amplification to pulse that arrives first

Clock output

InP platform fabricated by SMART photonics via JePPIX

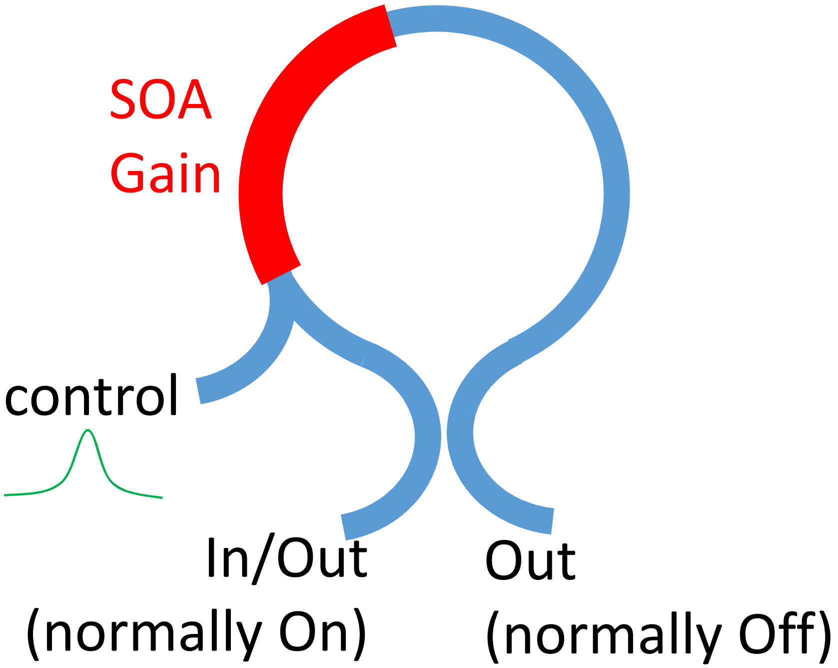




Another common electrical circuit locks a clock to a data stream—clock recovery. This relies on a phase detector. Our electro-optical equivalent is a delay discriminator, which compares the timing of incoming optical pulses to locally generated clock pulses [20]. Our device generates a slowly varying electrical output (kHz rates) compared to the GHz rates of the optical pulses. This is achieved by counter-propagating optical pulses within an optical amplifier; the first pulse to enter the amplifier gets the most gain: the second pulse sees the depleted gain due to the first pulse. Thus by measuring the relative intensities of the output pulse trains on a long timescale, their relative timing can be determined.

Electro-Photonic Curiosities: Sagnac Loop

The Sagnac Loop allows pulses to be sampled, perhaps using the clock generated by the delay discriminator in the previous slide.

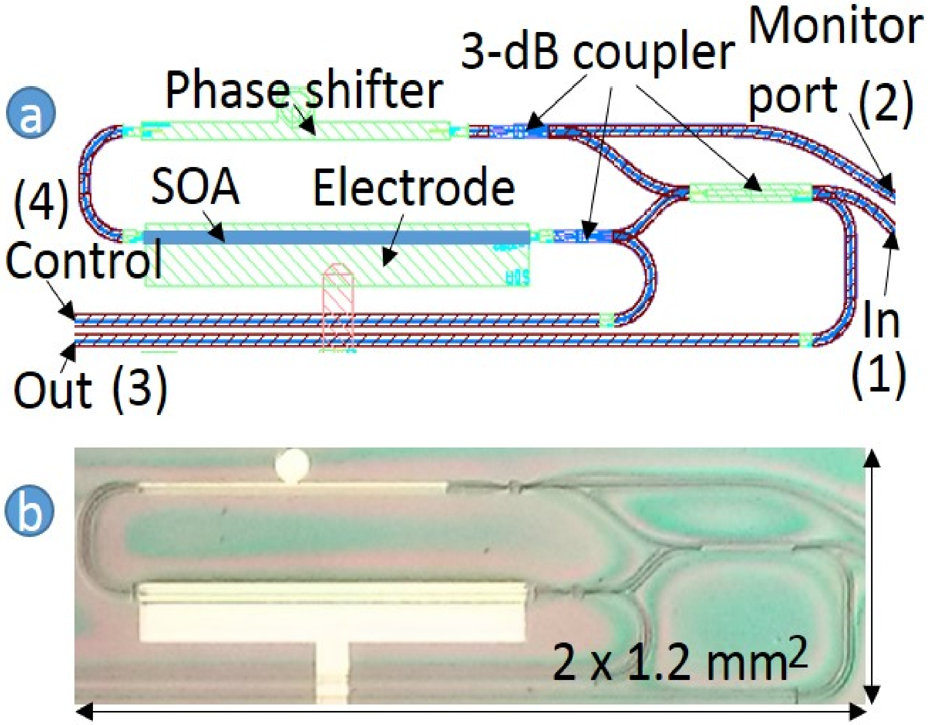


SOA
Gain

control

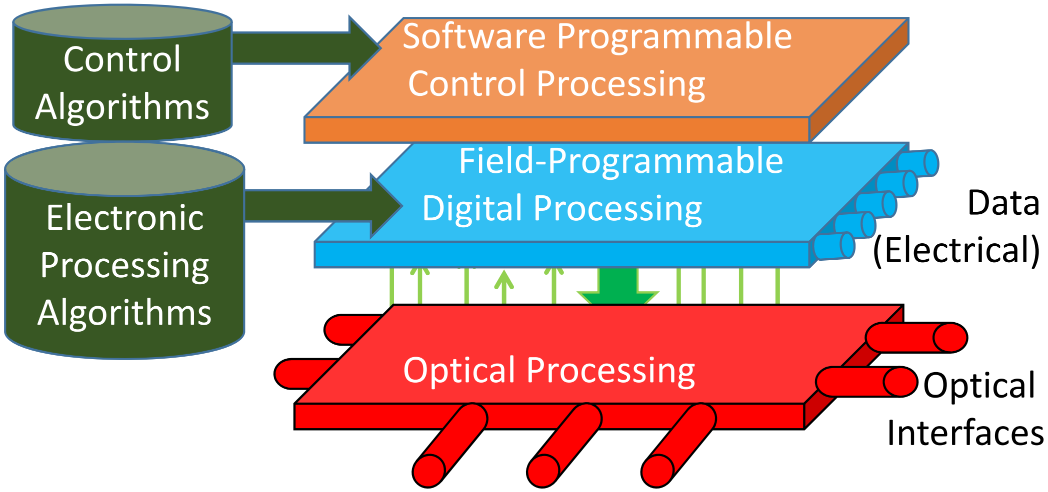
In/Out
(normally On)

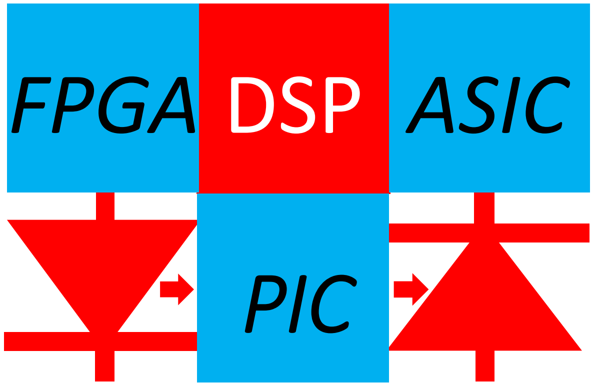
Out
(normally Off)



Leimeng Zhuang *et al.* "On-chip Optical Sampling using an Integrated SOA-based Nonlinear Optical Loop Mirror," European Conference on Optical Communications (ECOC 2015), held from September 18th to 22nd, 2016 in Düsseldorf, Germany.

The future: Integration of Photonics and Electronics





Electro-photonics benefits from considering combinations of photonic and electronic technologies to address current problems in generating, processing and receiving high-rate data communications channels. PICs can provide very wide communications capacities, but surprisingly, slow electronics can improve such channels. A key lesson from our work is that it is best to have teams that are well schooled in diverse areas, such as communications theory, photonic technologies, and electronic and microwave sub-systems, in order to make innovative advances.

Conclusions

- How do we process the THz bandwidth of optics using only GHz Electronics?
  - Look for the bandwidths of the actual processes
    - GHz in nonlinear interactions – in intensity domain
  - Use short pulses into the modulators to expand the modulated bandwidth
    - Universal transmitters
  - Look at RF techniques to mix THz tunability with MHz accuracy
    - The Wadley loop
  - Use Electro-Photonic Devices to extract MHz control signals from picosecond processes
    - SOA Discriminators

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