FPGA DSP ASIC PIC

Monash Electro-Photonics Laboratory

Application of Photonic Circuits for Optical ODFM and Nyquist WDM

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This OFC 2016 conference presentation was written up as:

A. Lowery, L. Zhuang, B. Corcoran, C. Zhu, and Y. Xie, "Photonic Circuit Topologies for Optical OFDM and Nyquist WDM," J. Lightwave Technology, DOI: 10.1109/JLT.2016.2618388 (In Press Nov. 2016, Web version avaliable) PDF

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Summary

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- Introduction
- Optical OFDM
  - Transmitter and receiver topologies
  - Implementing the Fourier transforms
  - DFT-spread OFDM
- Nyquist WDM
  - Transmitter and receiver topologies
  - Ring-Assisted Mach Zehnder Interferometers (RAMZI)
- Other closely-related signal formats
  - Chirped OFDM and Orthogonal TDM
  - Banded OFDM
- Conclusions

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Introduction

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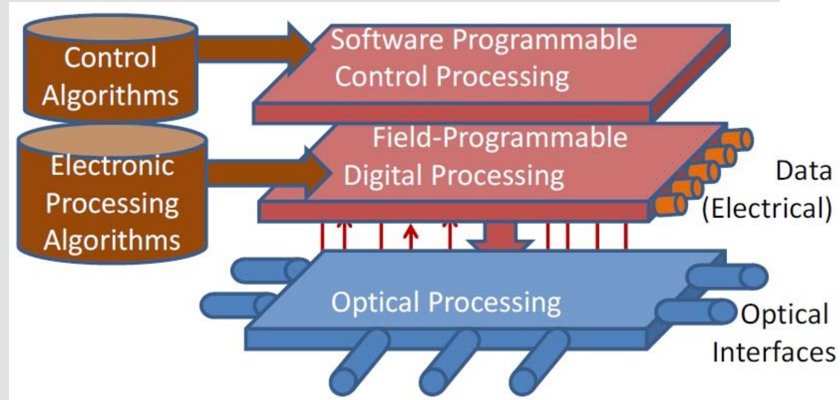
- Motivations
  - Compact (low volume)
  - High Bandwidth
  - High Spectral Efficiency
  - Multiple Channels / Superchannels
  - Low manufacturing costs
  - Reduced load on the electronic processing



- Aim is to use optimum combinations of DSP and OSP

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Disclaimers/Thanks

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- This is a talk about the topologies of circuits with some examples of implementation
  - Not about the technologies and fabrication of photonic chips
- I'd like to thank my research group, collaborators and service providers
  - Monash Electro-Photonics Laboratory
  - Foundries: IMEC, LioniX BV
  - Australian Research Council's Laureate Fellowship Scheme (FL130100041)
  - The Australian Research Council Centre of Excellence for Ultrahigh bandwidth Devices for Optical Systems, CUDOS (CE110001018)
  - Generous support from Monash University

OFDM

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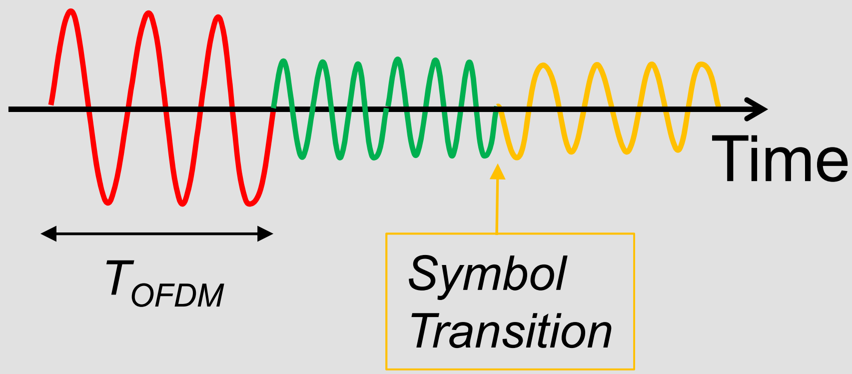
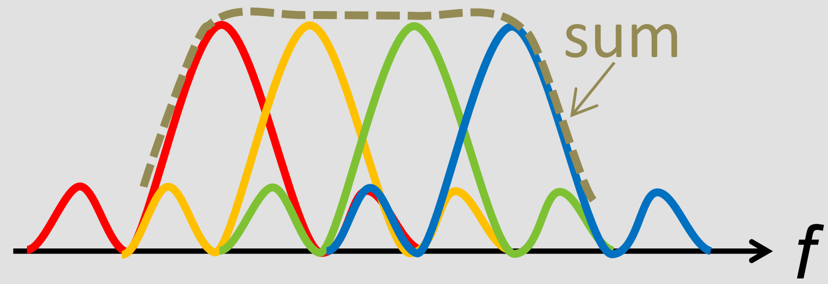
At the Transmitter

(only one subcarrier shown in each symbol)





No CP: $T_{OFDM} = 1/R$

A. J. Lowery and L. B. Du, "Optical orthogonal frequency division multiplexing for long haul optical communications: A review of the last five years," *Optical Fiber Technol.*, vol. 17, pp. 421-438 2011.

OFDM

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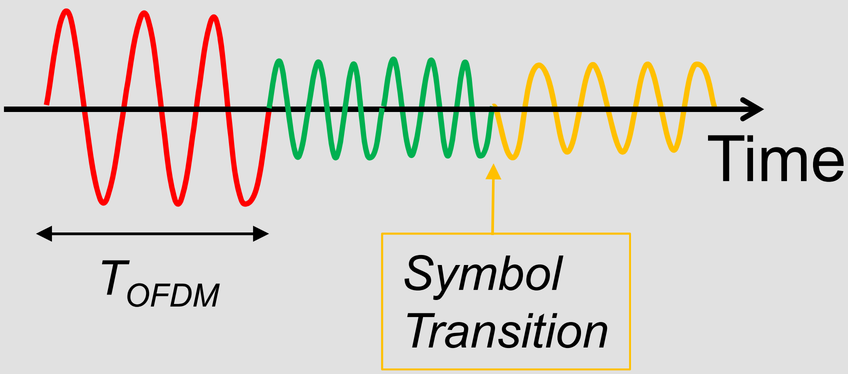
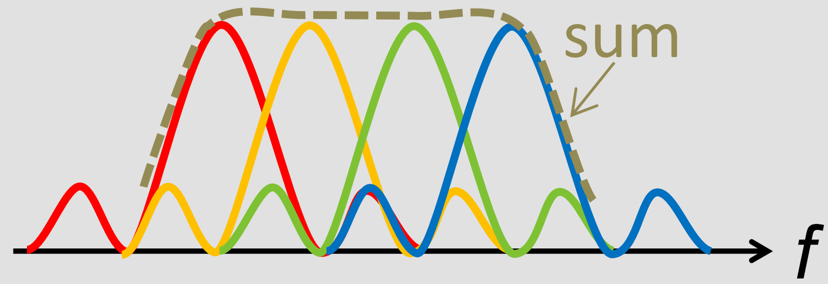
At the Transmitter

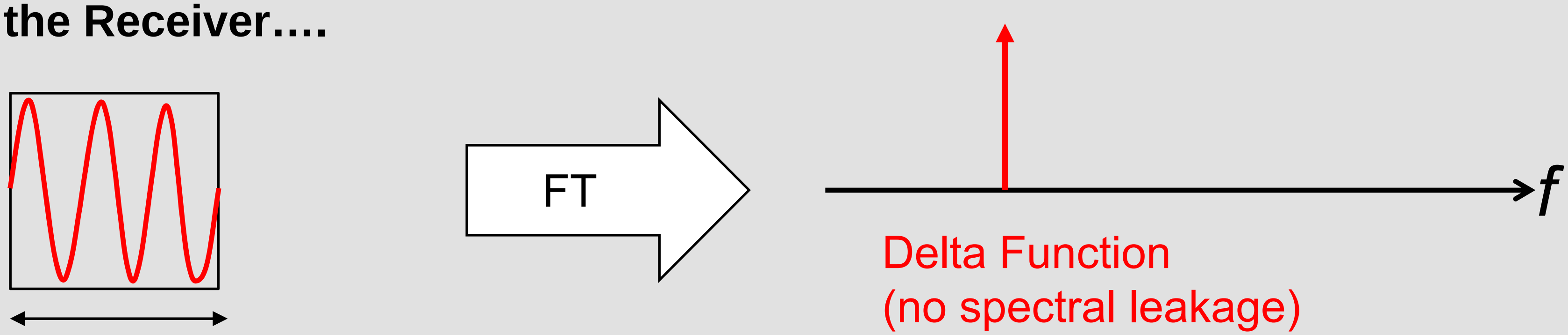
(only one subcarrier shown in each symbol)





No CP: $T_{OFDM} = 1/R$

At the Receiver….



Fourier Transform window

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OFDM

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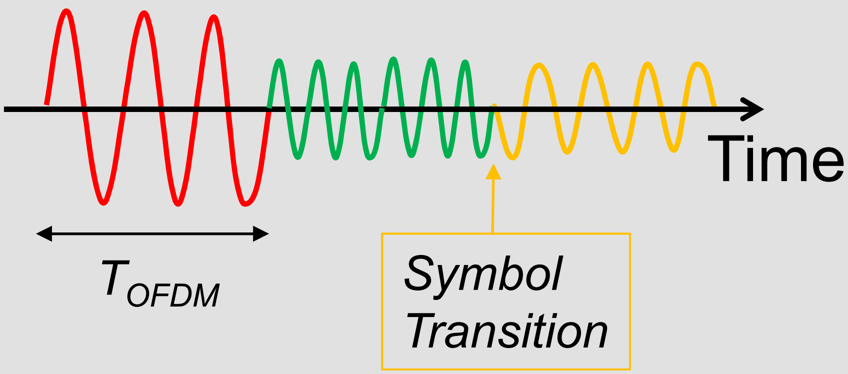
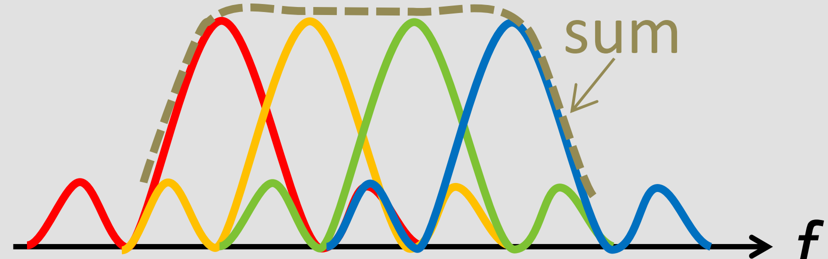
At the Transmitter

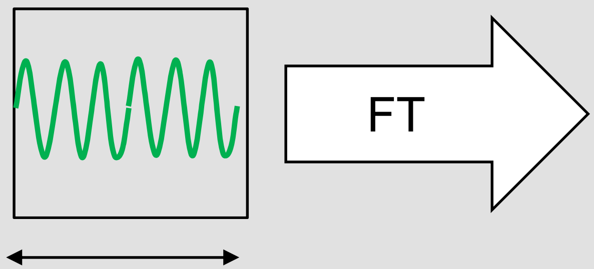
(only one subcarrier shown in each symbol)

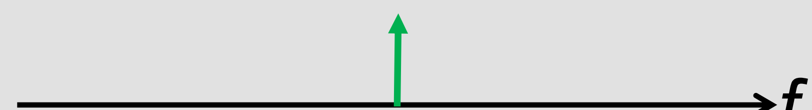




No CP: $T_{OFDM} = 1/R$

At the Receiver….





Delta Function
(no spectral leakage)

Fourier Transform window

OFDM

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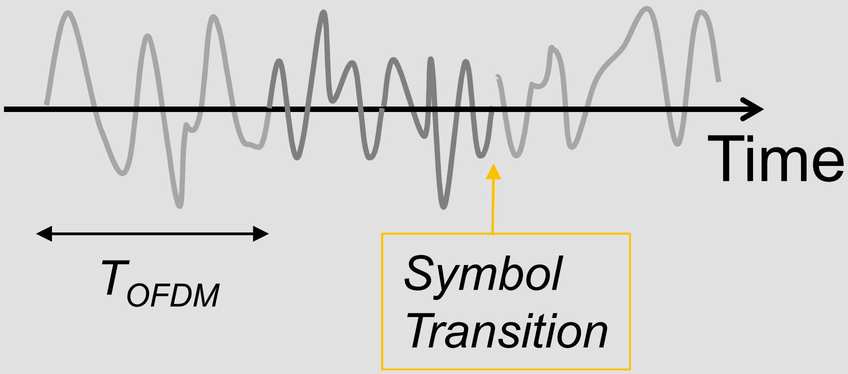
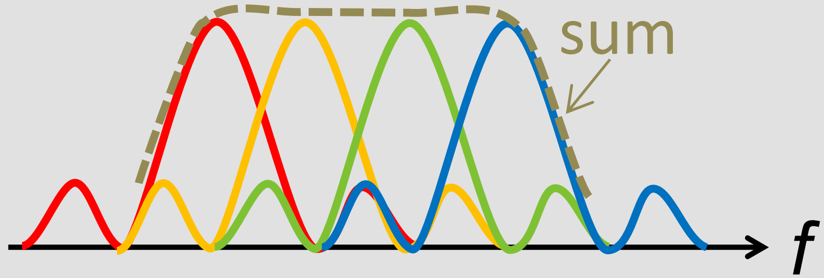
At the Transmitter

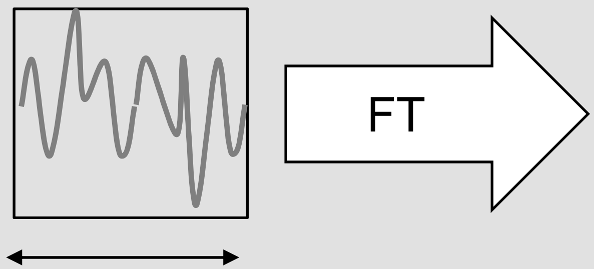
(multiple subcarriers shown in each symbol)



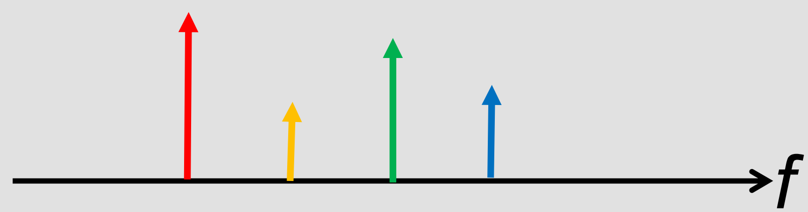


No CP: $T_{OFDM} = 1/R$

At the Receiver….



Fourier Transform window



Delta Functions
(no spectral leakage)

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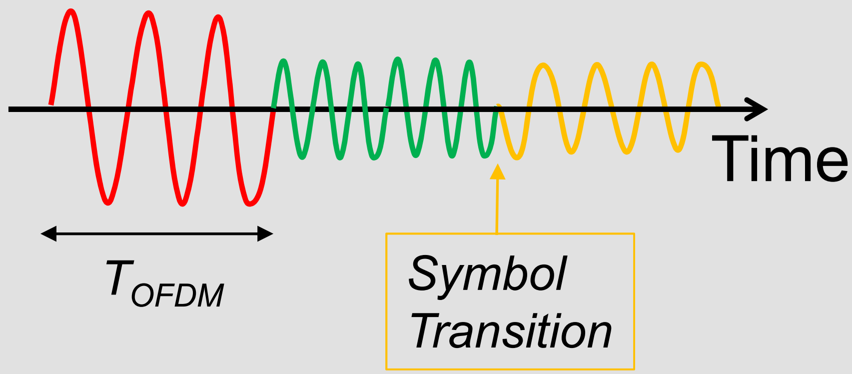
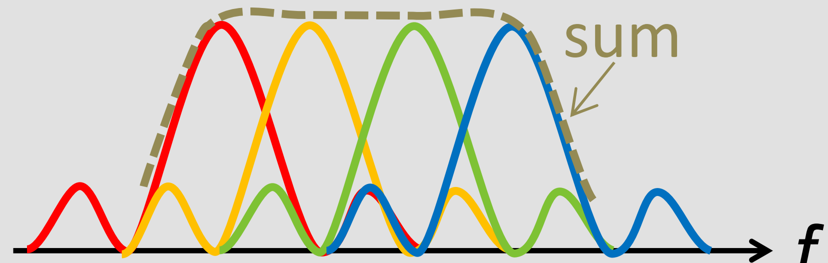
At the Transmitter

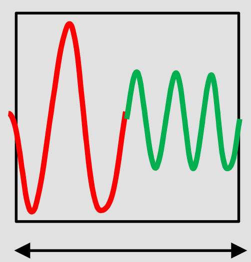
(only one subcarrier shown in each symbol)



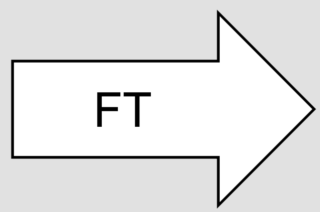


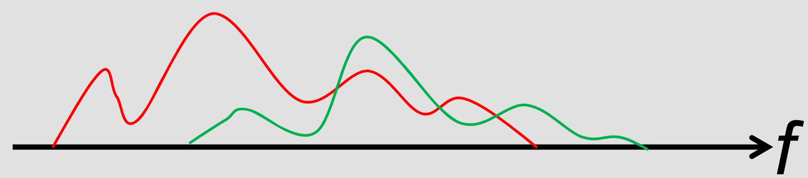
No CP: $T_{OFDM} = 1/R$

At the Receiver….



Fourier Transform window

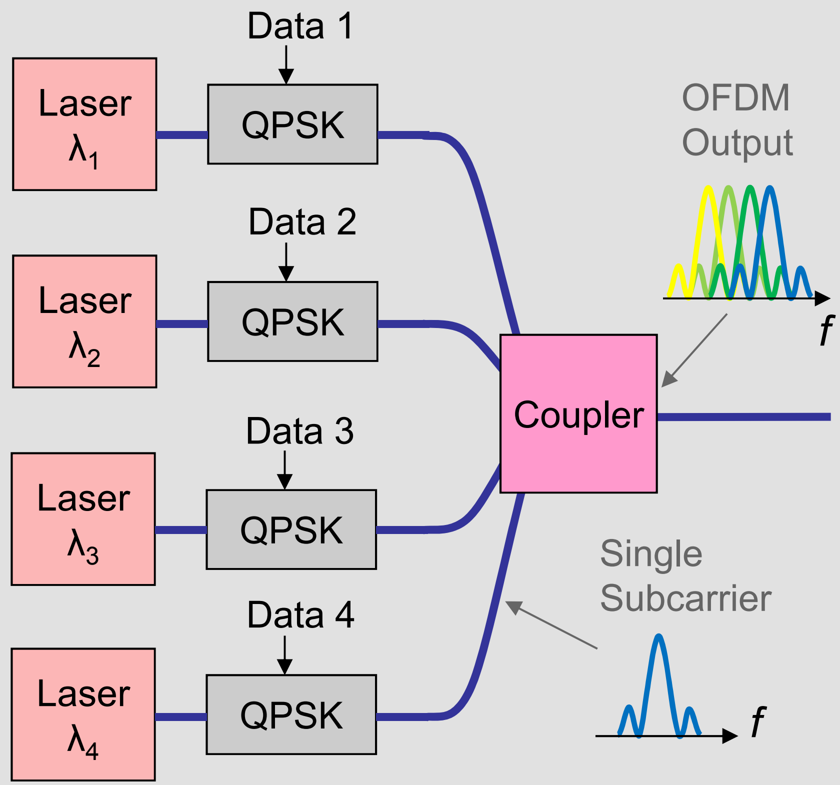




Spectral Leakage:
Inter-Carrier-Interference

Simple form of All-Optical OFDM

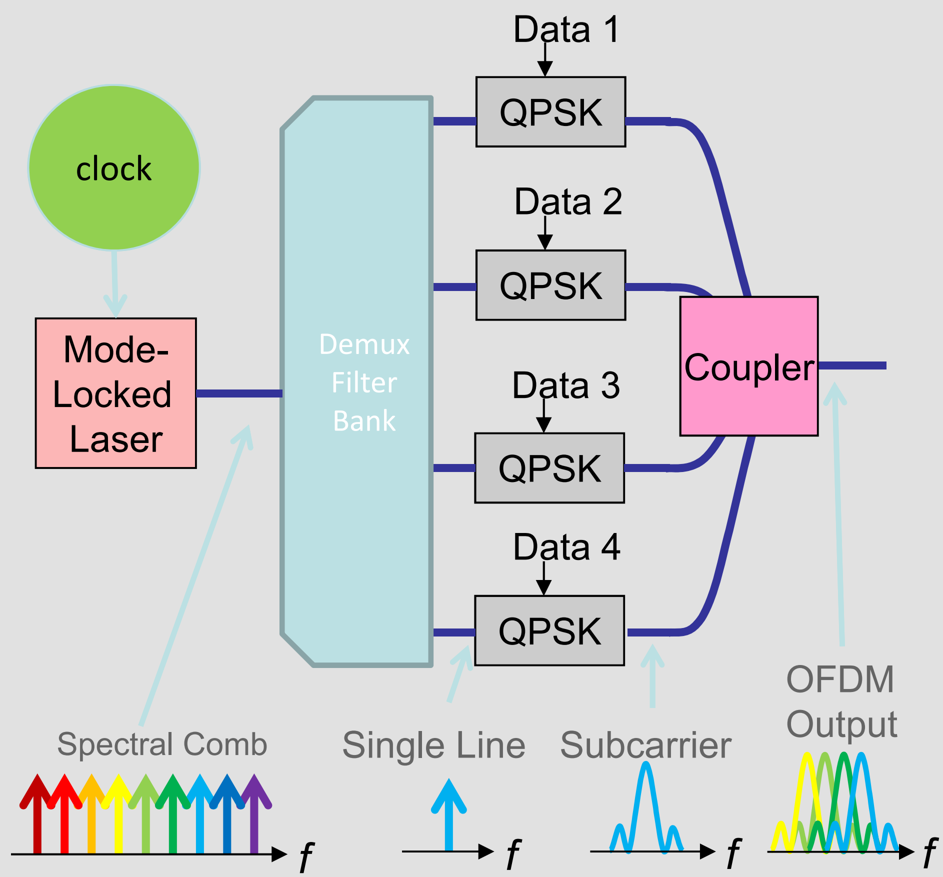
- Topologically identical to a WDM transmitter
- But the modulators have to **have much faster transitions than for a single channel**, to impose the same modulation state throughout each OFDM symbol
- The data transitions of all subcarriers must be aligned



S. Chandrasekhar and X. Liu,
Opt. Express 17(24), 21350–21361 (2009).

OFDM Transmitter using an Optical *Comb** Source

- The lasers can be replaced with an optical frequency comb generator and a demultiplexer
- The **modulators still need to be fast** – much faster than for a single channel system
- Generally these comb generators have good phase stability, which improves received signal quality
- The phase-locking can be used advantageously for 'Coherent WDM'



D. Hillerkuss, *et al.*, OFC, (2010) PDPC1

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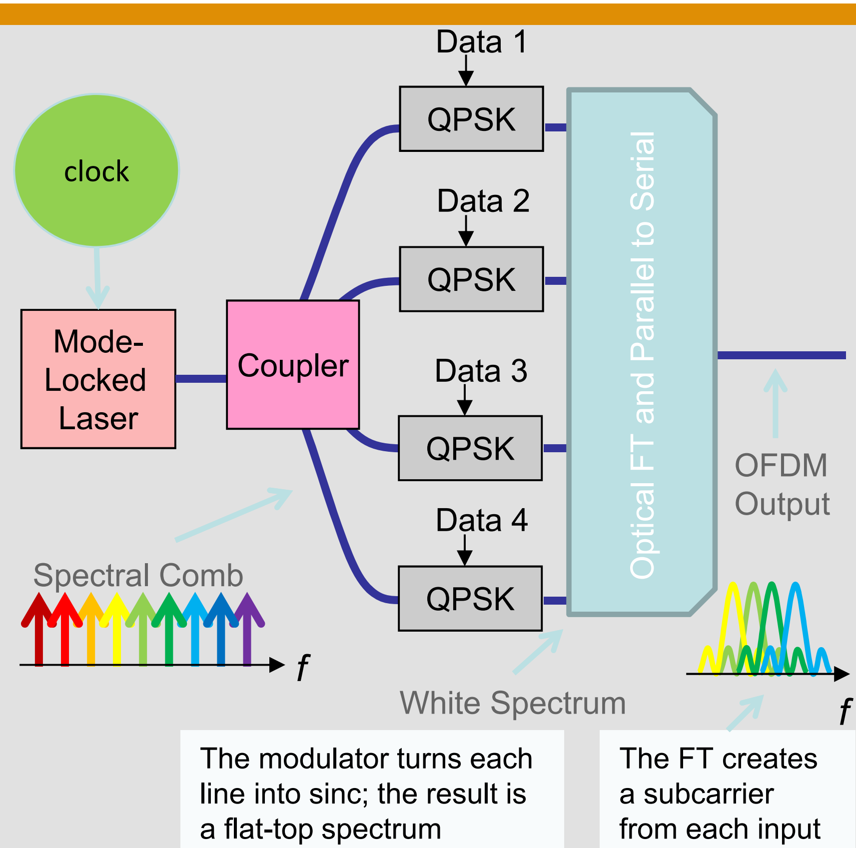
*Pulse sources generally have comb-like spectra

OFDM Transmitter using an Optical *Pulse* Source

- Swapping the positions of the demux and the coupler provides a huge benefit
- The **modulators still can be slow,** as they are sampled by the MLL pulses once per symbol
- The Optical FT can assign any frequency (or frequencies) to each input.
- The subcarrier frequencies need not align with the MLL comb



1. K. Lee, C. T. D. Thai, and J.-K. K. Rhee, Opt. Express **16**(6), 4023–4028 (2008)
2. Y-K. Huang, *et al.*, 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

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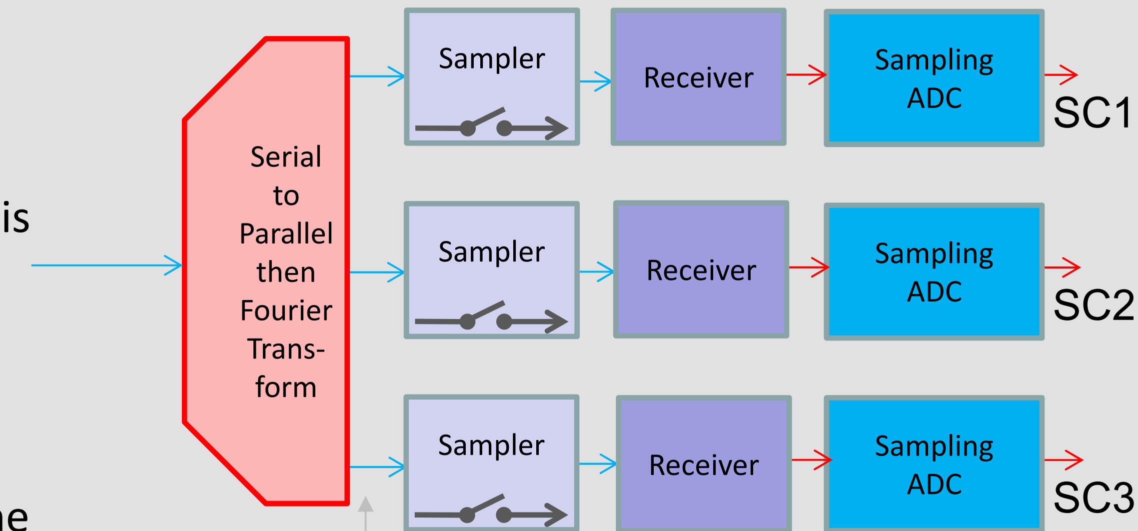
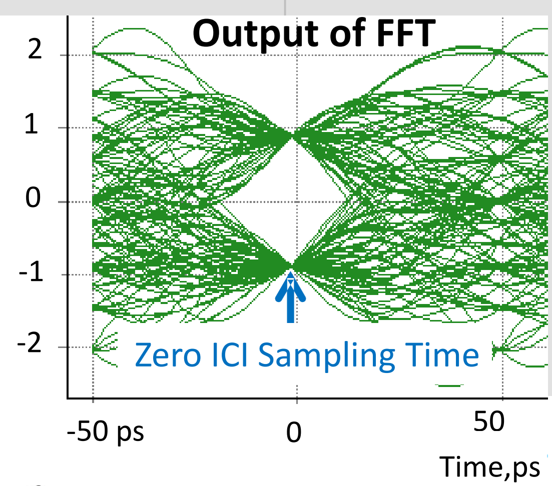
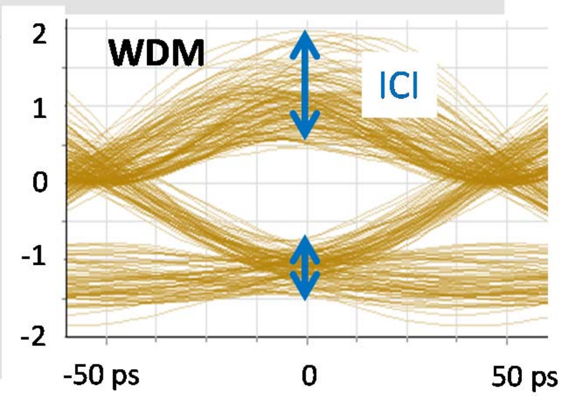
OFDM Receiver L:ayout using a Fourier Transform

- A Fourier transform is a matched filter for OFDM subcarriers.
- If implemented optically is is continually processing a sliding window across the received waveform.
- When this window aligns with the OFDM symbols, the subcarriers are demultiplexed orthogonally.
- A sampler is needed to select the FT output at this time.
- *Compare with the WDM eye*







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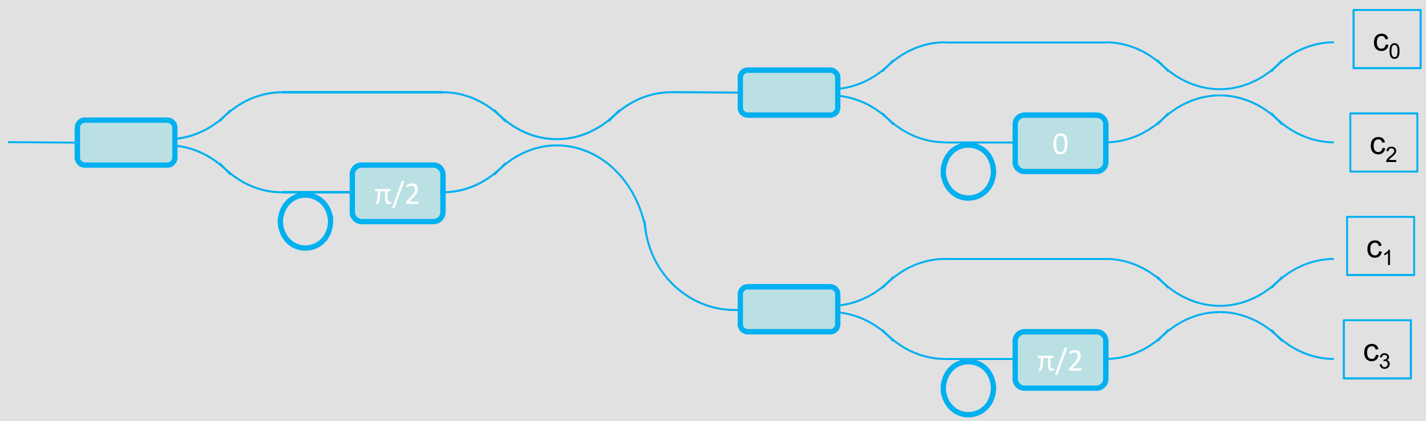
Implementing the Fourier Transform: couplers

Simplified "combined SP conversion and optical FFT"



CTho1.pdf CLEO 2011 Freude

Also see M. E. Marhic, "Discrete Fourier transforms by single-mode star networks," Opt. Lett., vol. 12, pp. 63-65, 198 for a design with cross-overs

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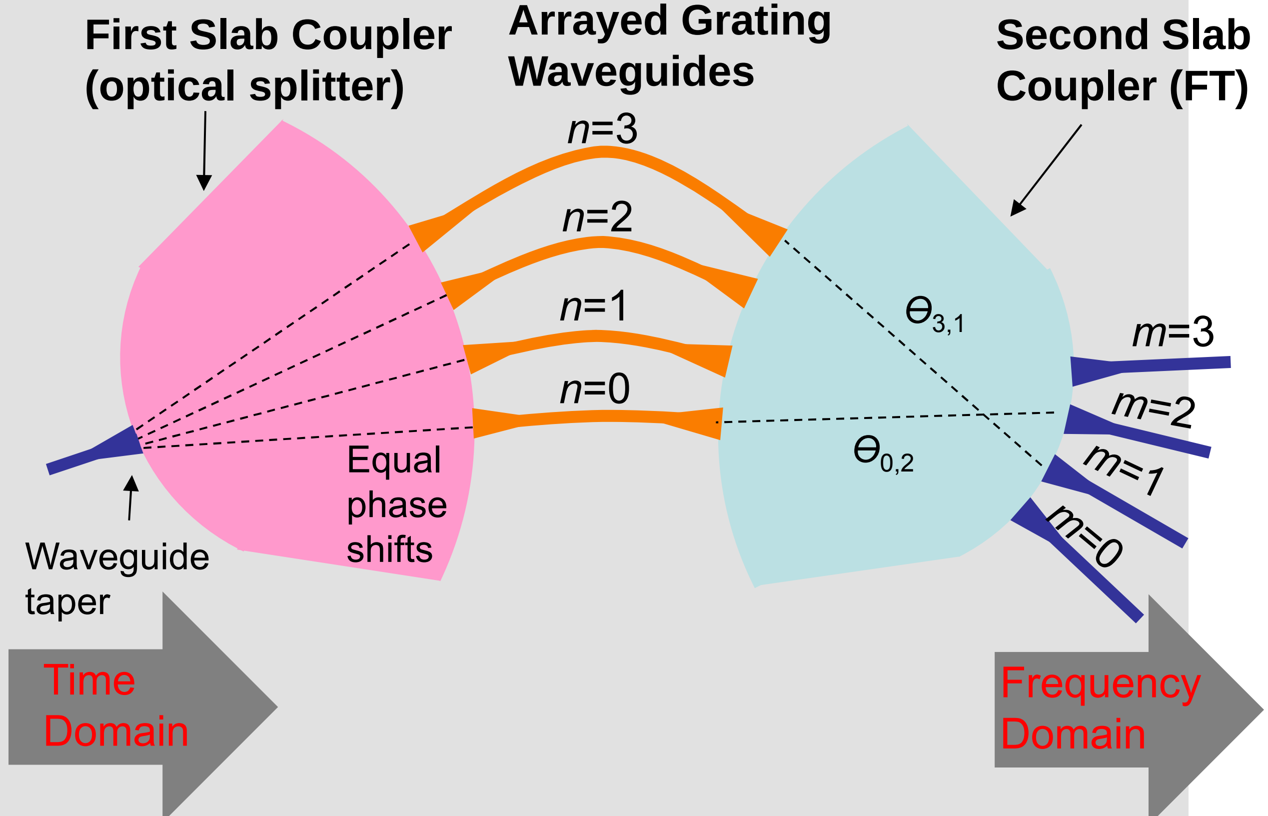
Implementing the Fourier Transform: AWGR

- The first slab coupler creates copies of the input waveform
- The arrayed waveguide grating router (AWGR) time-shifts each copy
- The second slab creates weighted sums of the inputs *n* at the outputs *m*, implementing the discrete FT summation
- Again, samplers are required at the outputs



The losses across all paths must be equal for a uniform-window FT

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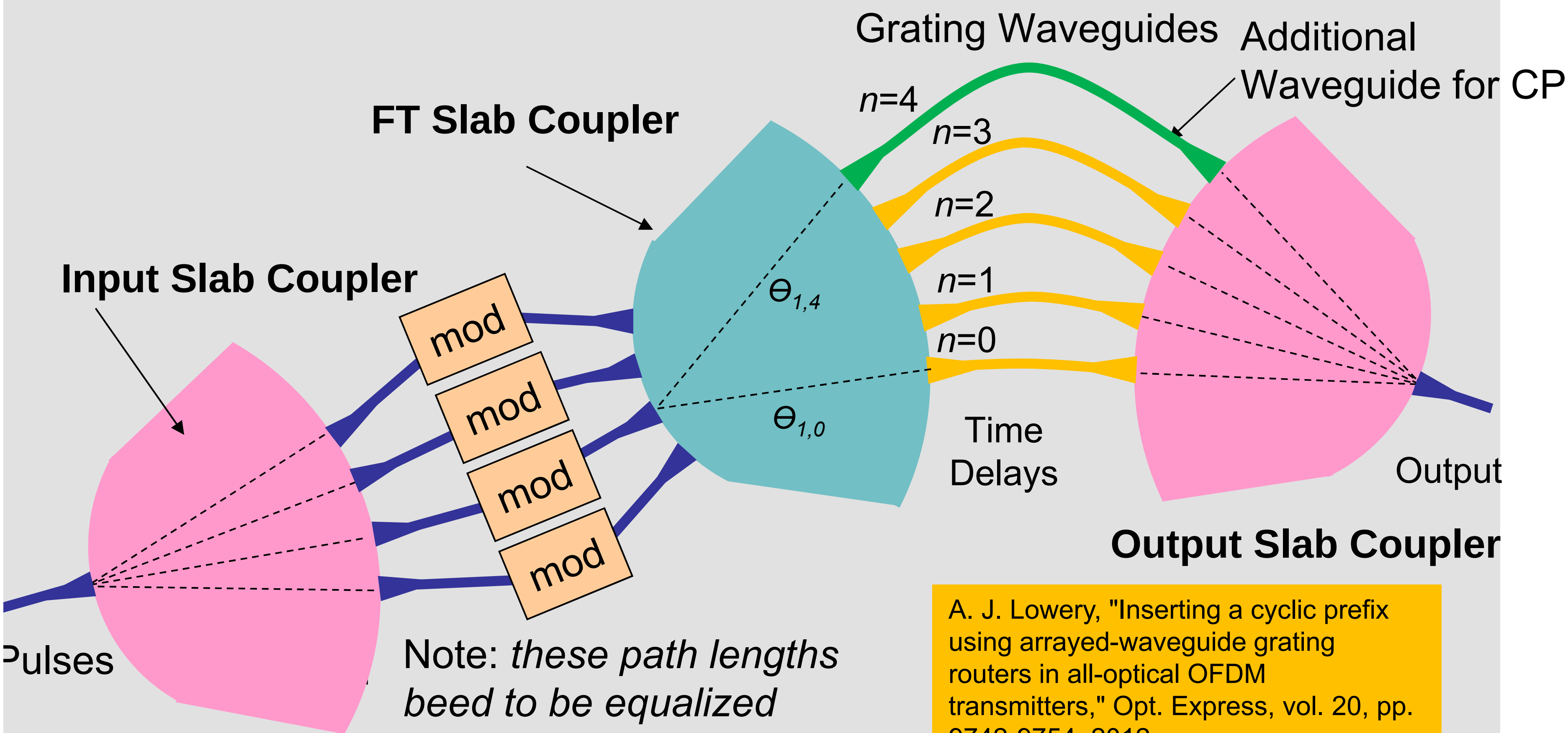
A. J. Lowery, "Design of arrayed-waveguide grating routers for use as optical OFDM demultiplexers," *Opt. Express,* vol. 18, p. 15, 2010.

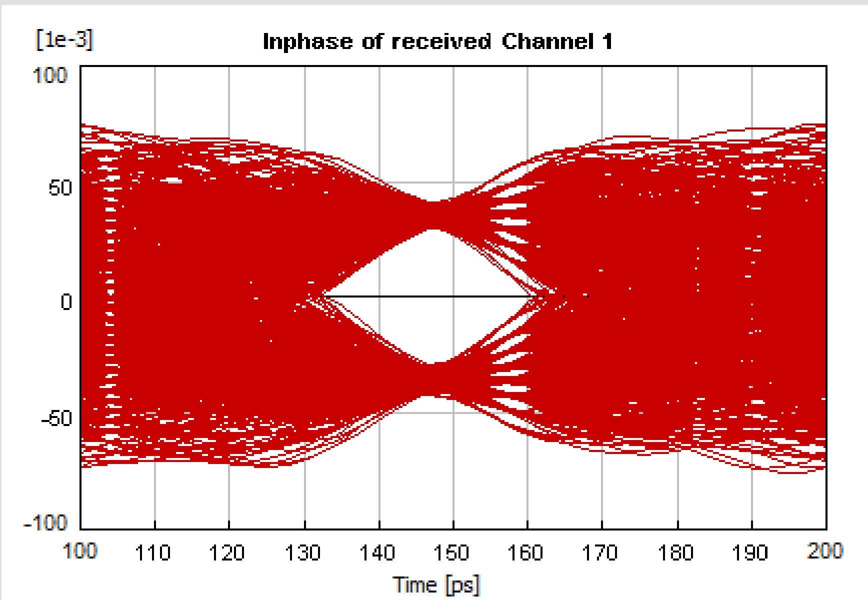
The AWGR as an Inverse FT (with a Cyclic Prefix)



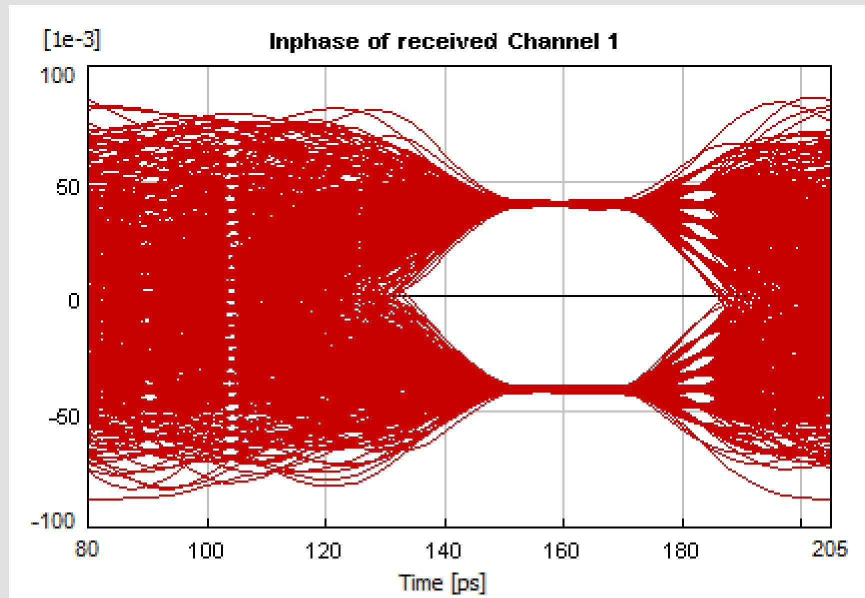
A. J. Lowery, "Inserting a cyclic prefix using arrayed-waveguide grating routers in all-optical OFDM transmitters," Opt. Express, vol. 20, pp. 9742-9754, 2012.

The AWGR as an Inverse FT (with a Cyclic Prefix)

Received: No CP



Received: with CP



The CP opens the eye and reduces ICI due to dispersion

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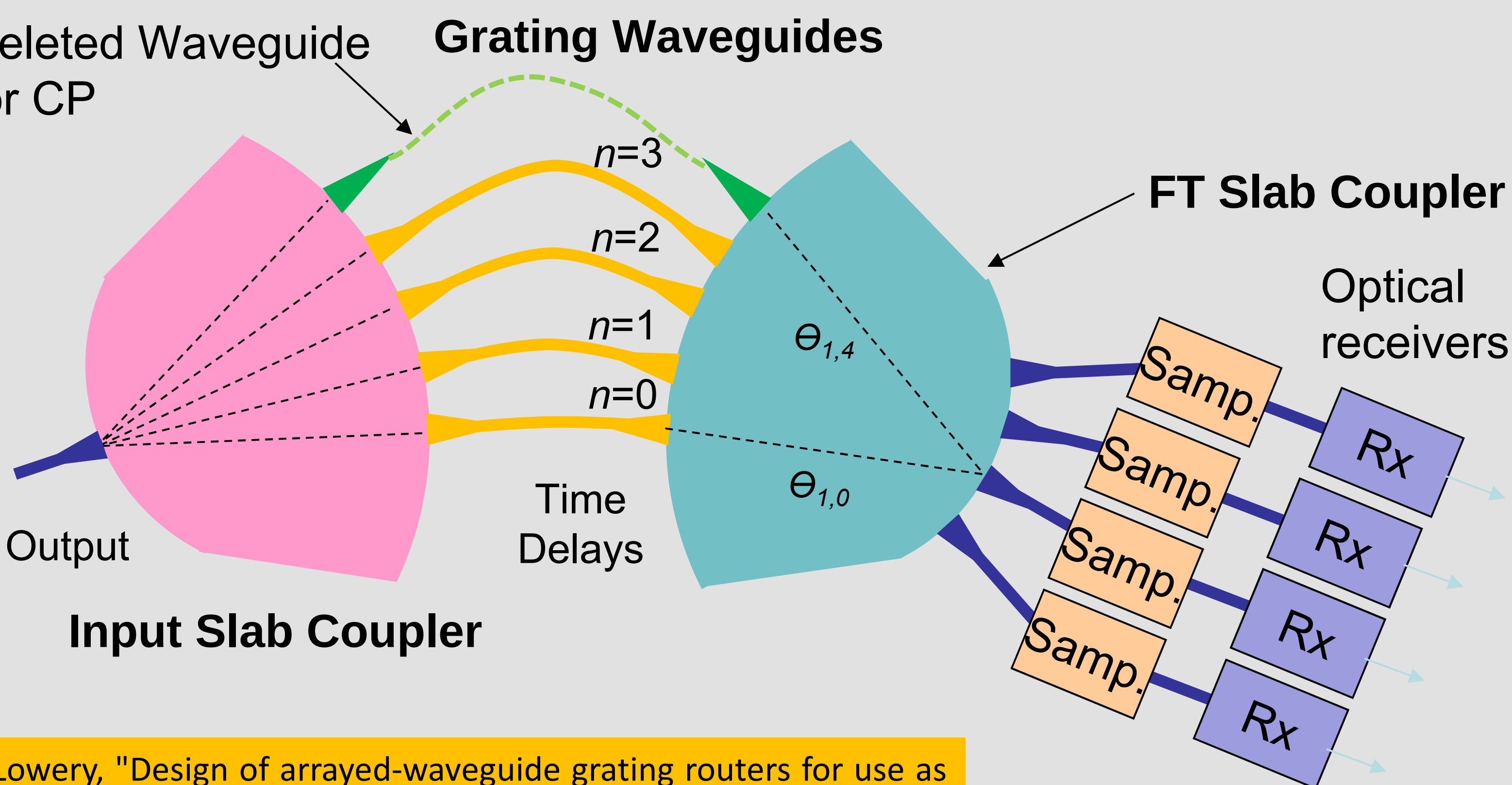
The AWGR an OFDM Demultiplexer



A. J. Lowery, "Design of arrayed-waveguide grating routers for use as optical OFDM demultiplexers," *Opt. Express,* vol. 18, p. 15, 2010.

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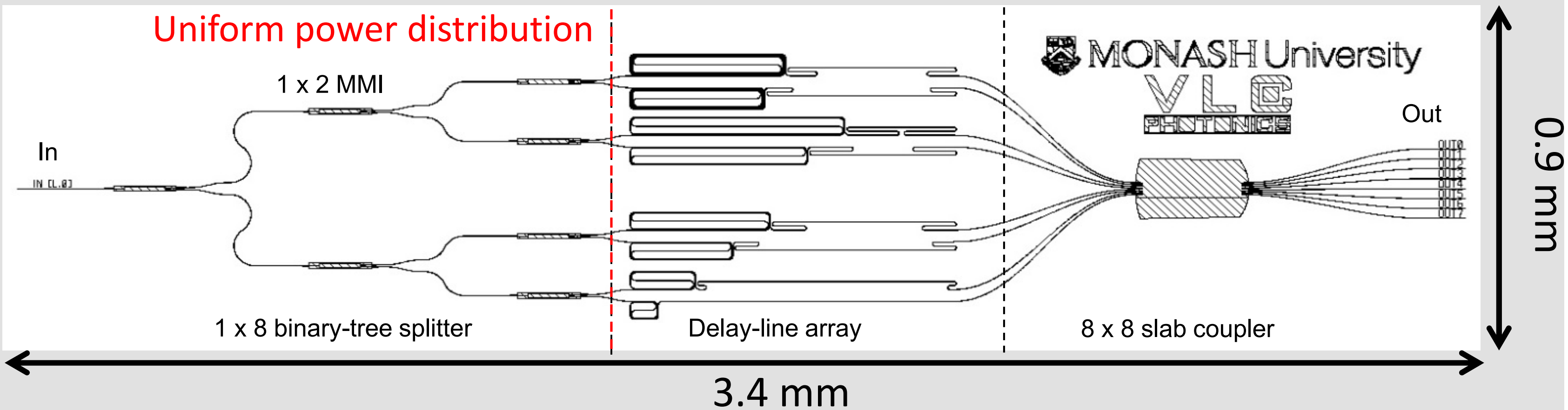
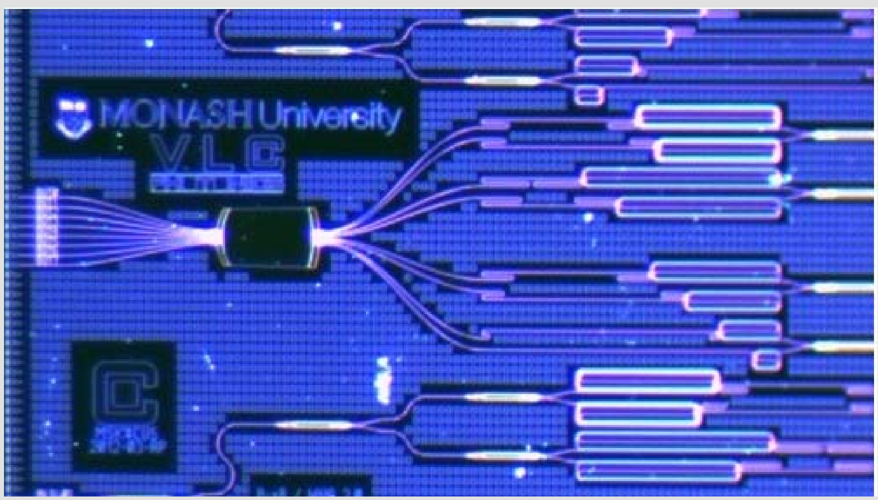
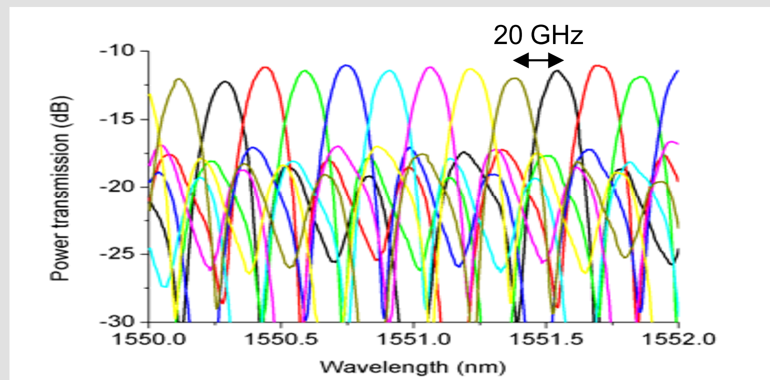
OFDM Photonic Integrated Circuit: Monash I







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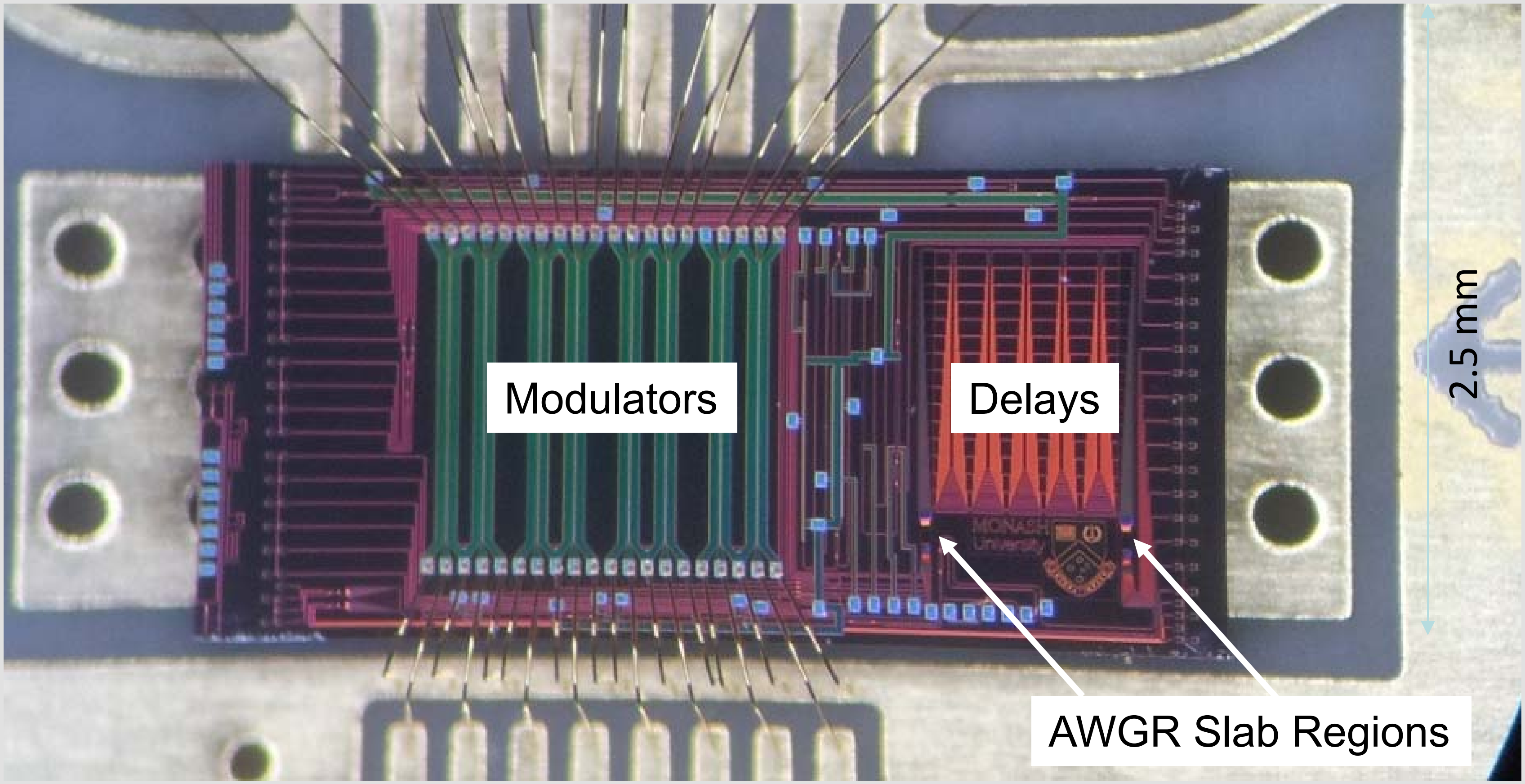
"All-optical coherent OFDM transmission of 8 x 40 Gb/s using an on-chip AWGR-FT 1x 8 decoder circuit," OFC2015, W3C.

OFDM Photonic Integrated Circuit: Monash I



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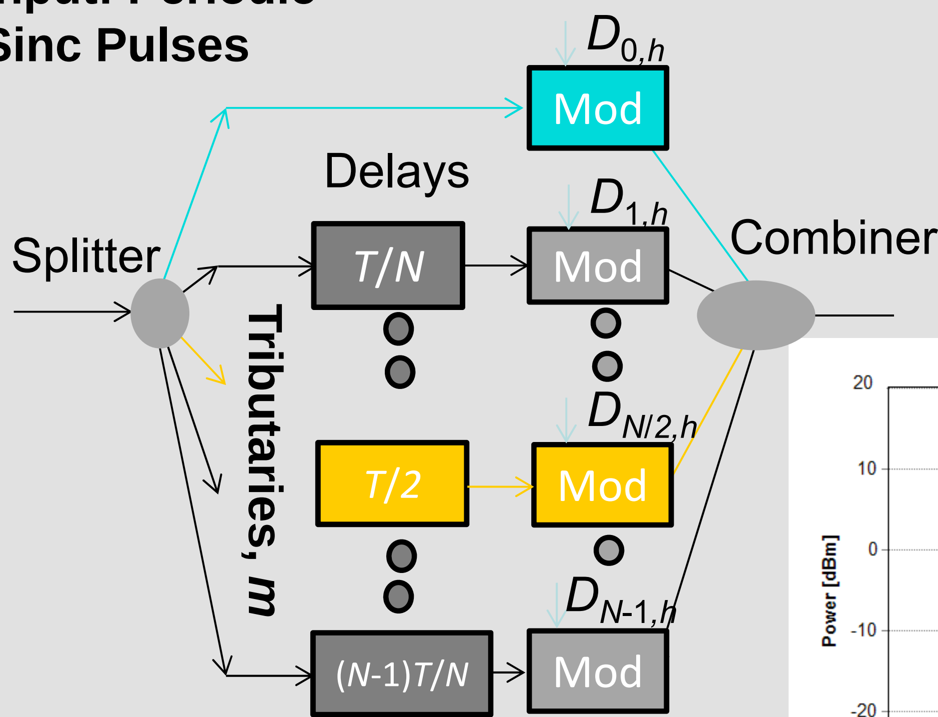
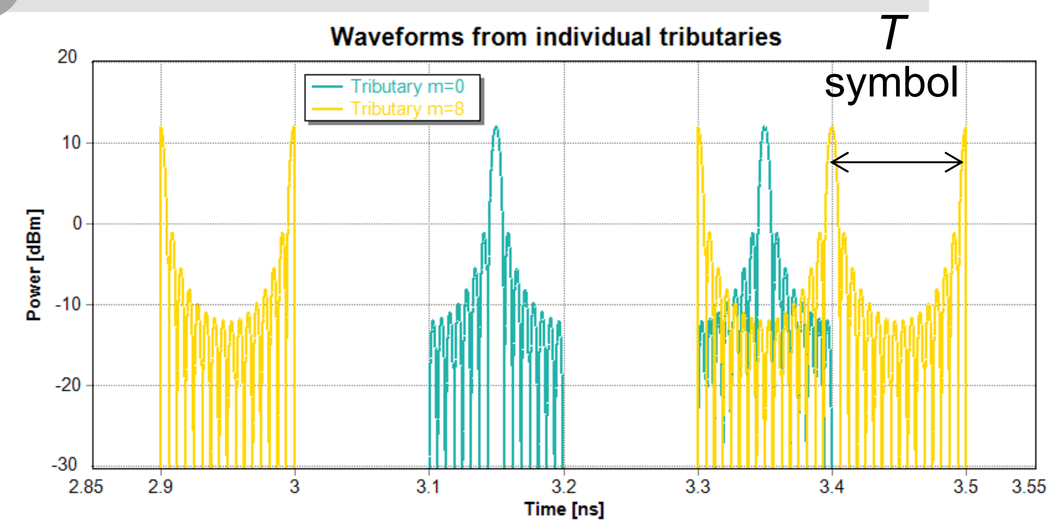
IMEC OFDM Tx chip in Silicon-on-insulator (SOI) with modulators and AWGR-based IFT

DFT-Spread OFDM

Input: Periodic Sinc Pulses

A. J. Lowery, C. Zhu, E. Viterbo, and B. Corcoran, "All-optical generation of DFT-S-OFDM superchannels using periodic sinc pulses," Optics Exp., vol. 22, pp. 27026-27041, 2014/11/03 2014.





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Nyquist-WDM

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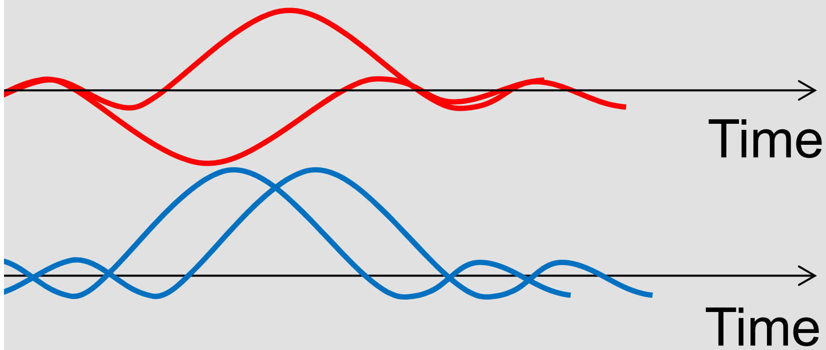
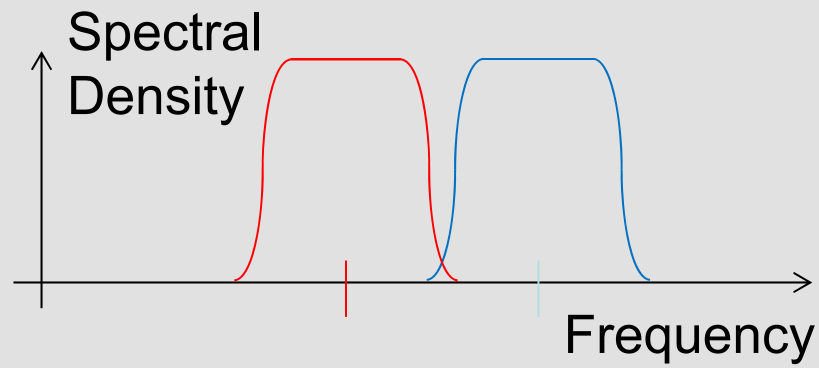
The modulation of Wavelength 1 is superposed sinc basis functions



Modulation of Wavelength 2



Distinct spectra (substantially non-overlapping) that can be separated (demultiplexed) with optical filters

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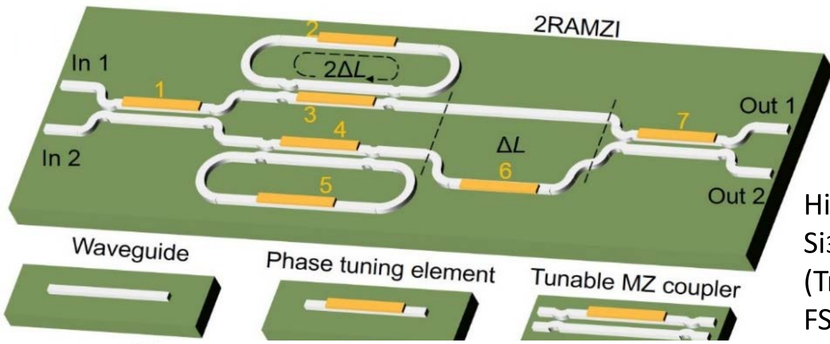
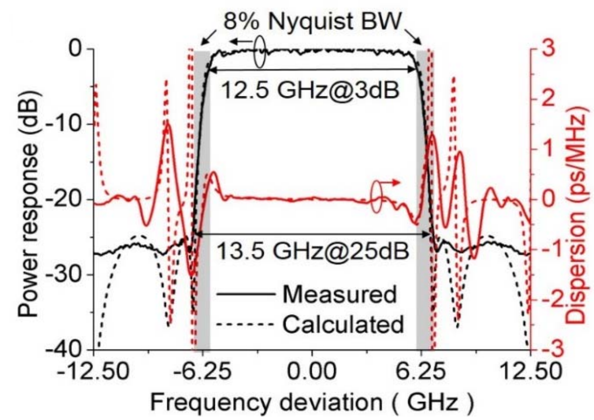
Nyquist Generation using RAMZI chip

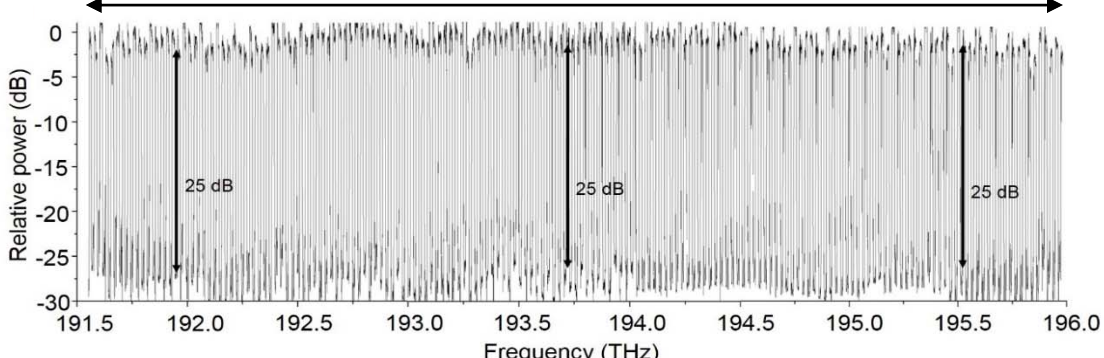


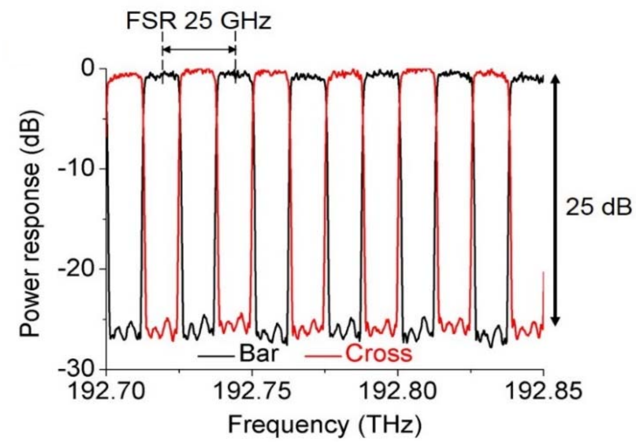
- 3 delay lines
- 4 couplers
- 7 tuning elements

High-index-contrast Si_3N_4 waveguide (TriPleX technology)
FSR = 25 GHz



Full-C-band coverage and simultaneously sub-GHz resolution





L. Zhuang, C. Zhu, Y. Xie, M. Burla, C. G. H. Roeloffzen, M. Hoekman, et al., "Nyquist-filtering (de)multiplexer using a ring resonator assisted interferometer circuit," J. Lightwave Technol., vol. 33, 2016.
And "Sub-GHz-resolution C-band Nyquist-filter interleaver on a high-index-contrast photonic integrated circuit," Opt. Express 24(6), 5715 (2016).

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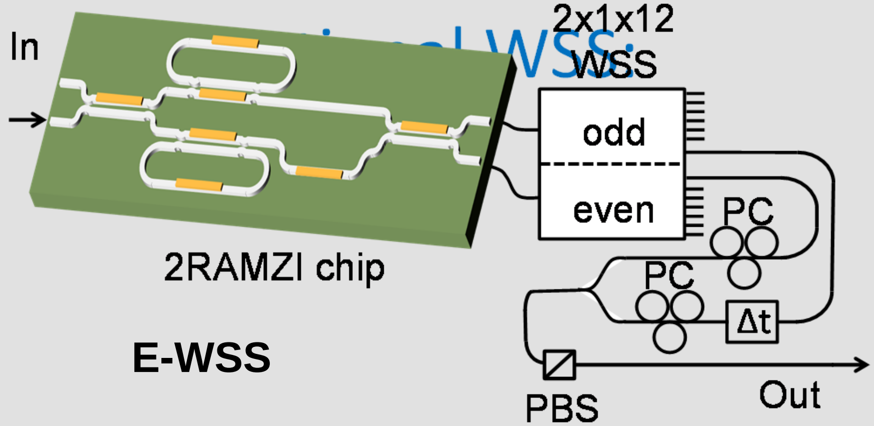
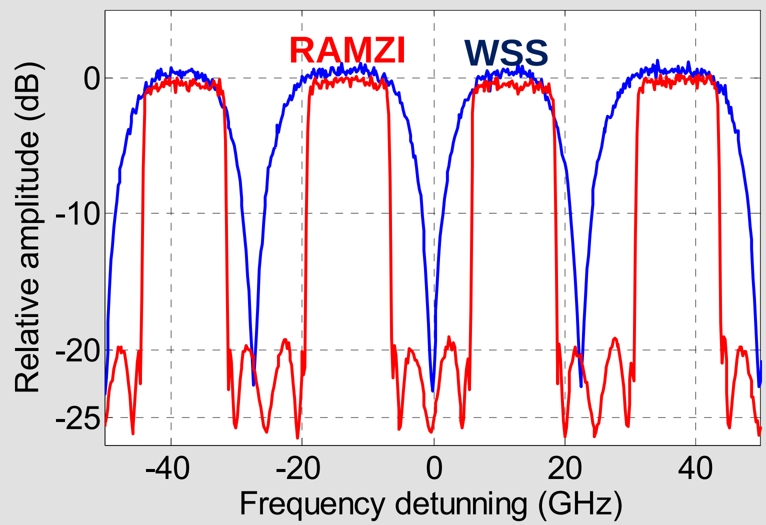
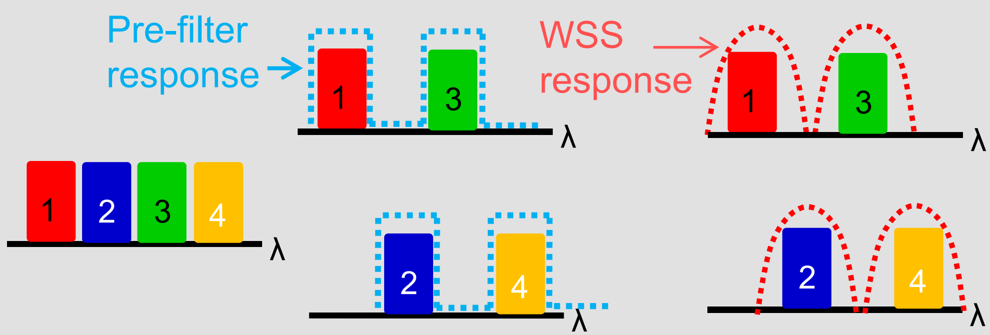
Enhanced WSS – switching without guard bands

- Enhanced WSS with RAMZI as pre-filter of



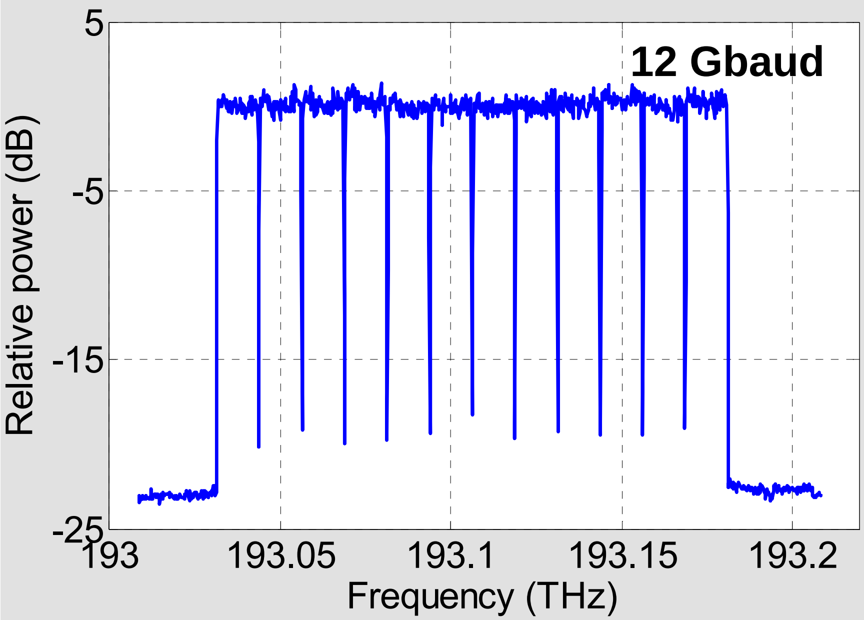




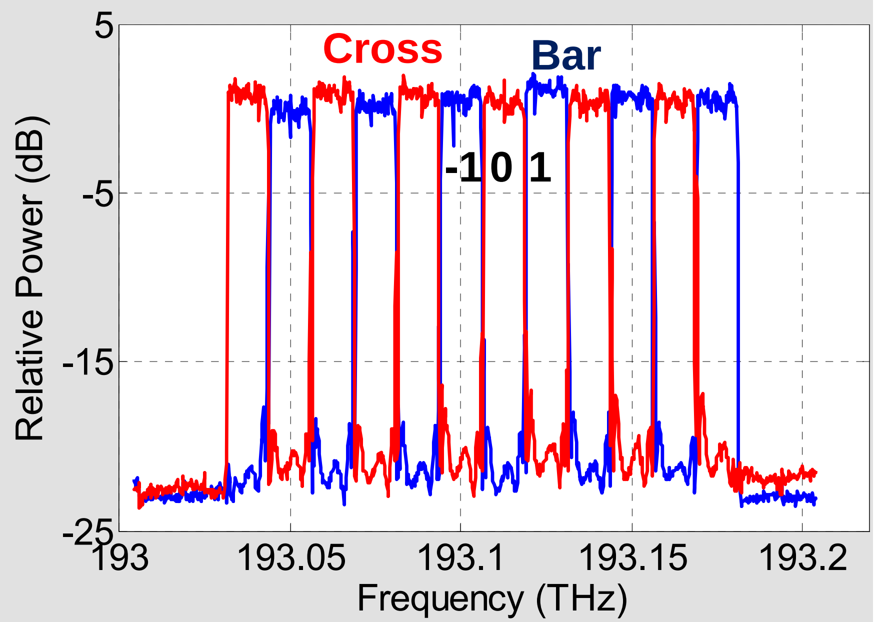
B. Corcoran, C. Zhu, J. Schroeder, L. Zhuang, B. Foo, M. Burla, W. Beeker, A. Leinse, C. Roeloffzen, A. Lowery, "A wavelength selective switch for optical add/drop multiplexing of sub-bands within Nyquist WDM super-channels," ECOC 2015, Tu.3.5.2.

Experimental Results

- Measured spectra:



Transmitted signals



After EWSS

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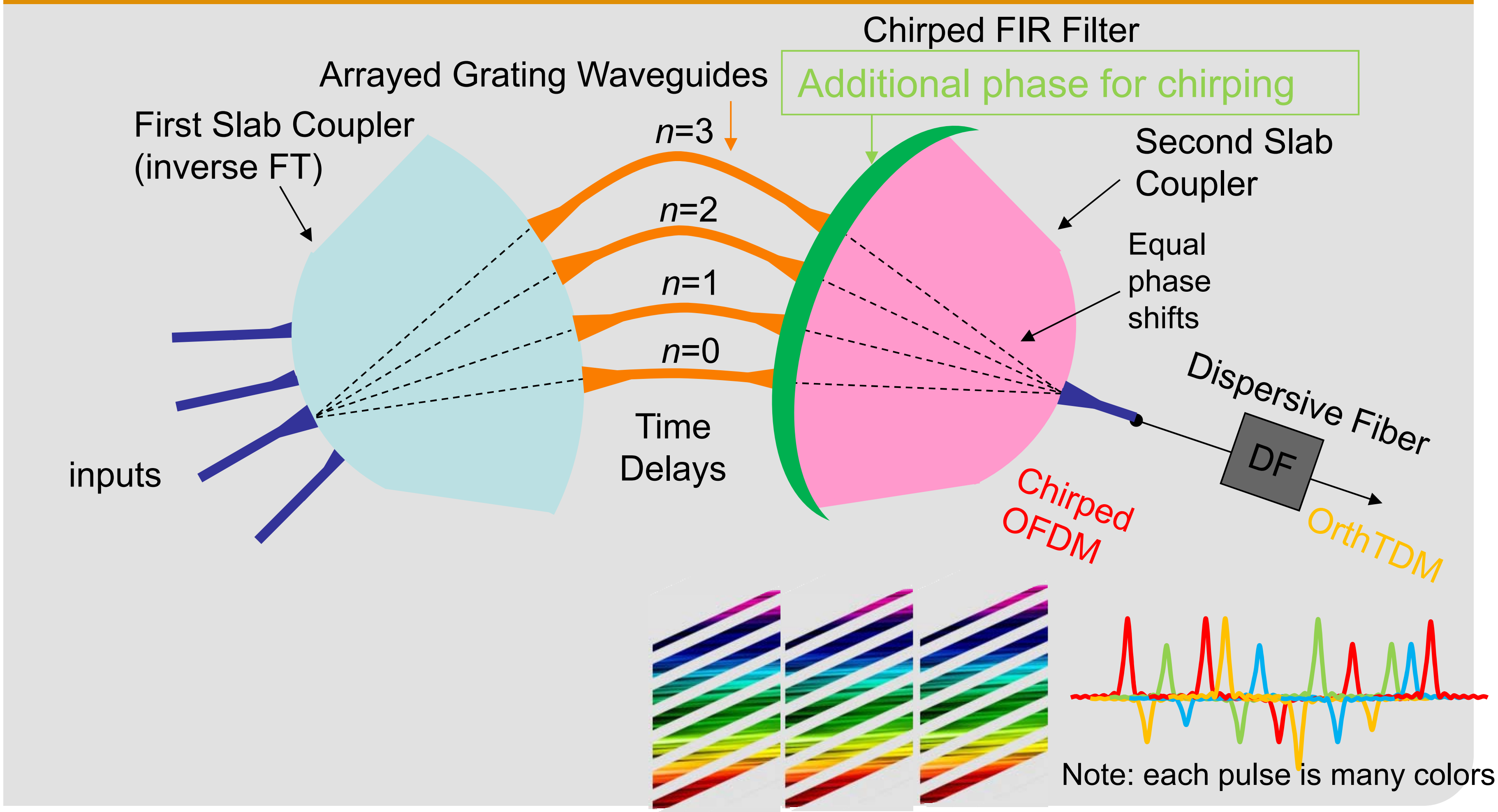
Fractional Fourier Transforms



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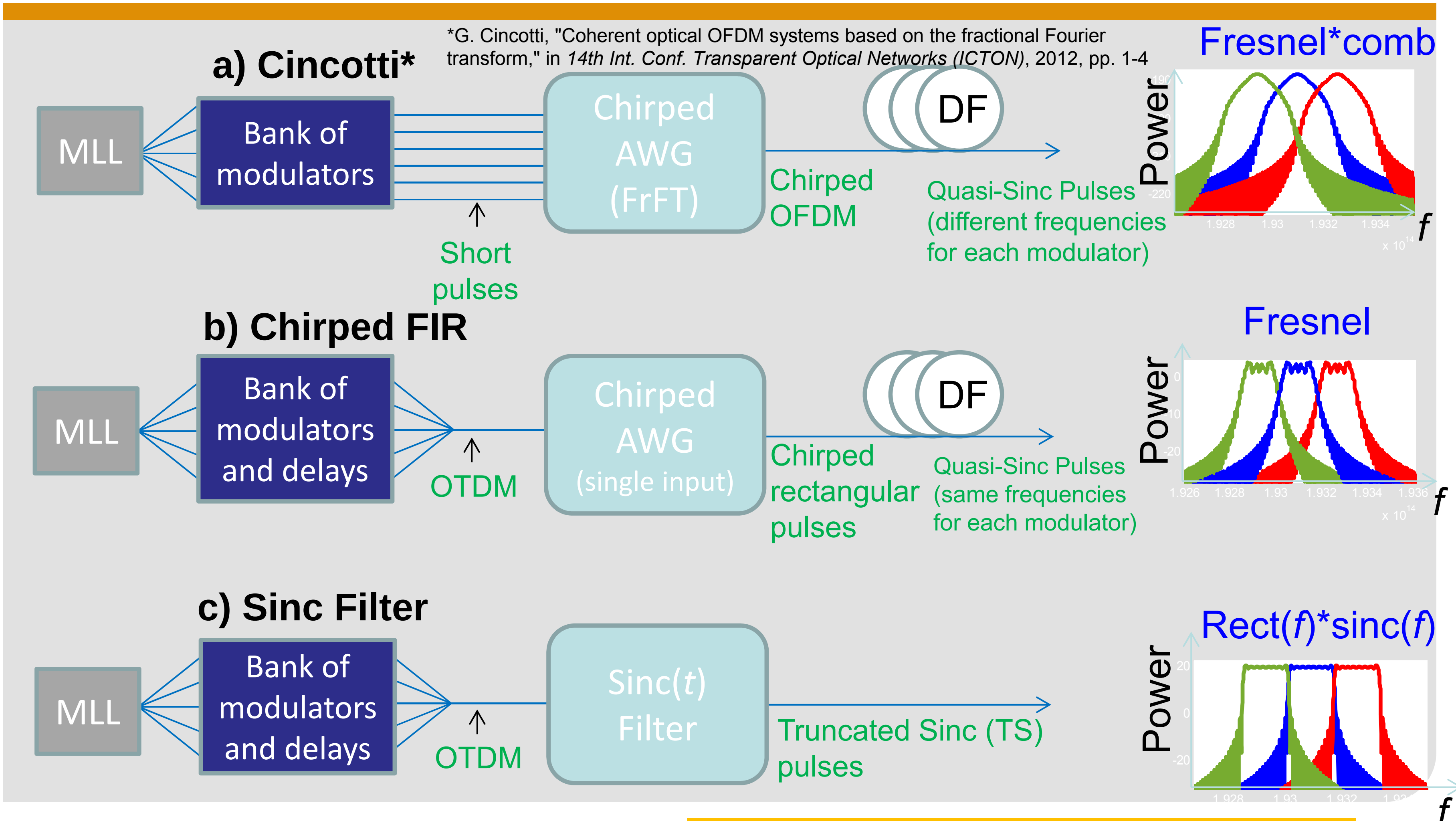
G. Cincotti, "Enhanced functionalities for AWGs," *J. Lightwave Technol.*, vol. 33, pp. 998-1006, 2015.

Reducing Spectral Width (for WDM)



A. J. Lowery, Y. Xie, and C. Zhu, "Systems performance comparison of three all-optical generation schemes for quasi-Nyquist WDM," *Opt. Express*, vol. 23, pp. 21706-21718, 2015/08/24 2015

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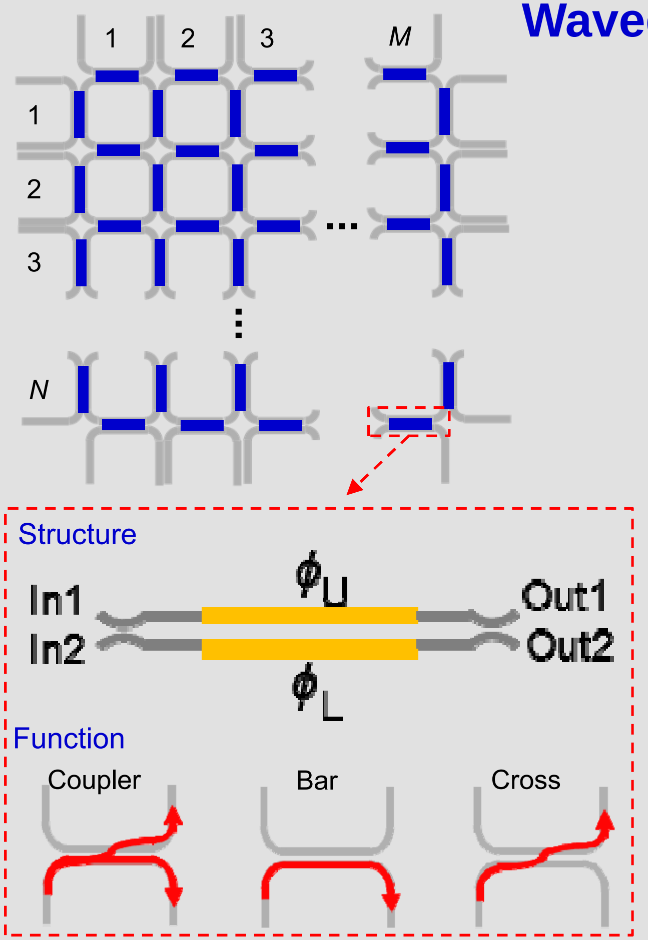
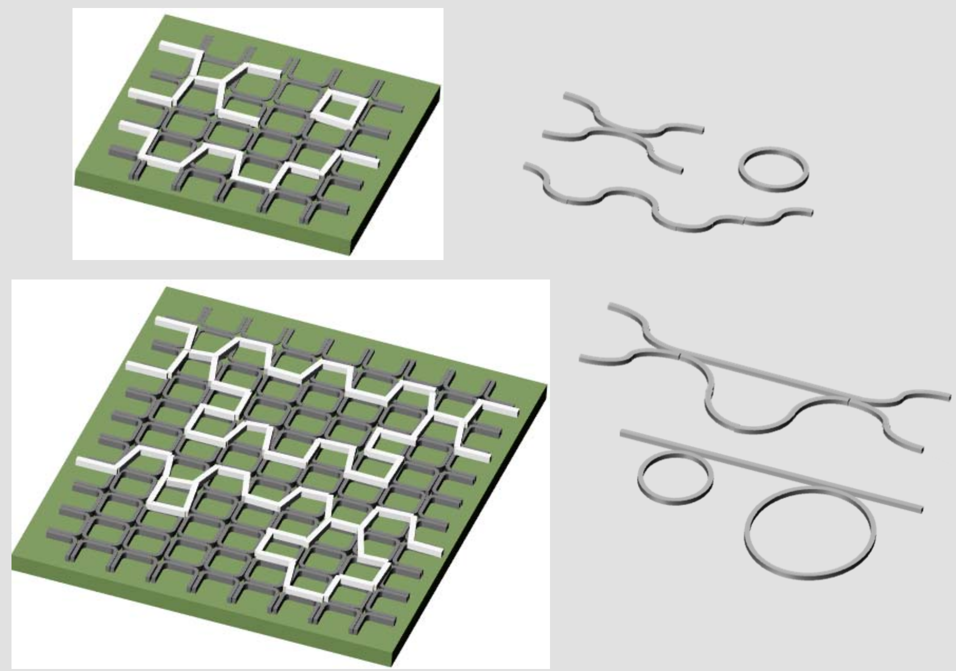
Future Chips – Programmable Arrays



Waveguide 2D mesh network



Leimeng Zhuang *et al.*, "Programmable photonic signal processor chip for radiofrequency applications," Optica 2(10), 854 (2015).

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Conclusions

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- Many signal types can be created by shaping (filtering) modulated optical pulses
  - OFDM
  - N-WDM
  - DFT-OFDM
  - Chirped-OFDM/ Nyquist TDM/ Orthogonal TDM/
- The Arrayed Waveguide Grating Router forms the basis of an FT
  - With an intrinsic parallel-serial conversion
  - Adding a chirp means the output signal (chirped OFDM) can be manipulated into Orthogonal TDM
- Ring-Assisted Mach Zehnder Interferometer
  - Very sharp transitions for N-WDM transmitter and receiver filters
  - Make excellent interleavers to eliminate ROADM guard-bands
- The generation method determines the spectrum
  - some formats are better for superchannels than others, due to their well confined spectral

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