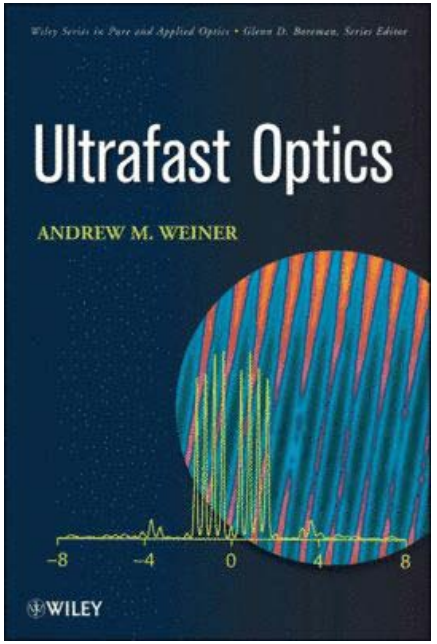
Shaping Ultrafast Laser Fields for Photonic Signal Processing

Andrew M. Weiner
Purdue University

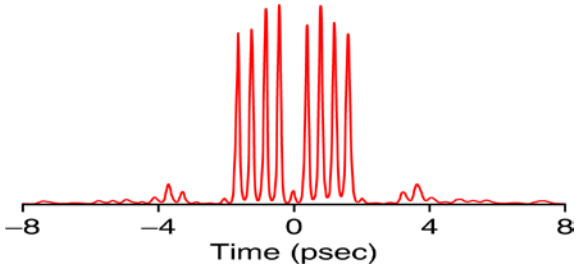
Gavriel Salvendy International Symposium on Frontiers in Industrial Engineering, May 5, 2012



ECE 616 “Ultrafast Optics” lectures, fall 2012, posted on http://nanohub.org/resources/11874

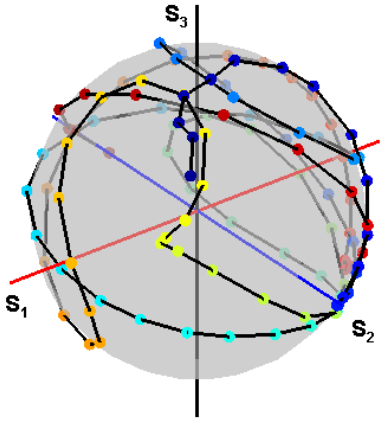
Outline

- Femtosecond pulse shaping
  - •Manipulating ultrafast photon signals
    at time scales far beyond the electronic bottleneck

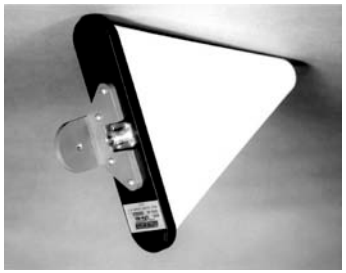


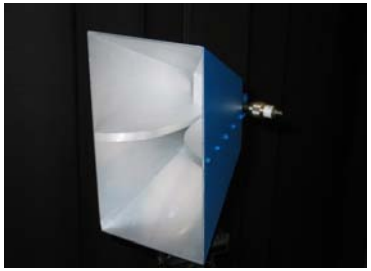
- Pulse shaping and fiber communications

  (with short aside back to pulse shaping)



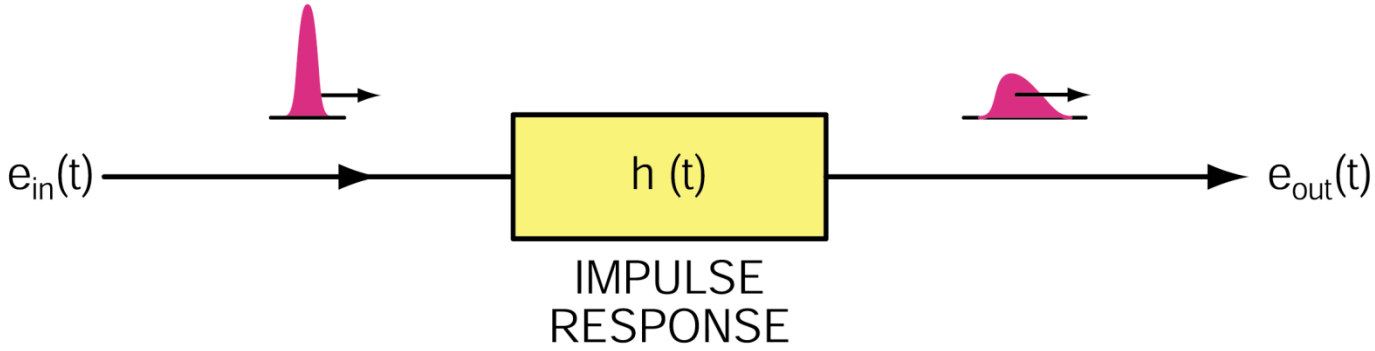
- Pulse shaping and ultrabroadband radio-frequency systems



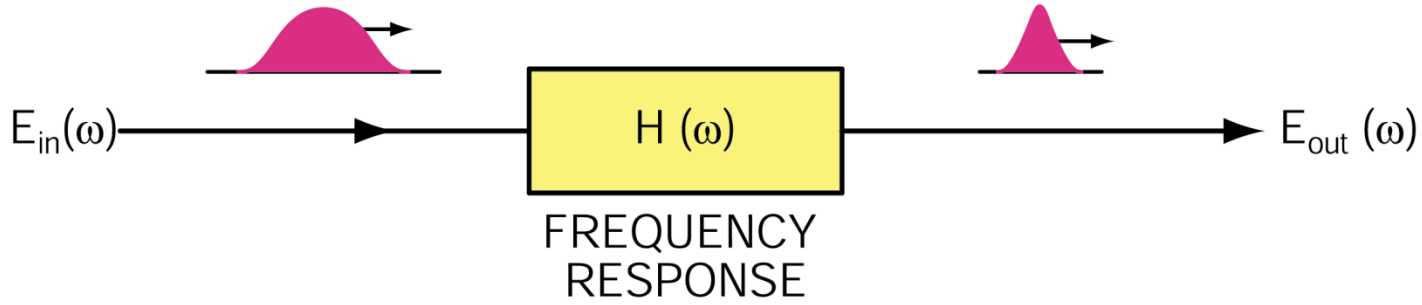


Pulse Shaping by Linear Filtering

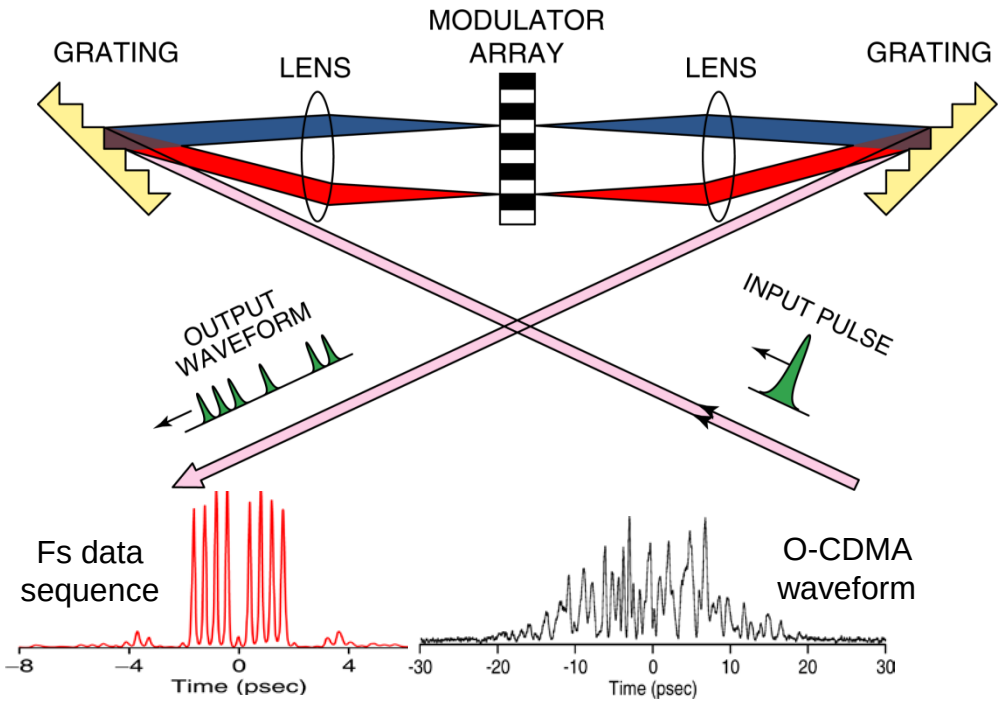
TIME DOMAIN $$e_{out}(t) = \int dt' \, h(t - t') e_{in}(t')$$

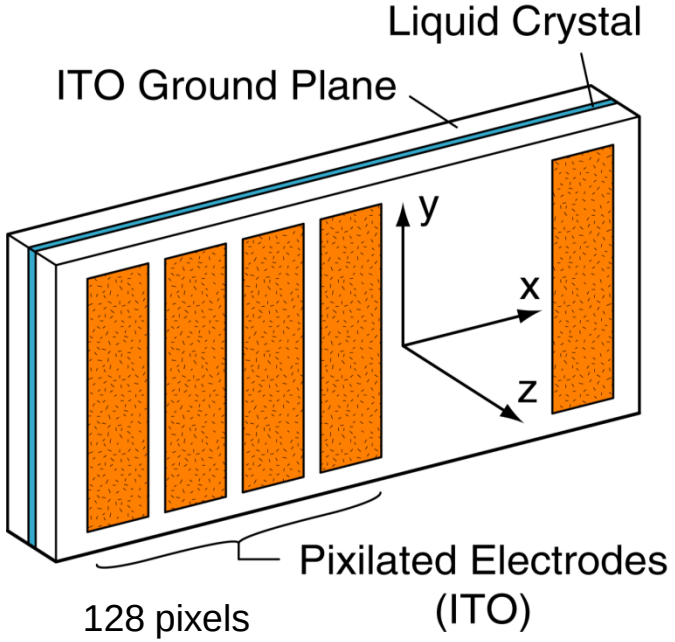


FREQUENCY DOMAIN $$E_{out}(\omega) = H(\omega) E_{in}(\omega)$$



Femtosecond Pulse Shaping



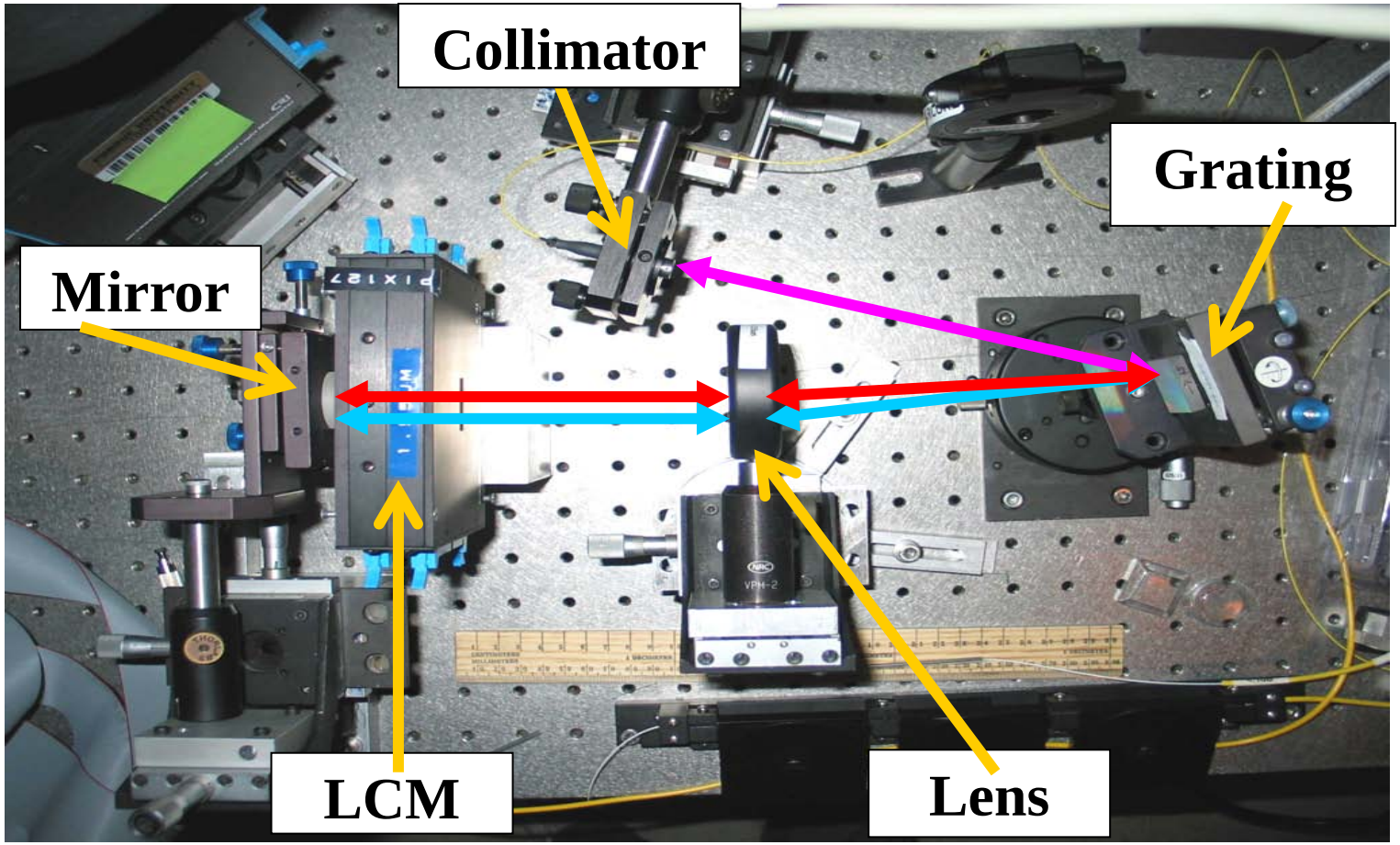


128 pixels
phase and intensity control
millisecond response

- **Fourier synthesis** via parallel spatial/spectral modulation
- **Diverse applications:** fiber communications, coherent quantum control, few cycle optical pulse compression, waveform characterization, nonlinear microscopy, RF photonics …
- **Pulses widths** from ps to few fs; **time apertures** up to ~1 ns

A.M. Weiner, Rev. Sci. Instr. **71**, 1929 (2000); Optics Communications **284**, 3669 (2011).

Reflective Pulse Shaper

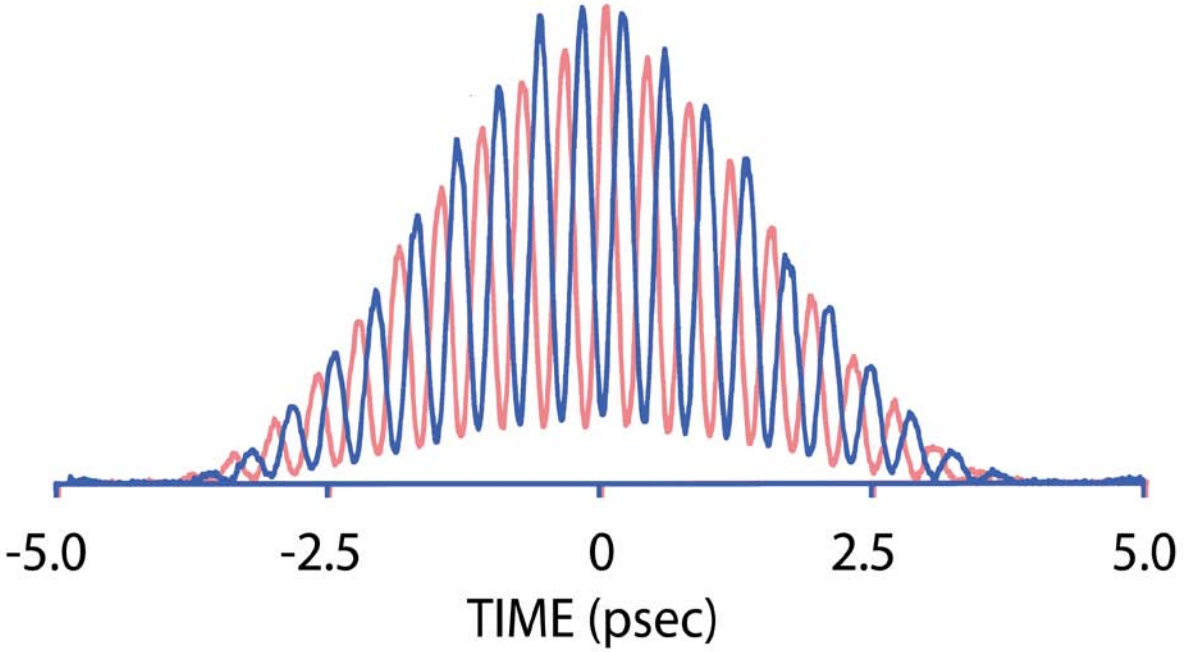


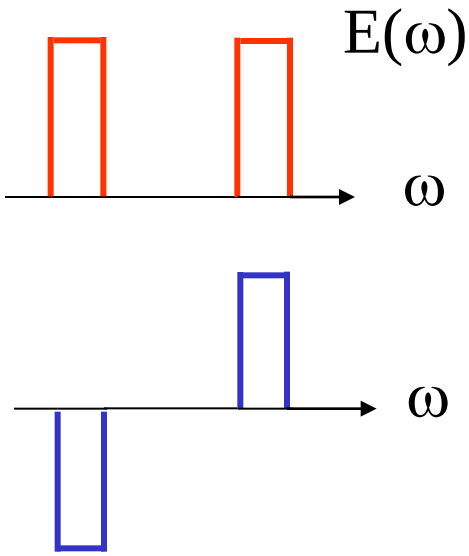
- Reduced size & component count
- Insertion loss as low as ~4 dB (including circulator!)

R.D. Nelson, D.E. Leaird, and A.M. Weiner, Optics Express (2003)

Pulse Shaping Data

(Intensity Cross-correlation)



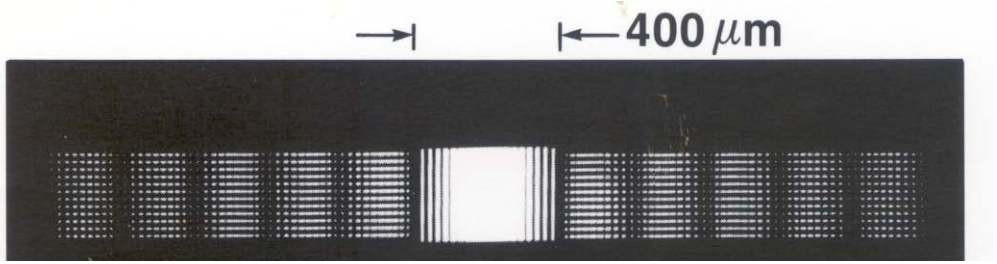


- Temporal analog to Young's two slit interference experiment
- Highly structured femtosecond waveform obtained via simple amplitude and phase filtering

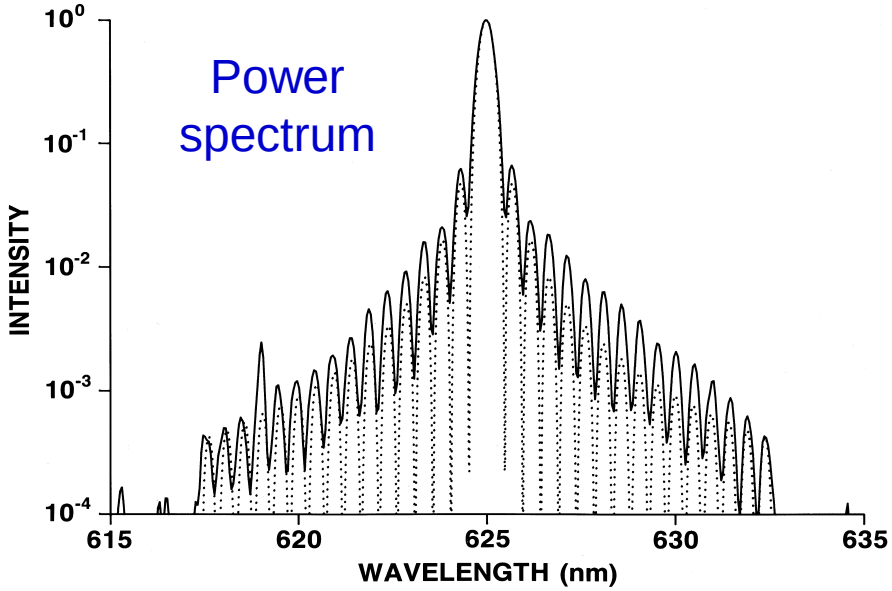
Weiner, Heritage, and Kirschner, J. Opt. Soc. Am B **5**, 1563 (1988).

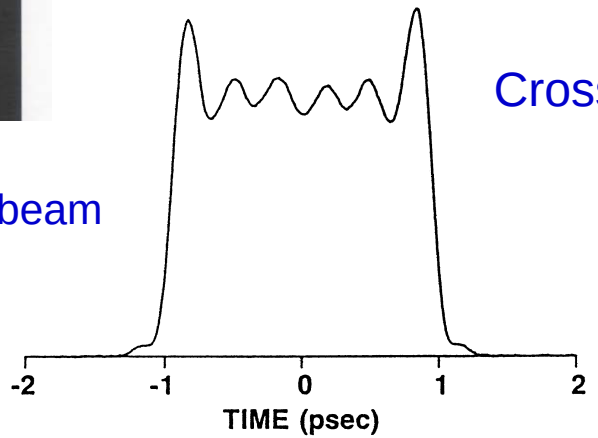
Synthesis of Femtosecond Square Pulses

Shaping via microlithographic amplitude and phase masks

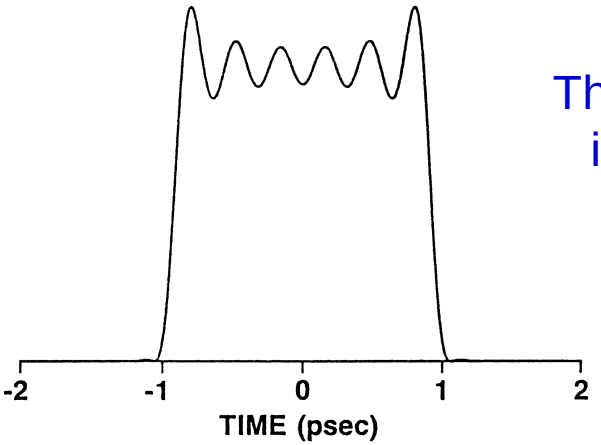


Amplitude mask:
gray-level control via diffraction out of zero-order beam





Cross-correlation data



Theoretical intensity profile

Weiner, Heritage, and Kirschner, J. Opt. Soc. Am B **5**, 1563 (1988)

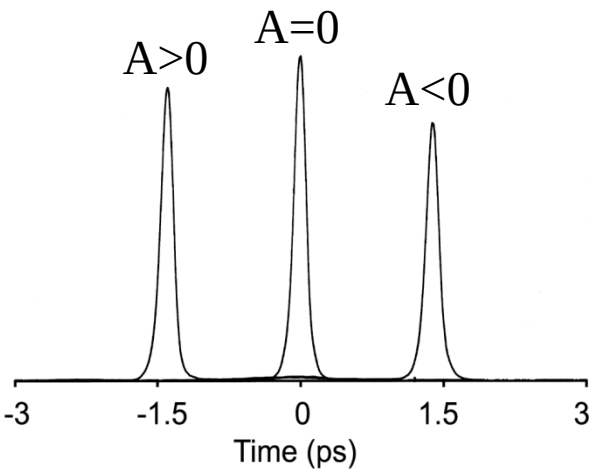
Pulse Shaping via Spectral Phase Control

Shaping via liquid crystal modulator array (LCM)

$$\tau(\omega) = \frac{-\partial\psi(\omega)}{\partial\omega}$$

Linear phase

$$\psi(\omega) = A(\omega - \omega_o)$$

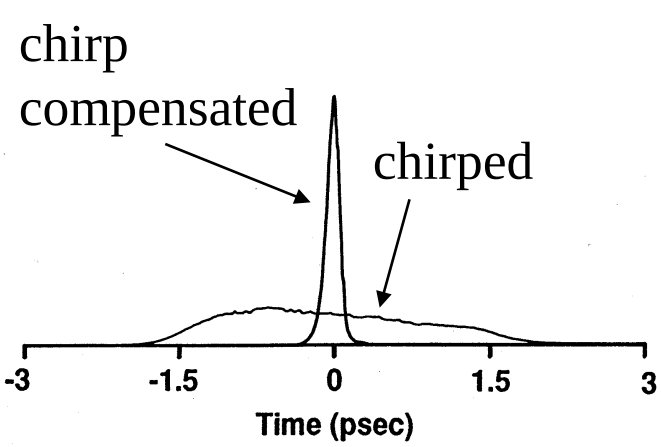


• Pulse position modulation

Weiner et al, IEEE J. Quant. Electron. **28**, 908 (1992)

Quadratic phase

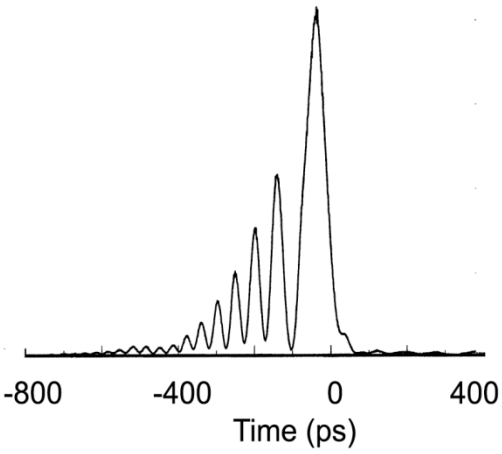
$$\psi(\omega) = B(\omega - \omega_o)^2$$



• Linear chirp

Cubic phase

$$\psi(\omega) = C(\omega - \omega_o)^3$$



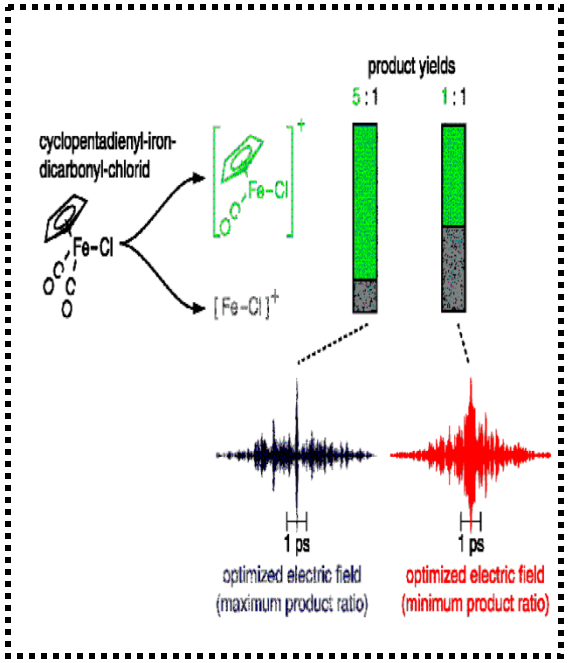
• Nonlinear chirp

Efimov et al, J. Opt. Soc. Am. B**12**, 1968 (1995)

Pulse Shaping Applications in Ultrafast Optical Science

Learning Control

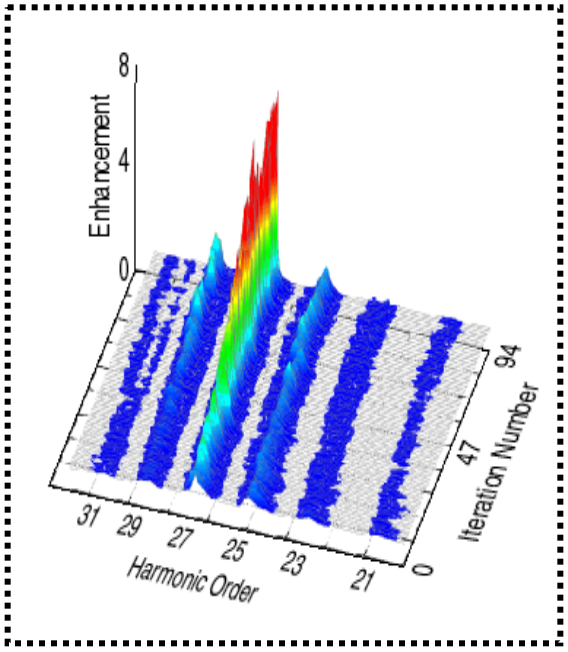
Quantum control of photofragmentation



Assion et al, Science **282**, 919 (1998)

Changing the pulse shape changes the ratio of photofragmentation products

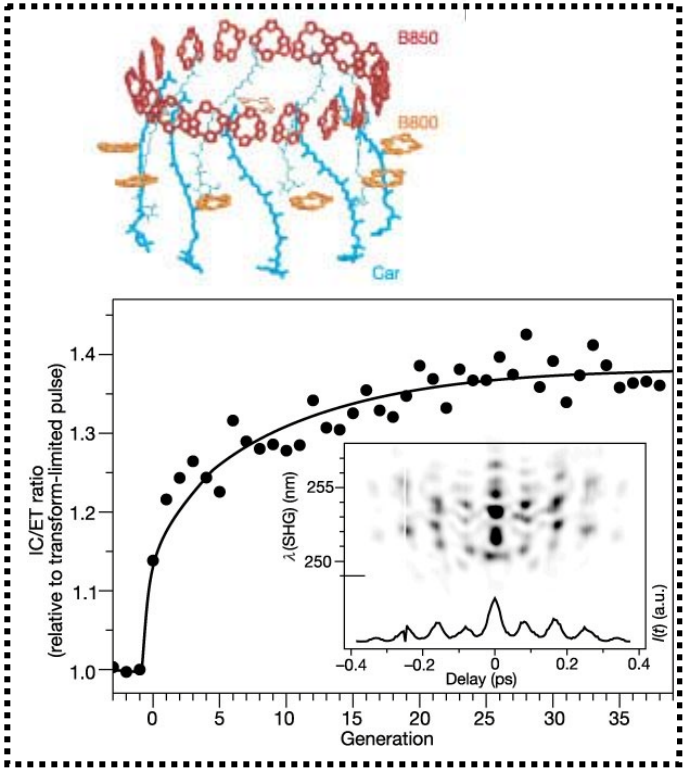
Enhancement of high harmonic generation



Bartels et al, Nature **406**, 164 (2000)

Programming the pulse shape for constructive interference of x-ray bursts from successive light cycles for selective enhancement of individual harmonics

Quantum control of energy flow in light harvesting



Herek et al, Nature **417**, 533 (2002)

Shaping the phase of the light field mediates energy transfer branching ratios in complex light harvesting biomolecules

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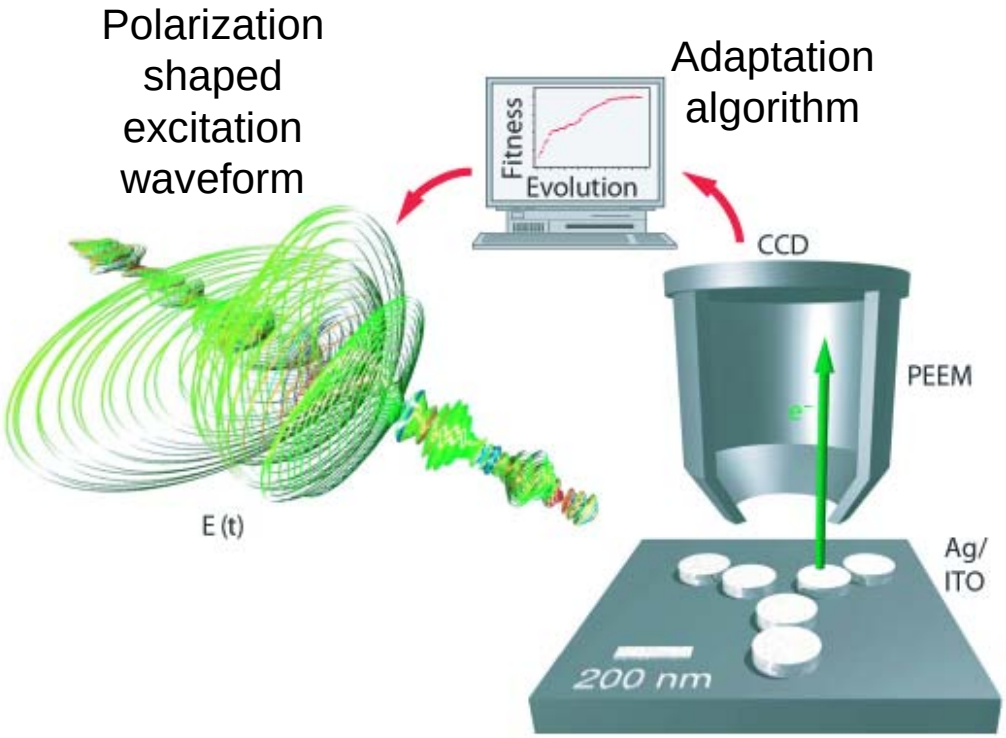
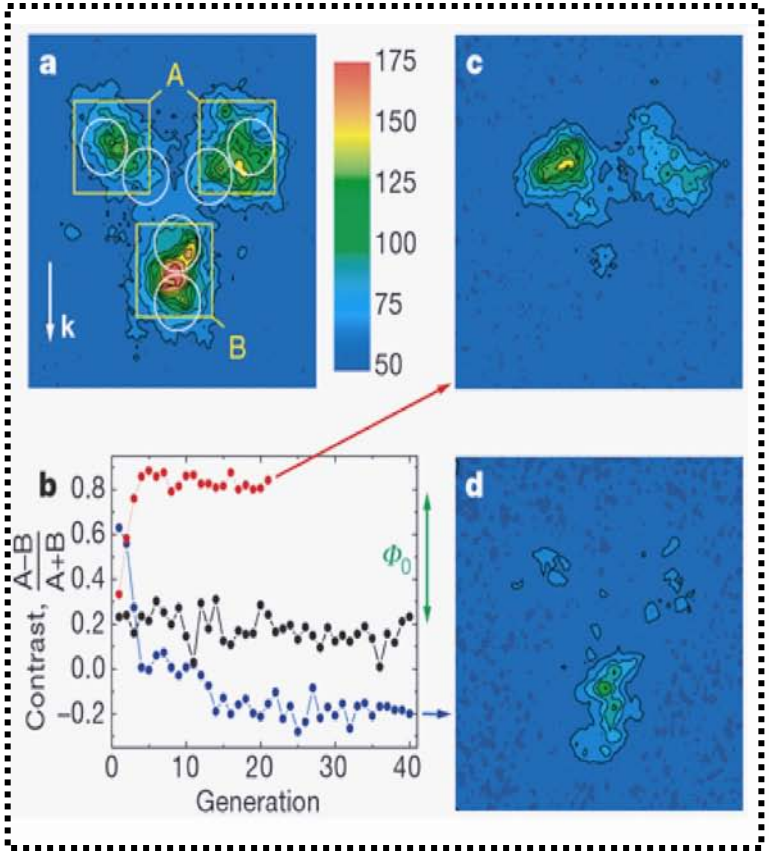
Pulse Shaping Control of Nano-optical Fields

Tailoring optical near-field on silver nanostructures via adaptive polarization shaping

Two photon photoemission electron microscopy images





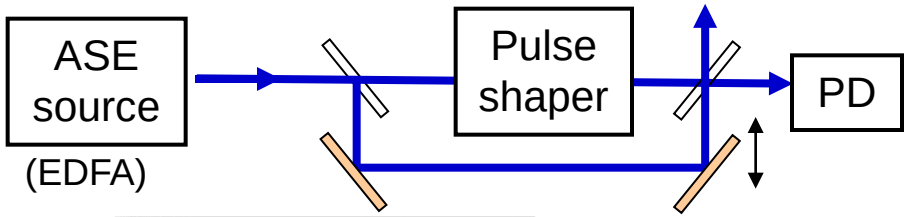
Spectral-temporal shaping of far-field waveform can affect sub-wavelength spatial degrees of freedom in the near-field.

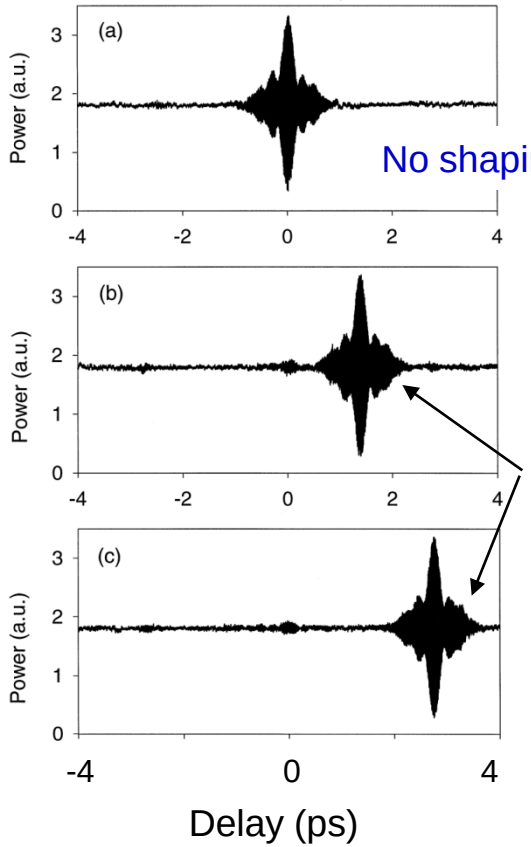
Aeschlimann et al, Nature **446**, 301 (2007)

"Shaping" of Incoherent and Nonclassical Light

Incoherent Light:

Shaping the elec. field cross-correlation function

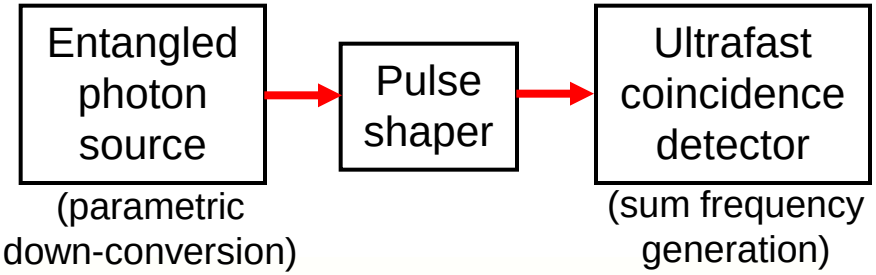




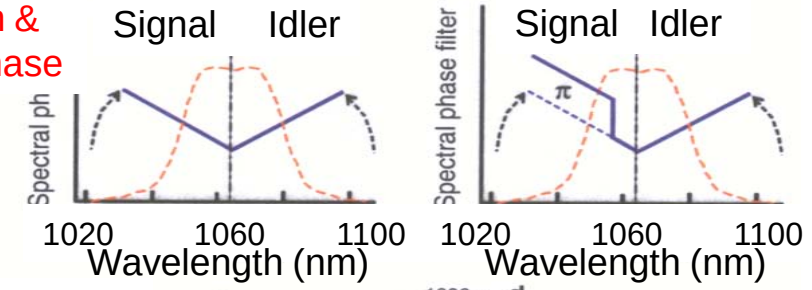
Wang and Weiner, Opt. Comm. **167**, 211 (1999)

Nonclassical (Quantum) Light:

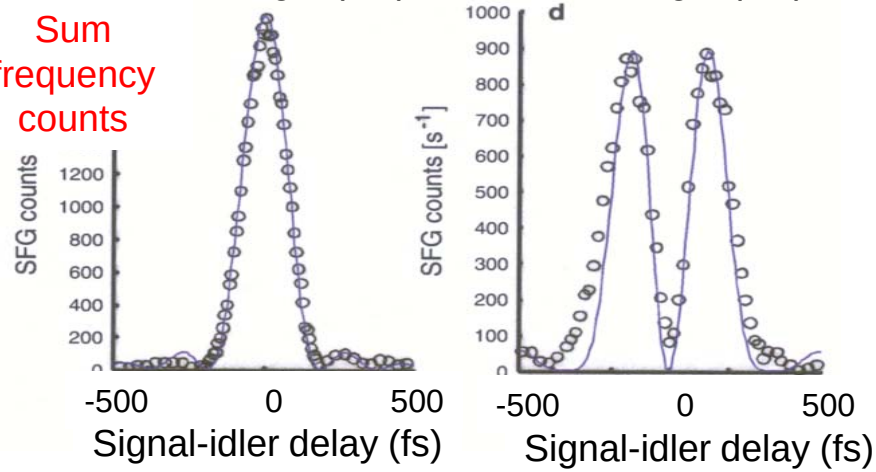
Shaping the two-photon wave function



Spectrum & spectral phase



Sum frequency counts



Pe'er, Dayan, Friesem, and Silberberg, Phys. Rev. Lett. **94**, 073601 (2005)

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Pulse Shaping and Fiber Optic Communications

Fiber Optics

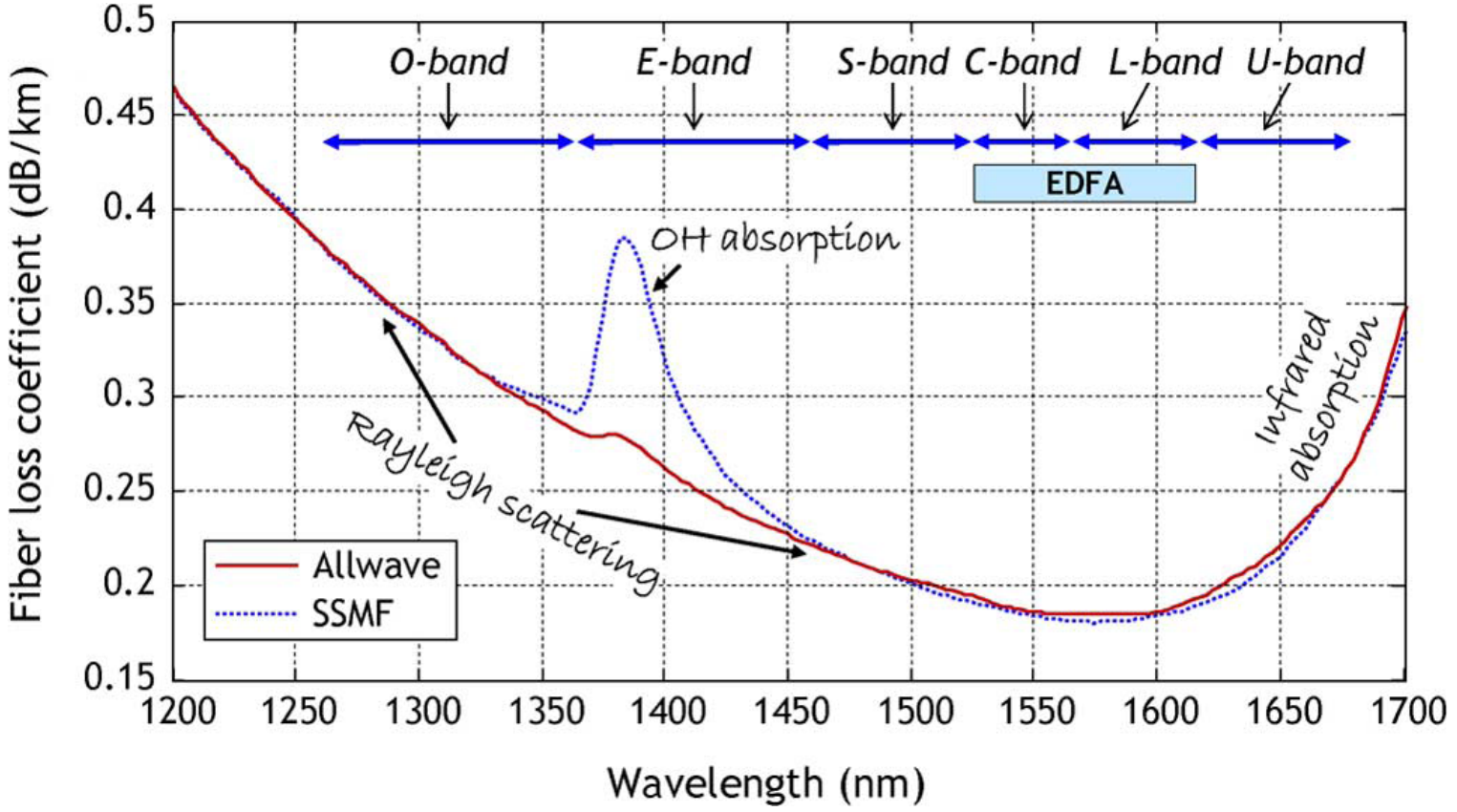
The Nobel Prize in Physics 2009

http://nobelprize.org/nobel_prizes/physics/laureates/2009/index.html

Charles K. Kao

"for groundbreaking achievements concerning the transmission of light in fibers for optical communication"

Bandwidth of Optical Fibers

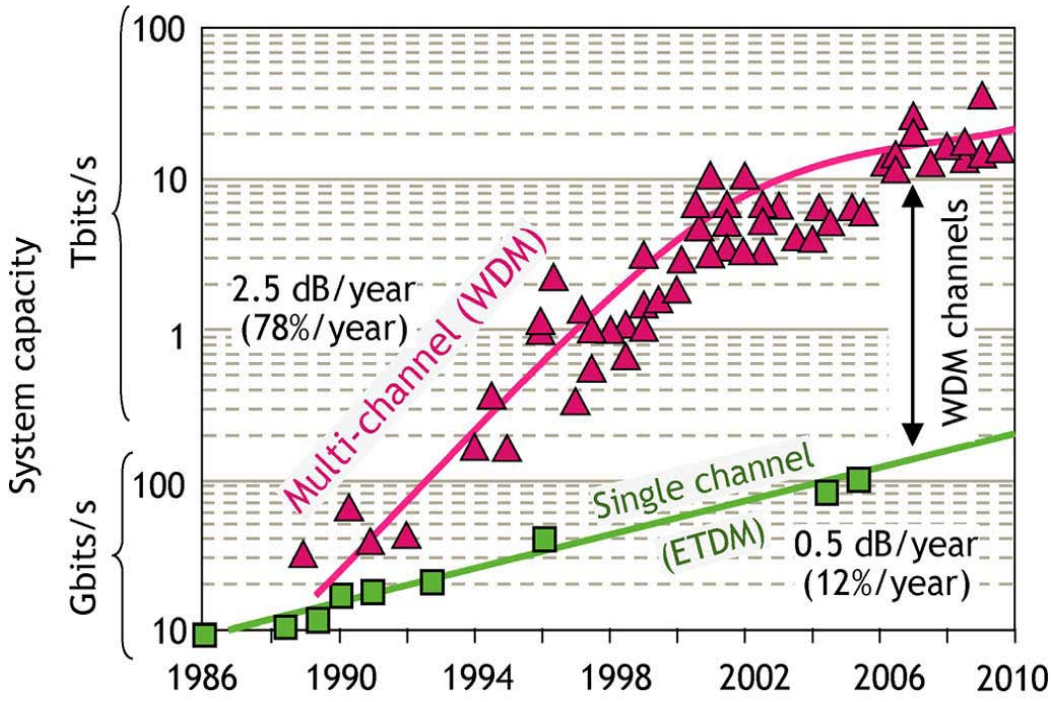


Silica glass fibers provide extremely low-loss transmission over tens of Terahertz!

- contrast to electrical cables: 100s of dB/km loss (at GHz frequencies)

R.-J. Essiambre, G. Kramer, P.J. Winzer, G.J. Foschini, and B. Goebel,
"Capacity Limits of Optical Fiber Networks," Journal of Lightwave Technology **28**, 662-701 (2010)

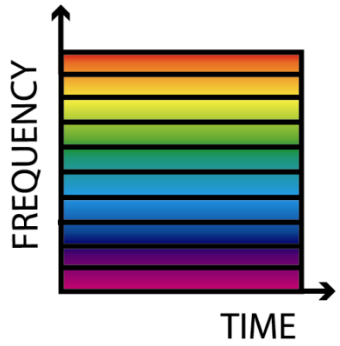
Bandwidth Partitioning for Optical Networks



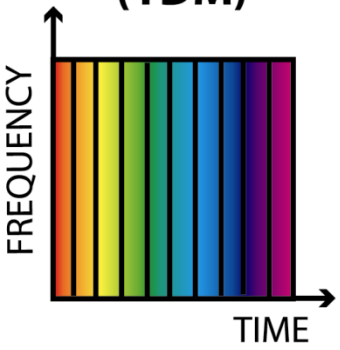
Historical evolution of record capacity of "hero experiments" in fiber-optic communication systems

R.-J. Essiambre et al, "Capacity Limits of Optical Fiber Networks," J. Lightwave Tech. **28**, 662-701 (2010)

WAVELENGTH-DIVISION MULTIPLEXING (WDM)

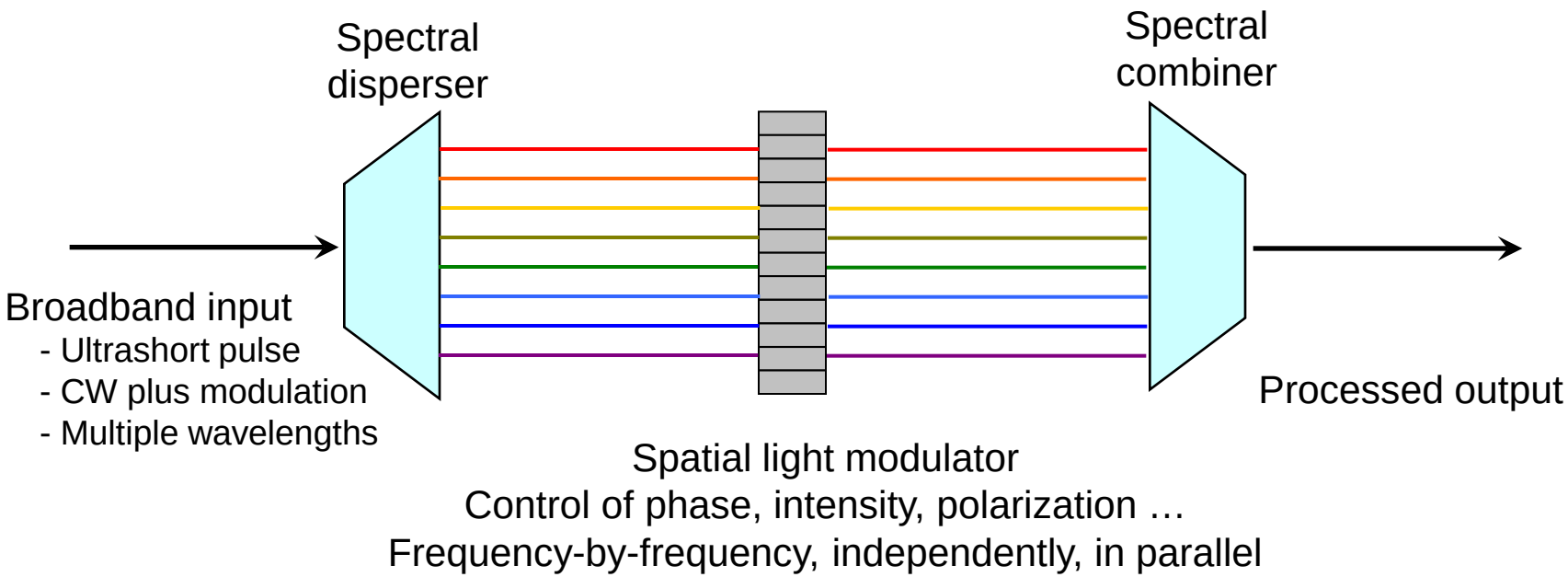


TIME-DIVISION MULTIPLEXING (TDM)



Pulse Shaping in Optical Communications

"Dynamic spectral processor"

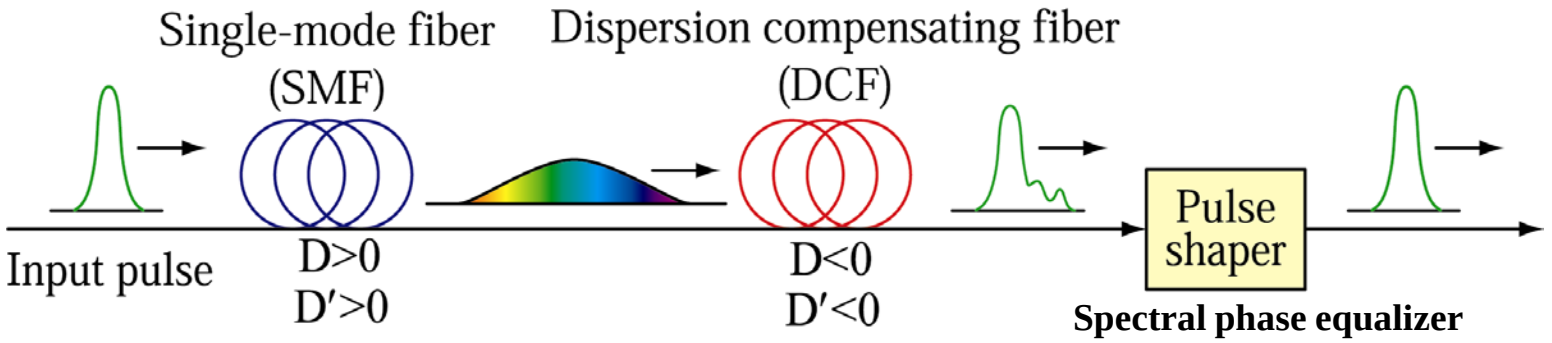


-Pulse shaping

-Dynamic spectral equalizers

-Dynamic wavelength processing

Programmable Fiber Dispersion Compensation Using a Pulse Shaper: Subpicosecond Pulses



- **Coarse dispersion compensation using matched lengths of SMF and DCF**
- **Fine-tuning and higher-order dispersion compensation using a pulse shaper as a programmable spectral phase equalizer**
- **Similar ideas apply to few femtosecond pulse compression**

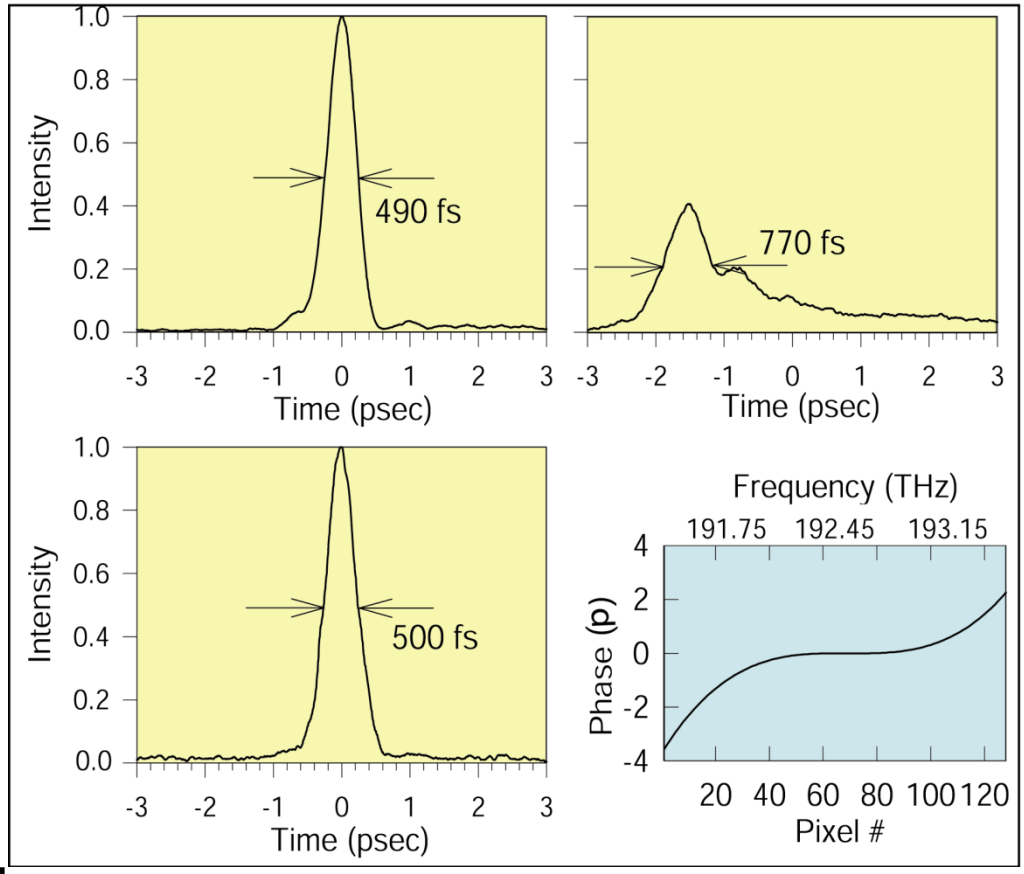
$$\tau(\omega) = \frac{-\partial\psi(\omega)}{\partial\omega}$$

A.M. Weiner, U.S. patent 6,879,426

Higher-Order Phase Equalization Using LCM

Input and output pulses from 3-km SMF-DCF-DSF link

Input pulse



Output pulse (**without** phase correction)

already compressed several hundred times

Output pulse (**with** quadratic & cubic correction)

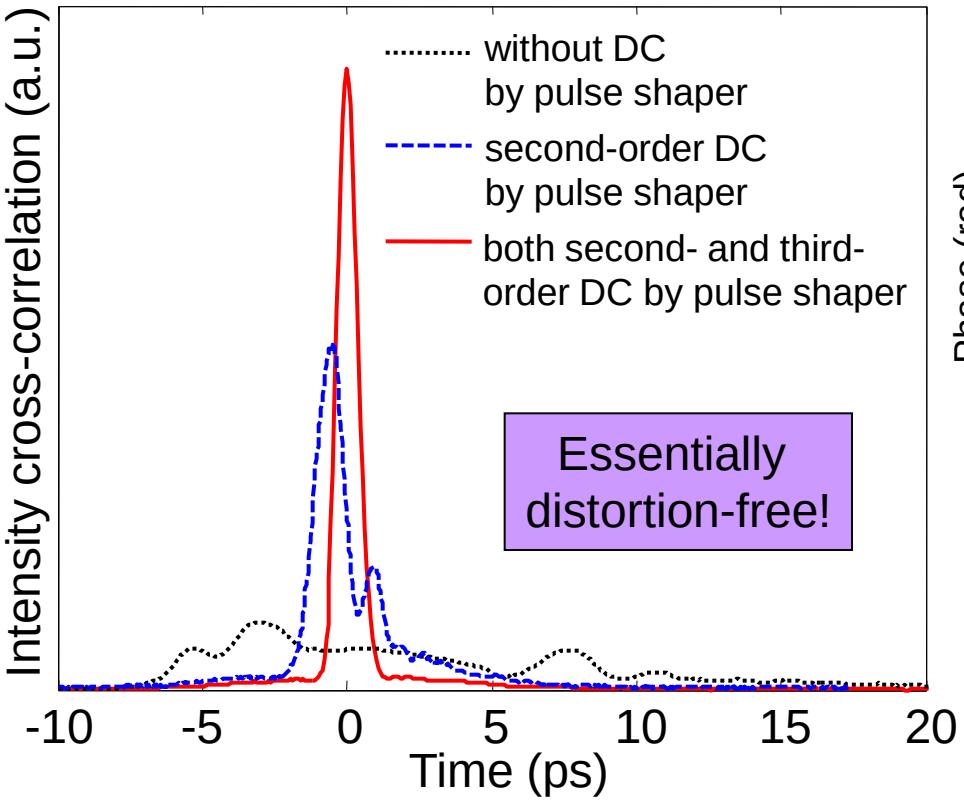
Applied phase

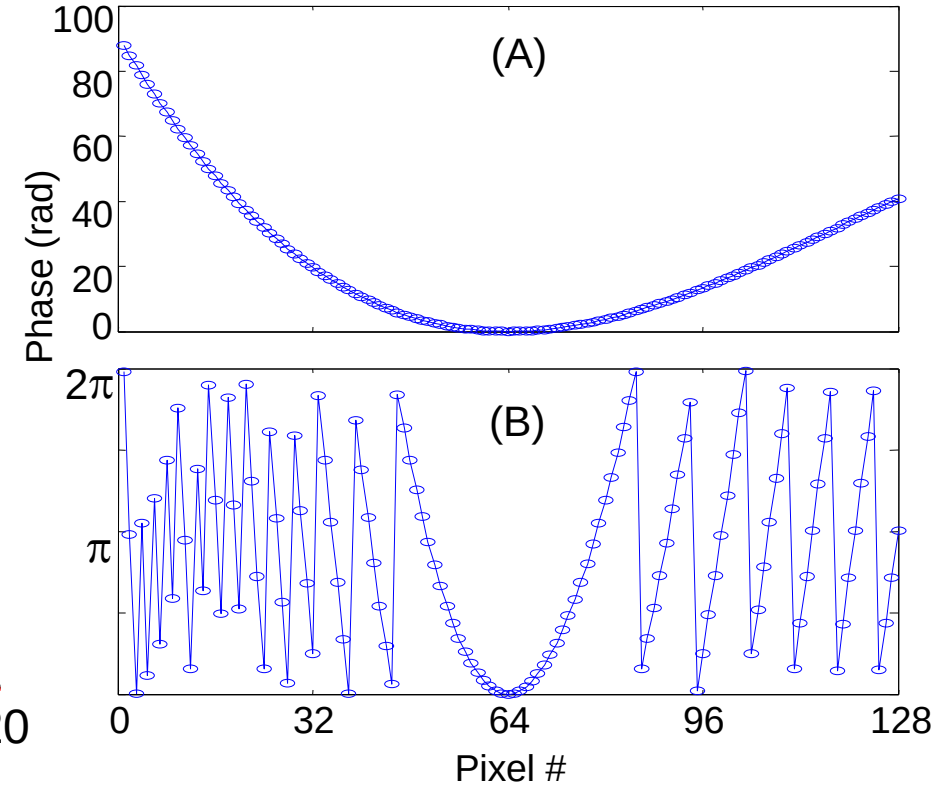
No remaining distortion!

Chang, Sardesai, and Weiner, Opt. Lett. **23**, 283 (1998)

460 fs transmission over 50 km SMF

Commercial DCF module (as is) with spectral phase equalizer



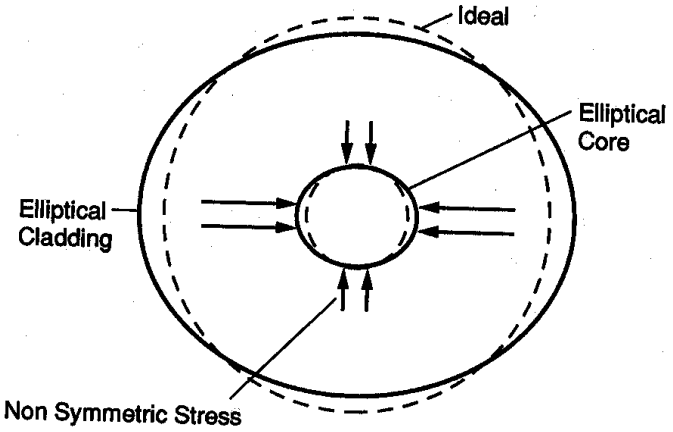


- ~ 5 ns after SMF
- 13.9 ps after DCF
- 470 fs after quadratic/cubic phase equalization

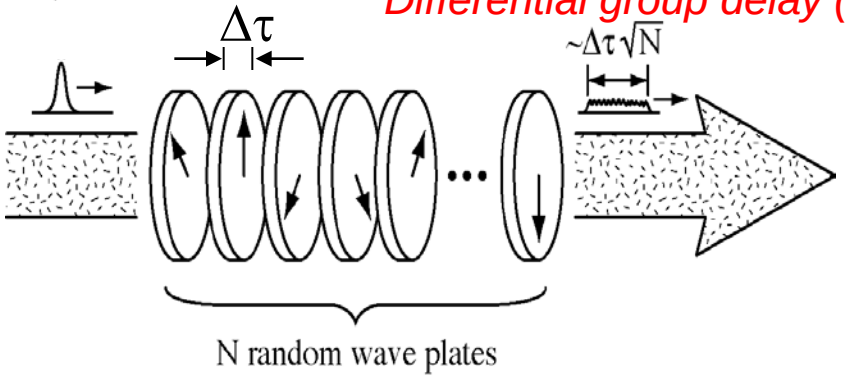
Z. Jiang, Leaird, and Weiner, Opt. Lett. **30**, 1449 (2005)

All-order Polarization Mode Dispersion (PMD) Compensation

Vector pulse shaping for compensation of vector distortions in fibers

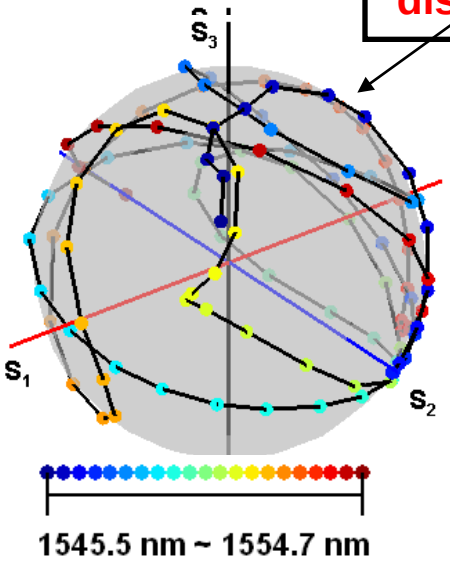


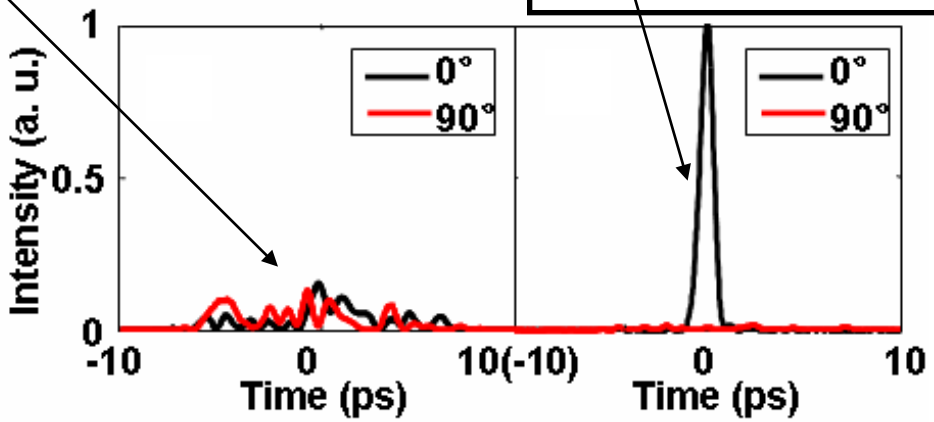
Differential group delay (DGD)



~800 fs pulse after distortion via ~ 5.5 ps PMD

Restored pulse after PMD compensation using custom 4-layer LCM

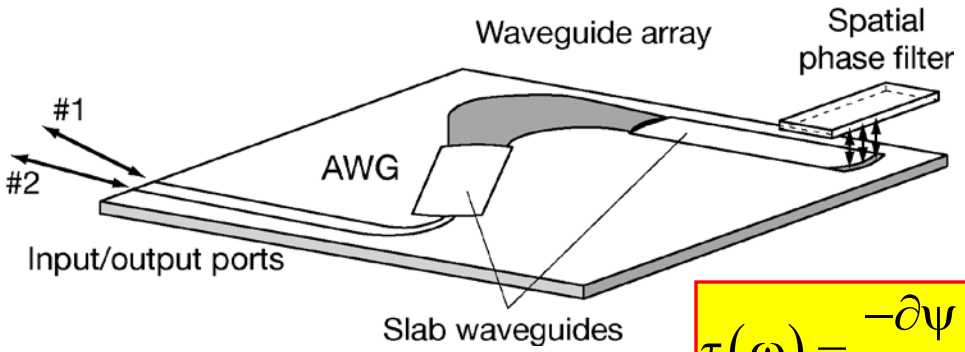




Miao, Weiner, Mirkin, and Miller, Opt. Lett. **32**, 2360 (2007)

"Pulse Shaping" in WDM: Dispersion Compensation Research

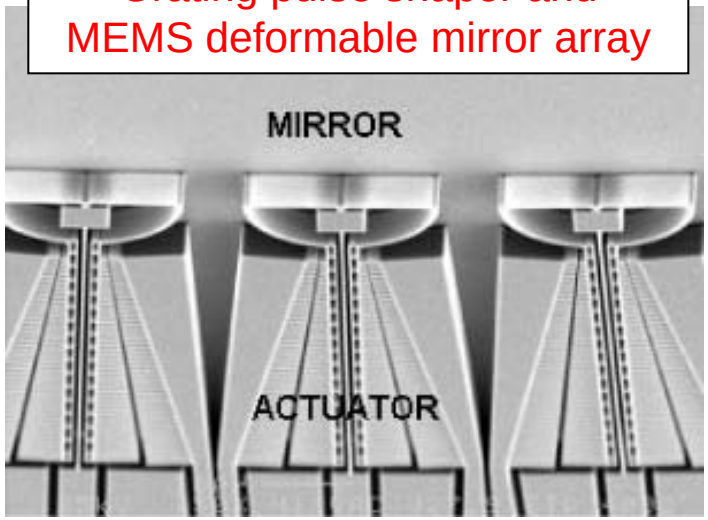
AWG pulse shaper and phase mask



Takenouchi, Goh and Ishii, OFC 2001 (NTT)

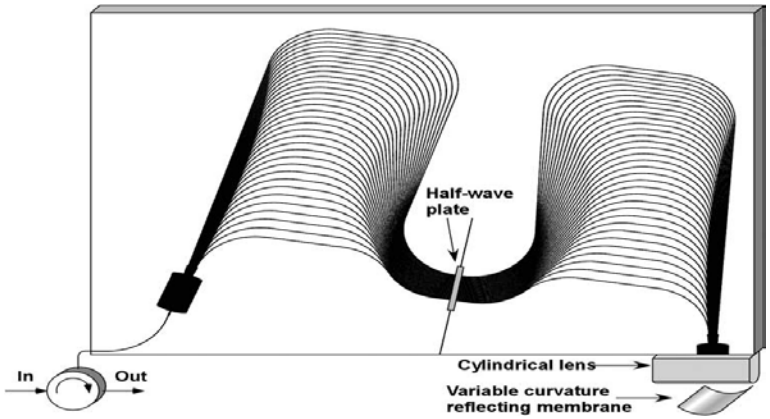
$$\tau(\omega) = \frac{-\partial\psi(\omega)}{\partial\omega}$$

Grating pulse shaper and MEMS deformable mirror array



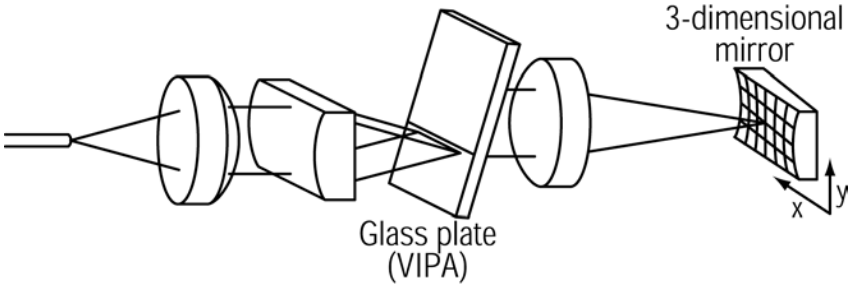
Sano et al, OFC 2003 (Sumitomo)

AWG pulse shaper and deformable mirror



Neilson et al, JLT **22**, 101 (2004) [Lucent]

VIPA pulse shaper and curved mirror



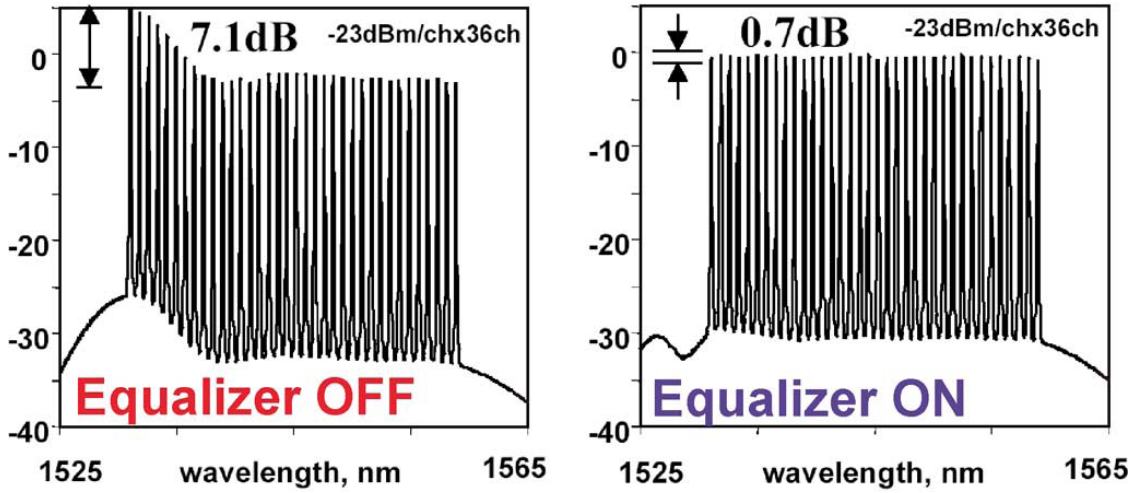
Shirasaki and Cao, OFC 2001 (Fujitsu/Avanex)

- Either colorless dispersion compensation or independent fine-tuning of different channels

“Pulse Shaping” in WDM: Intensity Control

Manipulation on a wavelength-by-wavelength basis
No concern for phase or for coherence between channels

Spectral gain equalizer



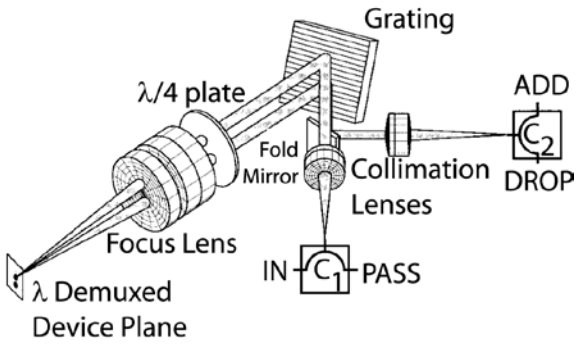
Ford et al, IEEE JSTQE **10**, 579 (2004) [Lucent]

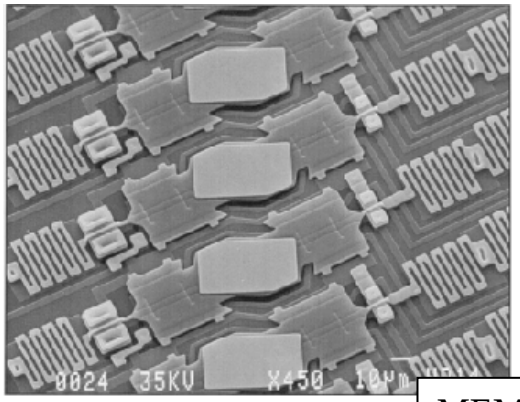
“Pulse Shaping” in WDM: Intensity Control

Manipulation on a wavelength-by-wavelength basis
No concern for phase or for coherence between channels

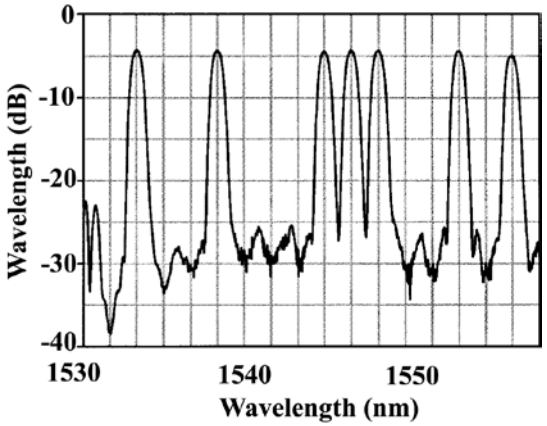
Wavelength selective add-drop multiplexer (and wavelength selective switches)

Early 2-spatial-channel example





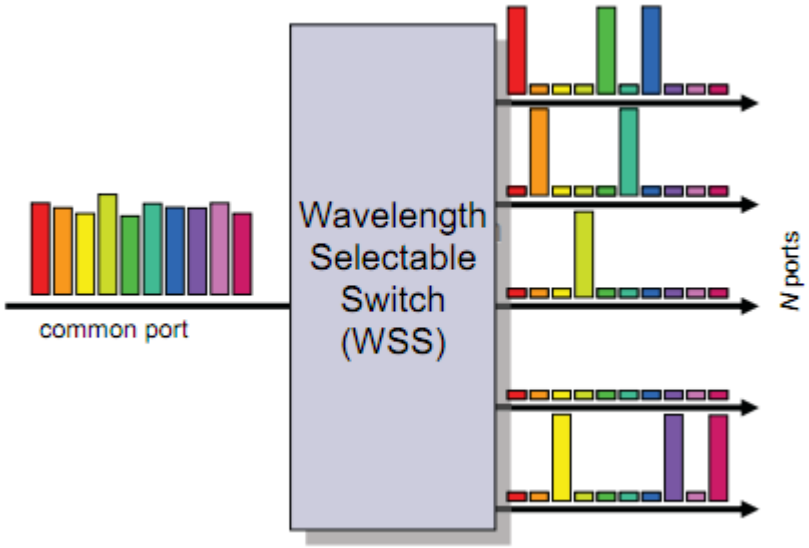
MEMS version



- Both MEMS and liquid crystals used as spatial light modulator technologies
  - MEMS version – above: Ford et al, J. Lightwave Tech. **17**, 904 (1999) [Lucent]
  - Liquid crystal version: Patel and Silberberg, IEEE PTL **7**, 514 (1995) [Bellcore]

“Pulse Shaping” in WDM

Wavelength Selective Switching – now heavily deployed in lightwave networks



http://www.fiberoptics4sale.com/wordpress/what-is-wavelength-selective-switchwss/

WSS's have now evolved to include phase – leading to commercial telco-format pulse shapers

Finisar

WAVESHAPER M SERIES
OEM Programmable Optical Processors

PRODUCT BRIEF

KEY FEATURES

- Designed for OEM Integration
- Fully compatible with S Series
- Control of Filter Shape
- Control of Filter Dispersion
- High Resolution
- Small Form Factor
- Supports Band-Pass, Band-Stop and Optical Comb Filters
- USB Interface
- Drivers for Windows and Linux

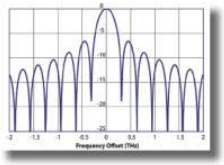
OVERVIEW

The WaveShaper 1000M and 4000M are the OEM versions of Finisar's industry-leading 1000S and 4000S Programmable Optical Processors. Designed for embedding into third-party equipment and instrumentation, they are based on Finisar's high-resolution, solid-state Liquid Crystal on Silicon (LCoS) optical engine. Containing no moving parts, the M Series provide extremely fine control of filter amplitude and phase characteristics.

WaveShaper M Series of OEM Programmable Optical Processors

COMPATIBLE WITH S-SERIES

The WaveShaper M Series are fully compatible with the WaveShaper 1000S and 4000S. This allows the developer to easily prototype and develop programs and optical functionality using the WaveShaper S Series, then easily transfer the optical profiles and control code developed to the M Series hardware. As for the S Series, the optical transfer function can be software-specified by the user across the entire 5 THz of operation, which allows the generation of arbitrary, complex filters as well as control of filter bandwidth and center frequency with 1 GHz resolution. Both the amplitude and phase of the transmitted light can be controlled, providing an unparalleled capability for signal shaping. Band-stop and optical comb filters are also supported. Any arbitrary filter can then be used as the switching transfer function for the Wavelength Switching capability of the 4000M.

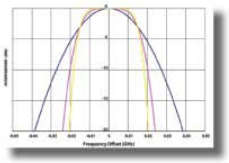


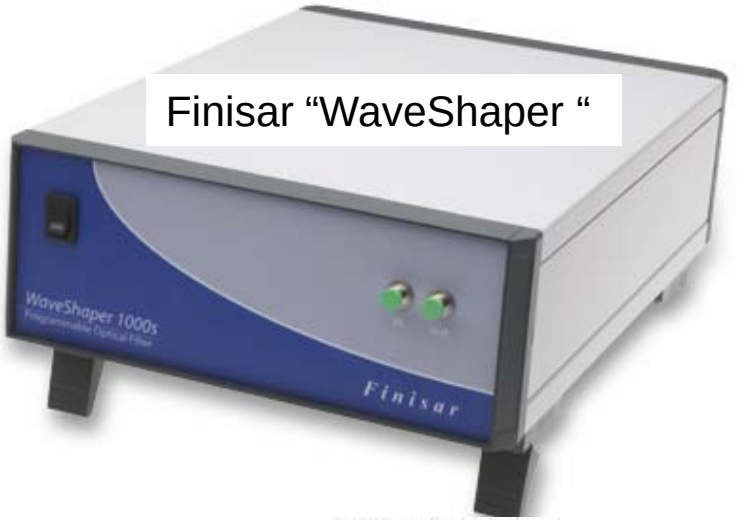
WINDOWS AND UNIX DRIVERS

Control software is provided for both Windows and Unix (Linux) which allows full control of the WaveShaper M Series' optical transfer function as well as providing hardware and firmware diagnostic and monitoring capabilities. A common API is used across both operating systems which makes it easy to develop and integrate into the user's system.

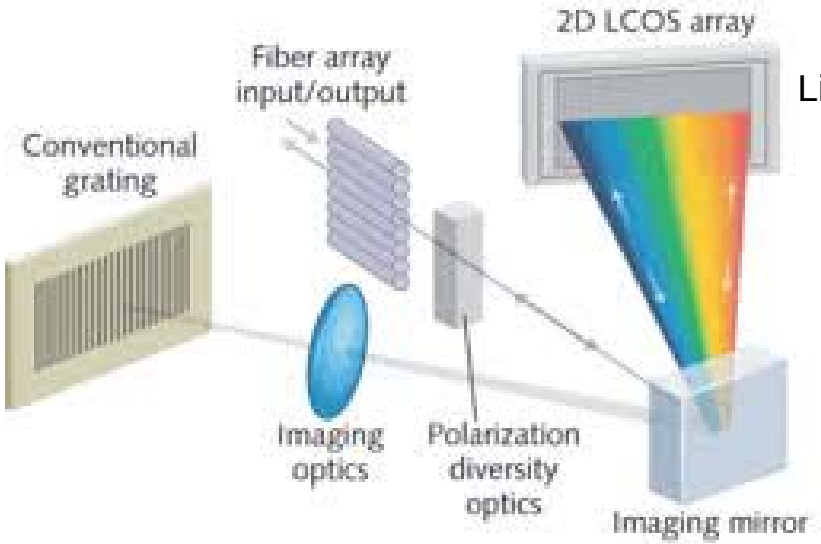
HIGH RELIABILITY

The WaveShaper M Series is based on Finisar's solid-state Liquid Crystal on Silicon (LCoS) optical engine which is used in Finisar's range of Wavelength Selective Switches. These are Telcordia qualified and installed in the core of telecom networks around the world. With no moving parts and a hermetically-sealed optical unit, the WaveShaper M Series of Programmable Optical Processors will provide years of maintenance-free operation.





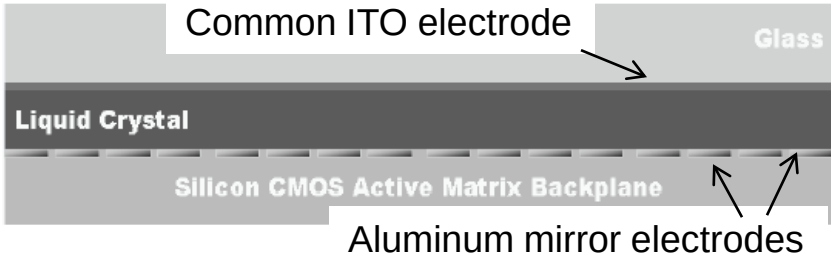
Finisar "WaveShaper "

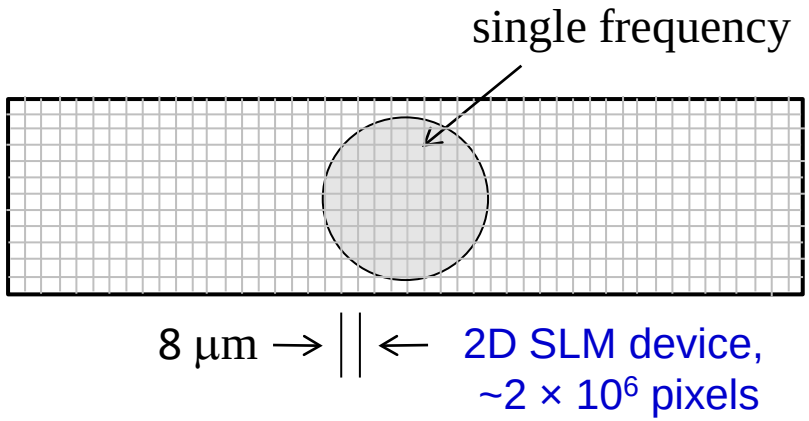


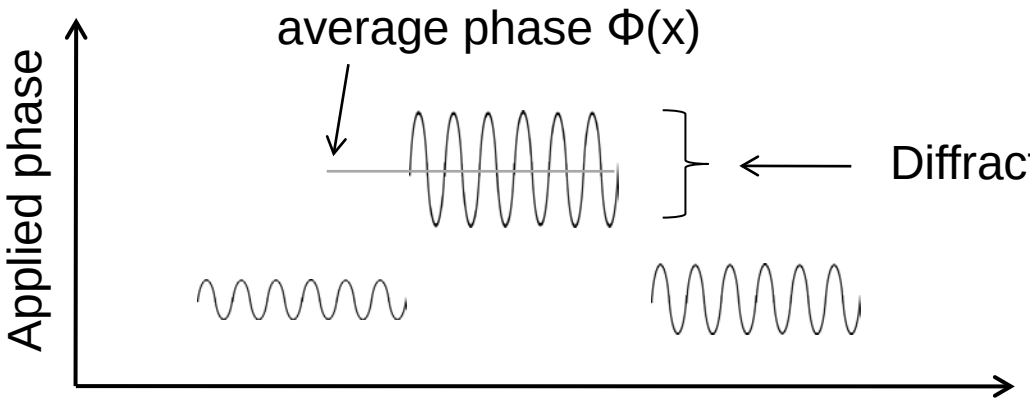
Liquid crystal on silicon

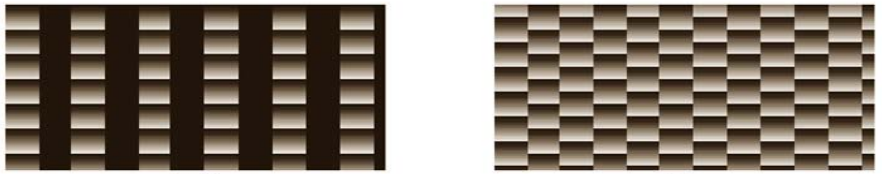
Liquid Crystal on Silicon (LCOS) Technology

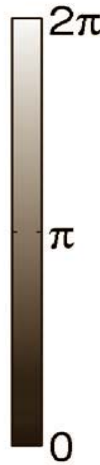
Thousands to millions of tiny pixels with phase-only response





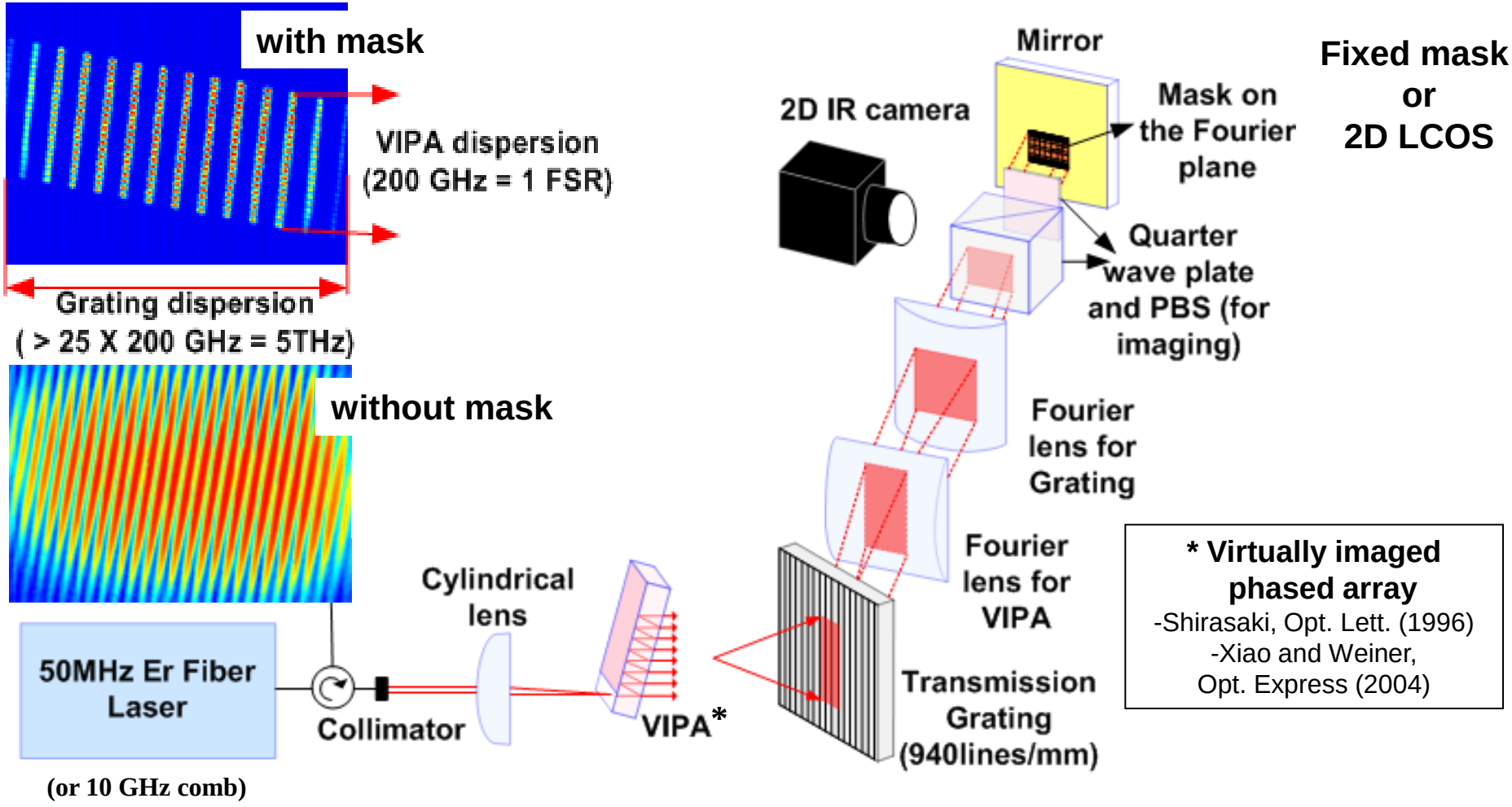






Frumker and Silberberg, J. Opt. Soc. Am. B **24**, 2940 (2007)

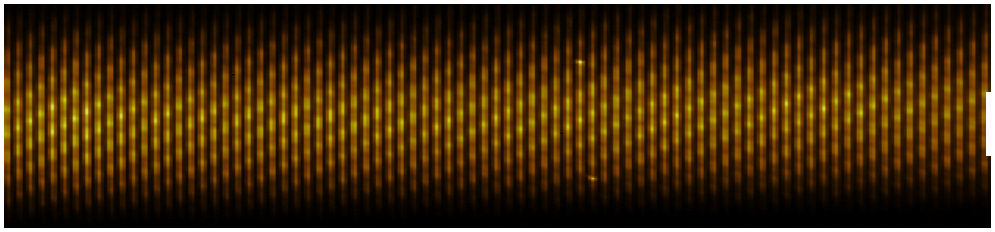
Two-Dimensional Grating-VIPA Pulse Shaper



Towards high spectral resolution **and** broad bandwidth
(Long time aperture and narrow pulse features)

Supradeepa, Huang, Leaird, and Weiner, Optics Express 16, 11878 (2008)

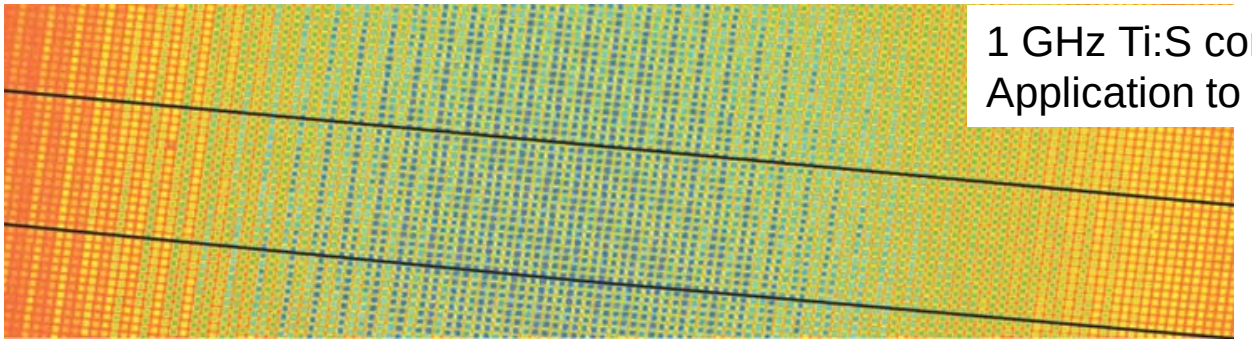
Two Dimensional Disperser Images



Wavelength-parallel polarimeter application
1500 channels from 1520-1552.8 nm

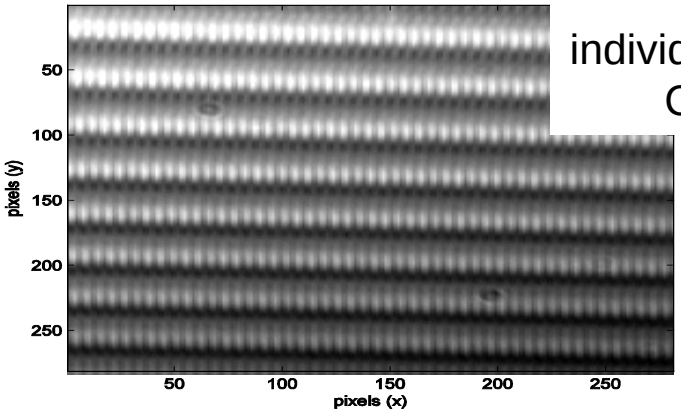
50 GHz

Wang, Xiao, and Weiner, Opt. Express **13** (2005)



1 GHz Ti:S comb, cavity filtered to 3 GHz
Application to comb spectroscopy of iodine

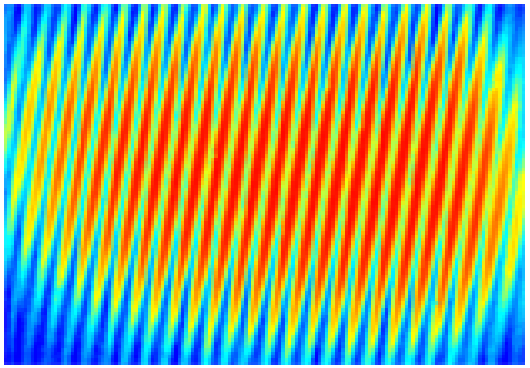
Diddams, Hollberg, Mbele (NIST), Nature (2007)



923 MHz Ti:S comb
individual lines directly separated
Collaboration with JILA

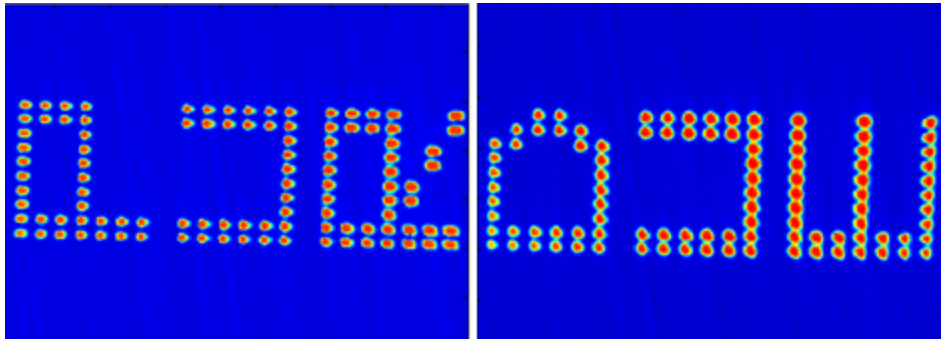
Willits, Cundiff, and Weiner, IEEE LEOS Annual Meeting (2008)

Supradeepa, et al, Opt. Express **16**, 11878 (2008)

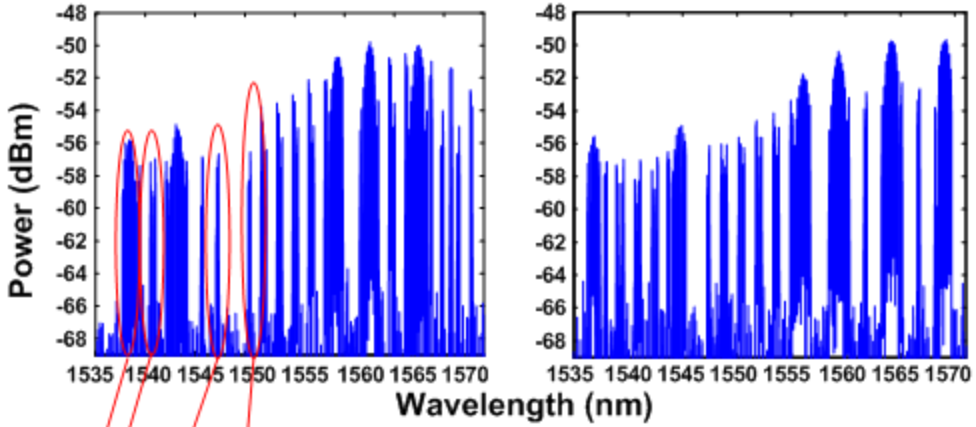


Enhanced Spectral Control Demonstration

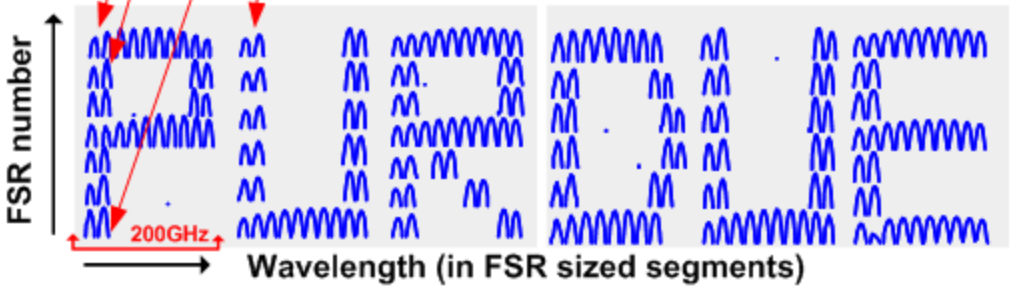
Spatial mask



OSA spectra



OSA spectra unraveled

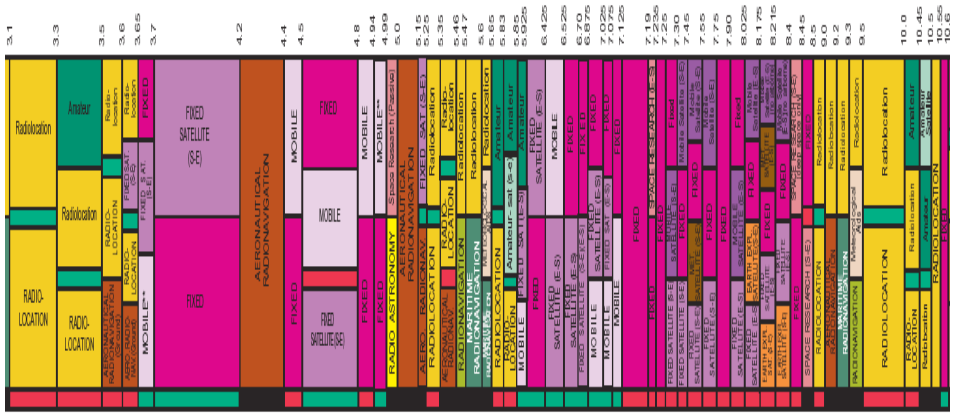


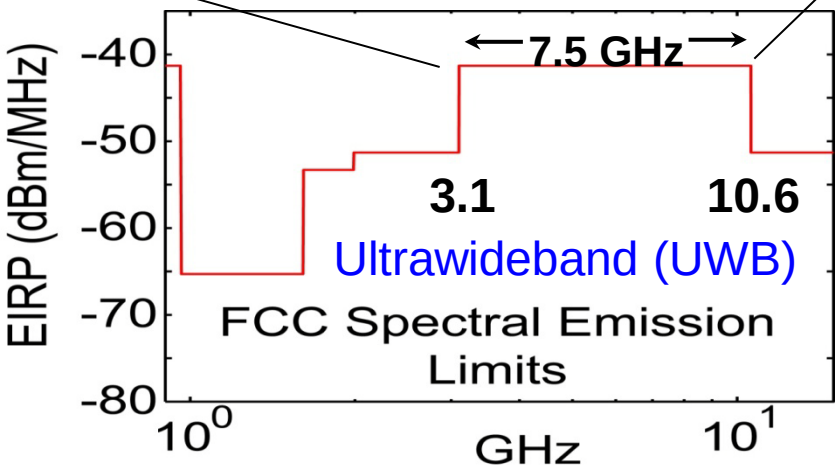
- Smallest feature is 10GHz, total bandwidth per spectrum ~4.5THz

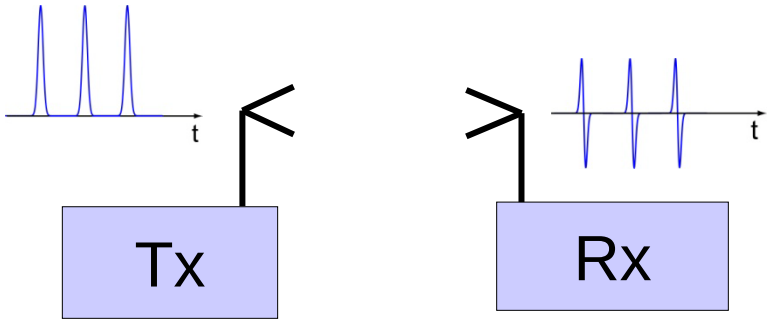
Supradeepa, Huang, Leaird, and Weiner, Optics Express 16, 11878 (2008)

Pulse Shaping and Ultrabroadband Radio-Frequency Systems

Narrowband (Frequency Domain) vs. Ultrabroadband (Time-Domain) RF Systems







UWB attributes

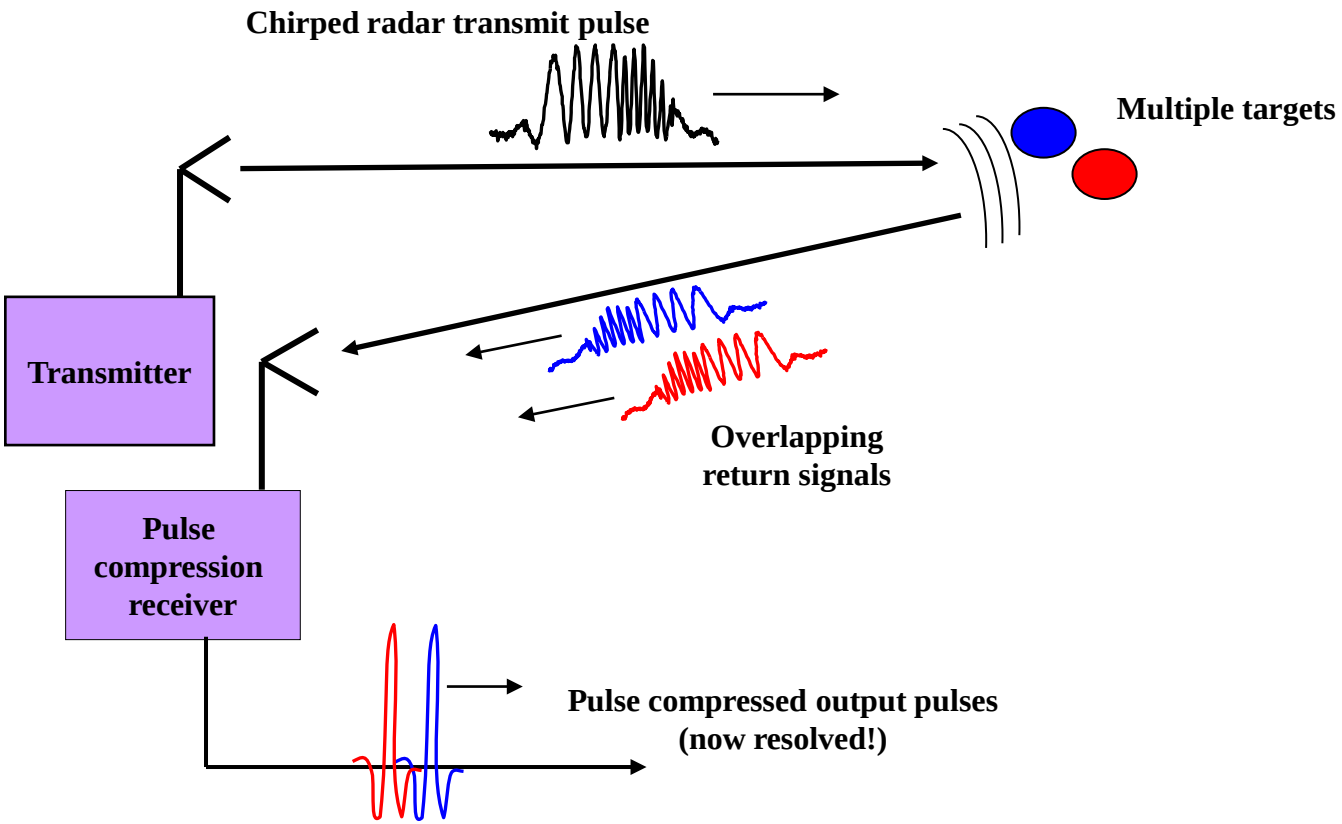
- high time resolution
- high data rate
- multi-path resistance
- overlay w/ narrowband services
- low probability of intercept

Application examples

- wireless communications
- security and defense (radar, sensing, electronic countermeasures)

Electronic solutions are insufficient to simultaneously cover the full frequency band

Chirped Radar



- Long chirped transmit pulses mitigate peak power limitations
  - Pulse compression receiver retains range resolution

- Can one extend these concepts to >10 GHz bandwidths?

Enable new ultrabroadband RF capabilities via photonic processing

•New technologies

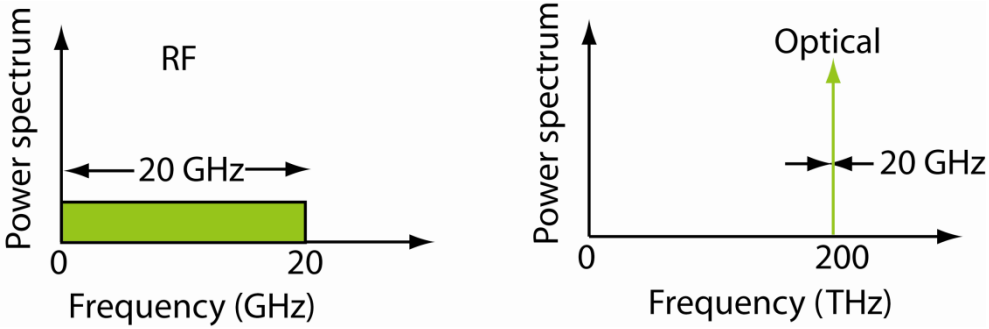
•New ways of thinking about RF systems

Ultrabroadband (time-domain) systems have been extensively explored in ultrafast optics

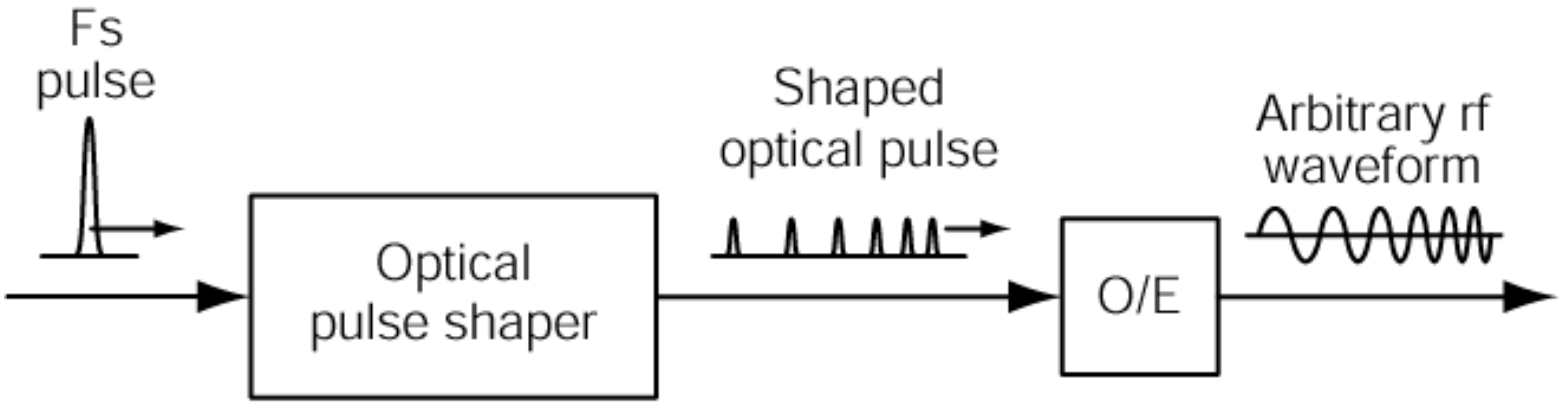
- Femtosecond pulses
- THz bandwidths
- Complex ultrabroadband phase control

Optics has high center frequencies

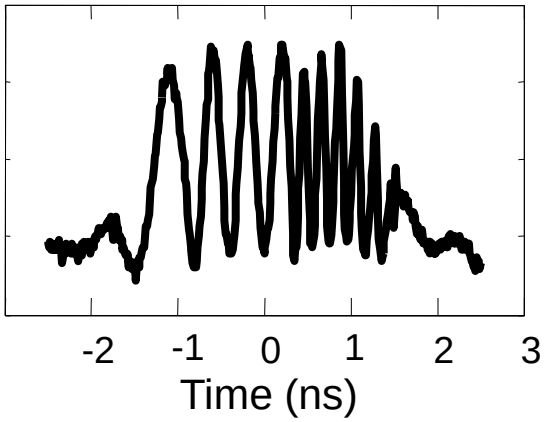
- 1.5 μm wavelength → $2 \cdot 10^{14}$ Hz
- 20 GHz instantaneous bandwidth, e.g., 0-20 GHz, very hard to deal with directly in RF domain; only 0.01% fractional bandwidth in optical domain



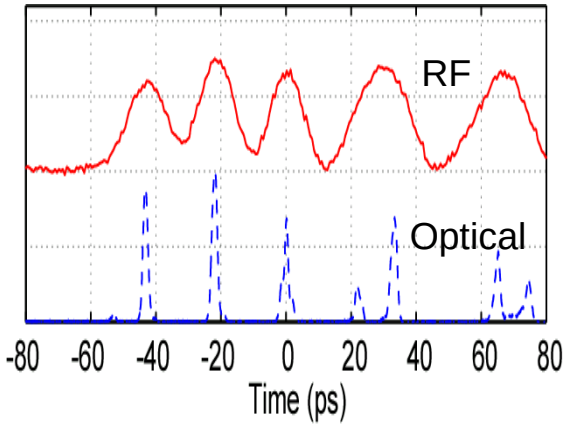
Photonics-Enabled RF Arbitrary Waveform Generation



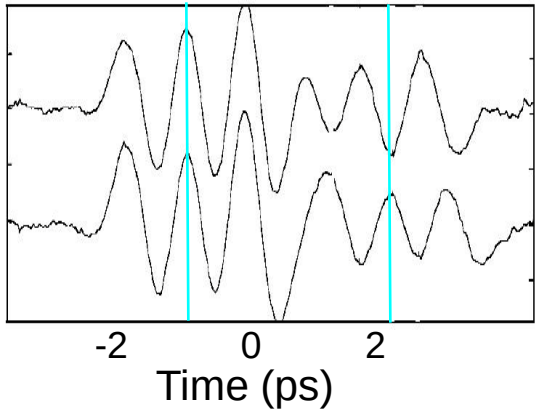
1.2/2.5/4.9 GHz FM Waveform



48/24 GHz FM Waveform



THz Phase Modulation

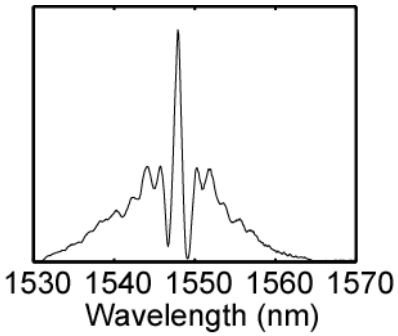


- **Exploitation of optical pulse shaping technology for cycle-by-cycle synthesis of arbitrary RF waveforms beyond the capability of electronics solutions**
- **Approach scales from Gigahertz to Terahertz**

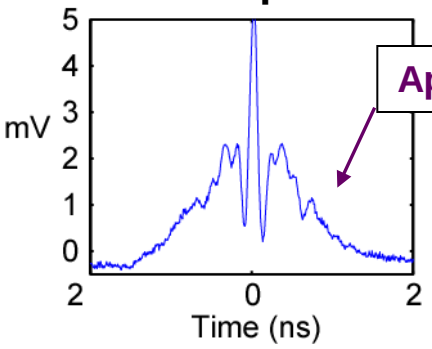
Spectral Engineering of Ultrabroadband RF Waveforms

(e.g., to conform to spectral occupancy constraints)

Optical Spectrum

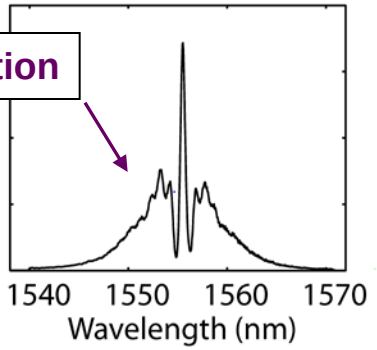


RF Impulse

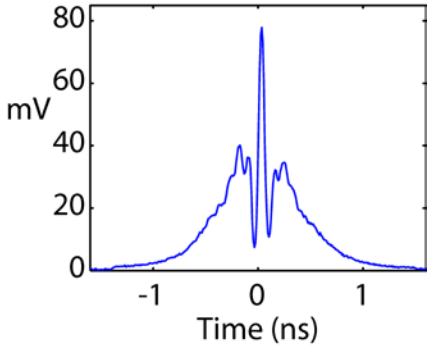


Apodization

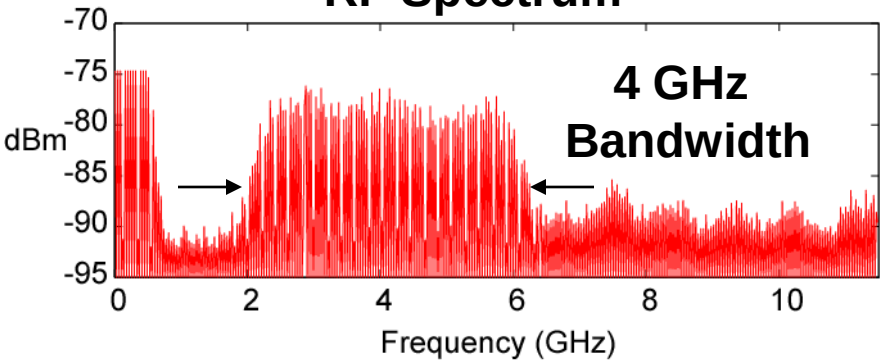
Optical Spectrum



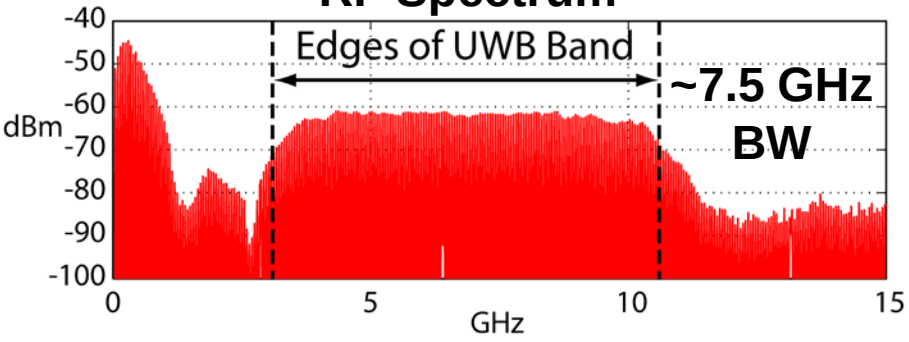
RF Impulse



RF Spectrum



RF Spectrum



- **RF spectral engineering via ultrafast optical pulse shaping, optical frequency-to-time conversion, and O/E conversion**

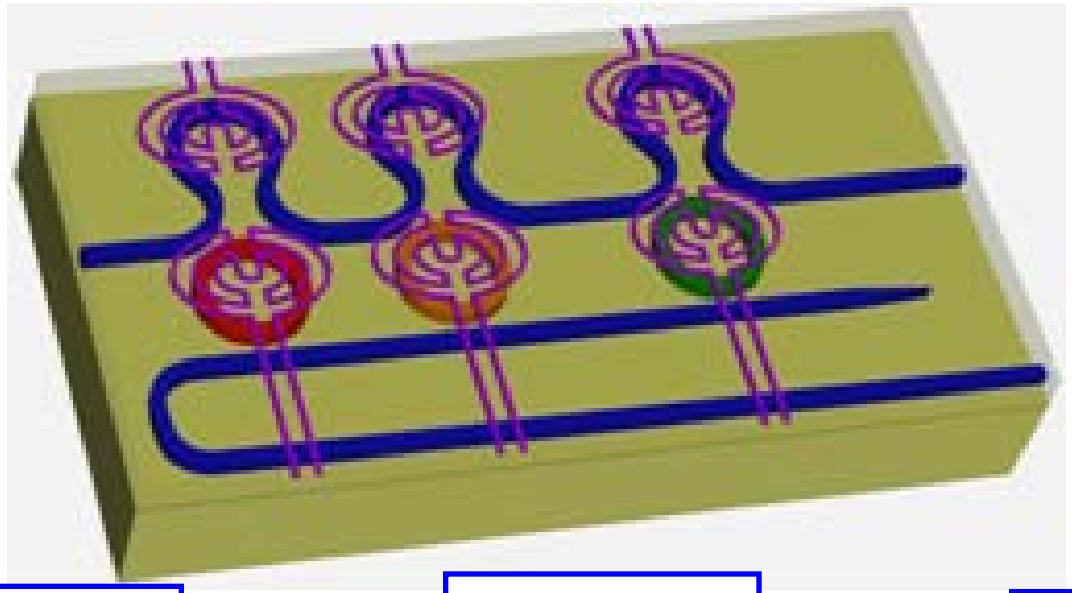
Conforms to FCC specified ultrawideband (UWB) frequency range of 3.1 – 10.6 GHz.

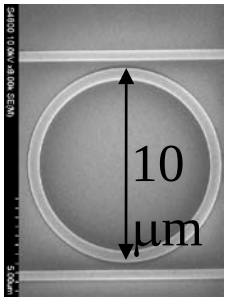
McKinney, Lin and Weiner, *IEEE Trans. Microwave Theory. Tech.* **54**, 4247 (2006)

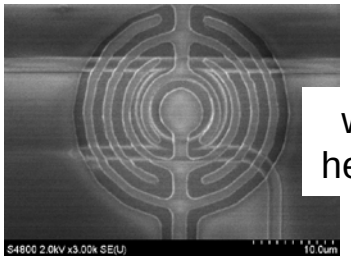
Silicon Photonics Cascaded Microring Device

RF waveform generation via integrated spectral shaper plus dispersive frequency-to-time converter

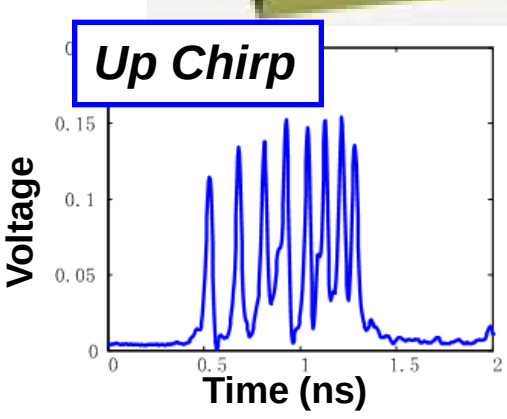
M. H. Khan, H . Shen, Y. Xuan, L. Zhao, S. Xiao, D. E. Leaird, A. M. Weiner, and M. Qi, Nature Photonics **4**, 117 (2010)

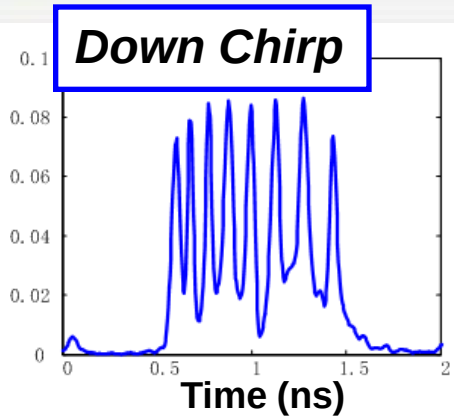


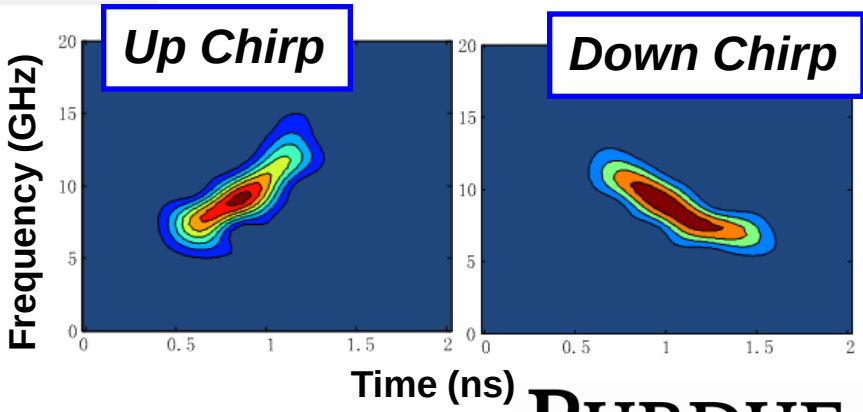




with heater







Impulse Excitation of "Frequency-Independent" Antennas

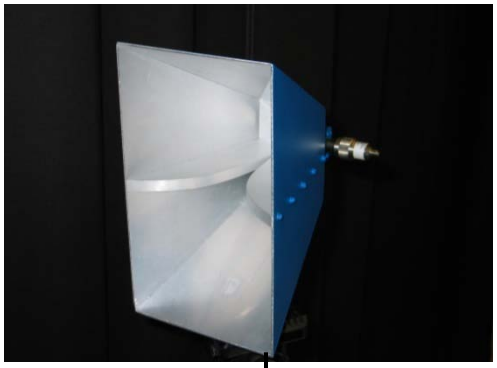
Many antennas are highly dispersive!

(Phase response becomes very important for time domain systems)

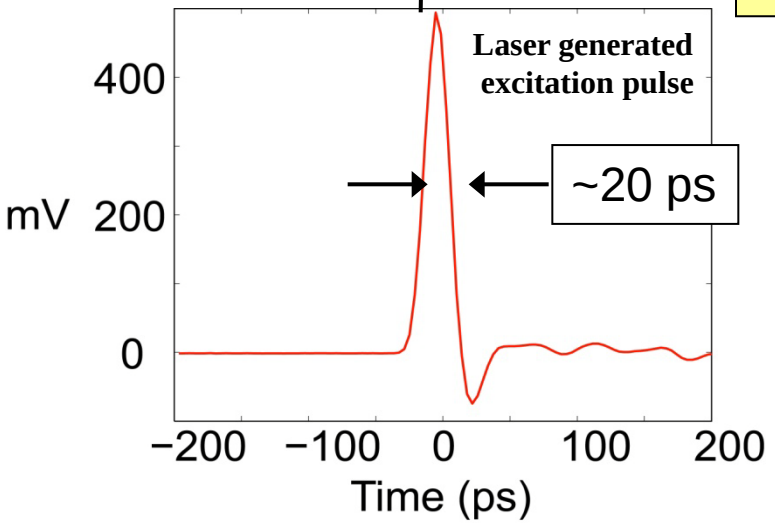
Transmitter – Log-Periodic

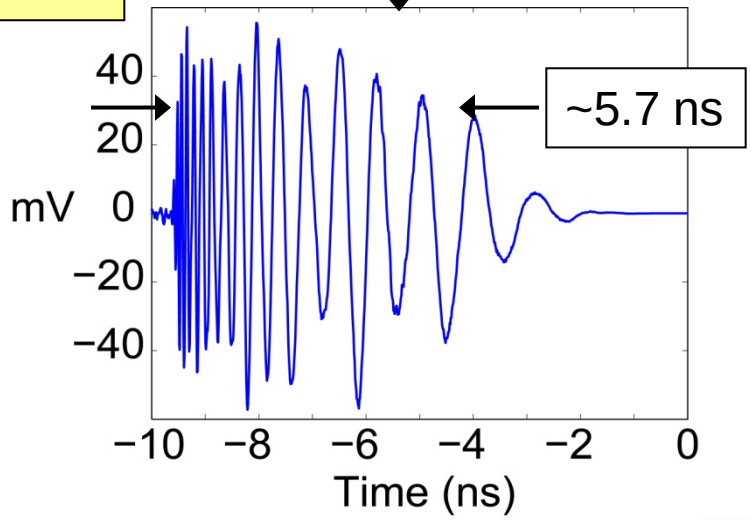
~1 - 2 m

Receiver – Ridged-Horn



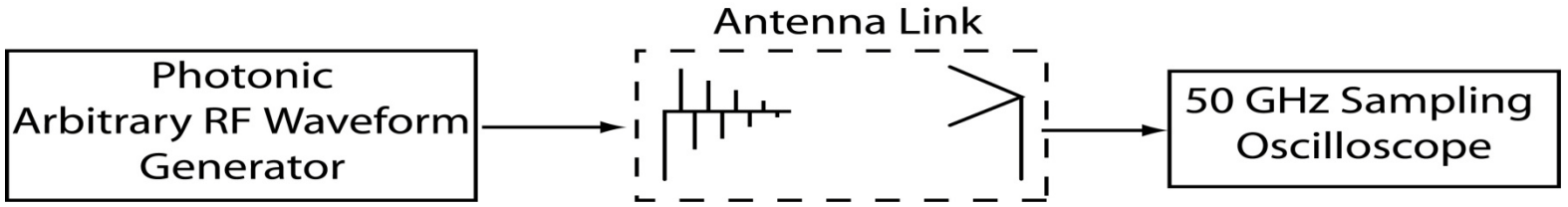
Impulse response

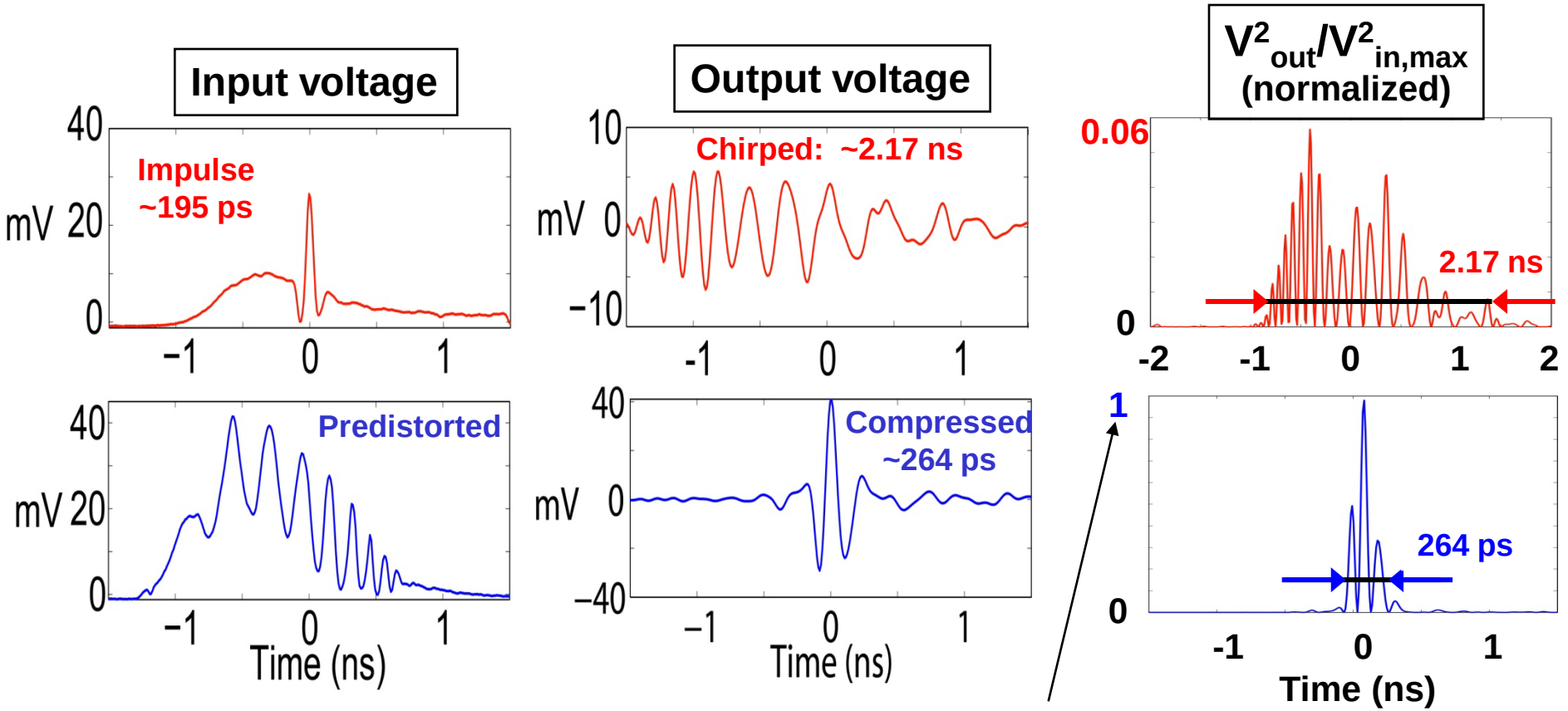




Precompensating Antenna Dispersion via RF-AWG!

Use waveforms that self-compress in antenna link





McKinney, Peroulis, and Weiner, *IEEE. Trans. MTT* (2008)

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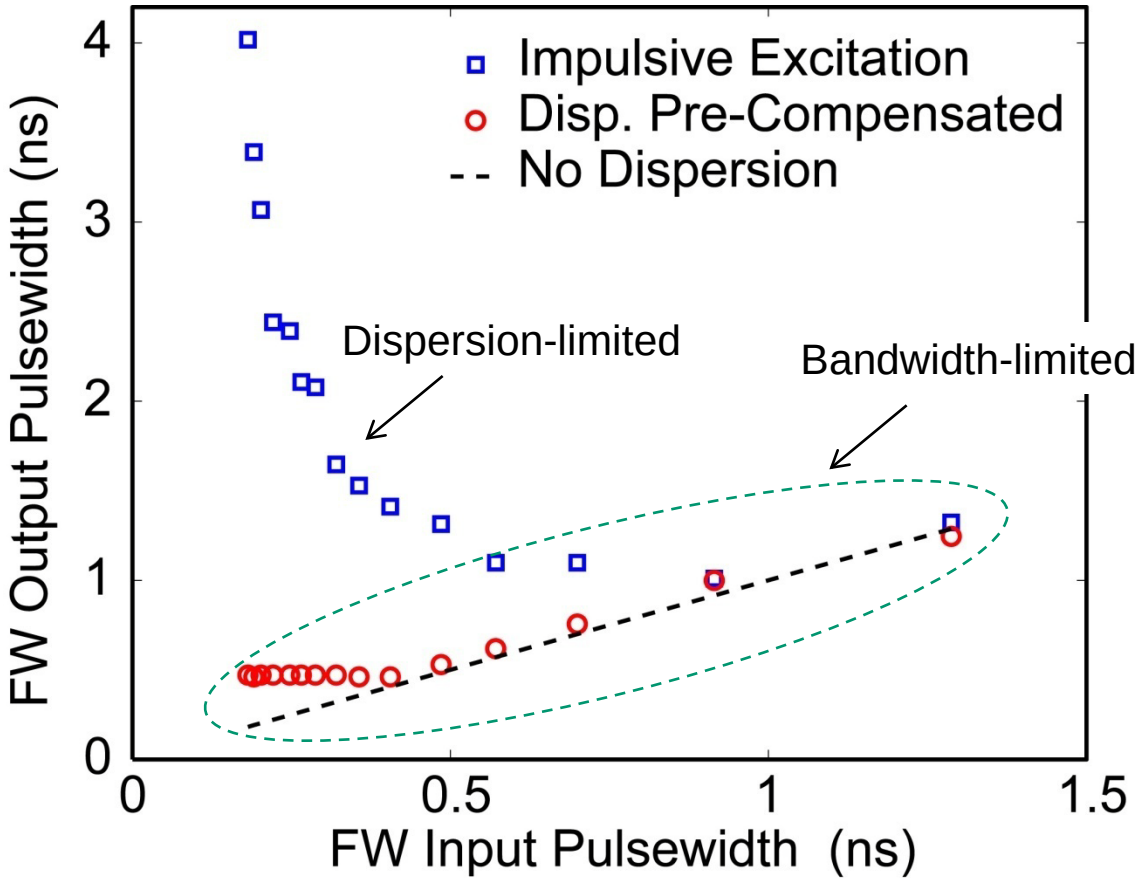
Spiral Antenna Pair – Dispersion Compensation

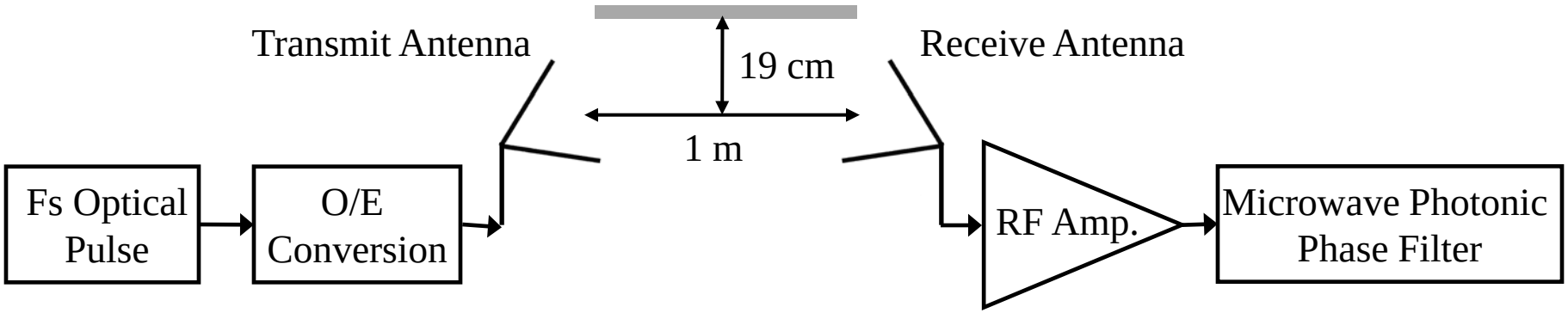


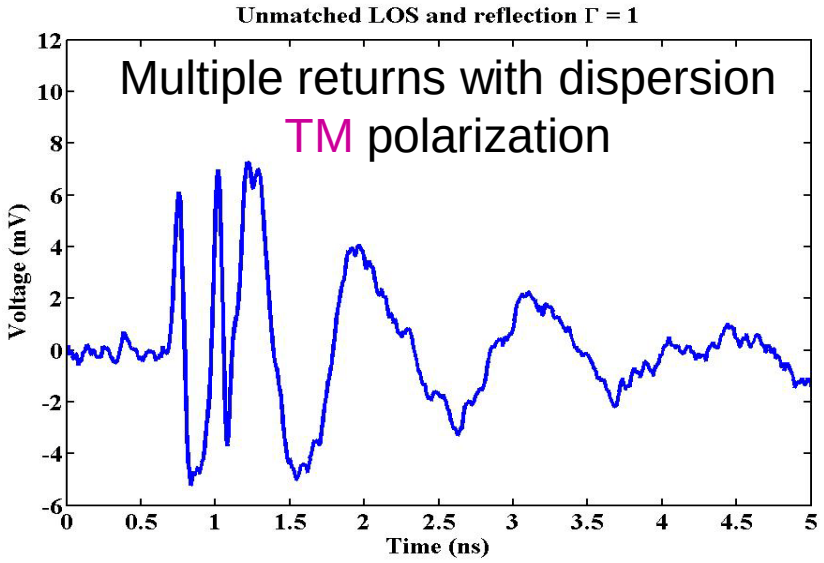
- Compression achieved for bandwidths up to BW ~6 GHz @ f_o = 6 GHz (100% fractional bandwidth)

- Limited by pulse shaping time aperture and antenna bandwidth

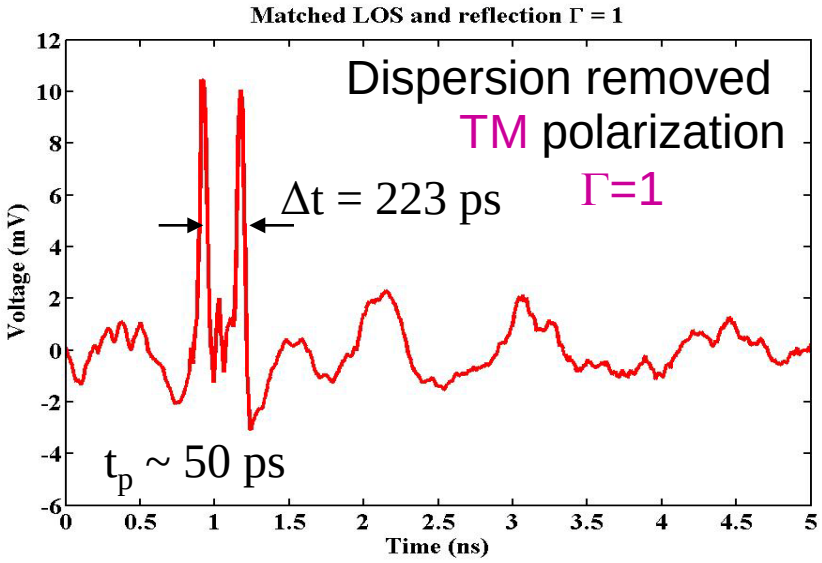
McKinney, Peroulis, and Weiner, *IEEE. Trans. MTT* (2008)

Multipath environment and UWB radar





5 nanoseconds



5 nanoseconds

Hamidi and Weiner, IEEE Trans. MTT **57**, 890 (2009)

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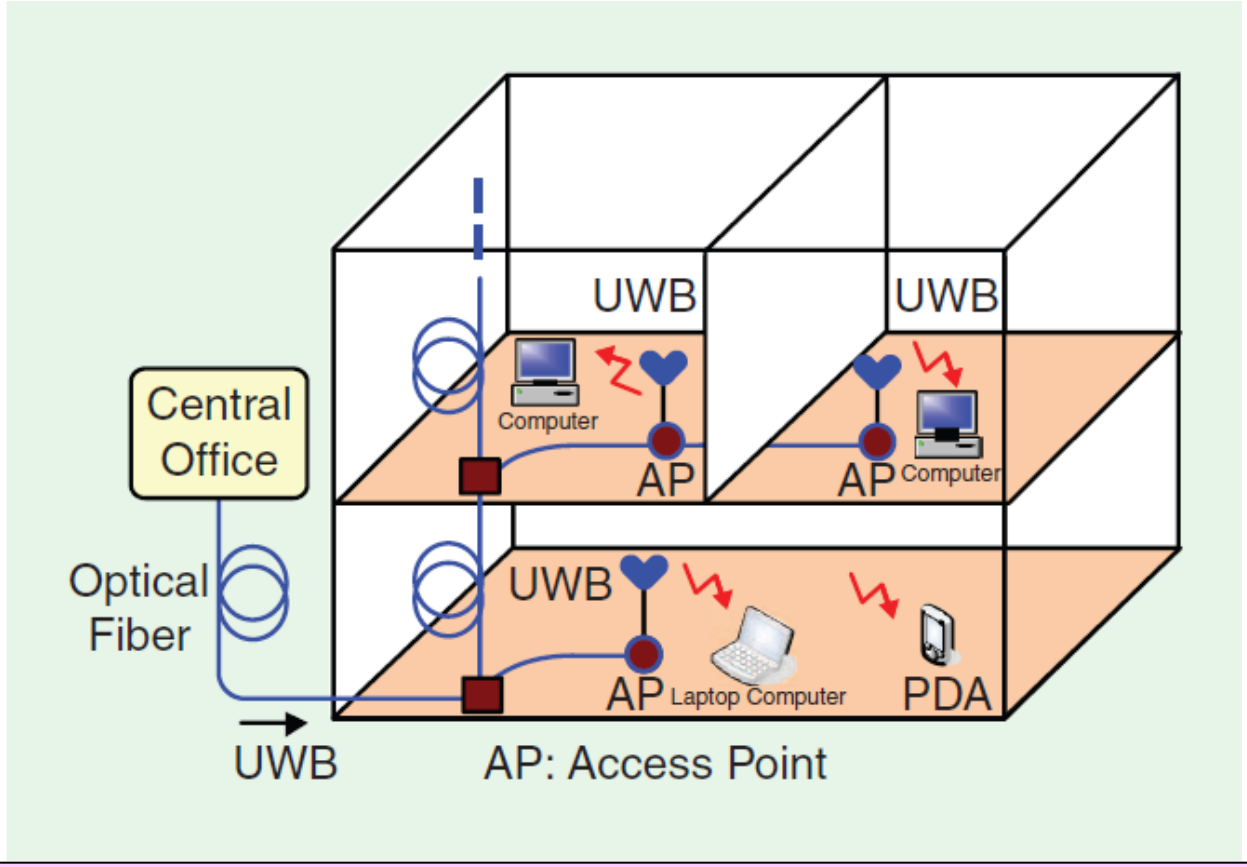
UWB-Over-Fiber



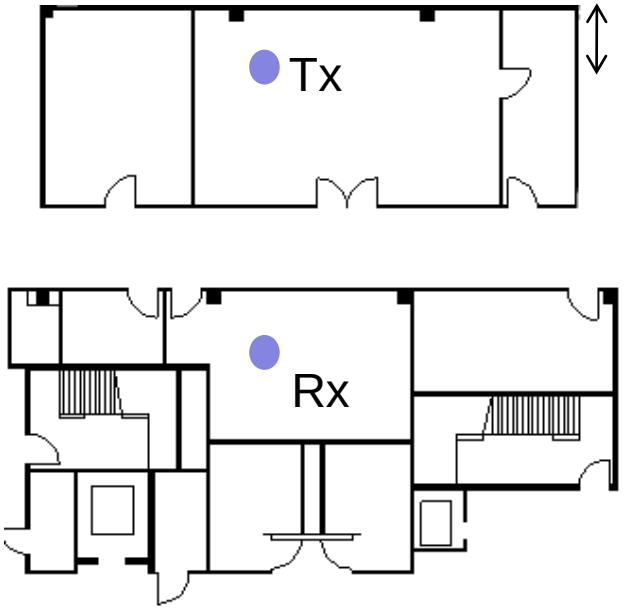
- Range of UWB wireless limited due to propagation loss and low transmit power
- Low loss & broad bandwidth of optical fibers offers potential for UWB signal distribution

J. Yao, "Photonics for Ultrawideband Communications", IEEE Microwave magazine, June 2009

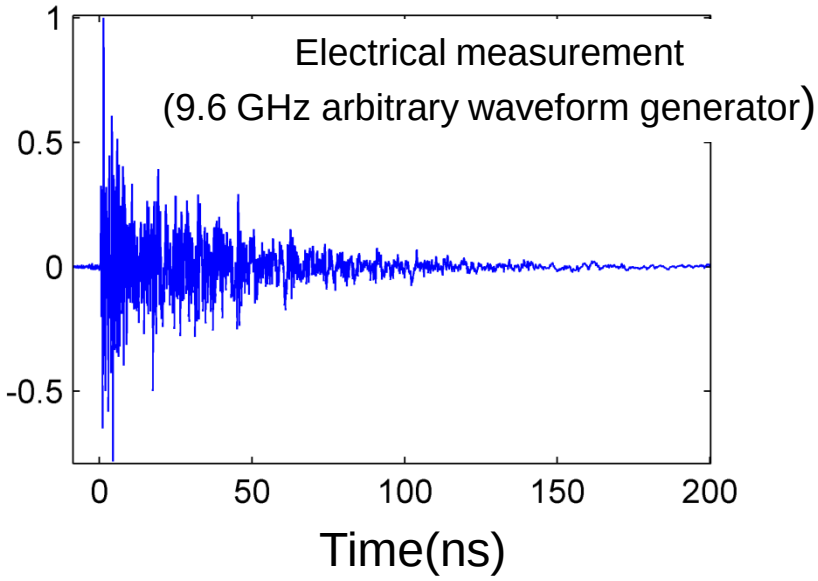
Multipath in Indoor Wireless

NLOS
15m propagation distance

Environment Layout



System impulse response



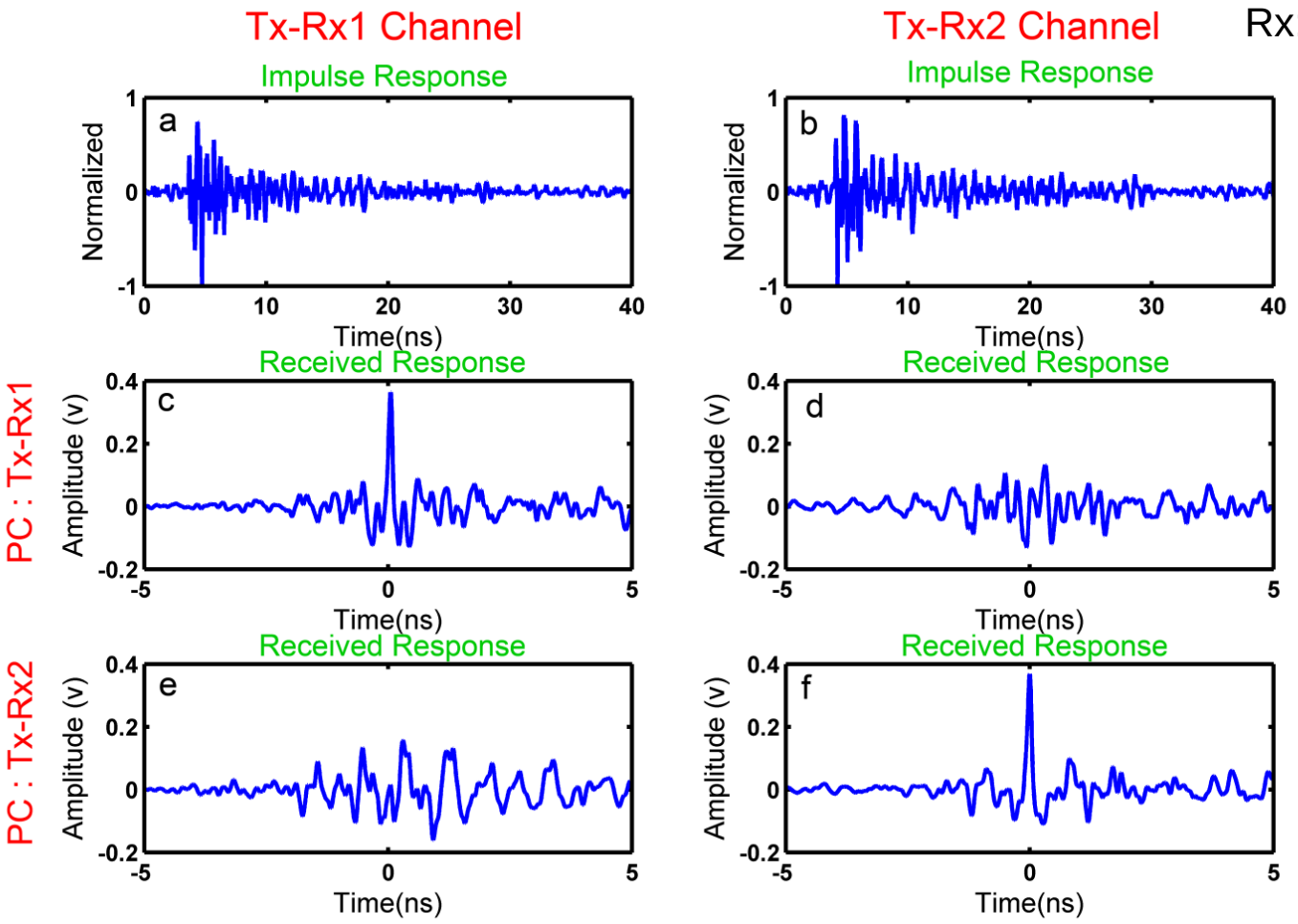
- Multipath delays broaden and distort the wireless channel.
- Unless compensated, severely limits data rates.

Amir Dezfooliyan and A.M. Weiner, to be published

Spatially Selective Compensation of the UWB Multipath

- Photonic arbitrary waveform generation over 2-18 GHz bandwidth
  (a factor of two beyond that available from commercial electronic waveform generators)

Tx: omni-directional antenna
Rx: horn antenna;



Non-line of sight
@ 10 m separation

Potential for covert communications & increased data rate

Amir Dezfooliyan and A.M. Weiner, to be published

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Thank you!