Space-Time Optical Systems for Encryption of Ultrafast Optical Data

J.-H. Chung, D. E. Leaird, J.D. McKinney,
N.A. Webster, and A. M. Weiner

Purdue University Ultrafast Optics and Optical Fiber Communications Laboratory

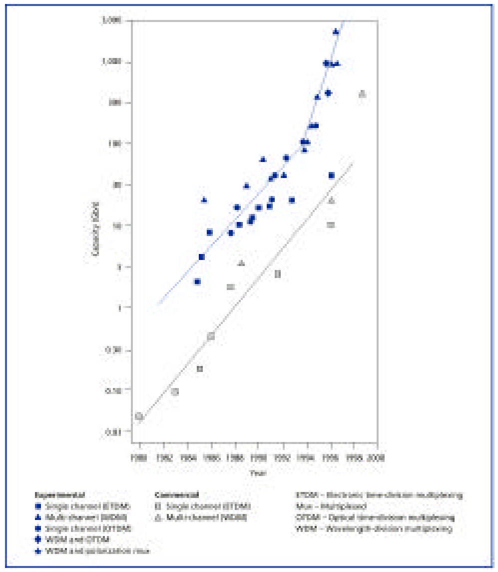
School of Electrical and Computer Engineering &

Center for Education and Research in Information Assurance and Security

Ultrahigh-Speed Optical Communications

- ***Capacity*** increased at over 2.5x per year.
  - Experiments with **1 Tb/s** and higher.
  - Commercial systems with **400-Gb/s.**
- ***Electronic encryption*** has difficulties above ~ **10Gbit/s**.
- Our research aims toward using **OPTICAL ENCRYPTION BOXES AT THE PHYSICAL LAYER** to achieve these high speeds.

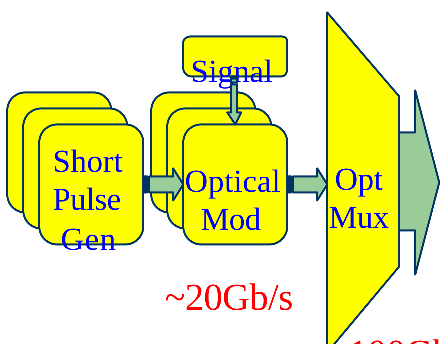
Progress in Network Capacity



[A. R. Chraplyvy; Bell Labs Technical Journal, Vol. 4, No. 1, 1999]

Optical Time-Division-Multiplexed (TDM) Transmission

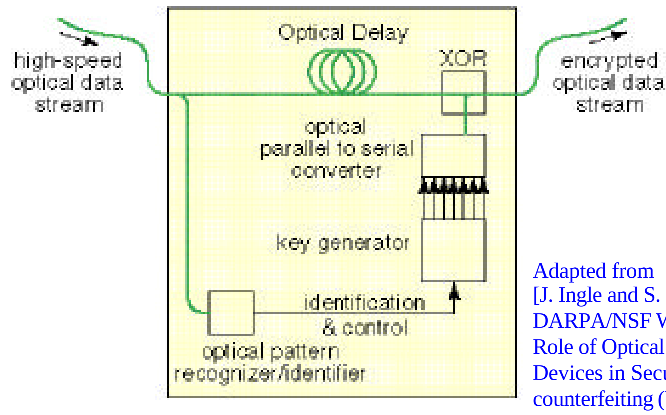
- Resembles **conventional electronic networks**.
- Focus on packet processing including **header recognition** and **encryption** of **TDM** optical data at **100 Gb/s** and beyond.



100Gb/s
~ 1Tb/s

Modified from
[S. Kawanishi, NTT; IEEE Journal of Quantum Electronics, Vol. 34, No. 11, Nov. 1998]

High-Speed Optical Encryption Box



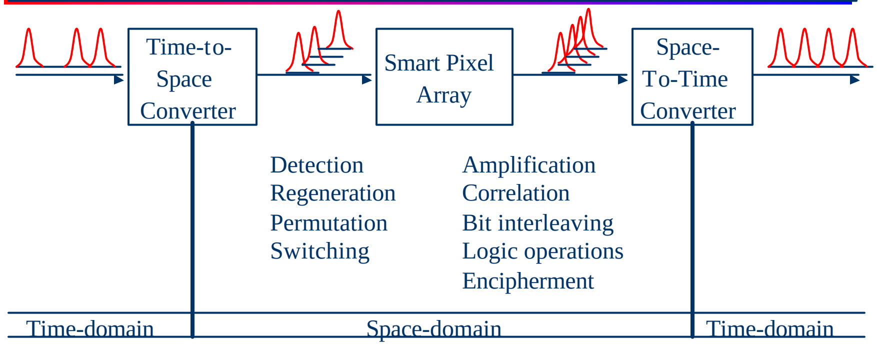
Adapted from [J. Ingle and S. McNown, DARPA/NSF Workshop on the Role of Optical Systems and Devices in Security and Anti-counterfeiting (Washington, D.C., 1996)]

Necessary Subsystems for Ultrahigh-Speed Optical Encryption

- **Serial-to-parallel converter** to allow header recognition and packet processing at rates compatible with electronics
- **Key generator array**
- Ultrahigh-speed **optical XOR gate** or array of high-speed **optoelectronic XOR gates** for stream cipher (for example)
- **Parallel-to-serial converter** to reform the ultrahigh-speed TDM data stream

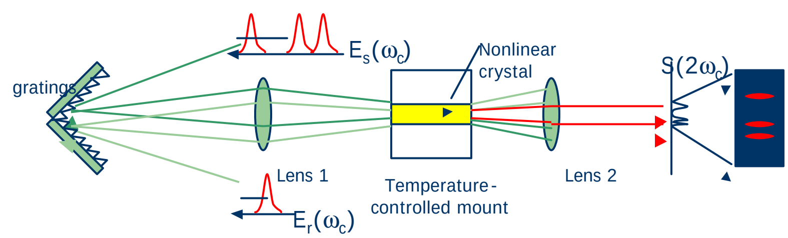
We are working on novel parallel optical/optoelectronic subsystems to implement the serial-to-parallel conversion, parallel XOR gating, and parallel-to-serial conversion.

Schematic of Generalized Space-Time Processing Systems



- Manipulates optical data in parallel to keep up with high speed stream.
- **Pulse shaper**: generate ultrafast test waveforms
- **Time-to-space converter**: Serial stream => Parallel data input
- **Smart Pixel optoelectronic array**: Digital logic operations like header recognition
- **Space-to-time converter**: Parallel data output => Serial stream

Time-to-Space Converter



1) Using a reference pulse, we create a spatial replica of the input signal pulses.
2) We have previously demonstrated 500x sensitivity improvement, which is key for operation at realistic power budgets in high-speed systems.
3) In current work, we are moving to a new center frequency, 1560nm, applicable to optical communications.

Previous References:
[A.M. Weiner and A.M. Kan'an; IEEE Journal of Selected Topics In Quantum Electronics, Vol. 4, No. 2, Mar/Apr.1998]]
Modified from [P.C.Sun, Y.T. Mazurenko and Y. Fainman; Journal of the Optical Society of America A, Vol. 14, P. 1159, 1997]

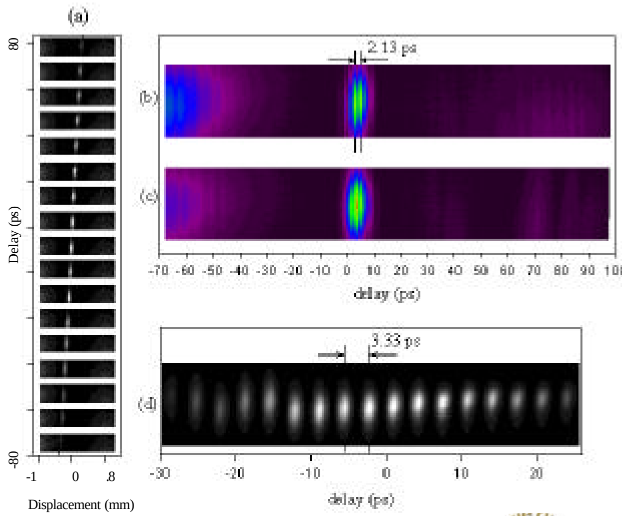
Time-to-Space Converter Output Images

(a) Stack of images produced by varying the delay

(b) Mapping image generated by a pulse doublet introduced into the signal beam only

(c) Correlation image for identical reference and signal pulse doublets

(d) Red spots sorted by the corresponding delay values

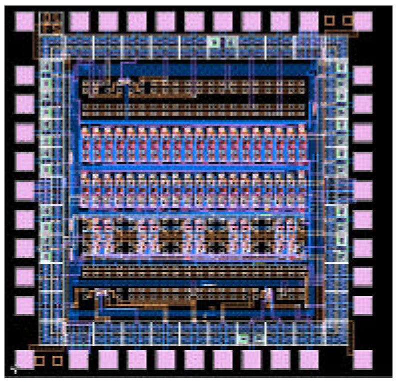


Digital Logic Operation of Smart Pixel Array

- Processes the spatially-converted data in parallel, using an array of detectors.
- The data would be XORed electronically with a stored key to implement a stream cipher.
- The processed data then drives an optoelectronic modulator array, inserted in a suitable space-to-time converter, to return the data to a serial ultrafast optical signal.
- Works out to frame rates of a few Gb/s to be able to achieve overall data rates exceeding 100 Gb/s.

Ultrafast Optics and Optical Fiber Communications Laboratory

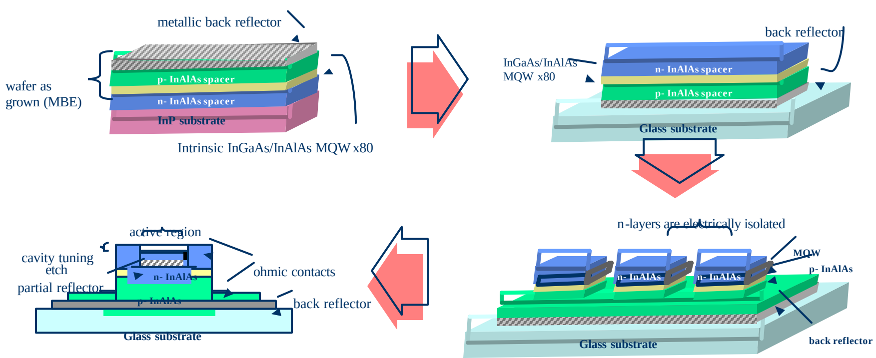
Optoelectric-VLSI Smart Pixel Array



- Hybrid CMOS/GaAs from Lucent foundry
- 200 Optical I/O's
- High-speed modulator array functionality for ultrafast optical packet generation
- AND gate array functionality for experiments on ultrafast optical header recognition
- XOR gate array functionality for experiments on ultrafast optical stream cipher

CERIAS

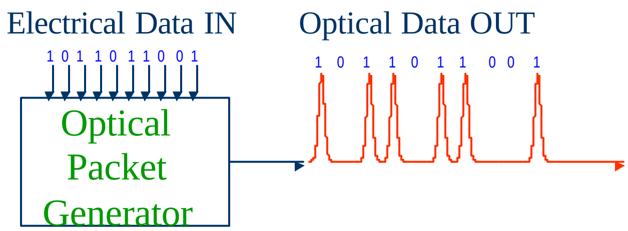
Optoelectronic Array Fabrication at Purdue



We have initiated a project to fabricate arrays of optoelectronic modulators operating in the 1.55 mm lightwave communications band. These modulators will be integrated with the direct space to time pulse shaper.

CERIAS

Optical 'Word' Generation
(Parallel – to – Serial Converter)



- High-speed optoelectronic modulator array combined with ultrafast optical parallel – to – serial conversion

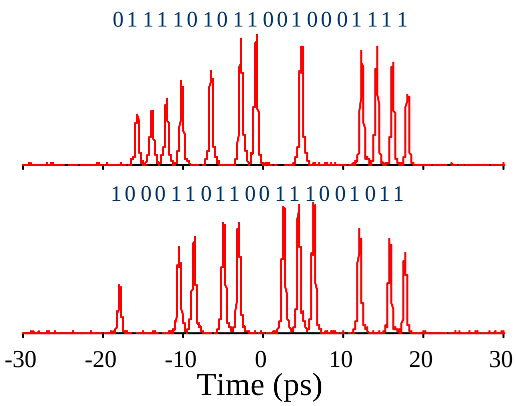
Direct Space-to-Time Pulse Shaping
(Optical Parallel-to-Serial Conversion) at 1.5 mm

- For high-speed optical encryption and transmission, high-speed sources, operating at communications wavelengths, are necessary. To this end, we are incorporating a high repetition-rate optical source, operating in the lightwave communications band.
  - → Actively modelocked Erbium Fiber laser

    (~1 ps pulses @ 10 GHz, 1.5 μm)
- To achieve "packets" with equal intensity features:
  - → Use a Diffractive Optical Element (DOE) for beam pixelation
  - → Utilize an integrated version of the DST pulse shaper: modified Arrayed Waveguide Grating (AWG)

Femtosecond Data Packets

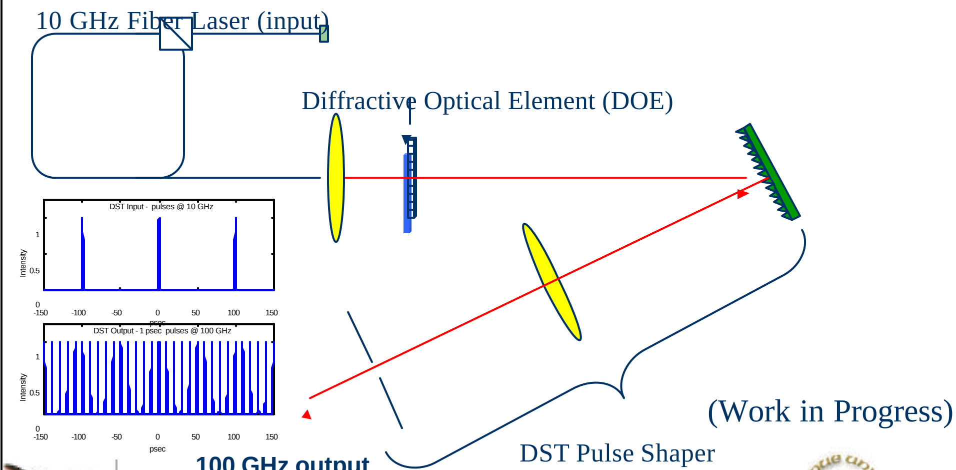
- Target application of DST.
- The 'state' of each temporal pulse is determined by the transmission at a unique spatial location.



[D.E. Leaird and A.M. Weiner; Optics. Letters Vol. 24, P. 853-856, 1999]

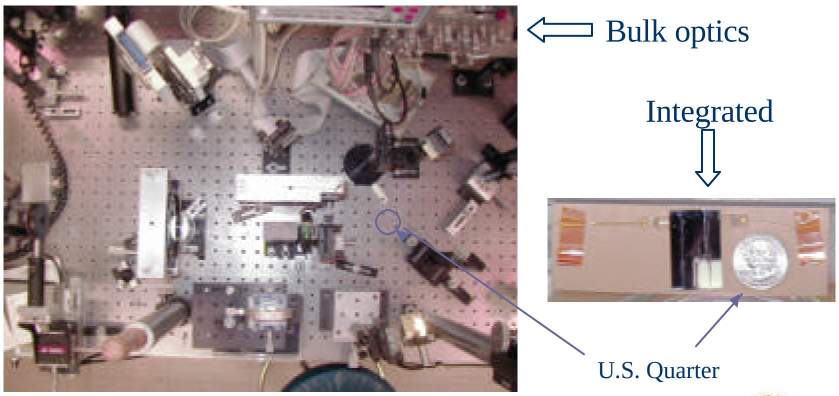
Rate Multiplication Using a DST Pulse Shaper

- Our method of optical parallel-to-serial conversion has the potential to enable extremely high-speed sources to be created for use in ultrahigh-speed lightwave systems.

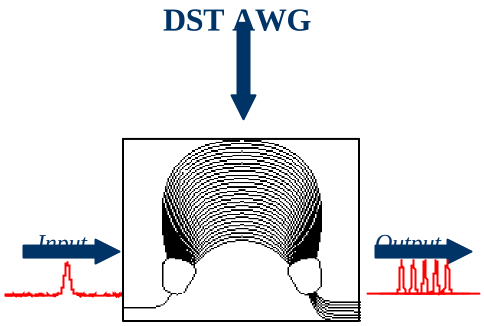


Integrated Implementation

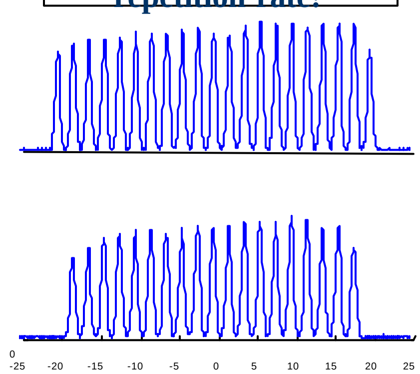
→For optical ‘word’ generation, the function of a bulk optics DST pulse shaper can be achieved in an integrated optic device!



DST Arrayed Waveguide Grating (AWG) (Integrated Direct Space-To-Time Pulse Shaper)



21 pulses at 500 GHz repetition rate!



Summary

- Using novel space-time processing techniques, we are developing exploratory technology that may allow us to encrypt optical data at the physical layer, with particular application to ultrahigh-speed optical TDM transmission.