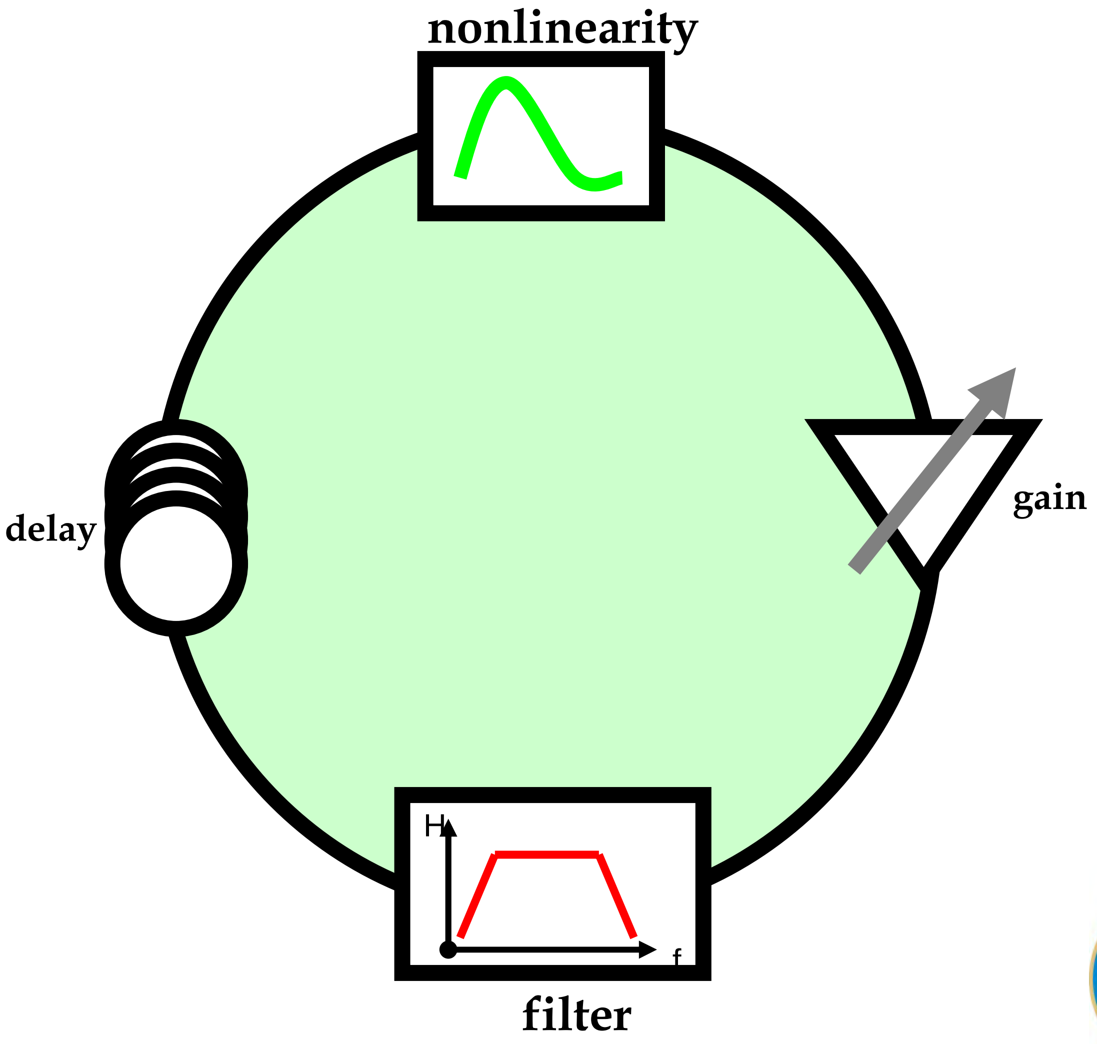
Exploiting Nonlinear Dynamics for Novel Sensor Networks (UMD-DUKE)



- **Network of nonlinear optoelectronic nodes for sensing applications**
- We have constructed, experimentally measured, and simulated coupled, time-delayed optical nonlinear systems with feedback.

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DEPARTMENT OF THE NAVY
ONR
Science & Technology

Nonlinear Photonic Sensor Networks

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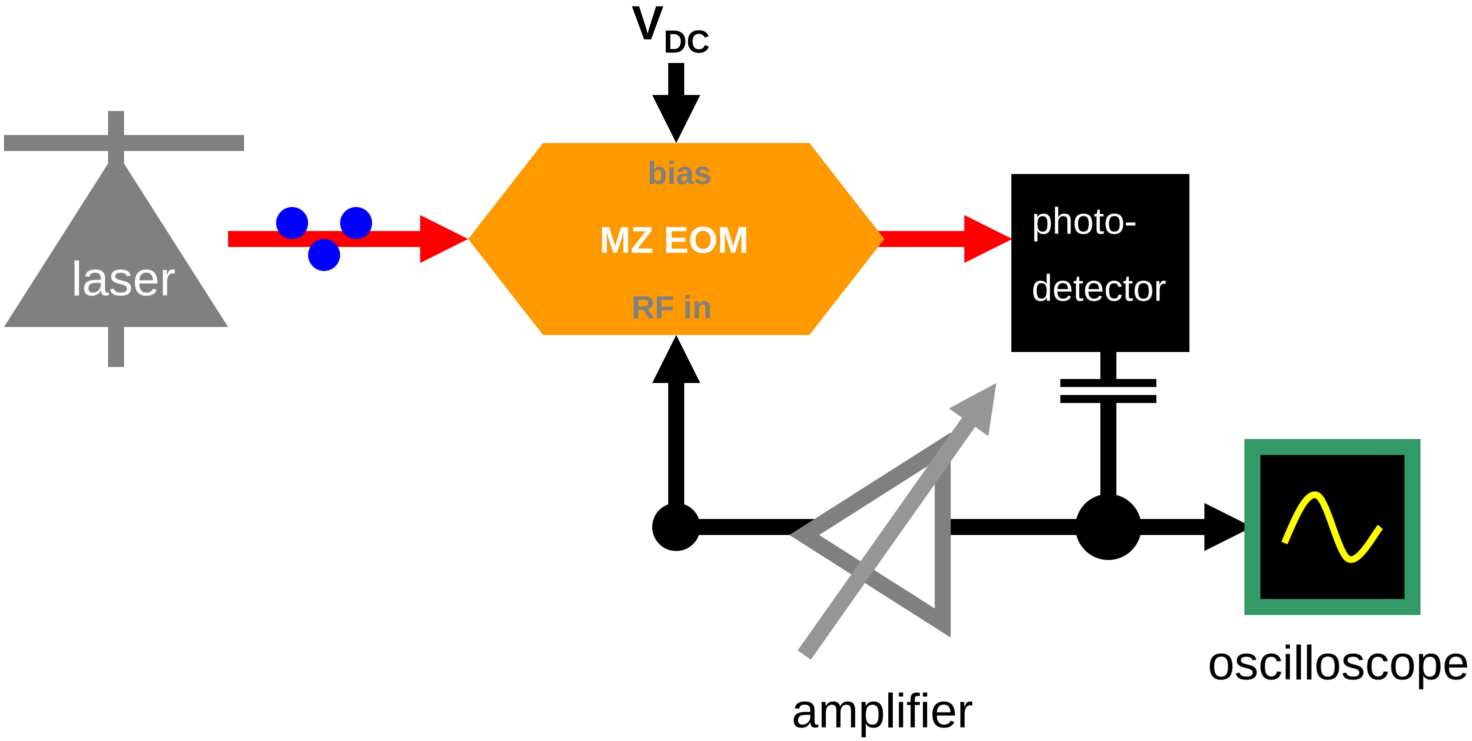
- Rajarshi Roy (IPST, Phys, IREAP)

- **Why photonics?**
- High speed, precise localization of perturbations
- Compact, durable, efficient, eye-safe, lightweight, rugged
- Combination of photonics and electronics allows implementation of novel sync algorithms and information processing with state-of-the-art DSP (digital signal processing) technology

First year goals

- Design single (optoelectronic) system best suited for generation of wide range of signals
- Develop accurate numerical model
- Incorporate digital signal processing technology
    - wide range of time scales
    - exceptional ability to vary coupling and time delays in network
- Explore coupling schemes and synchronization properties

Nonlinear Optoelectronic time-delayed feedback loop

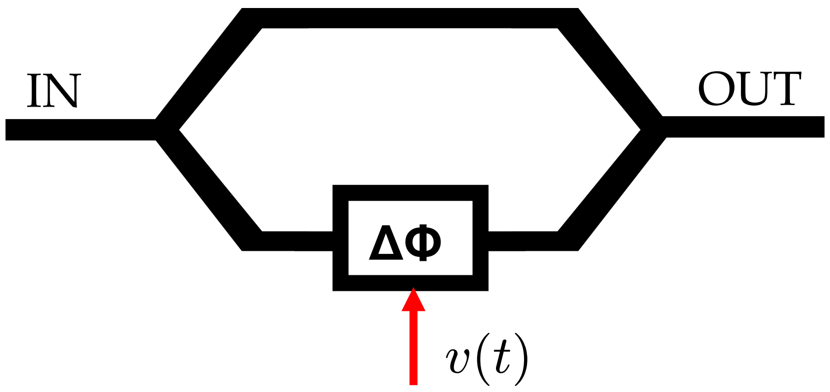


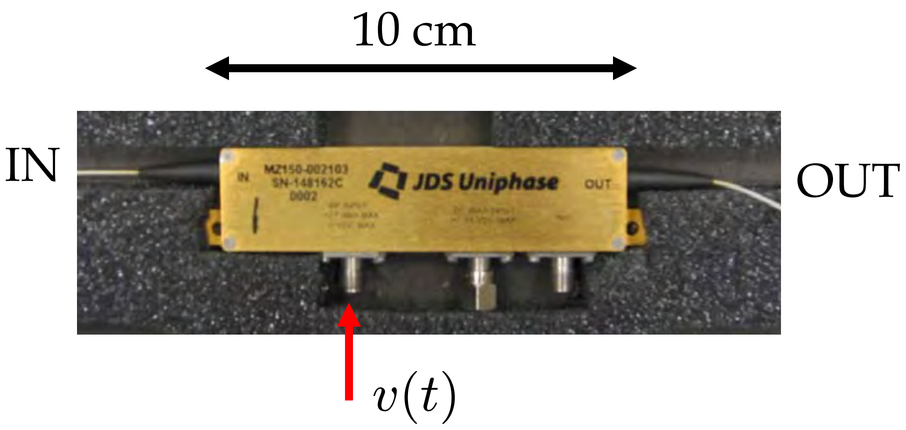
Loop delay: τ = 22.5 ns,

Bandpass filter: 1 MHz – 100 MHz

Mach-Zehnder electro-optic modulator

Principle : Interference of the optical signal along the two paths controlled electronically.

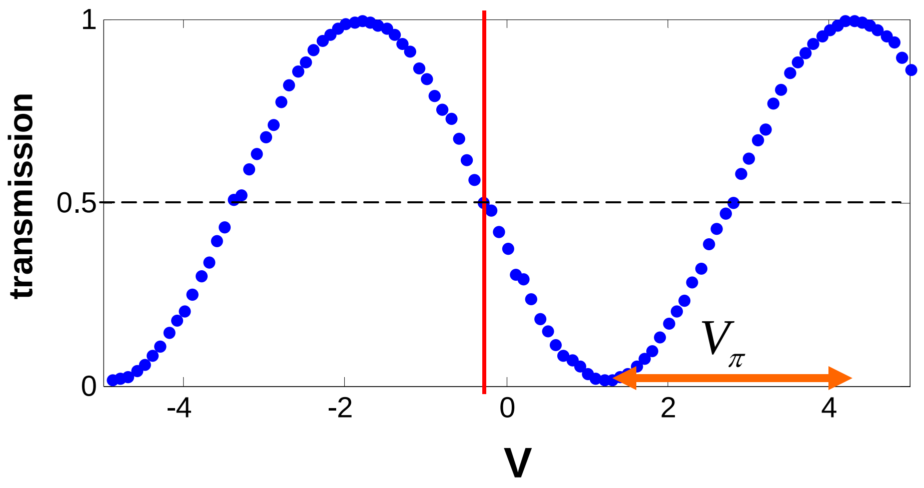




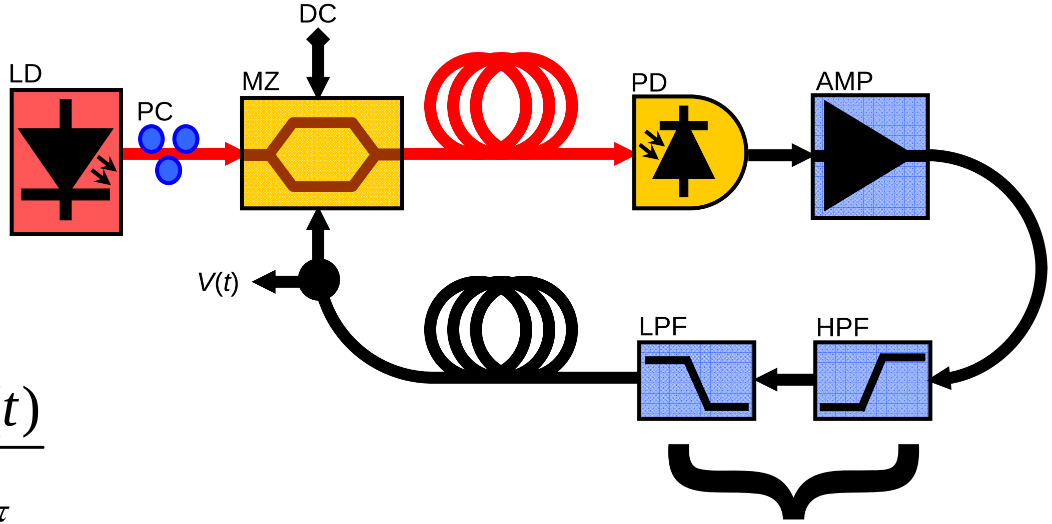
V_π = voltage needed to produce a π phase shift

$$P(t) = P_0 \cos^2\left(\frac{\pi}{2}\frac{v(t)}{V_\pi} + \phi_0\right)$$

$$V_\pi = 3.44\,\mathrm{V} \quad \phi_0 = \frac{\pi}{4}$$



- ✓ Such a system had been considered before by Kouomou *et. al.*, PRL **95,** 203903 (2005)



$$x(t) \equiv \frac{\pi V(t)}{2V_\pi}$$

two cascaded single pole filters

$$x + \tau \frac{dx}{dt} + \frac{1}{\theta}\int_{t_0}^{t} x(s)ds = \beta \cos^2(x(t-T_D)+\varphi)$$

where, τ is the low pass filter time constant

θ is the high pass filter time constant

T_D is the time delay in the loop

β is the feedback strength

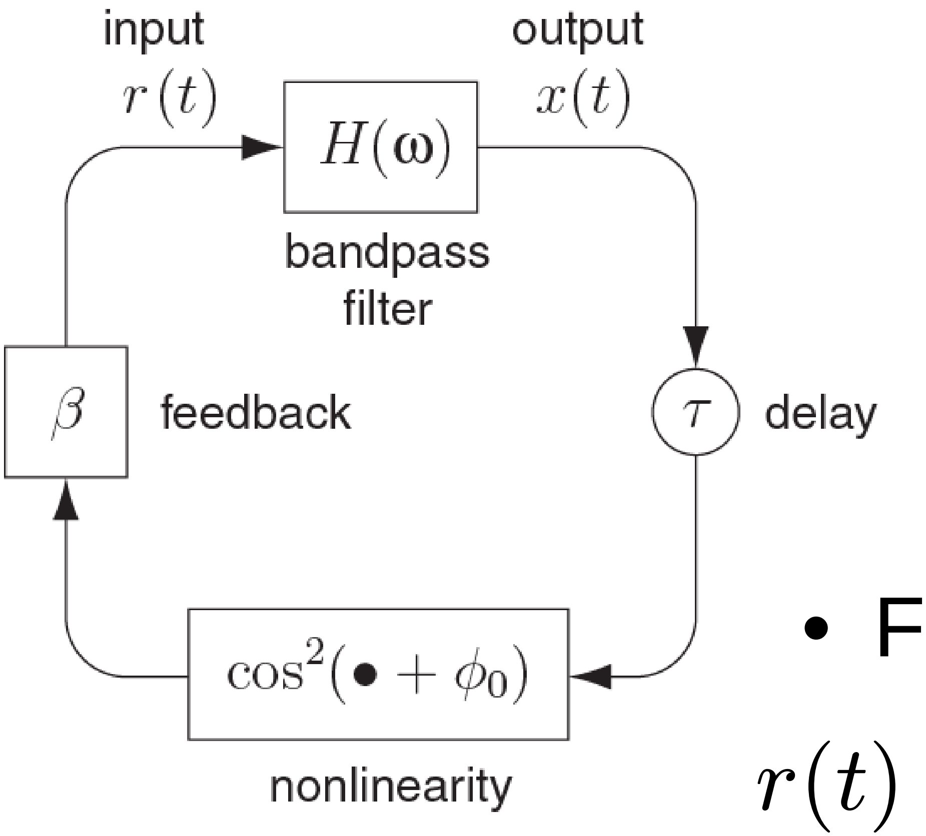
φ is the phase offset of the MZ transfer function

The feedback strength β is given by

$$\beta = \frac{\pi}{2}\frac{P_0 R G}{V_\pi}$$

- P_0 = optical laser power (W)
- R = photodiode responsivity (A/W)
- G = transimpedance amplifier gain (V/A)
- V_π = modulator half-wave voltage (V)

Generalized Model, with Arbitrary Filters



- Filter Equations:

$$\frac{d}{dt}\mathbf{u}(t) = \mathbf{A}\mathbf{u}(t) + \mathbf{B}r(t)$$

$$x(t) = \mathbf{C}\mathbf{u}(t)$$

- Feedback:

$$r(t) = \beta\cos^2\left[x(t-\tau) + \phi_0\right]$$

Experimental system: **u**(t) is 14x1 state vector

- 7th order Butterworth bandpass filter

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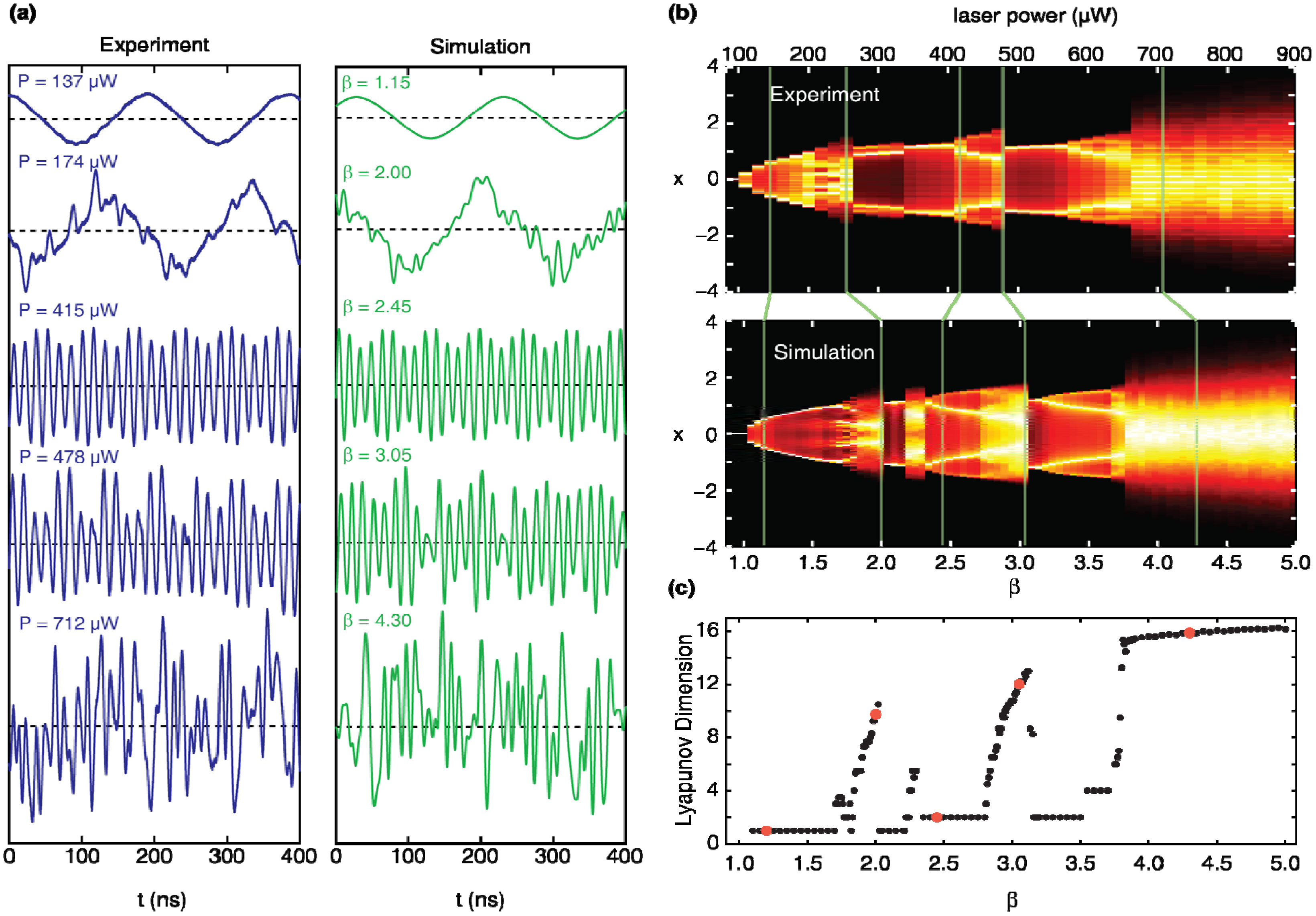
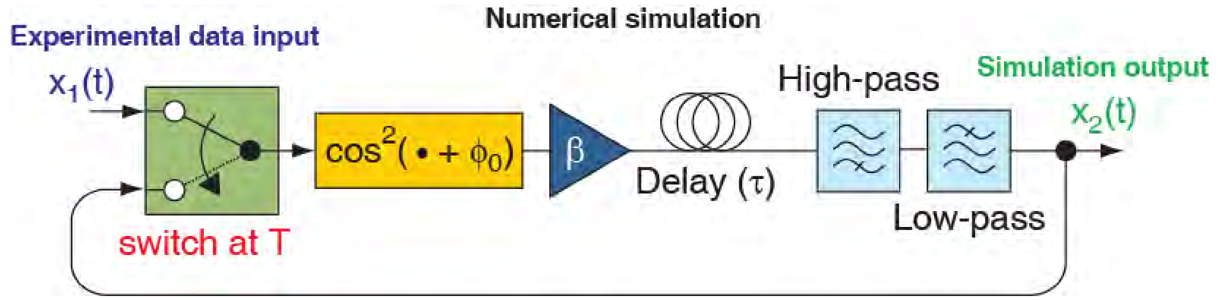
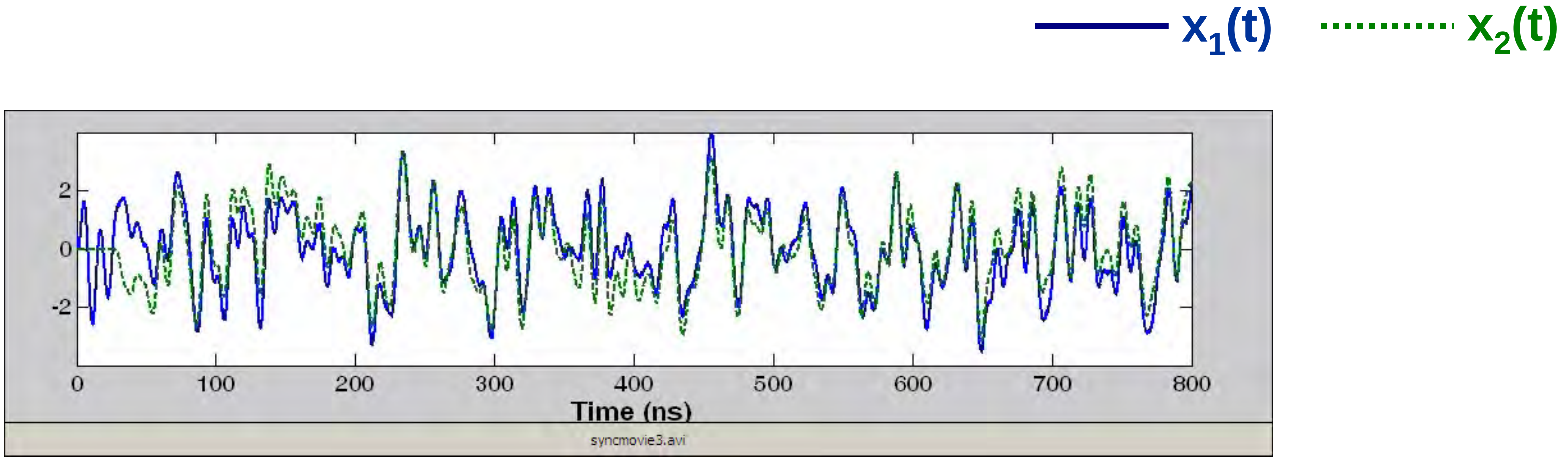
Comparison of experiment and computations



Data assimilation, synchronization, and prediction

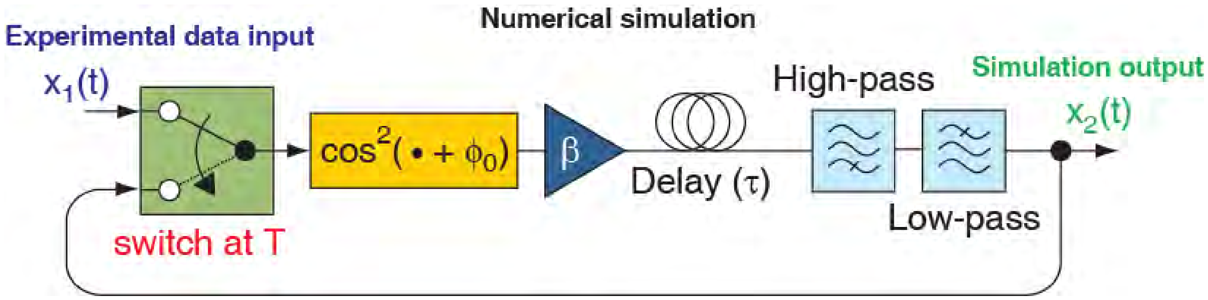


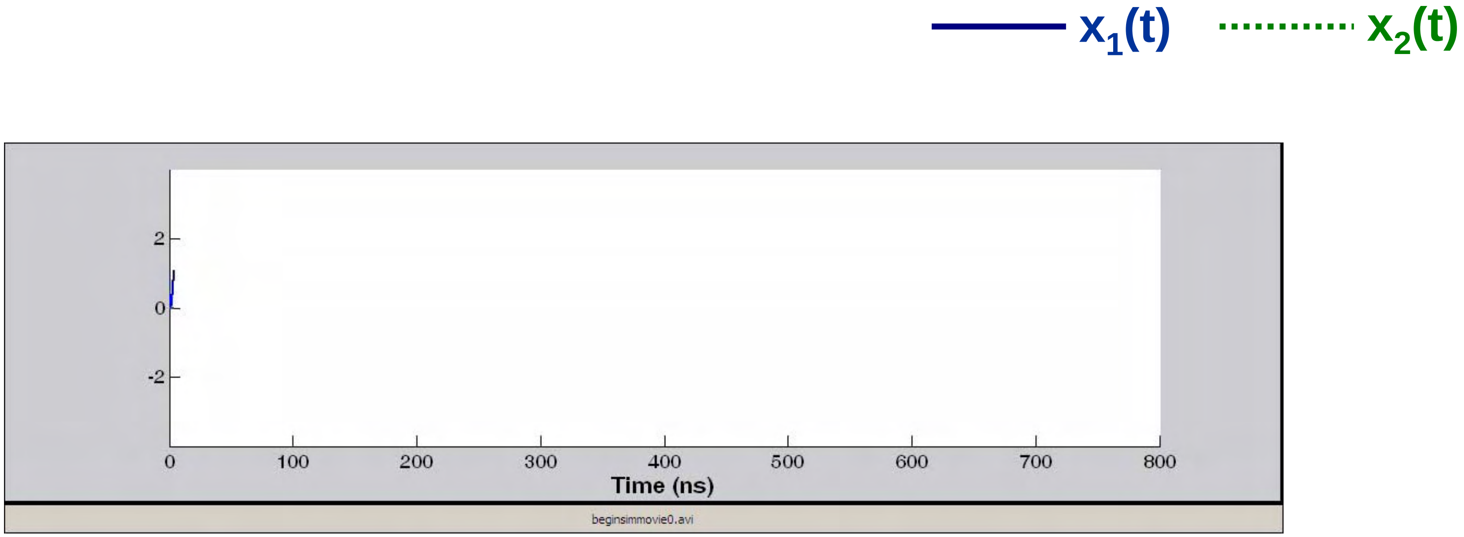


β = 5.0 **T = 7634 ns**

D_L = 16.1 ***t = 0 to 8200 ns***

Data assimilation, synchronization, and prediction

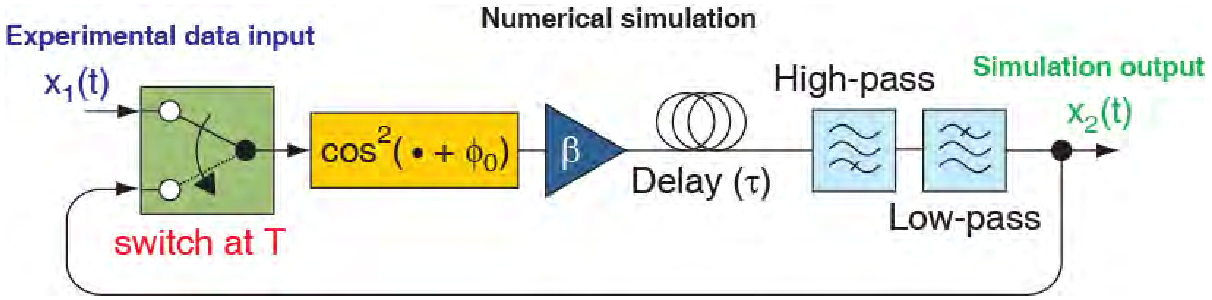




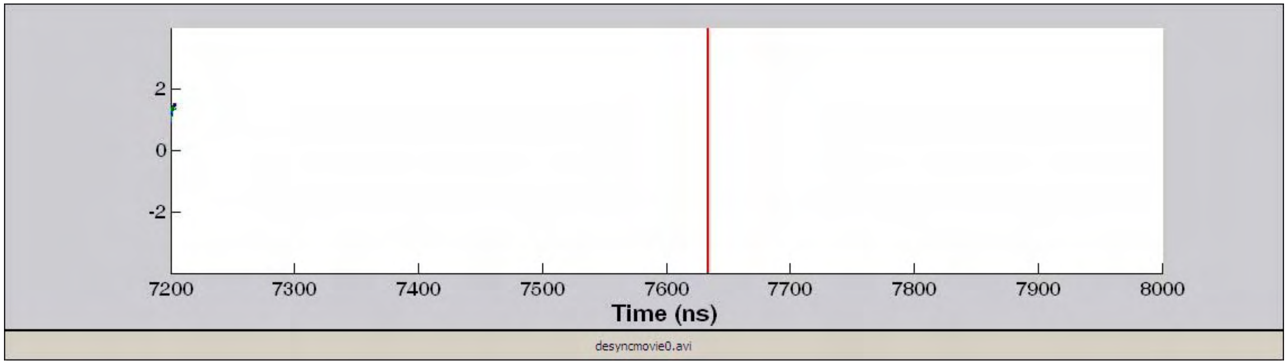
β = 5.0

D_L = 16.1 ***t = 0 to 800 ns***

Data assimilation, synchronization, and prediction



——— $x_1(t)$ ………… $x_2(t)$



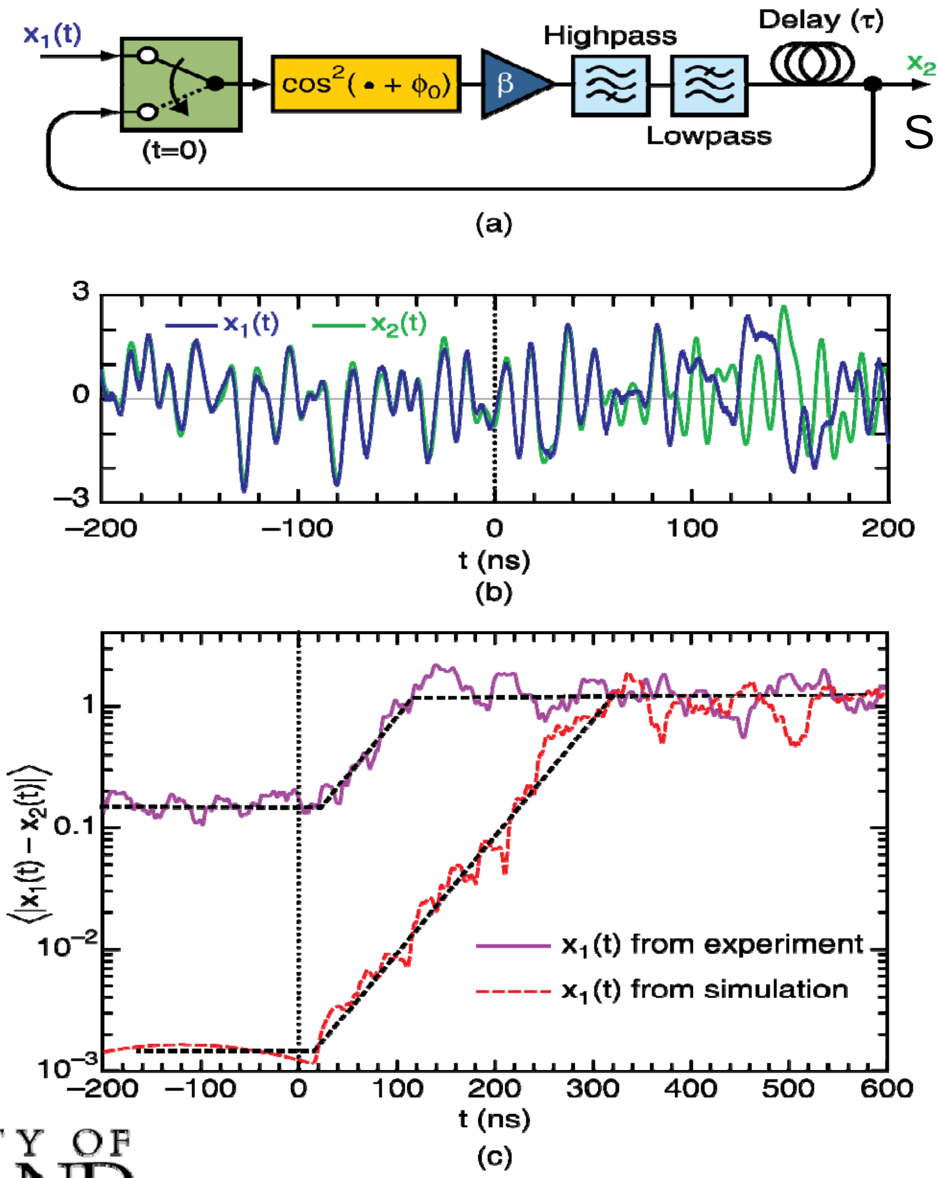
β = 5.0 **T = 7634 ns**

D_L = 16.1 ***t = 7200 to 8000 ns***

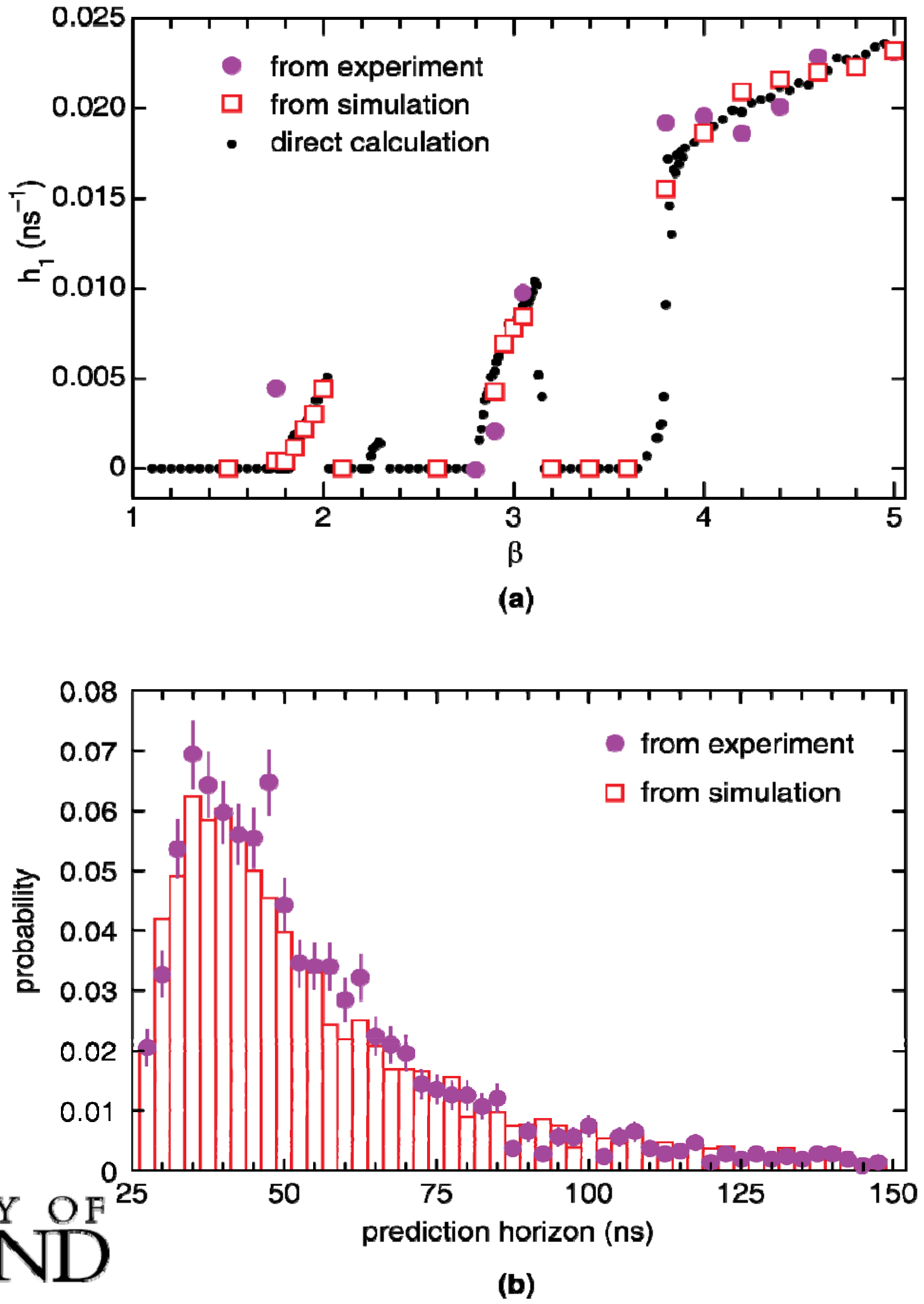
Synchronization between experiment and model

Experimental
Data input

Simulation model output



Global maximal Lyapunov exponents and probability distribution of prediction times



(a)

(b)

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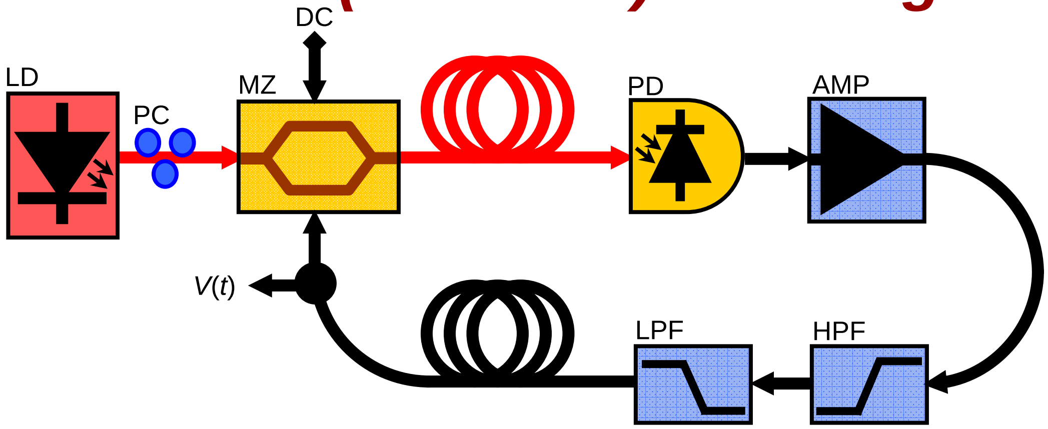
Summary I

- Designed optoelectronic feedback system: a modular element for the photonic sensor network
- Developed an accurate model
- Demonstrated data assimilation by synchronization of numerical model to experimental data, and prediction for high dimensional chaotic systems
- Accepted for publication:
  PRL October 2008

Scaling the Speed of the System

How FAST (or SLOW) can we go?



- Optical medium can support ***any*** modulation speed
- Advantages of using optical carrier
  - Low loss propagation (fiber: 0.2 dB/km)
  - Directionality (collimated beam)
  - Reduced size, weight, power
- Factors that limit speed:
  - Electrooptic modulator
  - Photoreceiver
  - Filters, amplifiers

$\Big\}$ **Bandwidth: DC to 40 GHz**

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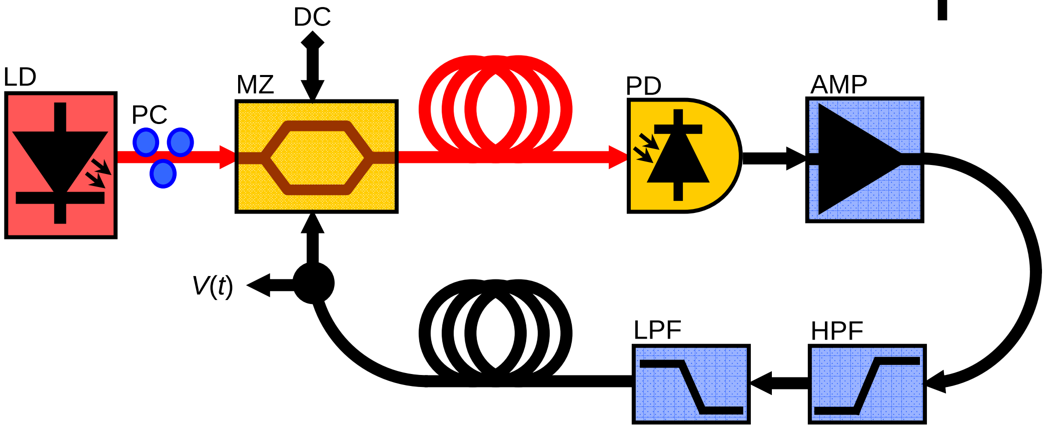
Scaling to Low Speed

GOAL: Slow down system by 10,000 X

- High frequency signals are not needed to sense static/slow moving objects
- Slower components are easier to engineer and model, exhibit near-ideal performance
- Retain advantages of an optical carrier
- Provide testbed for trying new ideas (before investing in costly RF components)

From VHF to Audio: Comparison



	VHF System	**Audio System**
Bandpass filter H(ω)	1 MHz – 100 MHz	100 Hz – 10 kHz
Time Delay (τ)	20 ns	200 µs
Propagation Distance (L)	4 m	**40 km**
Sampling Rate Required †	1 GS/s	100 kS/s

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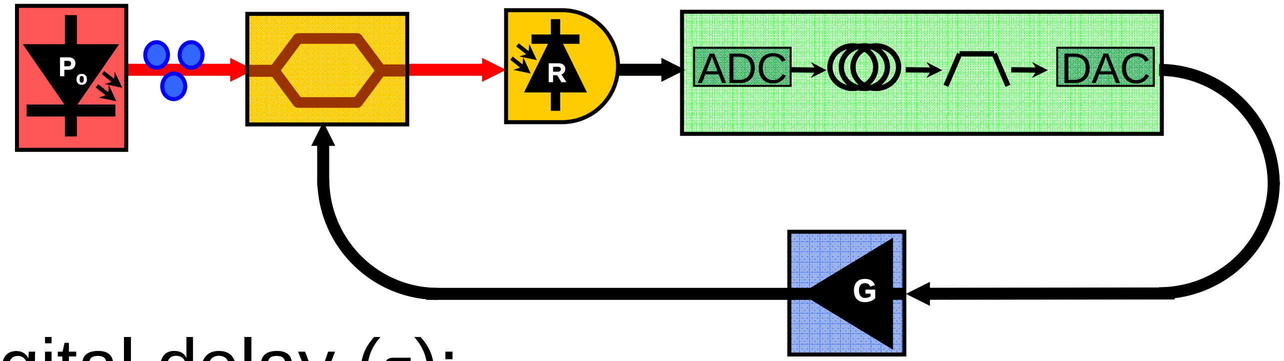
† in order to adequately resolve signal

Solution: Digital Signal Processing



- All digital delay (τ):
  - Limited only by memory:
    - Example:
      16 Mb on-board SDRAM
      16 bit ADC / DAC
      Sampling rate = 96 kS/s

Up to 88 seconds of digital delay, with 10 μs resolution

- All digital filter H(ω):
  - Can be precisely designed, controlled, matched
- Retain analog optical modulation, transmission, detection
  - Important for sensor applications

Advantages of DSP

- DSP systems are ubiquitous & inexpensive
  - Found in DVD players, cell phones, children’s toys, etcetera
- Arbitrary filtering is possible (subject to Nyquist limit)
- Easier to simulate:
  - Continuous-time DDE → Discrete map
- Easily scaled to MHz frequencies
- **Adaptive control of filter, coupling, delays**

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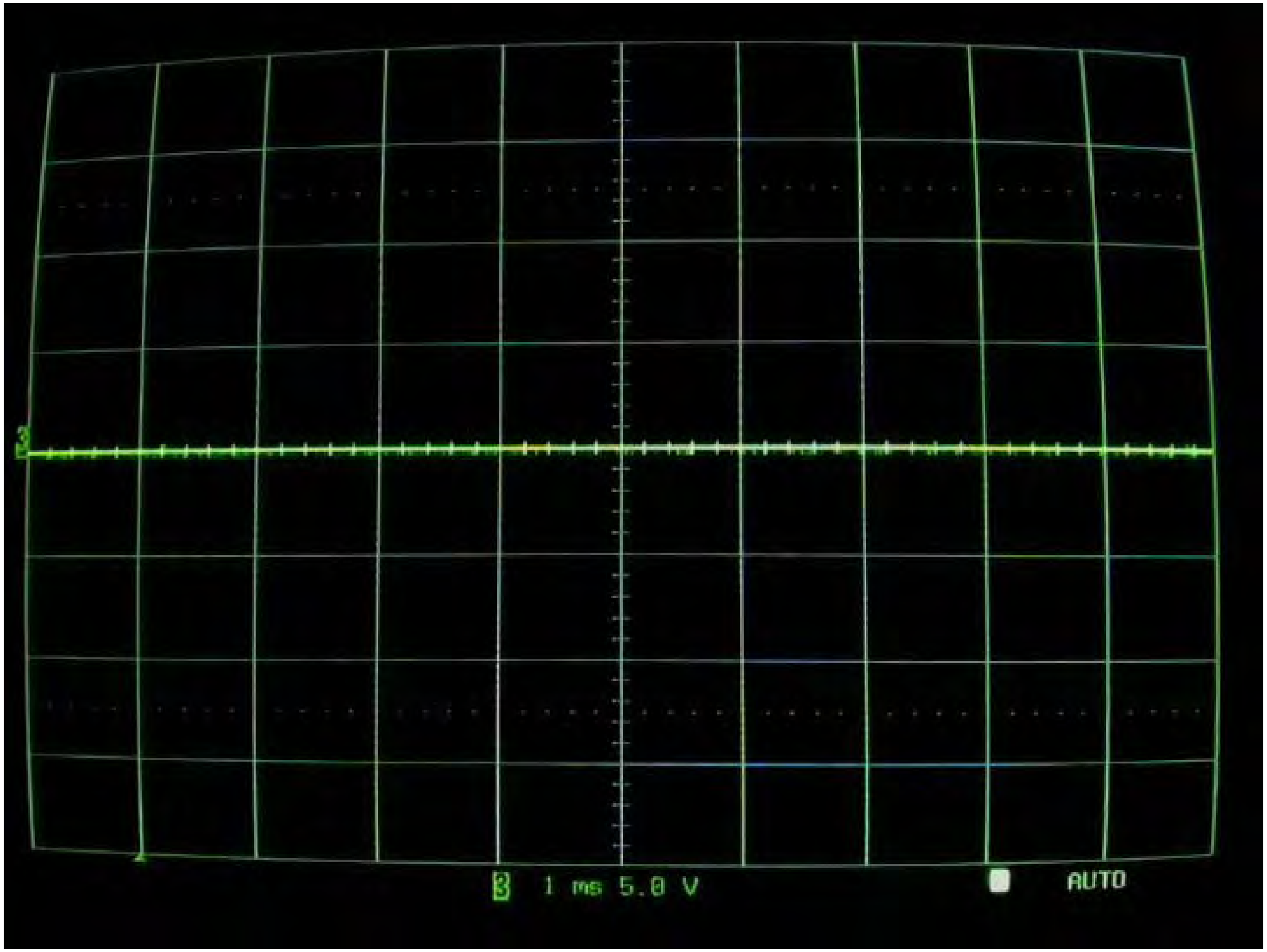
Adaptive Control of System Parameters



- Feedback strength (β) slowly increased from 0 to 8

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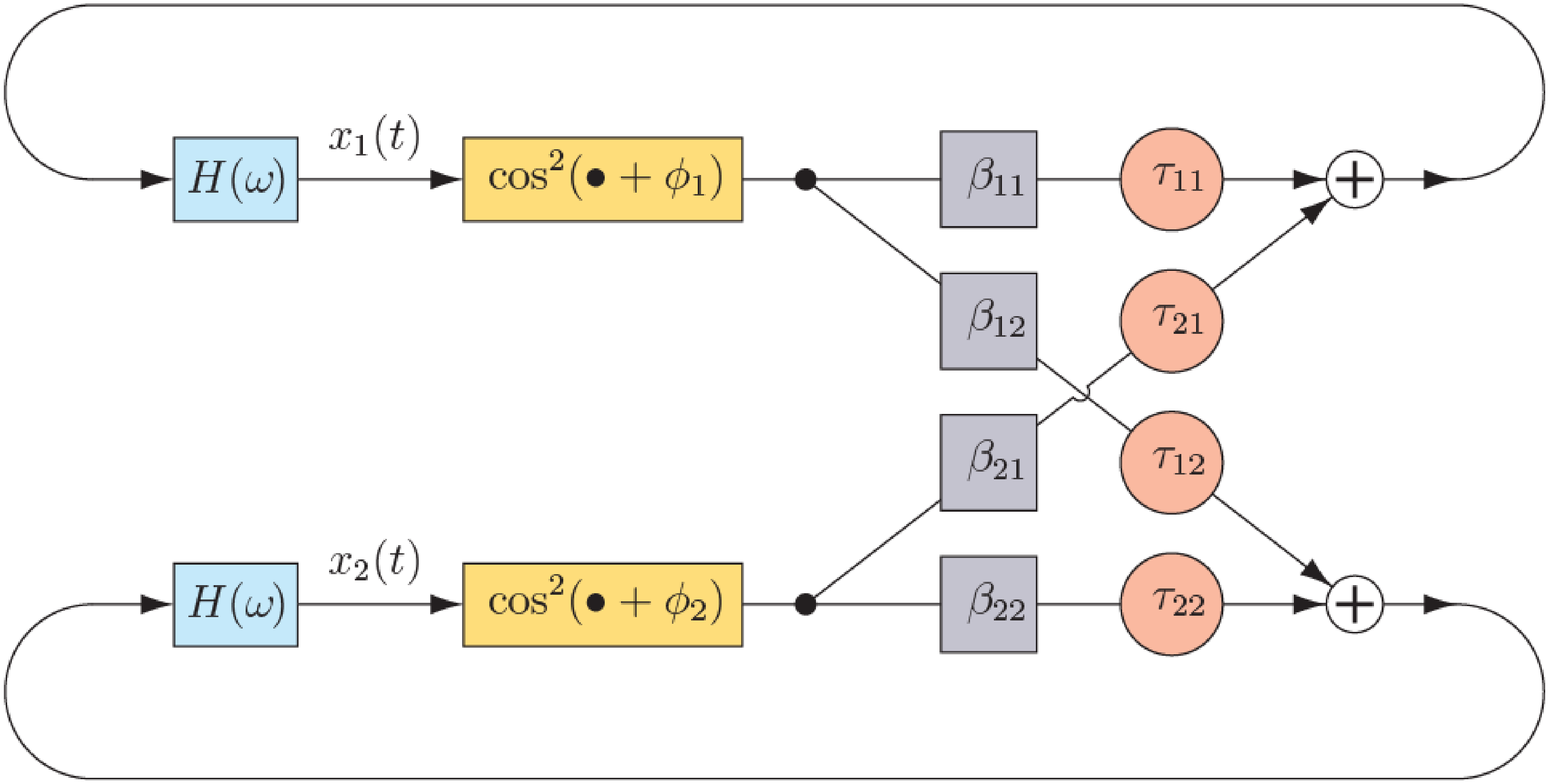
Coupling and Synchronization



Q: Under what conditions can these systems synchronize?

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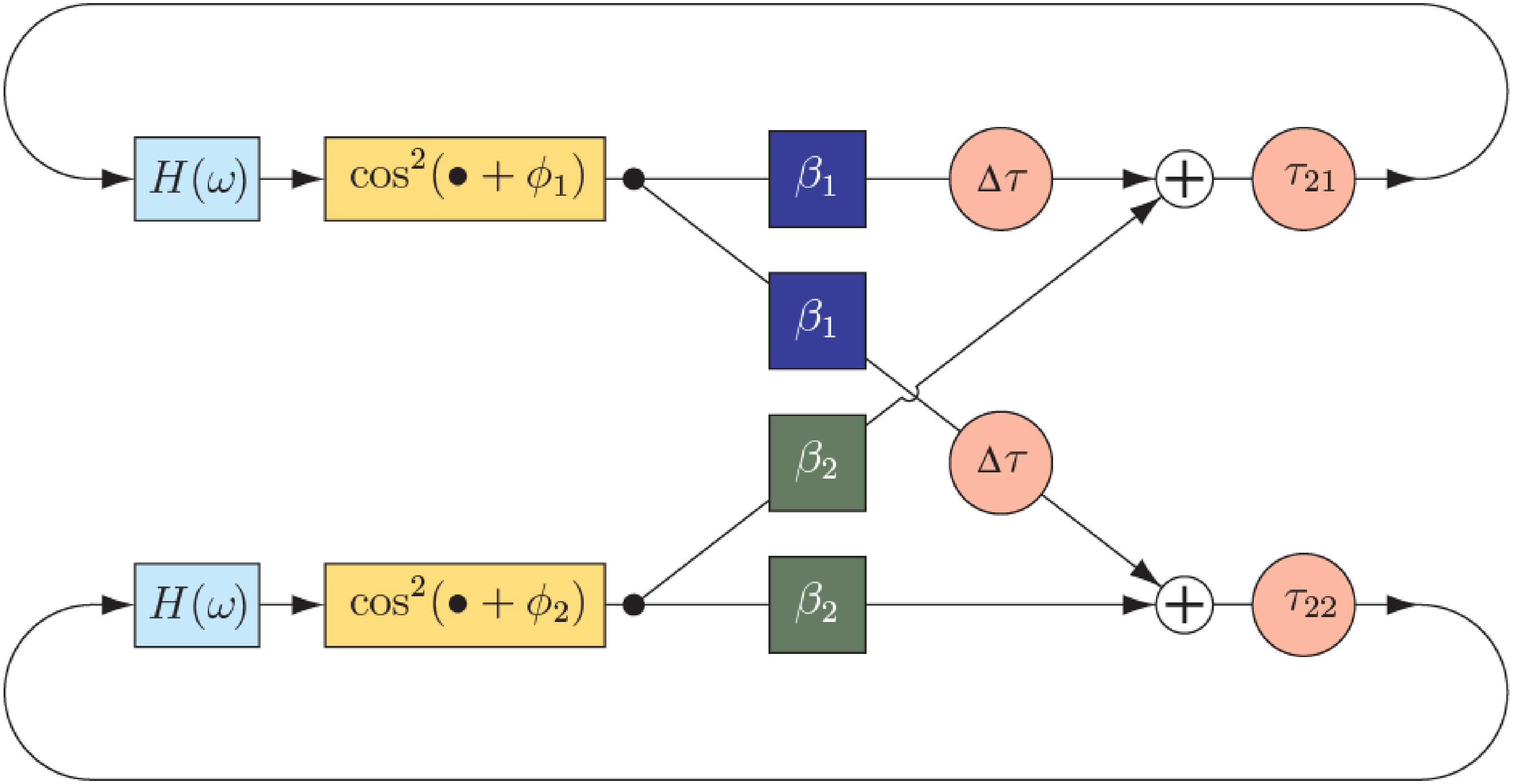
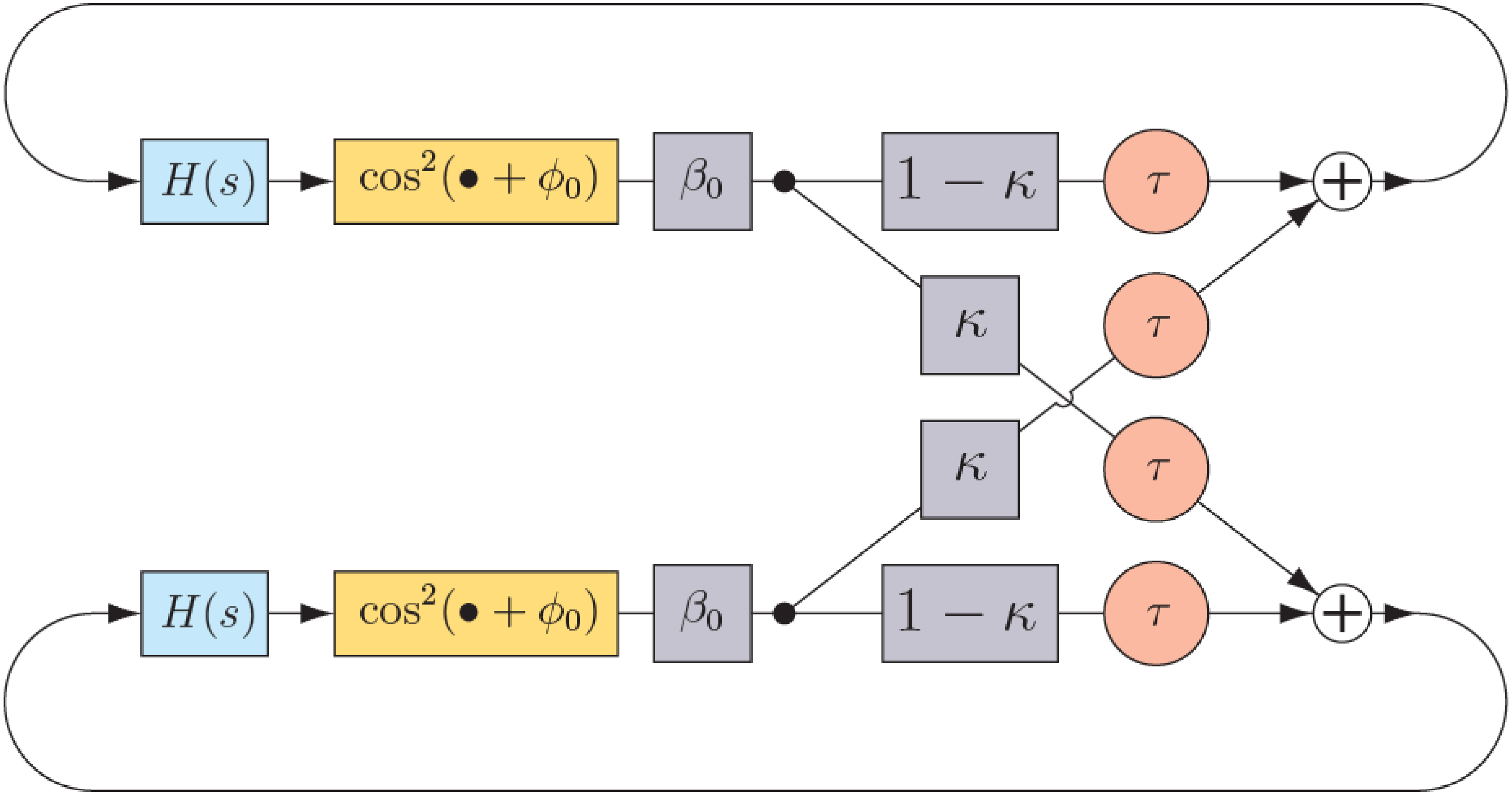
Synchronization – Method 1



- Synchronization is guaranteed

Synchronization – Method 2



- Synchronization is *possible* but NOT guaranteed (depending on κ)

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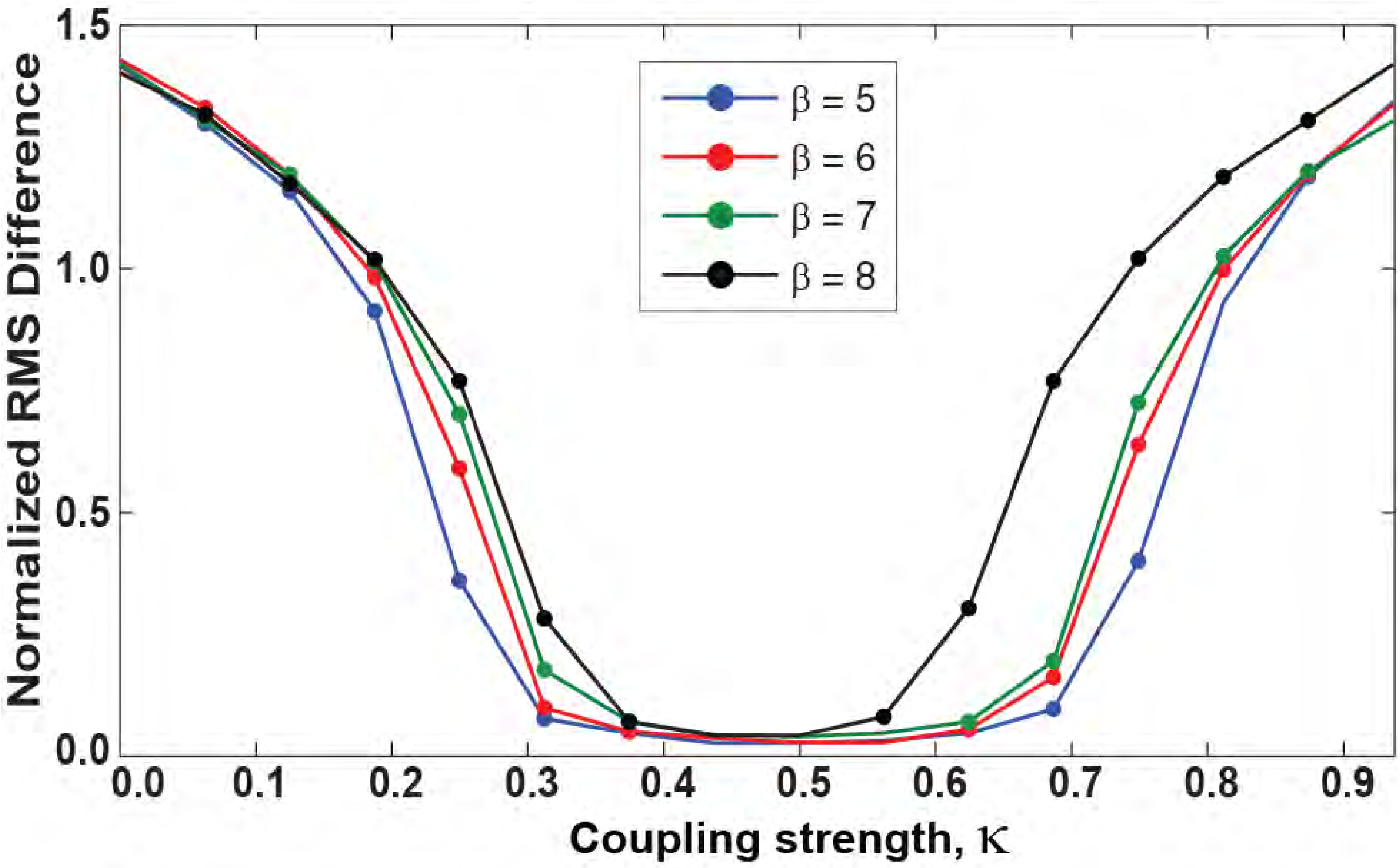
Bidirectional Synchronization



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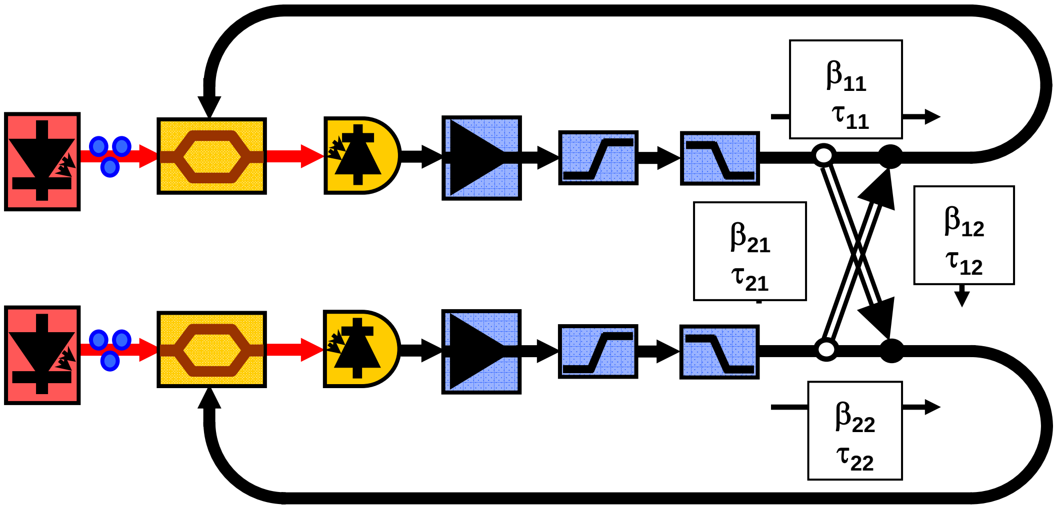
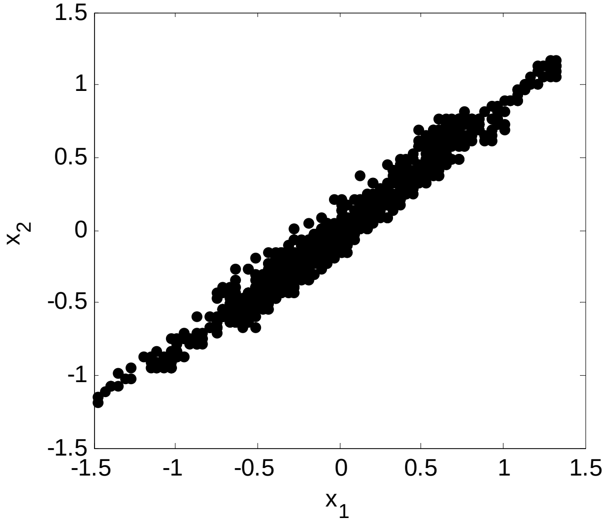
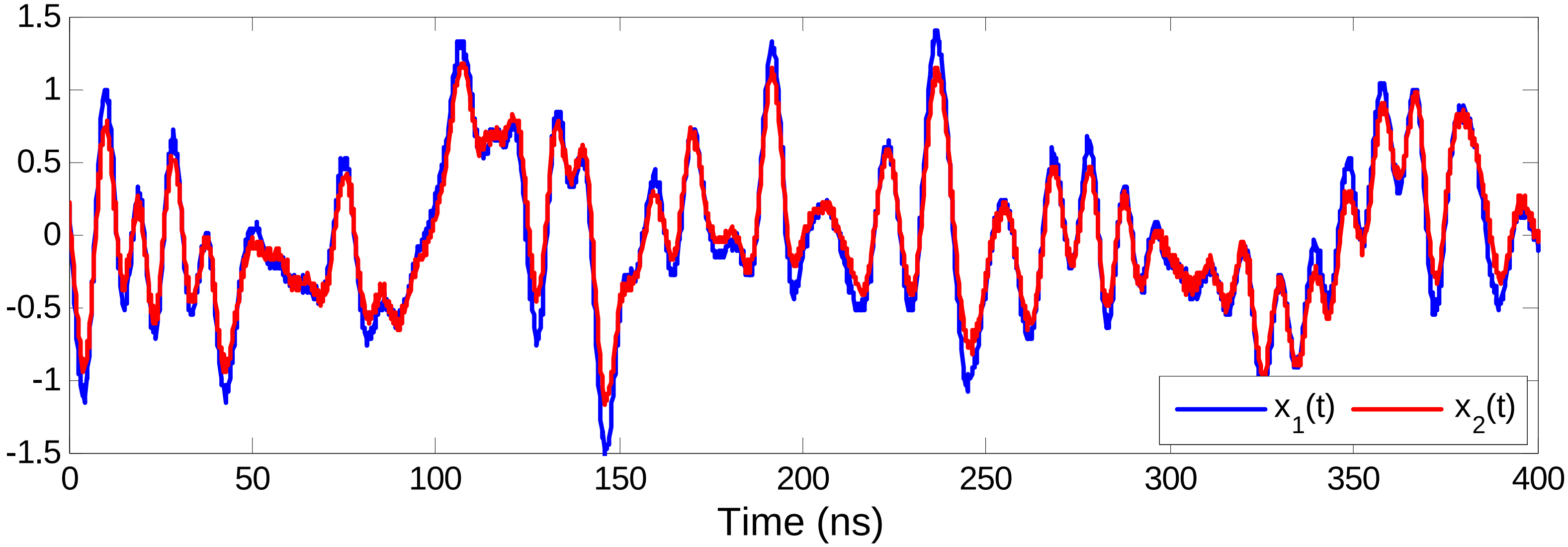
Synchronization Observed in Experiments







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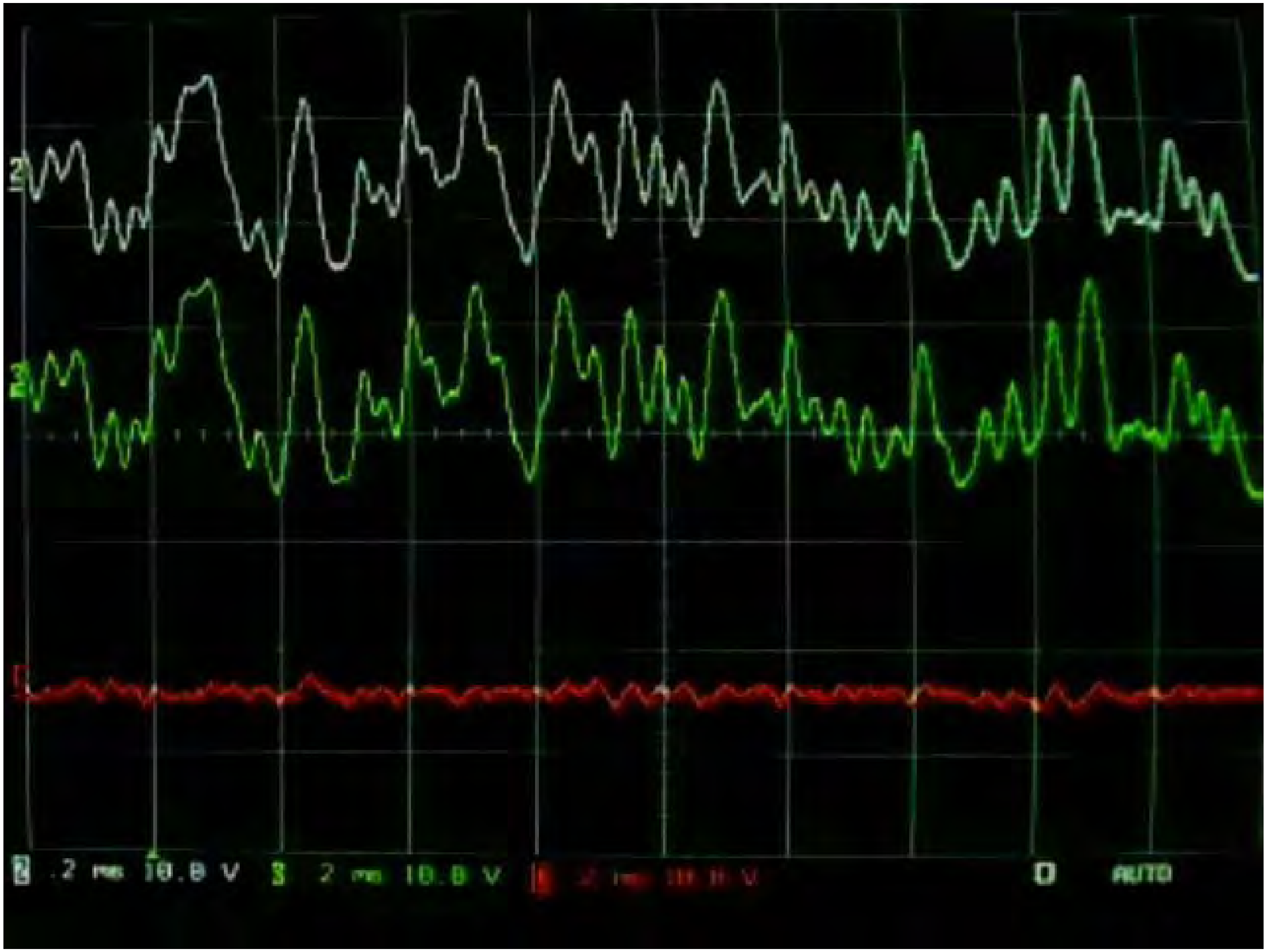
Synchronization at Low Speeds



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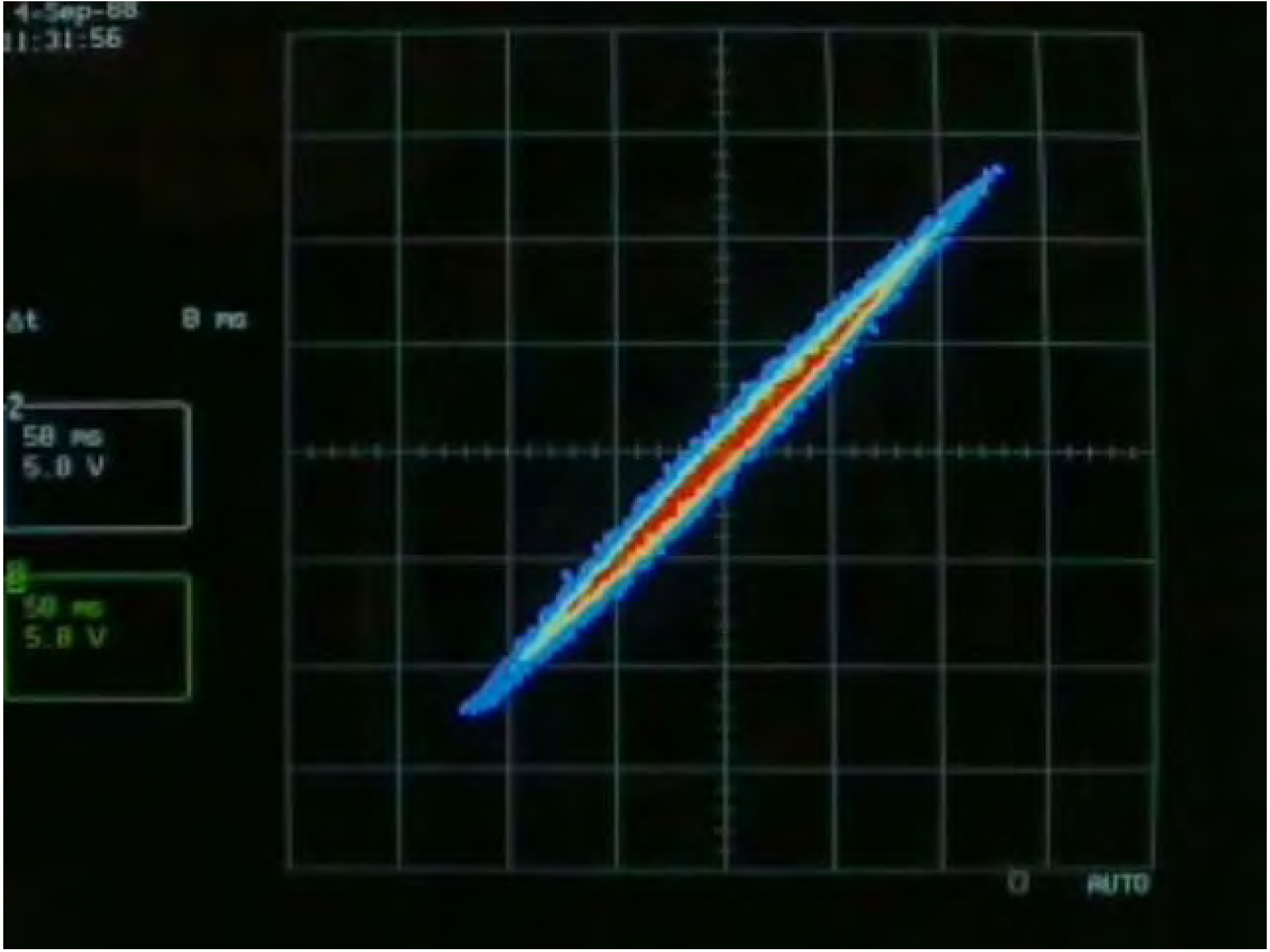
Synchronization at Low Speeds



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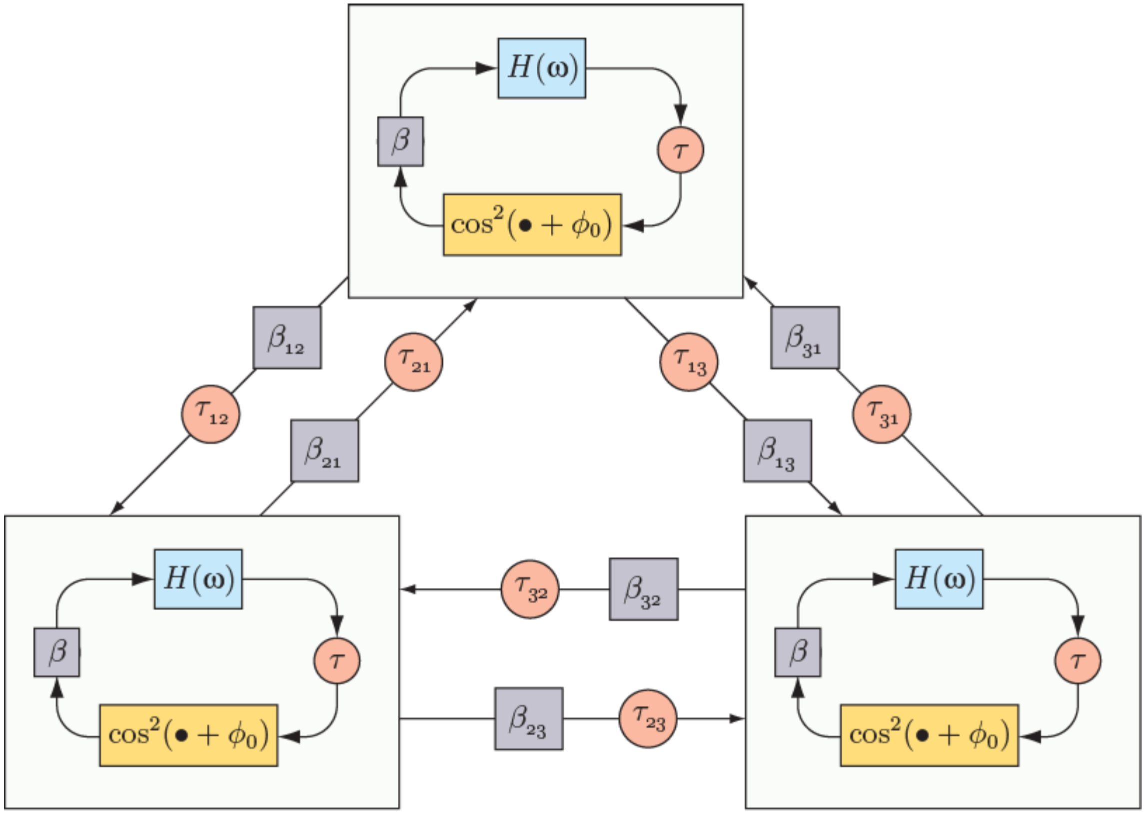
Sensor Networks (n≥3)



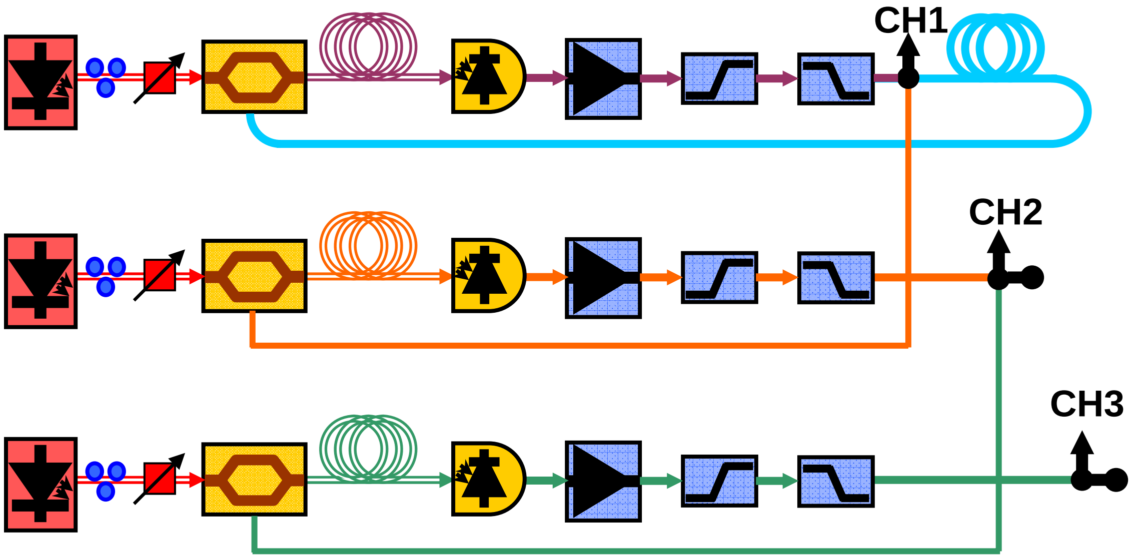
Scheme 1:

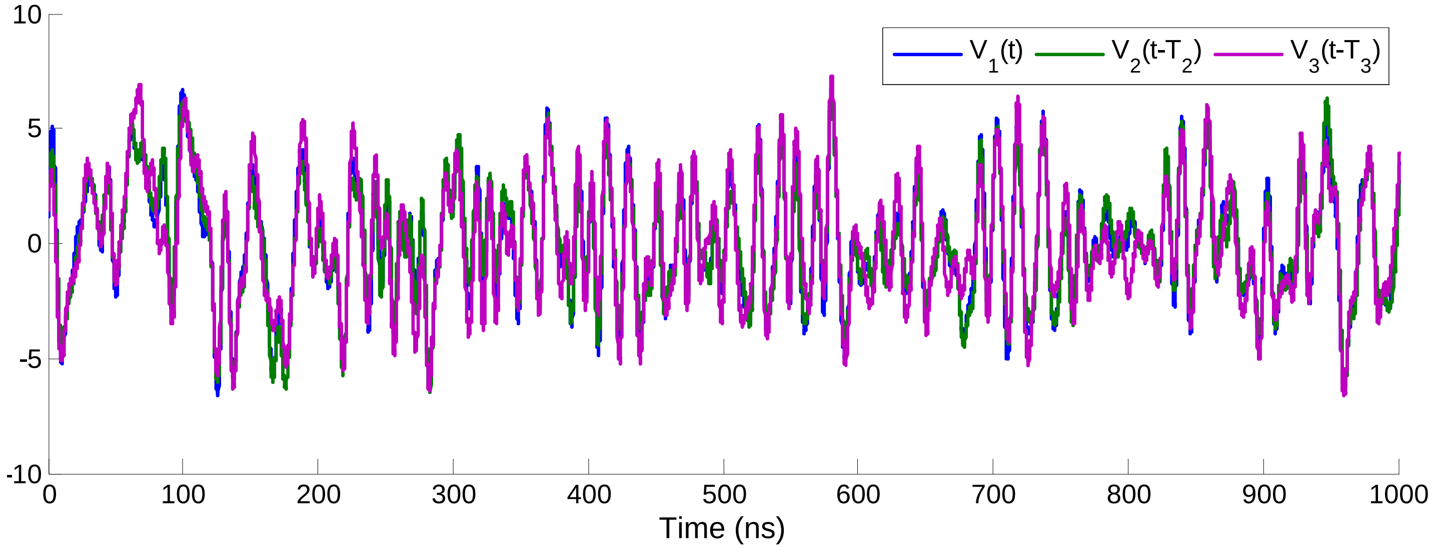
- Disturbance causes loss of synchronization

Scheme 2:

- Network dynamically adapts to maintain synchronization
  - Identification and tracking of β_{ij}

Unidirectional Synchronization (n=3)





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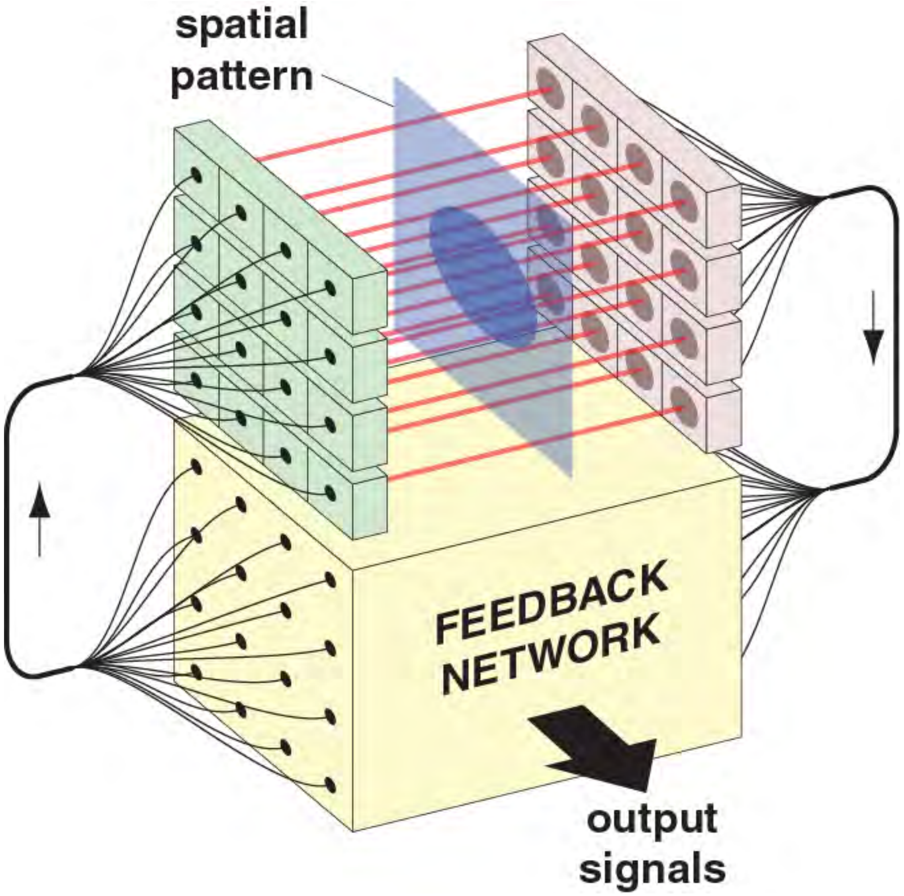
Sensor Networks (n > 60,000)

- Take advantage of parallel modulation and detection
  - Only one laser needed
- Applications in image and motion recognition
- Reconfigurable delay and feedback via FPGA
- DURIP Proposal:
  "Complexity-Based Optical Sensor Networks: Design and Characterization"
  (under consideration)



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Summary and Future Directions

SUMMARY

- Constructed and characterized modular optoelectronic feedback system
- Investigated synchronization between 2+ systems
- Implemented real-time DSP control of filters, couplings, and delays

FUTURE DIRECTIONS

- Investigate adaptive synchronization of networks
- More complex networks of systems
- Parallel modulation and detection using imaging technology:
  - Spatial light modulators
  - Focal plane array detectors

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