Nonlinear Delayed Optical Phase Oscillator for High Performance Chaos Synchronization: Dynamics and Chaos Commun. @ 10Gb/s

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May 25th / Snowbird

Outline

1. Introduction
   - Background, Motivations
   - Delay Dynamics in Optics
   - Modeling of Ikeda-like Dynamics
2. Electro-Optics Chaos Communications
   - Intensity Chaos
   - EO Phase Dynamics
   - Phase Chaos Cancellation
   - 10Gb/s Chaos Communications
3. Conclusions, Discussions, Perspectives
   - Security Issues
   - Enhanced and efficient phase chaos architecture

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From chaos synch. to optical communications

Why optical dynamics for chaos communications?

- Pecora & Carroll seminal paper (PRL 90)
- Signal synch. $\rightarrow$ Carrier for information transmission
- Broadband carrier $\rightarrow$ Security potential
- Physical layer encryption
- Fast optical dynamics matching high rate fiber comm.
- High dimensional chaos ($\infty-$dim. phase space, delays)
- Many setups in Optics (ECLD, Ikeda cavity, fiber laser,. . .)

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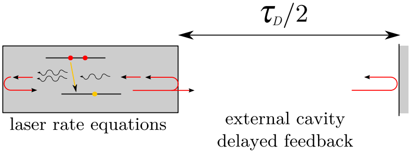
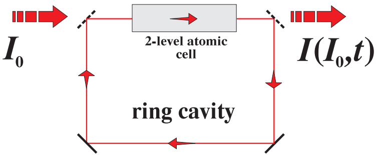
A few works in chaos communications

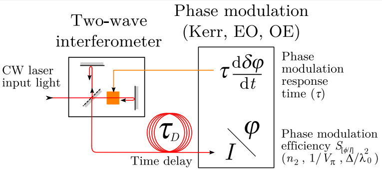


- **External Cavity Laser Diode:** Colet & Roy (1994), Mirasso (1996), Fischer & Davis (2000), Lenstra, Ohtsubo, Shore, Annovazzi-Lodi,. . .
- **Modulated / feedback micro-chip laser:** Uchida (1998)
- **Ring fiber laser:** Van Wiggeren & Roy (1998), Luo (2000)
- **Optoelectronic SC laser feedback** (Liu, 2001)

Dynamics ruled by the laser rate equations

The Ikeda delay dynamics principles





- **Kerr ring cavity:** Ikeda (Optics Commun. 1979)
- **Bulk EO interferometer:** Gibbs *et al.* (PRL 81)
- **Integrated optics MZ:** Neyer & Voges (IEEE JQE 82)
- **Wavelength chaos** Goedgebuer *et al.* (PRL 98)
- **Intensity chaos** Blakely *et al.* (PRL 04)

Dynamics ruled by a linear filtering, driven by a nonlinear delayed feedback

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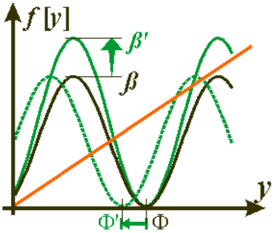
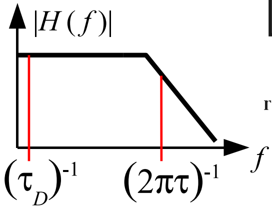
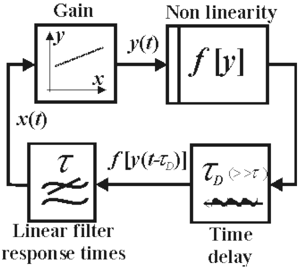
Generic Ikeda–like delay dynamics

- **The nonlinear delayed feedback loop "recipe".**
  - adiabatic nonlinear transformation $f[y]$
  - feedback gain (non–linearity strength), β
  - "dissipative" differential process:
    linear filtering with a response time τ
  - time delay $\tau_D >> \tau$

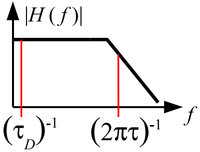






Linear Dynamical Process

- **Differential equation derivation.**
  - Fourier and time domains correspondance ($\times i2\pi f \leftrightarrow \mathrm{d}/(\mathrm{d}t)$)
  - Linear filter described by polynomial fractional
- **Low pass dynamics.**
  - Differential process: 1st order low pass filter
  - 2–time scales only (typ. large delay case $\tau_D >> \tau$, for Ikeda instabilities, period doubling)

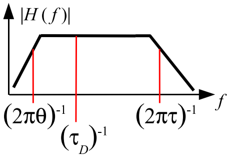


$$H(f) = \frac{1}{1 + i2\pi f\tau} = \frac{Z(f)}{X(f)} \leftrightarrow \tau\frac{\mathrm{d}x}{\mathrm{d}t}(t) + x(t) = z(t)$$

- For Ikeda–like dynamics, $z(t) = \beta \cos^2[x(t-\tau_D) + \Phi]$ is the self–feedback nonlinear delayed driving force.

. . . Linear Dynamical Process

- **Bandpass dynamics.**
  - Simplest polynomial fractional for a bandpass filter: 2nd order
  - Higher orders sometimes important (2nd order usually enough qualitatively)



$$H(f) = \frac{i2\pi f\theta}{(1+i2\pi f\theta)(1+i2\pi f\tau)} = \frac{Z(f)}{X(f)} \leftrightarrow \tau\frac{\mathrm{d}^2x}{\mathrm{d}t^2}(t)+(1+\tau/\theta)\frac{\mathrm{d}x}{\mathrm{d}t}(t)+x(t) = \frac{\mathrm{d}z}{\mathrm{d}t}(t)$$

or

$$\frac{1}{\theta}\int_{t_0}^{t} x(\xi)\,\mathrm{d}\xi + (1+\tau/\theta)x(t) + \tau\frac{\mathrm{d}x}{\mathrm{d}t}(t) = z(t)$$

- $z(t) = \beta f[x, t, t-\tau_D]$ is the nonlinear delayed feedback

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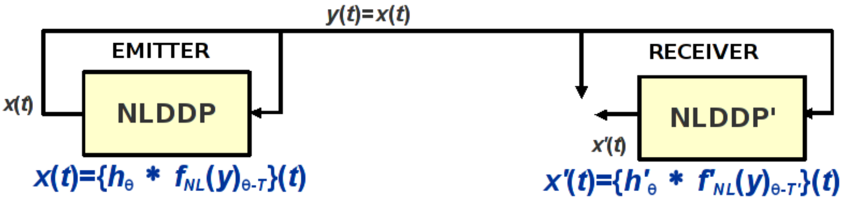
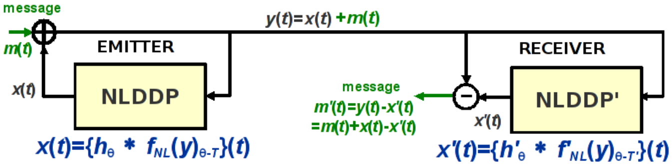
Emitter Receiver principle

- **Open loop synchronisation.**

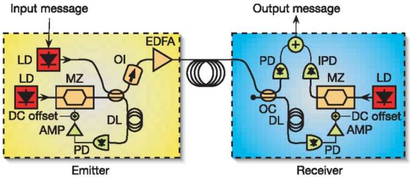


Emitter Receiver principle

- **Open loop decoding.**

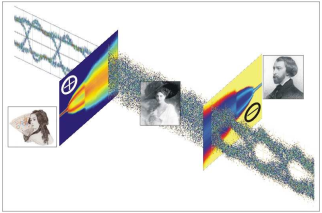


- **Experimental setup.**

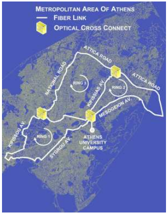


Encoding & decoding results

- **Intensity chaos “spy suitcases”.**


- **Field experiment during OCCULT @ 3Gb/s.**



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LETTERS

Chaos-based communications at high bit rates using commercial fibre-optic links

Apostolos Argyris[1], Dimitris Syvridis[1], Laurent Larger[2], Valerio Annovazzi-Lodi[3], Pere Colet[4], Ingo Fischer[5]†, Jordi García-Ojalvo[6], Claudio R. Mirasso[7], Luis Pesquera[8] & K. Alan Shore[9]

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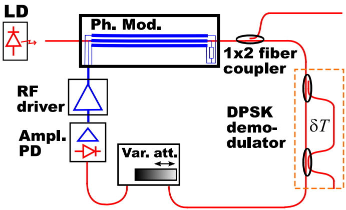
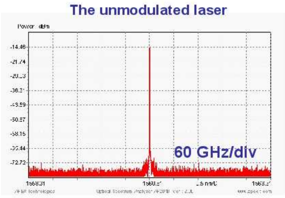
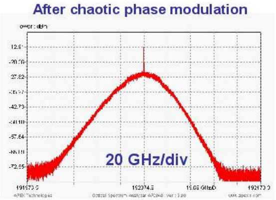
Dynamical mechanism

- **Setup, physical principles.**
  - DPSK optical modulation
  - Temporally nonlocal non linearity
  - Intrinsically high speed



- **Optical ΦM in the spectrum.**



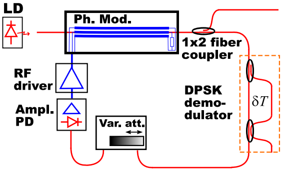


Modeling

- **The dynamics**
  - Integro-differential (linear bandpass filter) nonlinear delay equation

$$\frac{1}{\theta}\int_{t_0}^{t}\varphi(\xi)\,\mathrm{d}\xi + (1+\tau/\theta)\varphi(t) + \tau\frac{\mathrm{d}\varphi}{\mathrm{d}t}(t) = \beta\cdot\left[f_{(t-T)}(\varphi^\star)\right]$$

  - Non linearity via imbalanced interferometer (temporal non locality)
    - standard DPSK demodulator



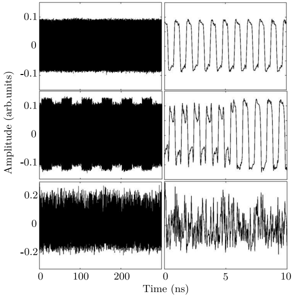
$$f_t(\varphi) = \{1+\cos[\varphi(t)-\varphi(t-\delta T)+\Phi_0]\}$$

    - generalized multiple wave interferometer

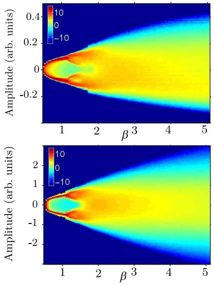
$$f_t(\varphi) = F_0\left|1+\sum_k \alpha_k\, e^{i[\varphi(t)-\varphi(t-T_k)+\Phi_k]}\right|^2$$

Bifurcations, route to chaos

- **4 time-scales dynamics ($\theta \gg T \gg \delta T \gg \tau$)**

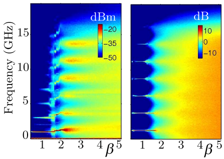


Temporal bif. diagrams →

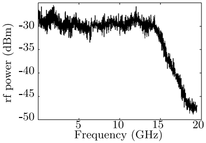


← Time traces

Spectral bif. diagram →



← Flat chaotic rf spectrum



Lavrov *et al.*, PRE (2009)

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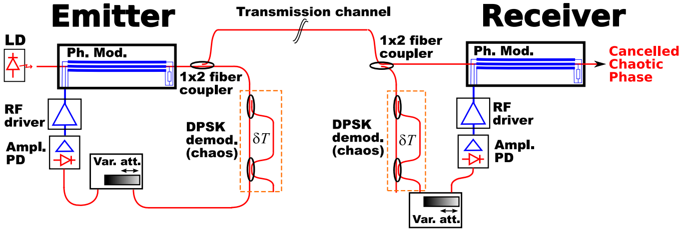
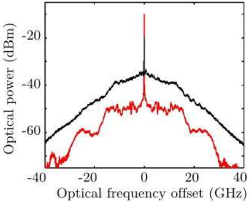
Phase chaos uni-directional coupling



- Optical Spectrum measurement of the phase chaos cancellation



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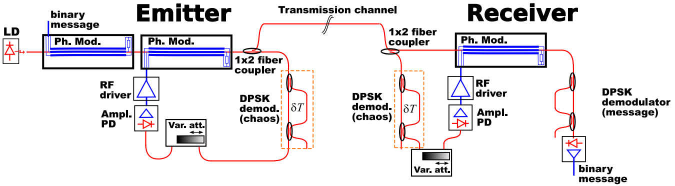
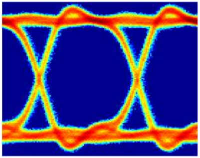
Back-to-back PRBS encryption

- **DPSK EO mod/demod & chaos masking/unmasking**

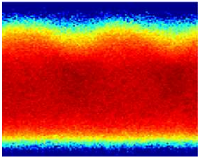


- **10Gb/s eye diagrams**

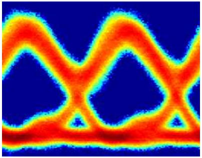
original PRBS,
NRZ data



standard DPSK
demodulation: RZ data

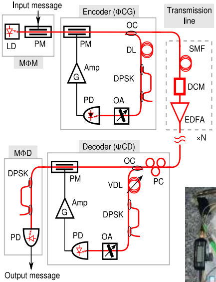


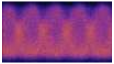
chaotic carrier cancelled,
+ DPSK demod.: RZ data

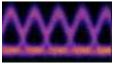


Field experiment @ 10 Gb/s

Emitter setup packaged on a A4-alumni board

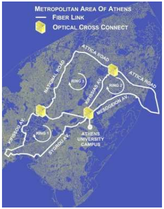






Receiver setup packaged on a A4-alumni board

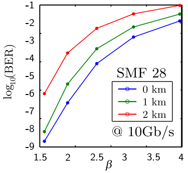
“Lumière” brothers ring network in Besançon, France (22km)

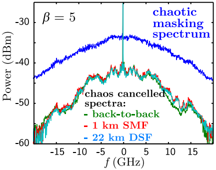


Athens, Greece, metropolitan fiber network (116km)

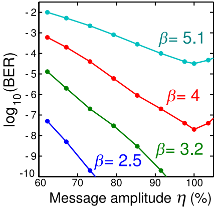
Lavrov *et al.*, IEEE JQE (2010)

Operational parameter settings



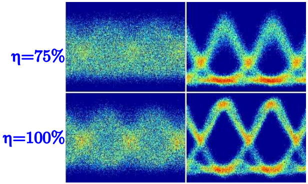


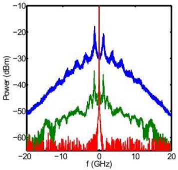
Back-to-back measure

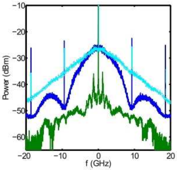


- Strong but manageable dispersion effects
- Trade-off security / decoding quality
- BER 10^{-7} @ 10Gb/s, 116km
- Error free @ 3Gb/s, 116km

Eye diagram (β=2.5)







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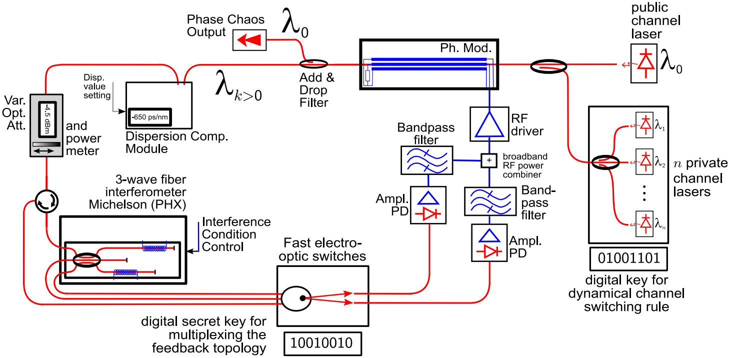
Chaos communication is (nearly) secure,. . .

- **Parameter mismatch sensitivity**
- **Succesfull parameter identification**
- **Phase space reconstruction**
- **Proper cryptanalysis is lacking**
- **Proof of principle for chaos communication**
- **Extreme experimental versatility**
- **Parameter masking architectures**
- **Cryptographic protocols, information theory**
- **Improved architectures do exist. . .**

Enhancing the phase chaos architecture complexity



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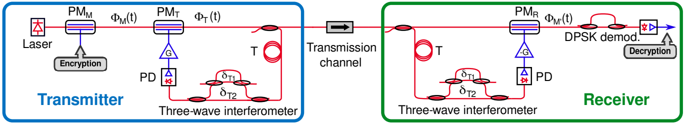
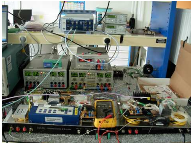
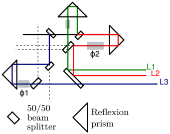
Customized multiple delays nonlocal non linearity

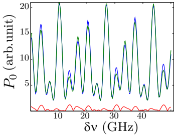
- 3-wave interferometer phase chaos setup

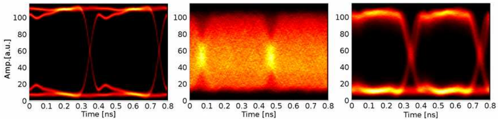




- Matching accuracy, and eye diagram @ 3Gb/s



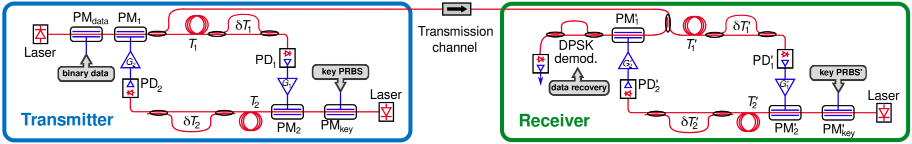




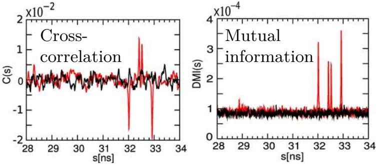
Oden *et al.*, in preparation (2011)

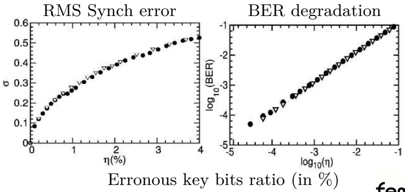
Amplified entropy with hybrid digital / analog setup

- Digital key in a phase chaos setup via PRBS/chaos mixing



- Time delay concealment, and digital key sensitivity





Nguimdo *et al.*, submitted (2011)

Aknowledgements

Aknowledgements

Thank you

for attention . . . !!!