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

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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. → Carrier for information transmission
- Broadband carrier → Security potential
- Physical layer encryption
- Fast optical dynamics matching high rate fiber comm.
- High dimensional chaos (∞−dim. phase space, delays)
- Many setups in Optics (ECLD, Ikeda cavity, fiber laser,...)
Introduction

Background, Motivations

Delay Dynamics in Optics

Modeling of Ikeda-like Dynamics

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Intensity Chaos

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Enhanced and efficient phase chaos architecture
A few works in chaos communications

- **Modulated / feedback micro-chip laser**: Uchida (1998)
- **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), $\beta$
  - “dissipative” differential process:
    - linear filtering with a response time $\tau$
  - time delay $\tau_D \gg \tau$

$$f[y]$$

$$|H(f)|$$

($)$(2\pi \tau)^{-1}$

($)$(\tau_D)^{-1}$

Gain

Non linearity

$x(t)$

$y(t)$

$y'[t]$
Linear Dynamical Process

- **Differential equation derivation.**
  - Fourier and time domains correspondence ($\times i2\pi f \leftrightarrow d/(dt)$)
  - Linear filter described by polynomial fractional

- **Low pass dynamics.**
  - Differential process: $1^{st}$ order low pass filter
  - 2–time scales only (typ. large delay case $	au_D >> \tau$, for Ikeda instabilities, period doubling)

\[
H(f) = \frac{1}{1 + i2\pi f \tau} = \frac{Z(f)}{X(f)} \leftrightarrow \tau \frac{dx}{dt}(t) + x(t) = z(t)
\]

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

- Simplest polynomial fractional for a bandpass filter: 2\textsuperscript{nd} order
- Higher orders sometimes important (2\textsuperscript{nd} order usually enough qualitatively)

\[
H(f) = \frac{i2\pi f \theta}{(1 + i2\pi f \theta)(1 + i2\pi f \tau)} = \frac{Z(f)}{X(f)} \leftrightarrow \tau \frac{d^2 x}{dt^2}(t) + \left(1 + \frac{\tau}{\theta}\right) \frac{dx}{dt}(t) + x(t) = \frac{dz}{dt}(t)
\]

or

\[
\frac{1}{\theta} \int_{t_0}^{t} x(\xi) d\xi + \left(1 + \frac{\tau}{\theta}\right) x(t) + \tau \frac{dx}{dt}(t) = z(t)
\]

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

- Open loop synchronisation.

**EMITTER**

\[ x(t) = \{h_\theta \ast f_{NL}(y)_{\theta-T}\}(t) \]

**RECEIVER**

\[ x'(t) = \{h'_\theta \ast f'_{NL}(y)_{\theta-T'}\}(t) \]

**Diagram:**

![Diagram](image-url)
Emitter Receiver principle

- Open loop decoding.

\[ y(t) = x(t) + m(t) \]

- Experimental setup.

Experimental setup diagram:

- Input message
- Output message
- EDFA
- LD
- MZ
- OI
- PD
- IPD
- MZ
- LD
- DC offset
- AMP
- DL
- PD
- OC

SIAM DS11, MS118, 5/25/11, Snowbird
Encoding & decoding results

- Intensity chaos “spy suitcases”.

- Field experiment during OCCULT @ 3Gb/s.

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

Apostolos Argyris¹, Dimitris Syrriatis¹, Laurent Langer¹, Valerio Annovazzi-Lodi², Pere Colet³, Ingo Fischer⁴, Jordi Garcia-Ojalvo⁵, Claudio R. Mirasso⁶, Luis Poyzuer⁷ & K. Alan Shore⁸

LETTERS
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Dynamical mechanism

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

- **Optical $\Phi M$ in the spectrum.**
The dynamics

- Integro-differential (linear bandpass filter) nonlinear delay equation

\[
\frac{1}{\theta} \int_{t_0}^{t} \varphi(\xi) \, d\xi + (1 + \tau/\theta) \varphi(t) + \tau \frac{d\varphi}{dt}(t) = \beta \cdot [f(t-T)(\varphi^*)]
\]

- 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

\[
f_t(\varphi) = F_0 \left| 1 + \sum_k \alpha_k e^{i[\varphi(t) - \varphi(t - T_k) + \Phi_k]} \right|^2
\]
4 time-scales dynamics $(\theta \gg T \gg \delta T \gg \tau)$

- Temporal bif. diagrams $\rightarrow$
- Time traces $\leftarrow$
- Spectral bif. diagram $\rightarrow$
- Flat chaotic rf spectrum $\leftarrow$

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

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

Receiver setup packaged on a A4-alumni board

Lavrov et al., IEEE JQE (2010)
Operational parameter settings

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

Back-to-back measure

Eye diagram ($\beta=2.5$)

\[ \eta=75\% \]

\[ \eta=100\% \]
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Chaos communication is (nearly) secure,

- Parameter mismatch sensitivity
- Successful 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

Security Issues
Enhanced phase chaos communications

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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

Nguiamdo et al., submitted (2011)
Aknowledgements
Thank you for attention . . . !!!