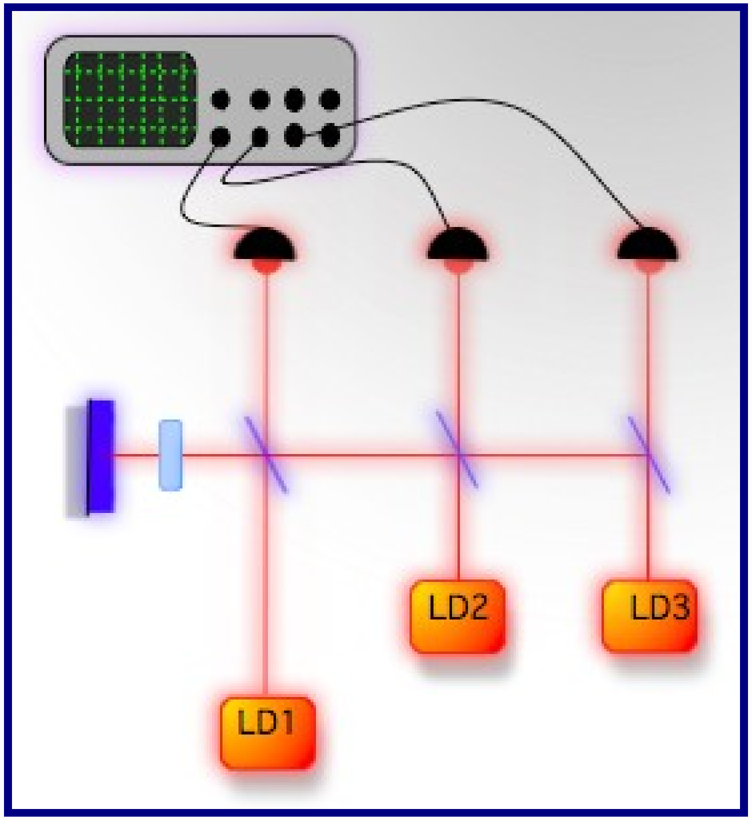
From clustering to synchronization in a semiconductor laser array



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Outline

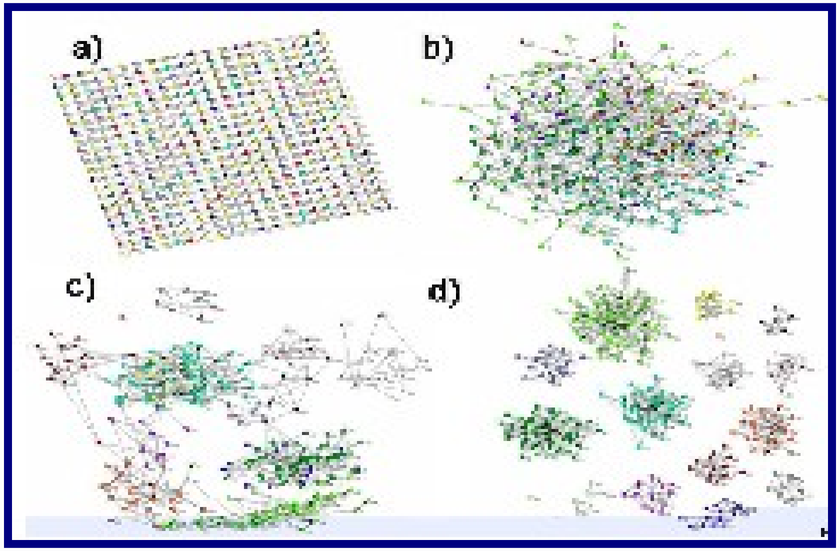
- Introduction.
- Route to synchronization with three coupled semiconductor lasers.
- Numerical results.
- Conclusions.

Introduction

- Synchronization phenomena is normally studied in two limiting situations

1. Network of coupled elements

- Synchronization and cluster formation



D. Centola, J. C. Gonzalez-Avella, V. M. Eguiluz, M. San Miguel,"Homophily, cultural drift and the co-evolution of cultural groups", ***arxiv:physics/0609213*** (2007)

E. Hernandez-Garcia, C. Lopez, ***Phys. Rev. E* 70** ,016216 (2003)

S. C. Manrubia, A. S. Mikhailov, ***Phys. Rev. E* 60**, 1579, (1999)

Introduction

2.Two coupled elements

Adjustment of rhythms of oscillating objects due to their weak interaction.

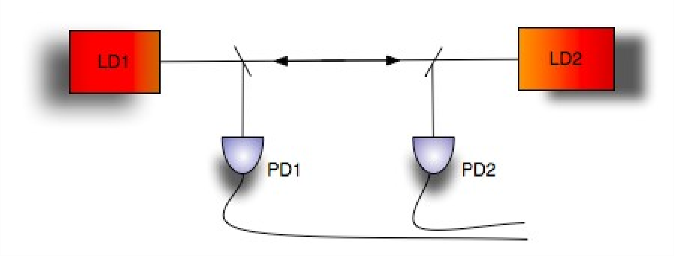
- Lag synchronization: $\mathbf{x_1(t)=x_2(t-\tau)}$.

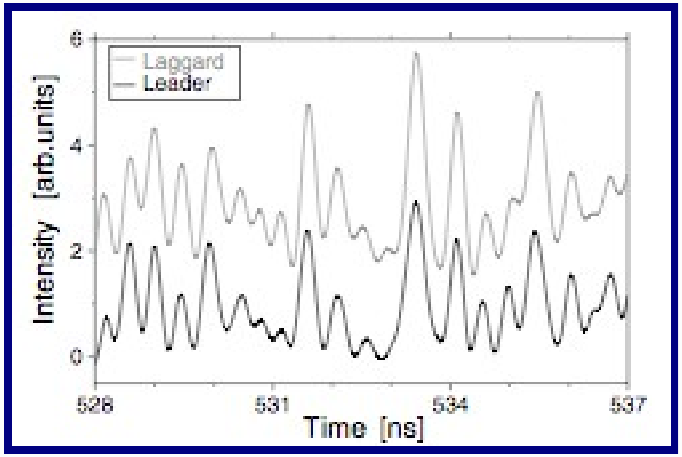
In the context of the lag synchronization of semiconductor lasers, different ways of coupling produces different characteristic lag or achronal synchronization.

The delay is determined by the fly time between the subsystems.

Introduction

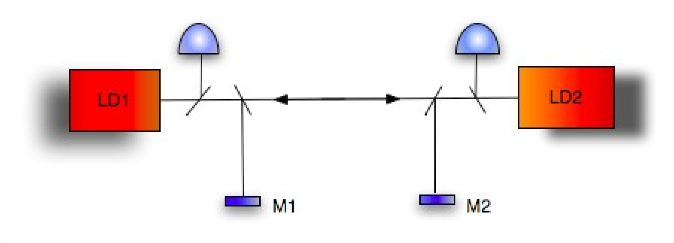
Bidirectionally coupled lasers

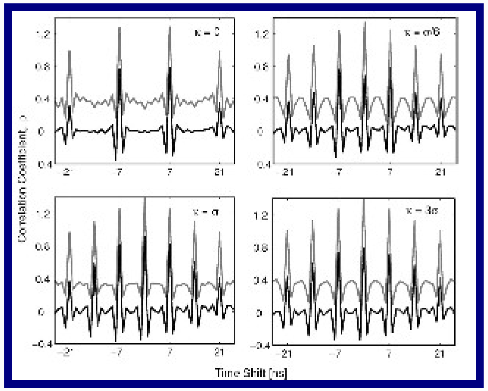




T. Heil, I. Fischer, W. Elsässer, J Mulet, C. Mirasso, ***Phys. Rev. Lett***. **86**, 795 (2001)

J. Mulet, C. Masoller, C. Mirasso, ***Phys. Rev. A*** **65**, 063815 (2002)





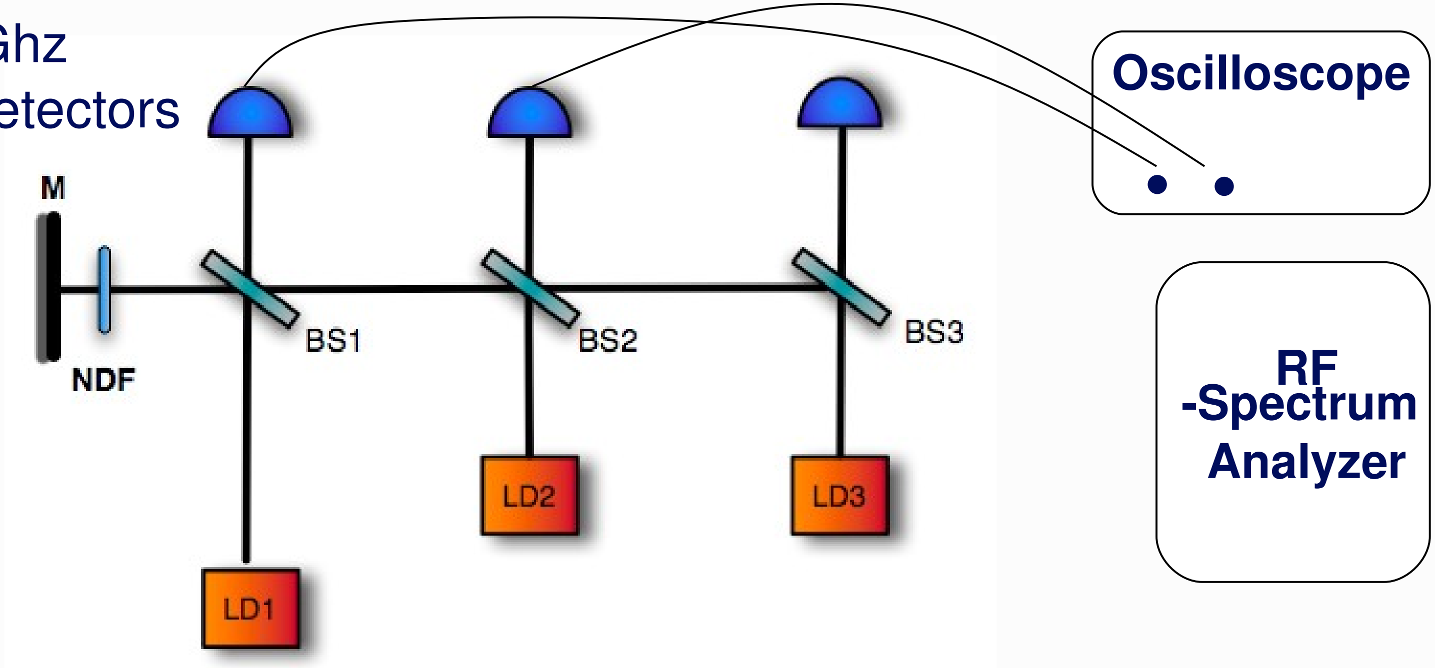
E. Klein, N. Gross, M. Rosembluh, W. Kinzel, L. Khaykovich, I. Kanter, ***Phys. Rev. E*** **73**, 066214 (2006)

Experimental Setup

Synchronization via cluster formation

How the system loses its synchrony

1 Ghz photodetectors



Oscilloscope

RF -Spectrum Analyzer

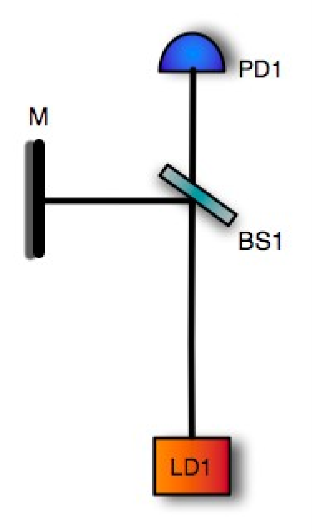
Three AlGaInP index-guided and multiquantum well semiconductor lasers

with feedback, mutually coupled trough a mirror (λ =650 nm)

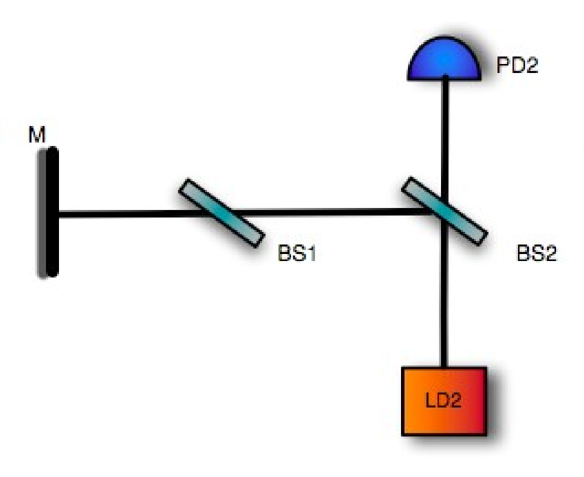
Experimental Setup

1. Mirror (M) supplies the feedback of each laser

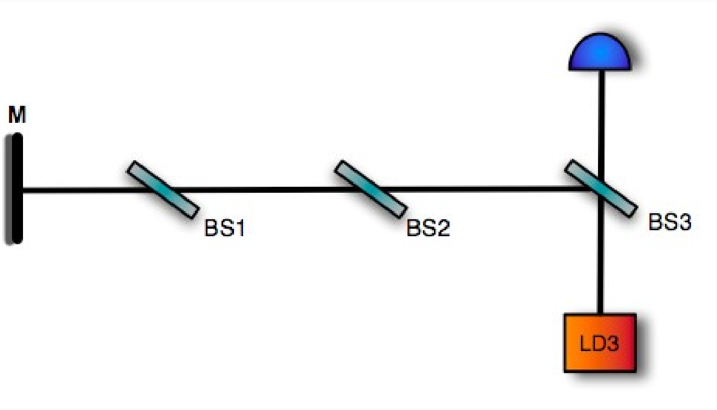
LD1 with optical feedback due to the incoming light reflected in an external mirror.



LD2 with different feedback conditions. The light passes through two beamsplitters before is fed back into the laser.



LD3 with different feedback conditions also. The light passes through three beam splitters before is fed back into the laser.



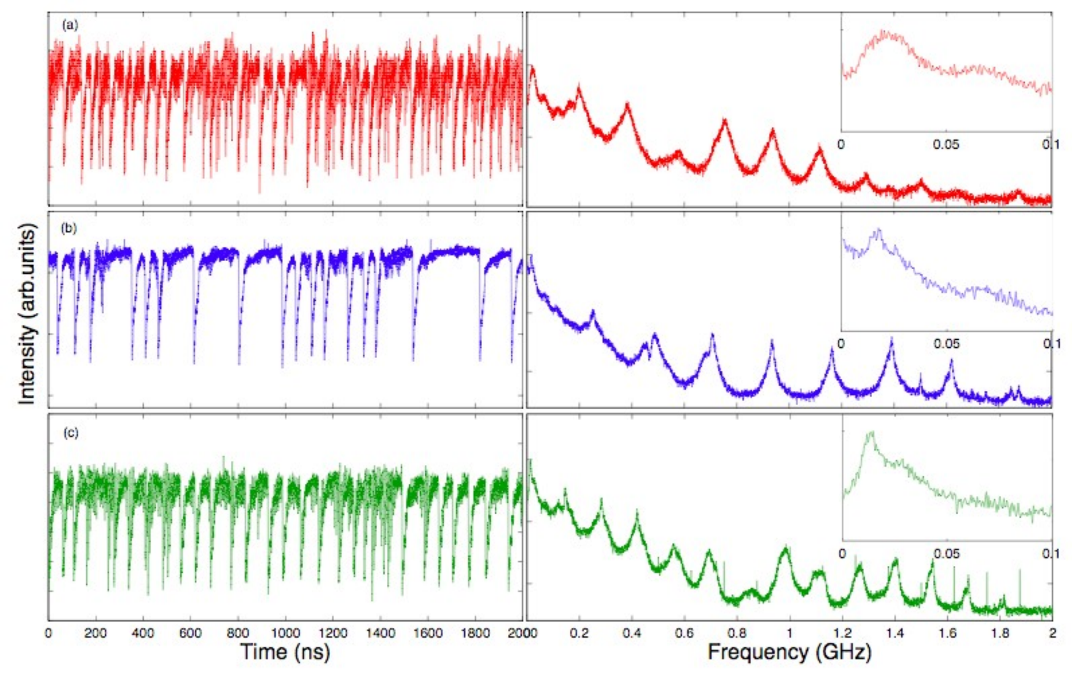
Feedback time **$\tau_{11} = 5.43$ ns**

$\tau_{22}=4.8$ ns

$\tau_{33}=7.3$ ns

Experimental Setup

Laser intensities and RF spectra for uncoupled lasers.



Mean inter-dropout events

Inset, low frequencies

External cavity frequencies $(1/\tau_{ii}$

Harmonics

Mean time between dropouts:

LD1= 200ns

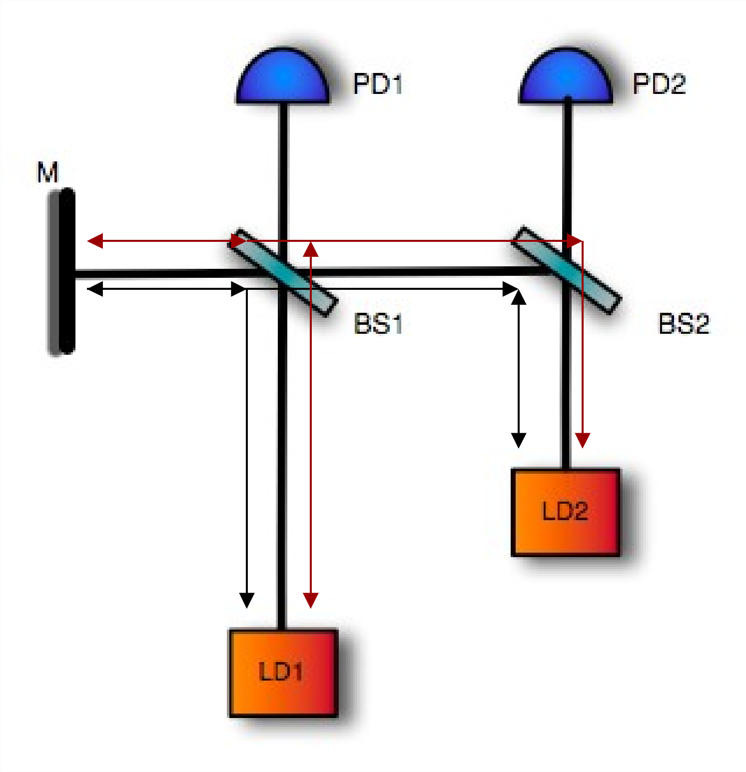
LD2= 100 ns

LD3= 150 ns

Experimental Setup

2. Mirror also supplies the injection

Each laser with the other two bidirectionally coupled.



Coupling times: $\tau_{c1} = \tau_{c2}$

Feedback times: $\tau_{f1} \neq \tau_{f2}$

$\tau_{12}=\tau_{21}$= 5.0 ns

$\tau_{13}=\tau_{31}$= 6.4 ns

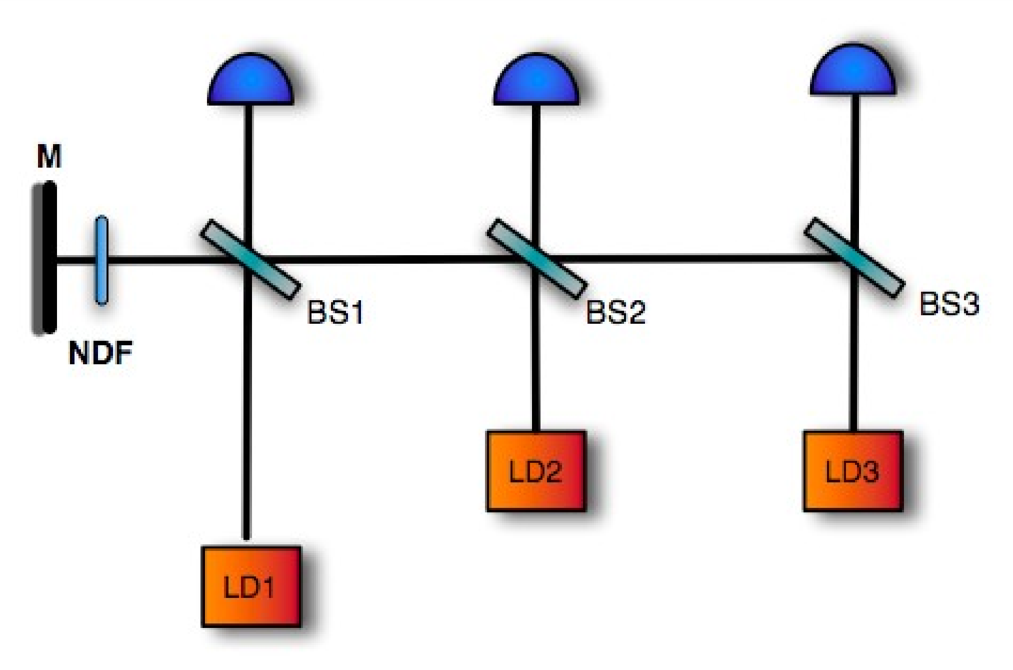
$\tau_{23}=\tau_{32}$= 6.0 ns

→ LD2 to LD1 injection and LD2 feedback

→ LD1 to LD2 injection and LD1 feedback

Experimental Setup

Injected light → NDF, neutral density filter



Variation
100% reflected light

↓

~63% light

How the lasers lose their synchrony as the total injected light decreases

Experimental Results

Synchronization

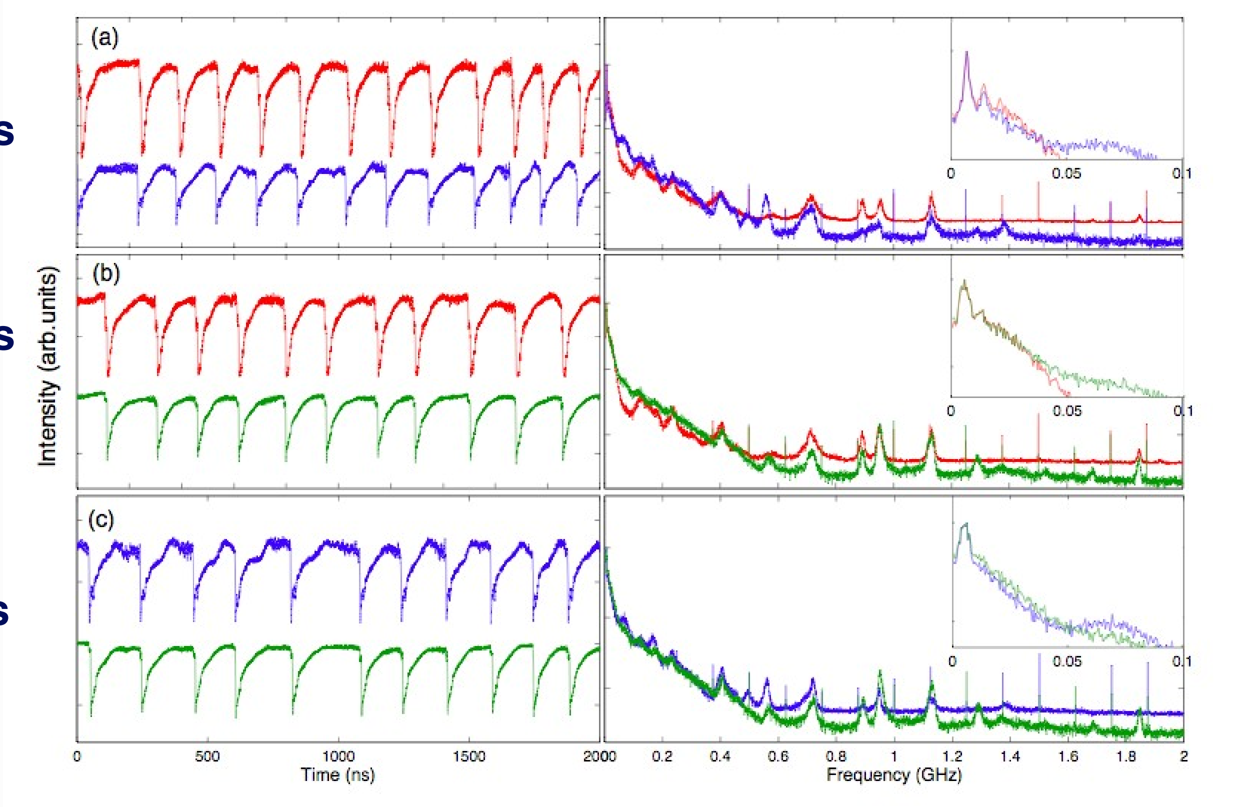
100% incoming light

lag times

Ld1-Ld2 ~-10ns

Ld1-Ld3 ~0.5ns

Ld2-Ld3 ~10ns



LD1-LD2

LD1-LD3

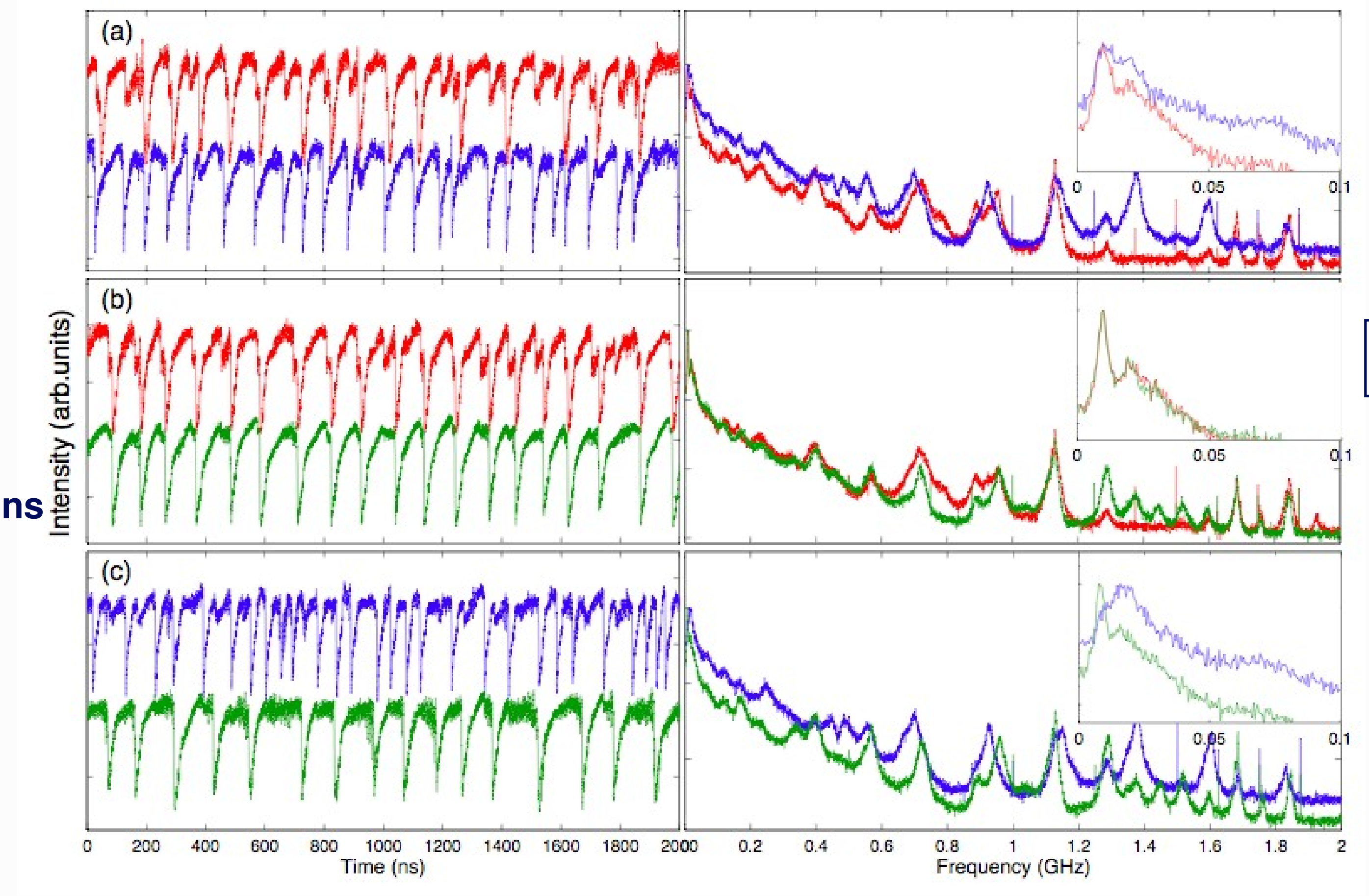
LD2-LD3

Mean time between dropouts ~165 ns

Experimental Results

Clustering

NDF 63% Transmitivity



LD1-LD2

LD1-LD3

cluster

LD2-LD3

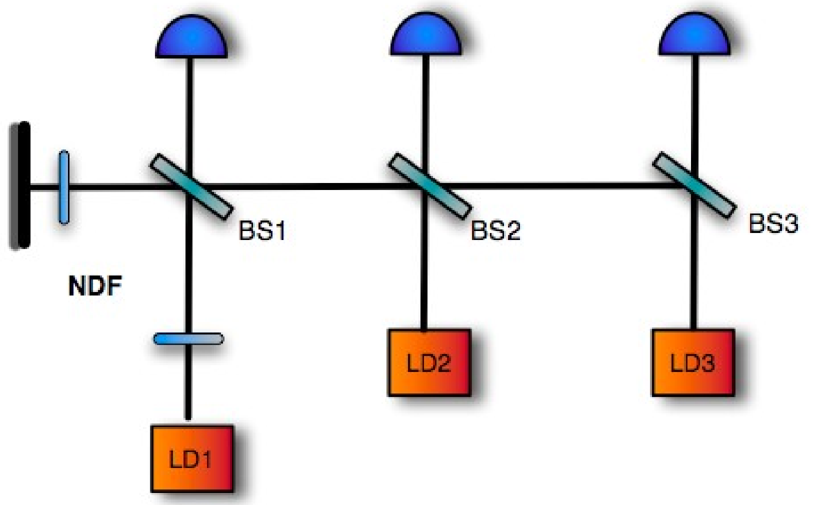
lag time

LD1-LD3~0.5ns

Mean time between dropouts ~100 ns

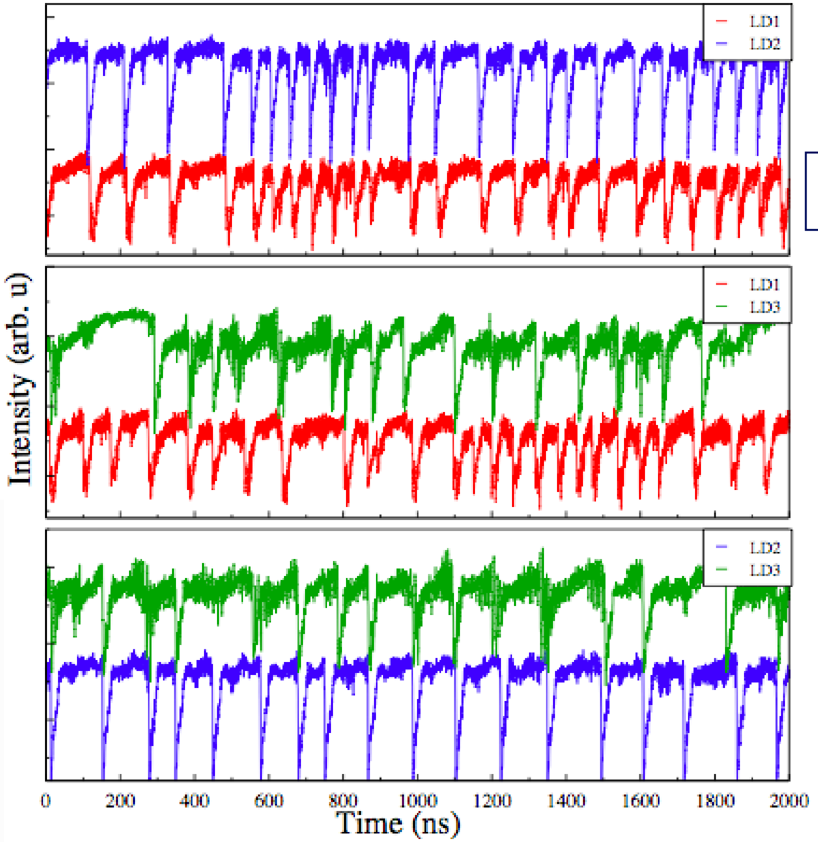
Experimental Results

Change of lasers of the cluster



lag time LD1-LD2 ~5 ns.

Maintained in synchronization state



cluster

LD1-LD2

LD3 out

Numerical Results

Rate equations for slowly-varying complex amplitude and the carrier density, in ith laser[1]

$$\overset{r}{E}_i = \iota\omega_\iota E_\iota + \kappa(1+\iota\alpha)E_\iota + \sqrt{\Delta}\,\xi_\iota(\tau)$$

$$+ \underset{\varphi=1}{\overset{3}{¥}}\eta_{\iota\varphi}E_\varphi(\tau-\tau_{\iota\varphi})\varepsilon^{(-\iota\omega_0\tau_{\iota\varphi})}$$

$$\overset{r}{N}_\iota = \gamma_\nu(I - N_\iota - N_\iota\left|E_\iota\right|^2)$$

ω_i: solitary frequency

ω_0: reference common frequency.

$\omega_0 = 2\pi\ c/\lambda_0$

κ : cavity loss coefficient

D: spontaneous emission strength

α : linewidth enhancement factor

η $_{ij}$: coupling coefficients between Ld_i and Ld_j

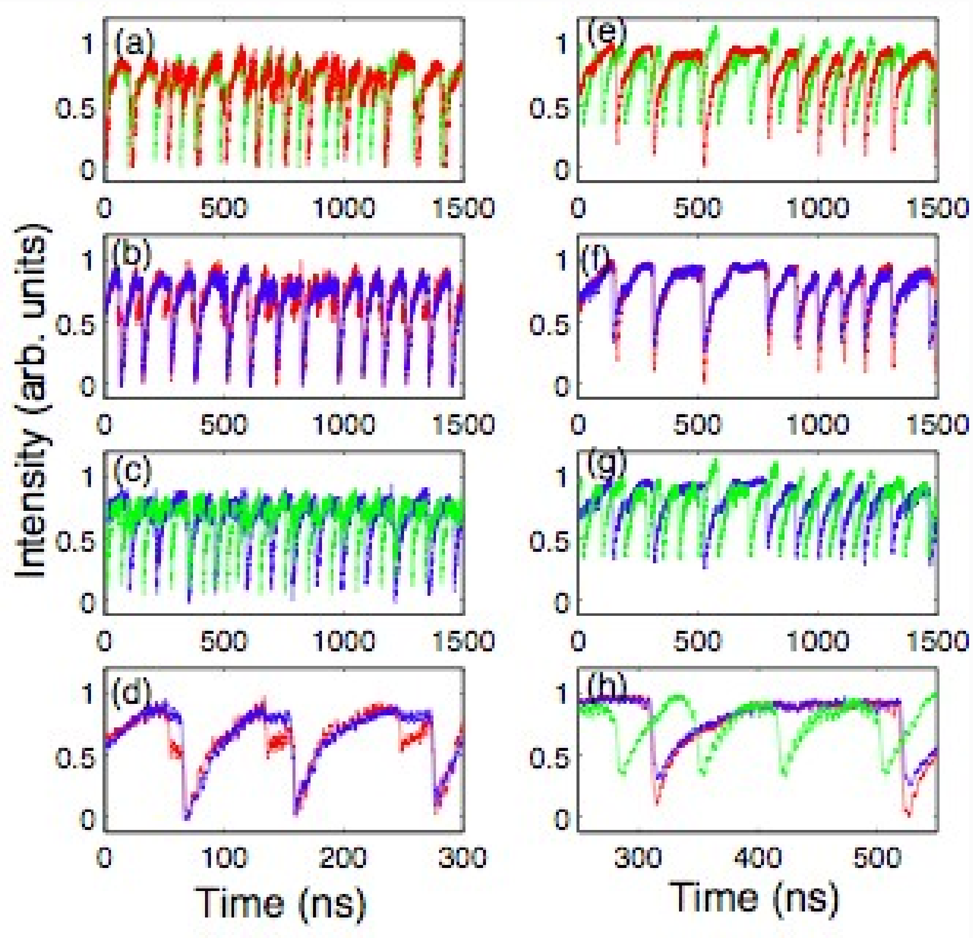
[1] R. Lang, K. Kobayashi, ***J.Quantum Electron*** **16**,346 (1980);
J. Garcia-Ojalvo, J. Casademont, M.C. Torrent, C.R. Mirasso, J.M. Sancho, ***Int. J. Bif. Chaos*** **9**,2225(1999),
G. Kozyreff, A. G. Vladimirov, P. Mandel, ***Phys. Ref. Lett***. **18**, 3809 (2000)

Numerical Results

Cluster formation.

Experiment

Simulations



LD1-LD2

LD1-LD3

LD2-LD3

Cluster

$\eta_{11} >> \eta_{22} > \eta_{33}$

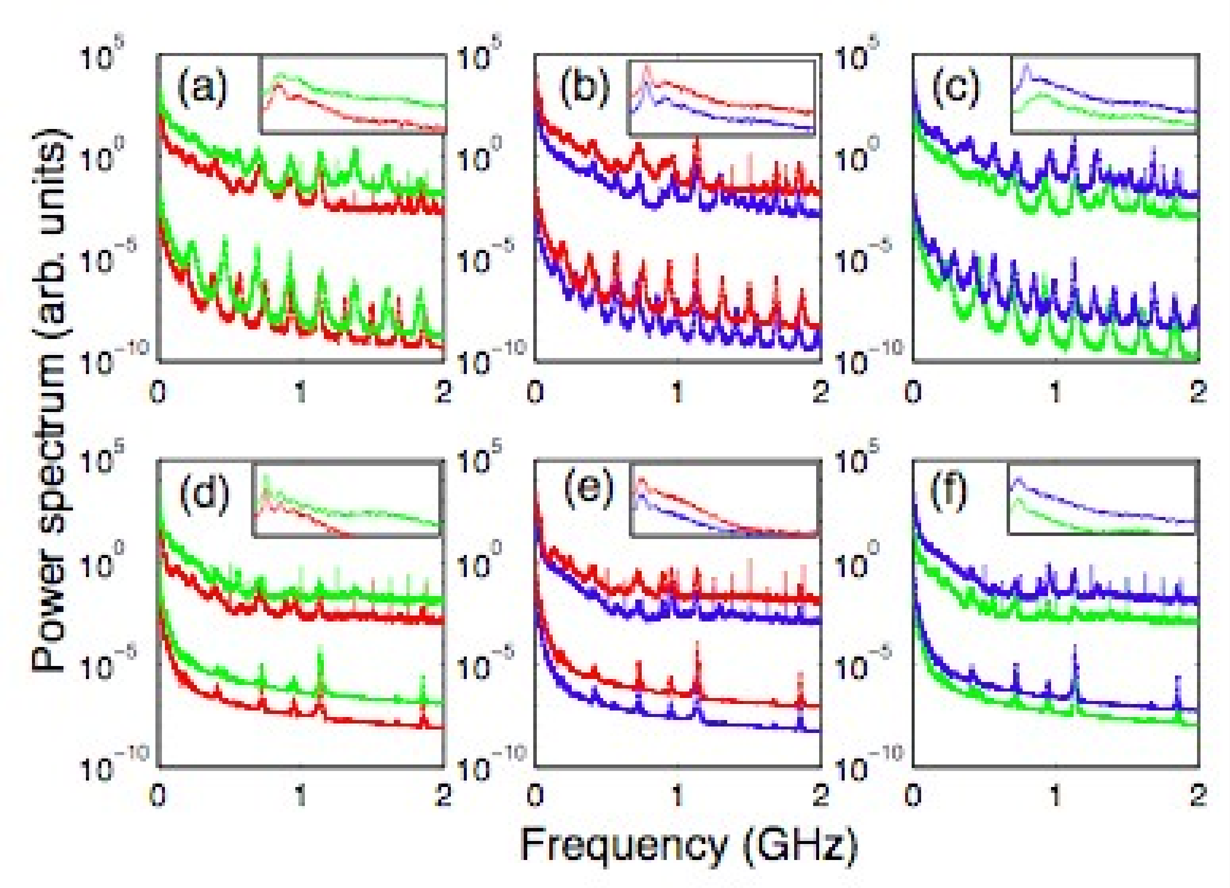
$\eta_{12} >> \eta_{13} > \eta_{23}$

Detuning:

$\omega_2 > \omega_3 > \omega_1$

Numerical Results

RF spectrum



Weak coupling

Cluster

Harmonics
begin to adjust

Strong coupling

Synchronization
Overlapping at low
and high frequencies

Conclusions

- We have studied a small network of delay-coupled semiconductor lasers with distributed coupling strengths and delays.
- Synchronization emerges with increasing coupling.
- On the route to synchronization, lasers cluster in pairs:
  - External optical injection (coupling+ feedback) modifies the lasers' optical frequencies. The frequencies decrease proportionally to the total injected light.
  - The dominant laser (LD1) has the strongest shift.
  - The third laser (LD2) needs an extra detuning (higher coupling strength) to become synchronized with the other two.