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Open vs Closed Loop Receivers in all-Optical Chaos-Based Communication Systems

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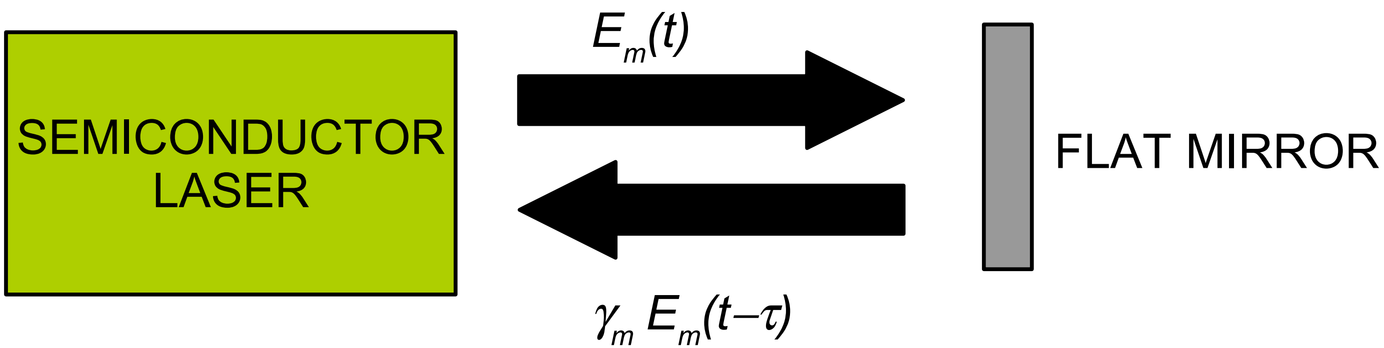
CLEO/Europe-EQEC Conference

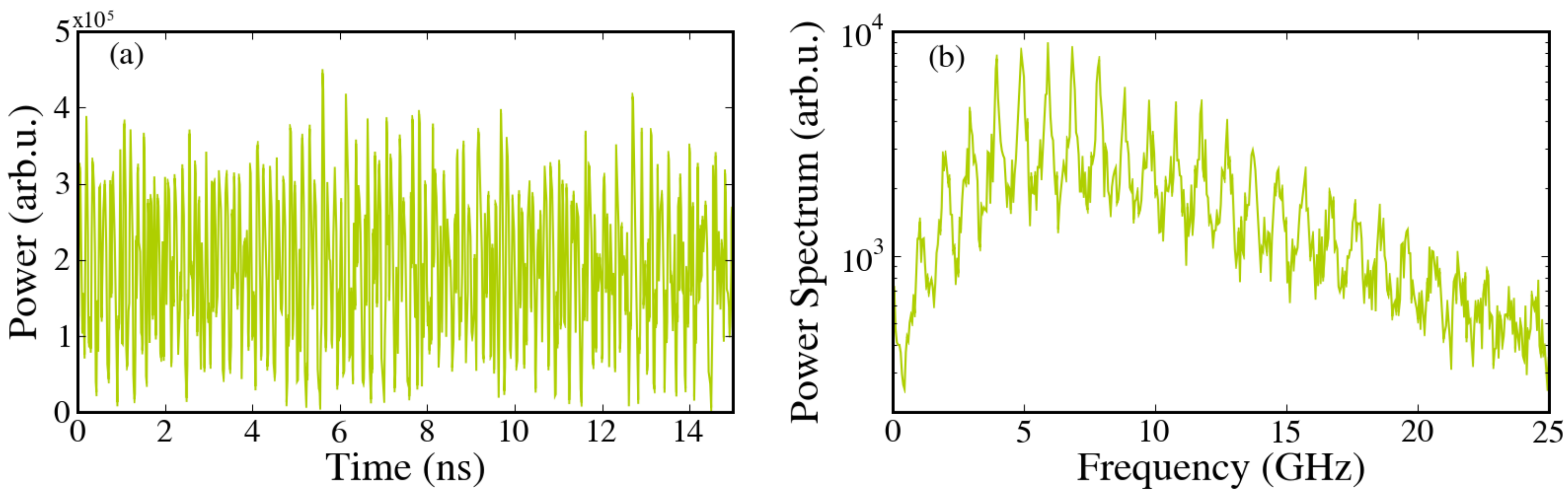
IFISC

CSIC

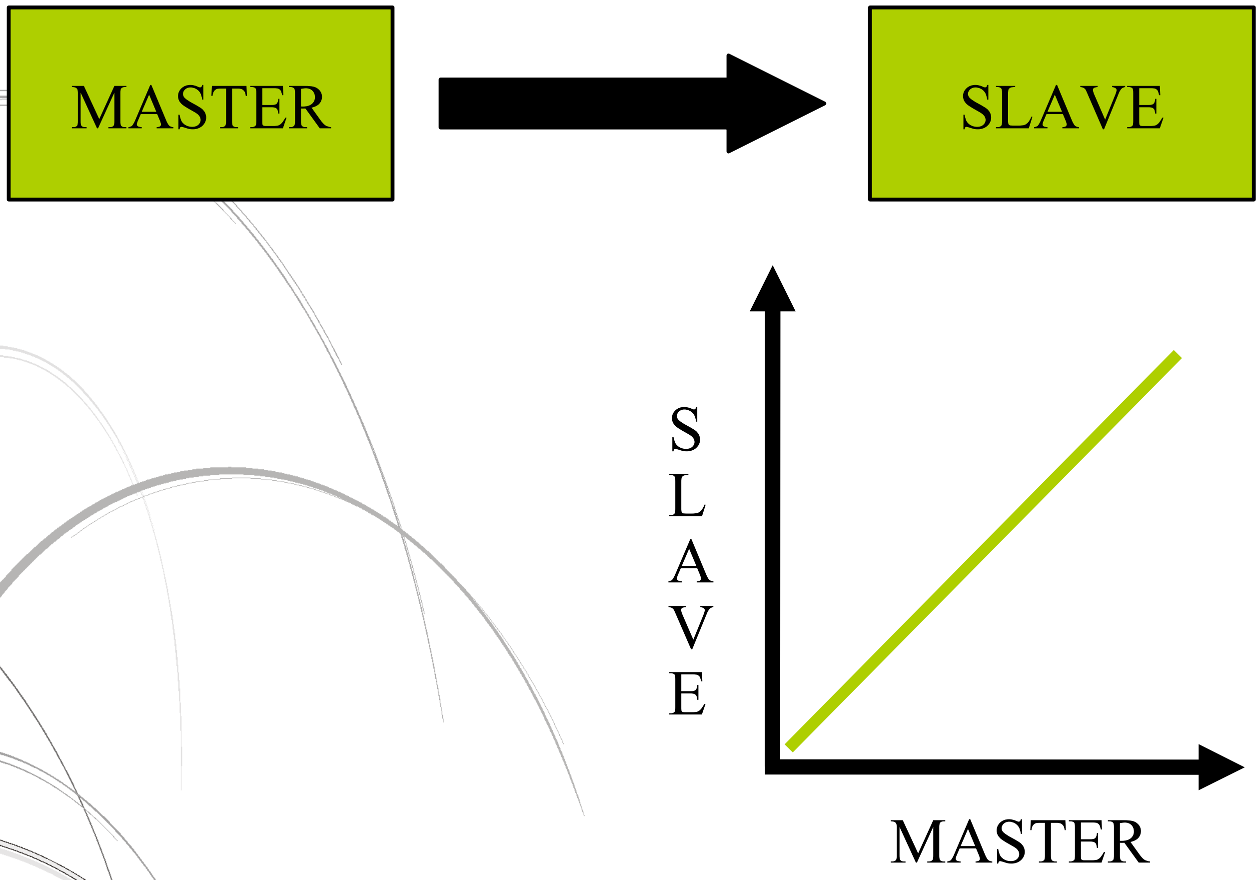
UIB

Conventional Optical Feedback

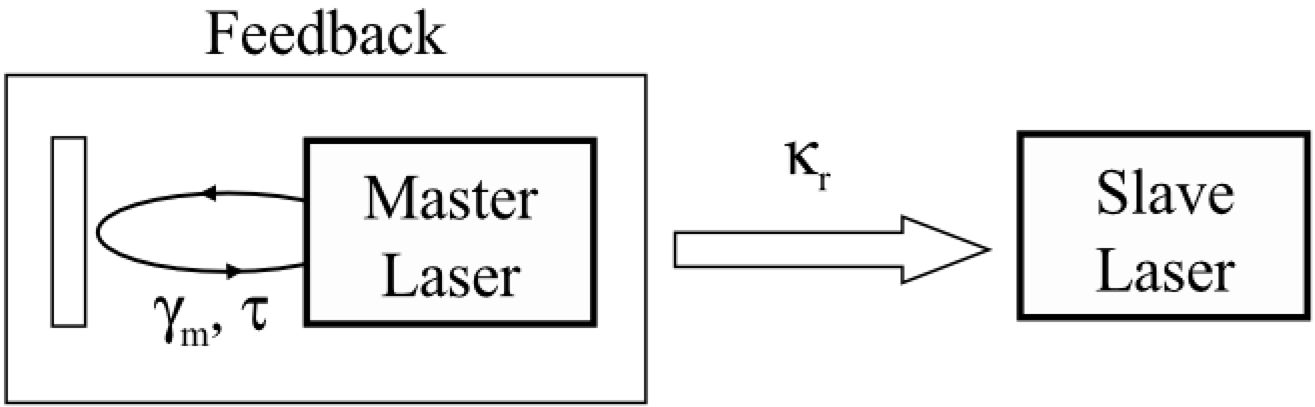




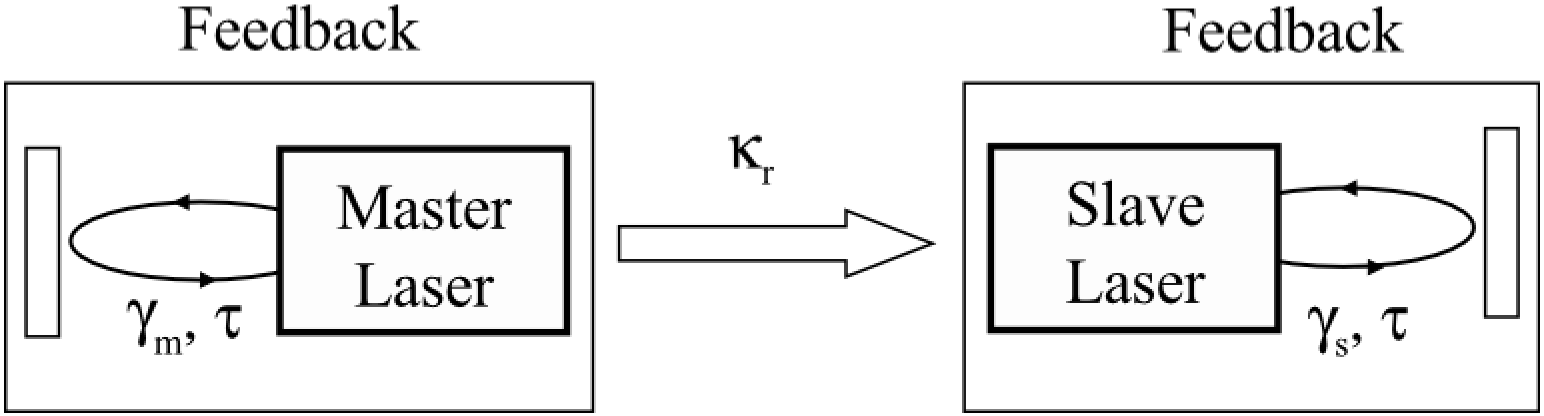
Master-Slave Chaos Synchronization



Open Loop



Closed Loop



- Semiconductor laser, solitary case:
  - Electric field and carriers

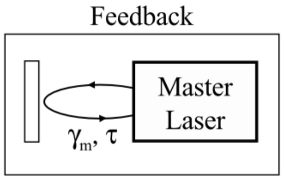
$$\dot{E}(t) = \frac{(1+i\alpha)}{2}\left[G - \frac{1}{\tau_p}\right] \quad (1)$$

$$\dot{N}(t) = \frac{I}{e} - \frac{N}{\tau_N} - G|E|^2 \quad (2)$$

$$G = \frac{g(N-N_o)}{1+s|E|^2}$$

Parameter	Description	Value
α	linewidth enhancement factor	5
τ_p	photon lifetime	2 ps
τ_N	carrier lifetime	2 ns
g	differential gain coefficient	$1.5 \cdot 10^{-8}$ ps^{-1}
N_o	carrier transparency	$1.5 \cdot 10^{8}$
s	gain compression coefficient	$5 \cdot 10^{-7}$
I_{th}	threshold current	14.7 mA

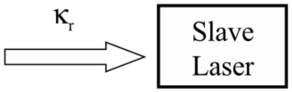
- Master Laser (m)



$$\dot{E}_m(t) = \frac{1+i\alpha}{2}\left[G_m(t) - \frac{1}{\tau_p}\right]E_m(t) + \gamma_m E_m(t-\tau)e^{-i\Phi_m}$$

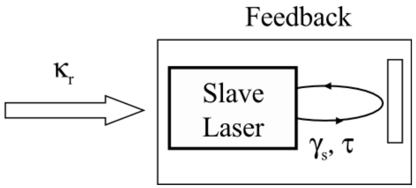
Feedback strength (→ γ_m) Feedback delay (→ τ)

- Slave Laser (s): Open Loop



$$\dot{E}_s(t) = \frac{1+i\alpha}{2}\left[G_s(t) - \frac{1}{\tau_p}\right]E_s(t) + \kappa_r E_m(t)$$

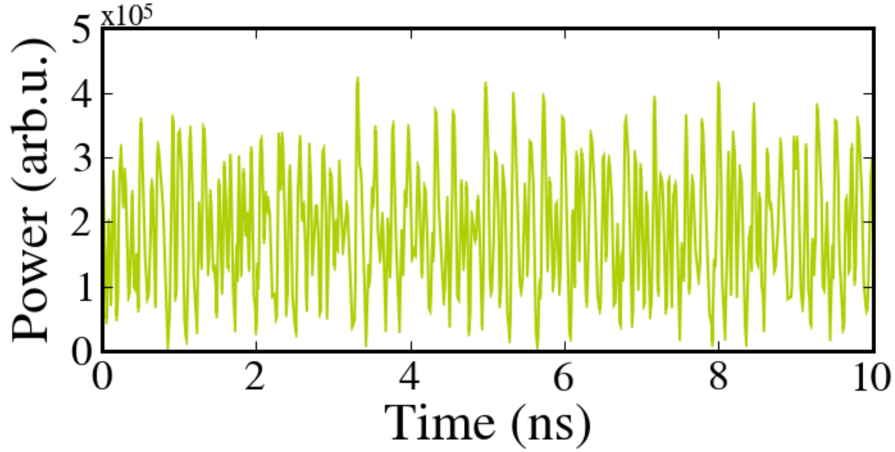
- Slave Laser (s): Closed Loop



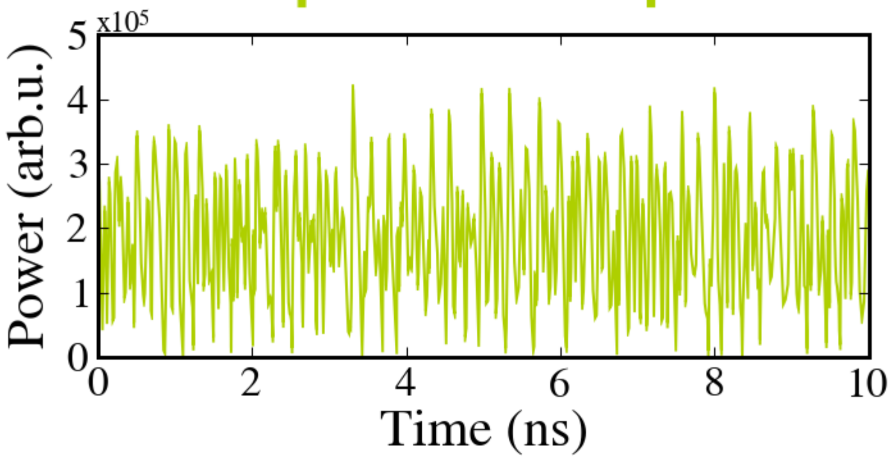
$$\dot{E}_s(t) = \frac{1+i\alpha}{2}\left[G_s(t) - \frac{1}{\tau_p}\right]E_s(t) + \gamma_s E_s(t-\tau)e^{-i\Phi_s} + \kappa_r E_m(t)$$

Synchronization between master laser and slave laser

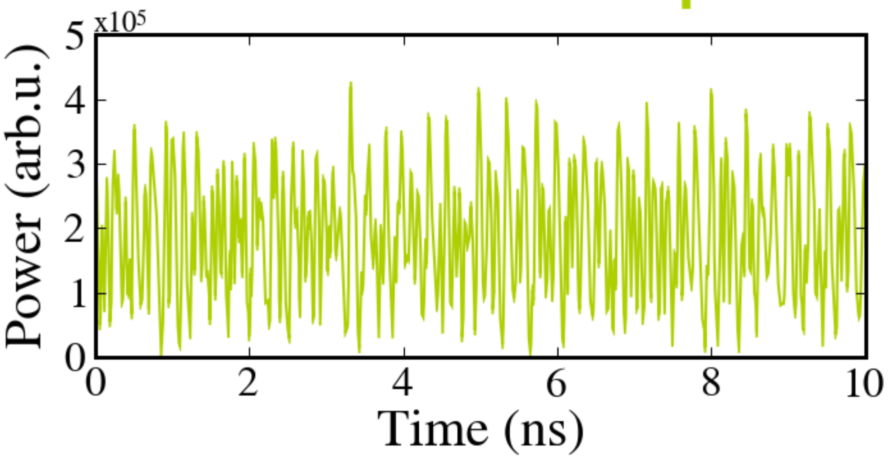
– Time-traces ($P_{m,s}=|E_{m,s}|^2$): chaotic fluctuations at $I=2I_{th}$



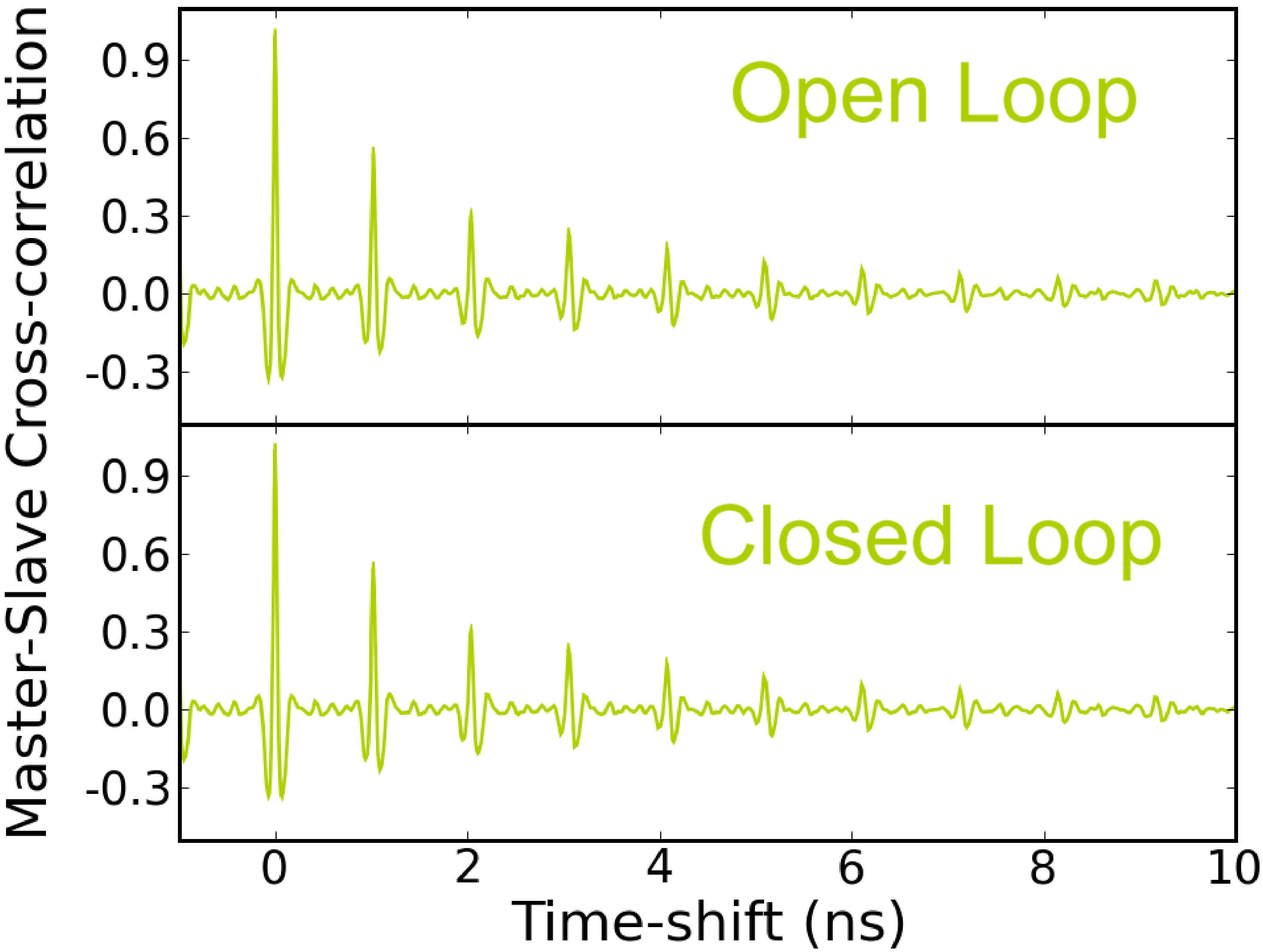
Open Loop



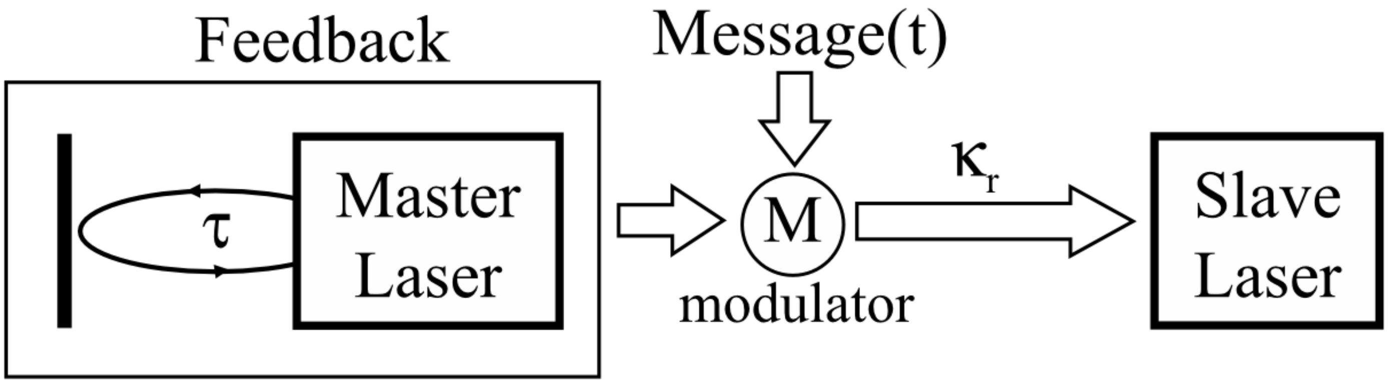
Closed Loop



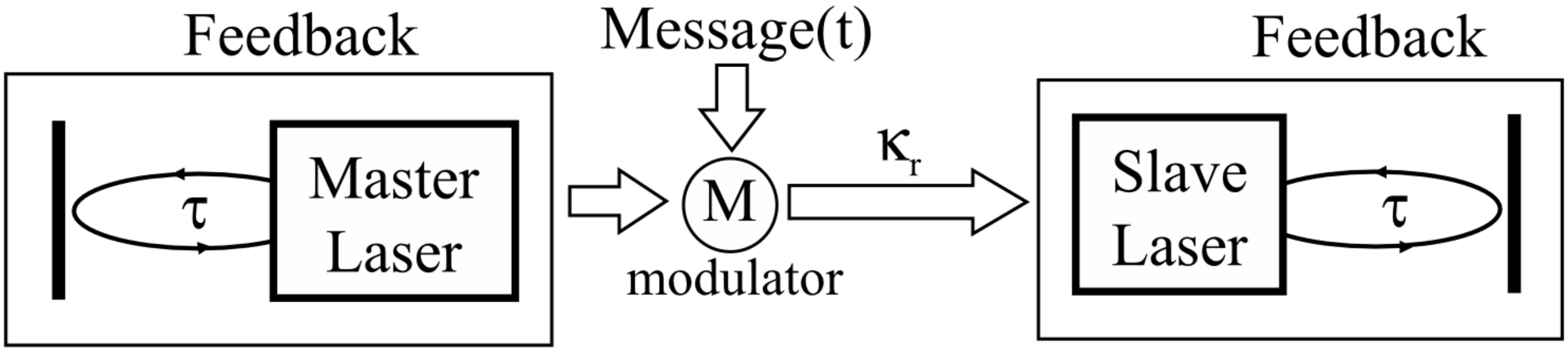
* Coupling Strength Optimum


Open Loop
Closed Loop
Master-Slave Cross-correlation
0.9
0.6
0.3
0.0
-0.3
0.9
0.6
0.3
0.0
-0.3
0
2
4
6
8
10
Time-shift (ns)

Open Loop

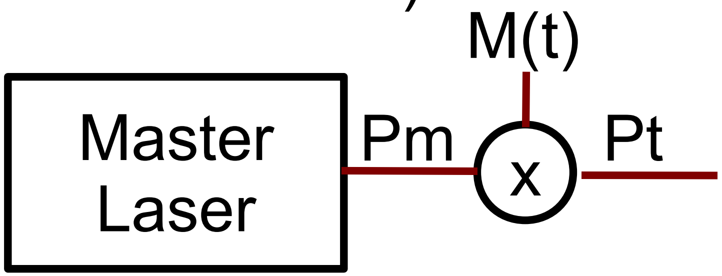


Closed Loop



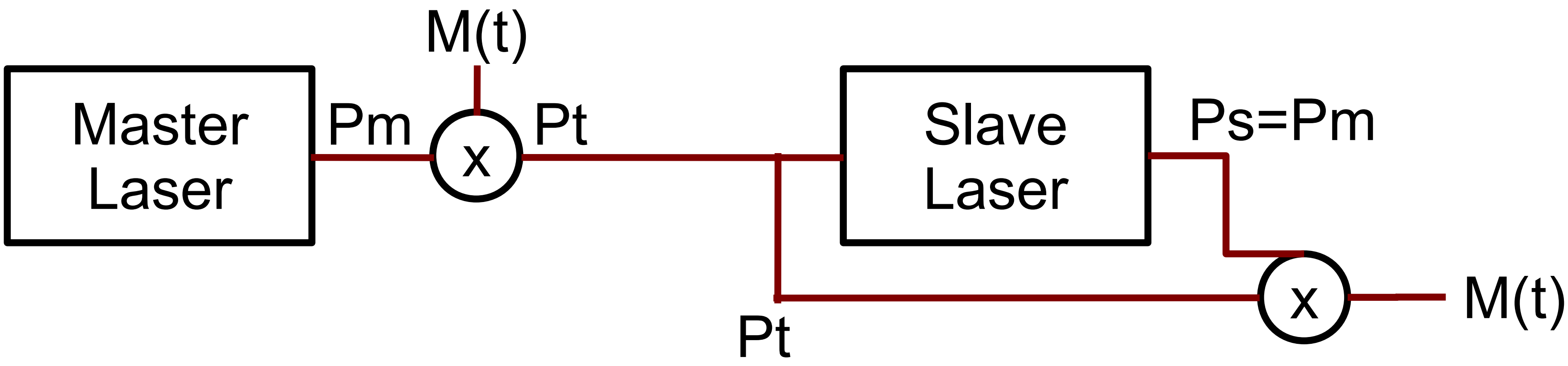
Encryption Method: Chaos Modulation

- Small perturbation of the power (chaotic carrier)
- Pt=Pm(1-εM(t))
  - M(t)=[0 0 1 0 1.......1 1]
  - ε=0.05



Message Extraction: Chaos Filtering

- Chaos synchronization on the slave laser acts as a chaos filter



Quantifying chaos filtering

- Synchronization Master Laser <-> Slave Laser

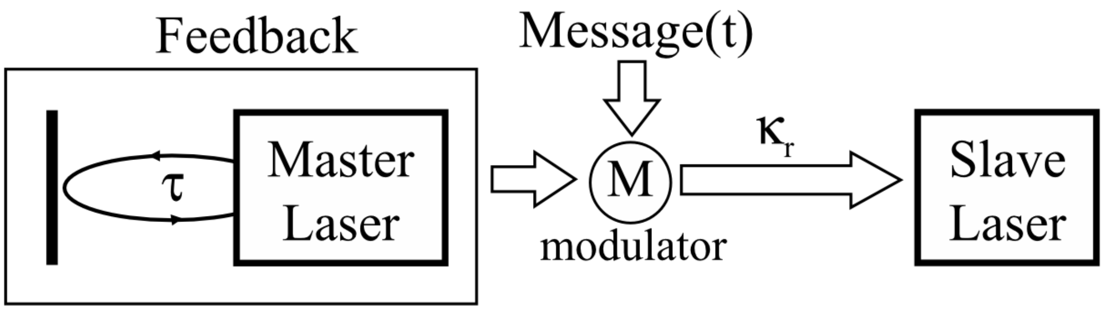
  Mutual Information *(J)*: non-linear measure of similarities between two quantities

$$J_{xy} = \sum_{i,j} p_{ij} \log_2 \frac{p_{ij}}{p_i p_j}$$

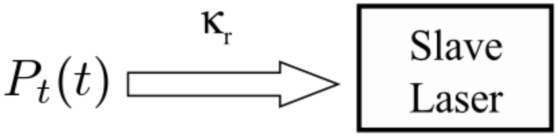
where p_{ij} is the joint probability of $x = x_i$ and $y = y_j$, p_i (p_j) is the probability of $x = x_i$ ($y = y_j$). For two independent signals $p_{ij} = p_i p_j$, and J_{xy} is zero. Otherwise, J_{xy} will be positive.

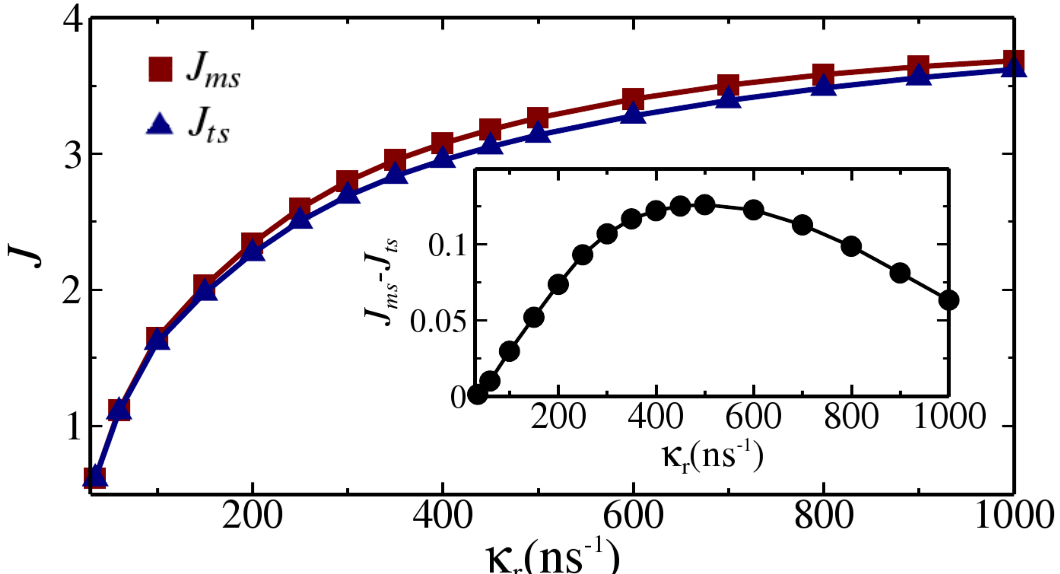
- More appropiate than the cross-correlation to resolve small differences

Open Loop



$$P_t(t) = \left(1 - \epsilon\, m(t)\right) P_m(t)$$

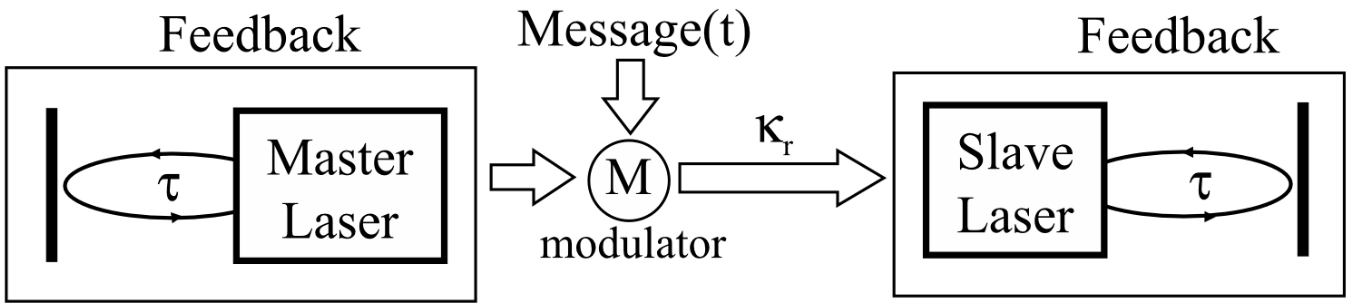




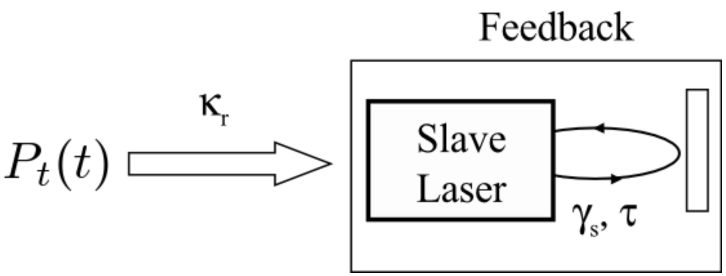
In the synchronization regime $J_{ms} > J_{ts}$

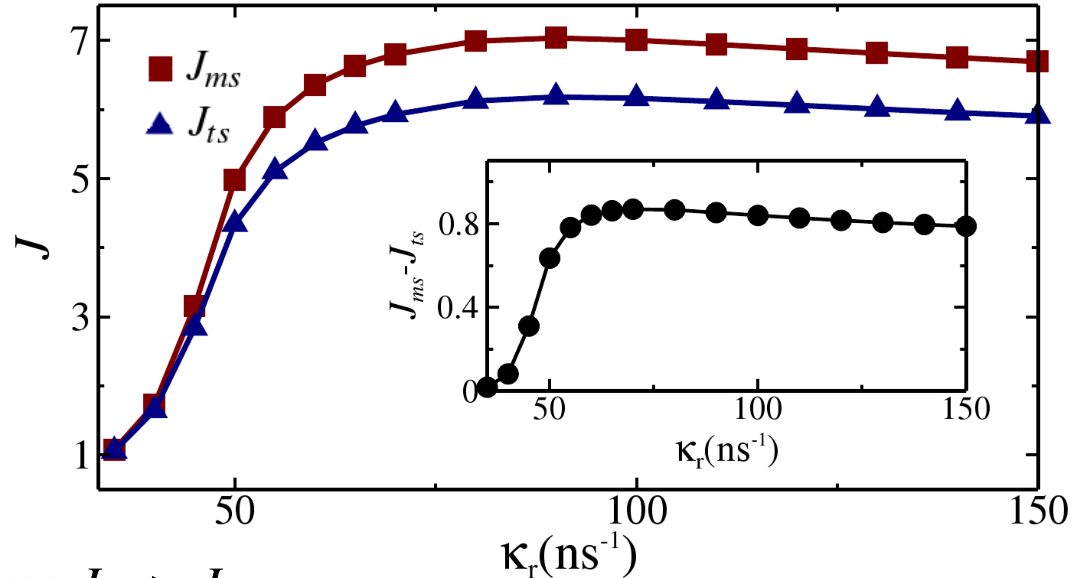
In the injection locking regime $J_{ts} > J_{ms}$

Closed Loop



$$P_t(t) = \left(1 - \epsilon\, m(t)\right) P_m(t)$$





In the synchronization regime $J_{ms} > J_{ts}$

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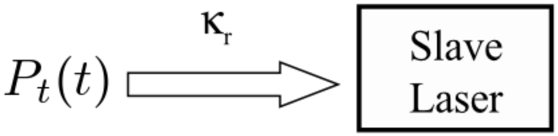
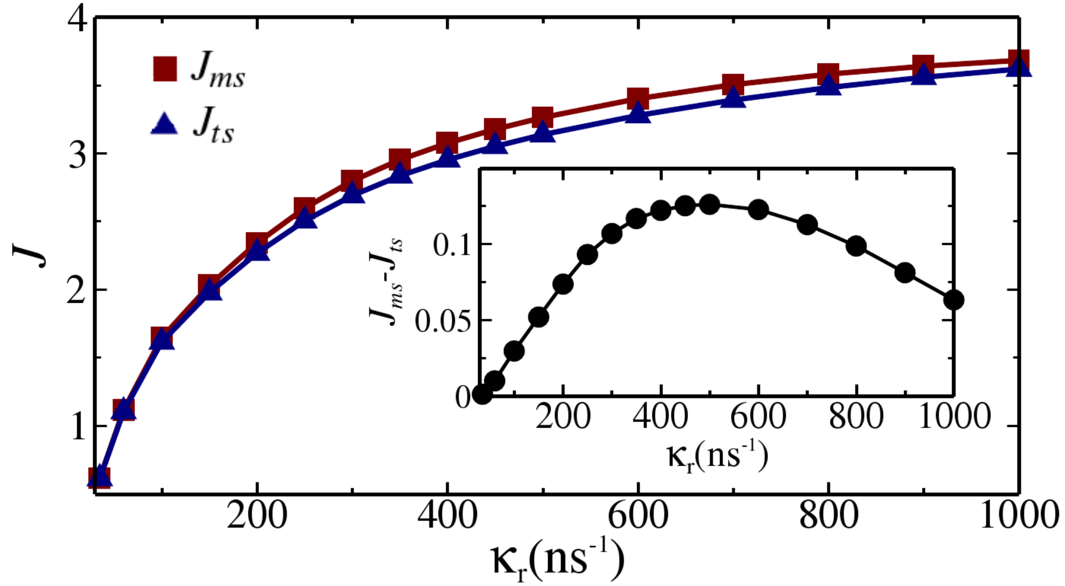
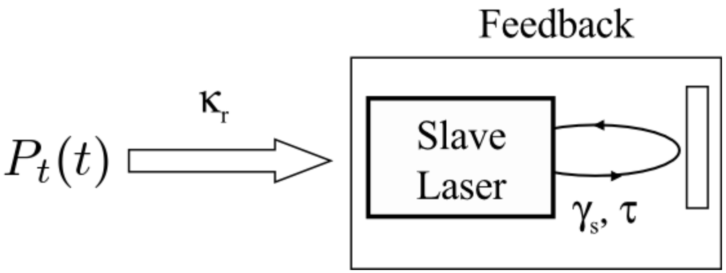
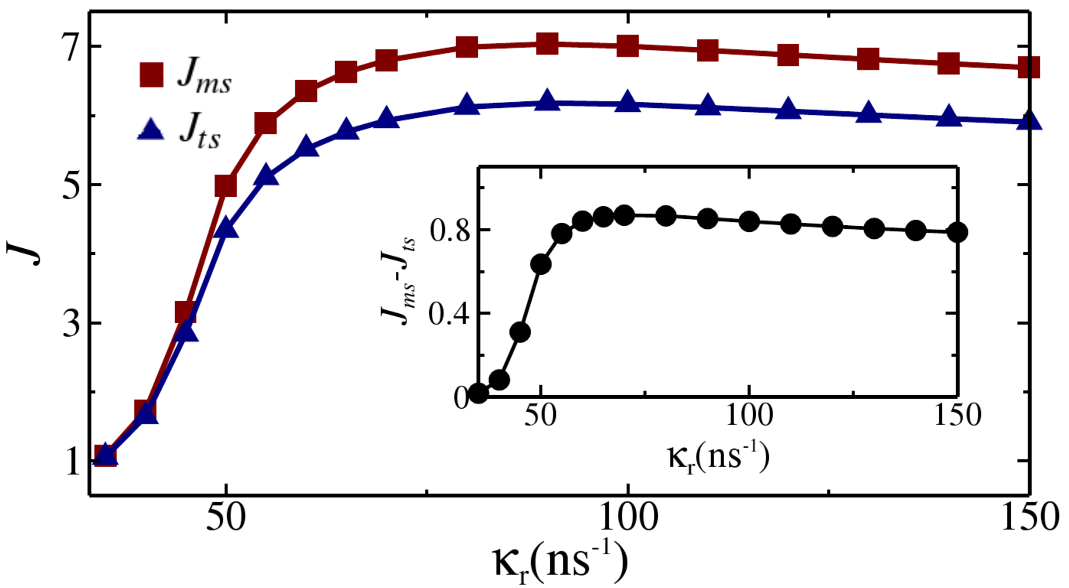


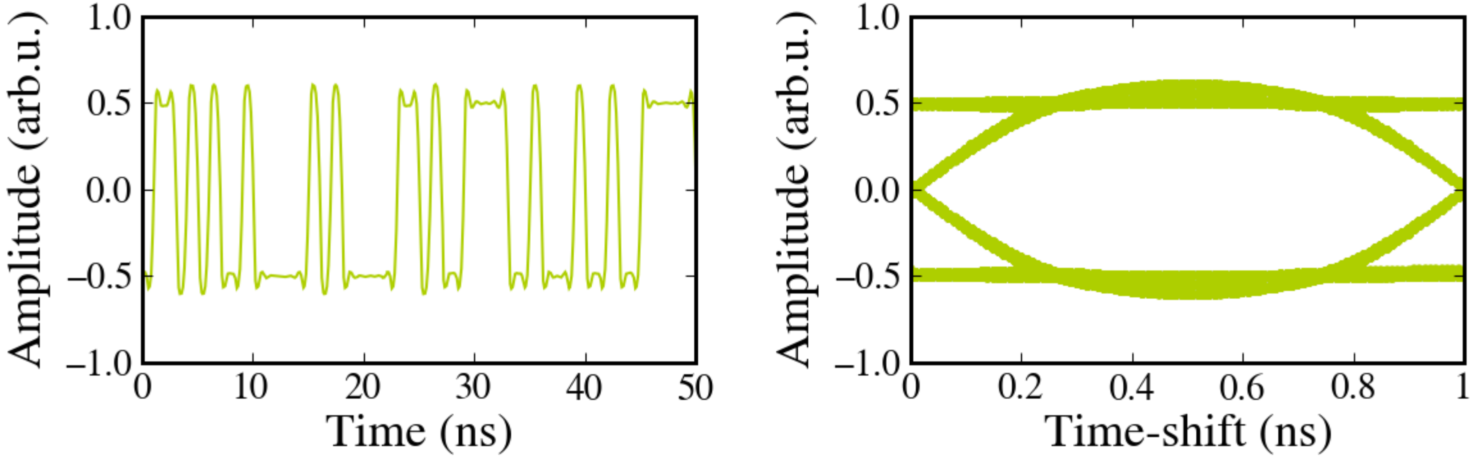


$$P_t(t) = \big(1 - \epsilon\, m(t)\big)\, P_m(t)$$





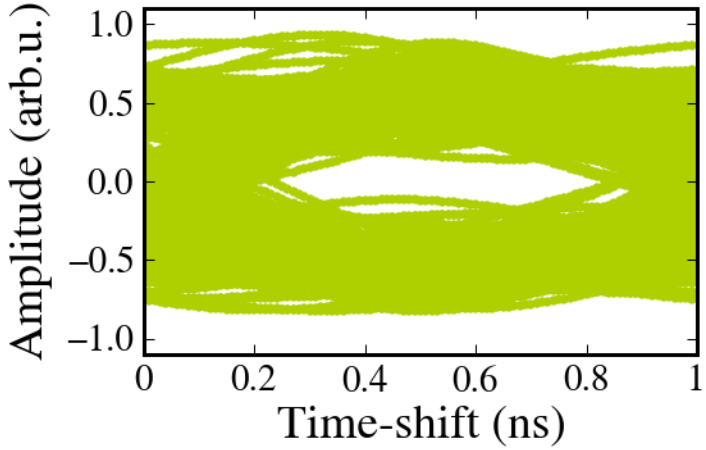
- Message decoding



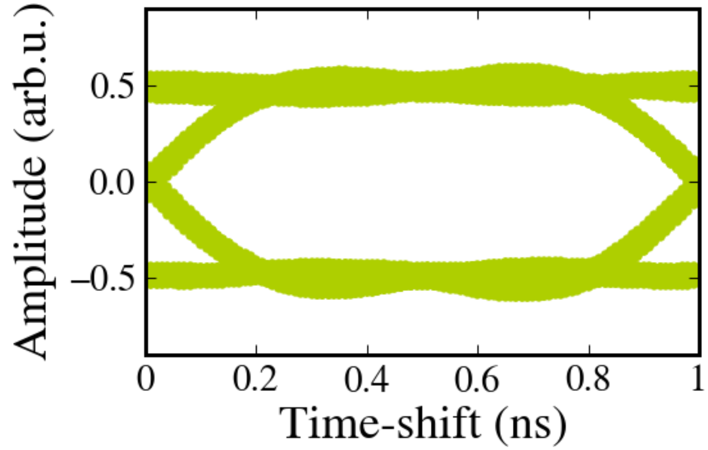
$$Q = \frac{<S_1> - <S_0>}{\sigma_1 + \sigma_0}$$

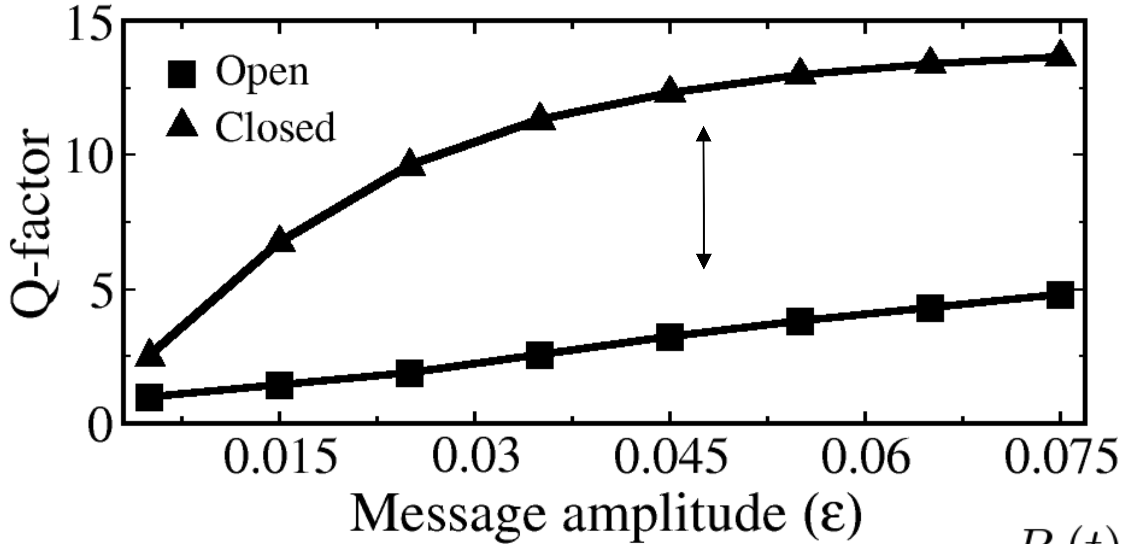
where $< S_1 >$ and $< S_0 >$ are the average optical power of bits "1" and "0", and σ_1 and σ_0 are the corresponding standard deviations.

Open Loop



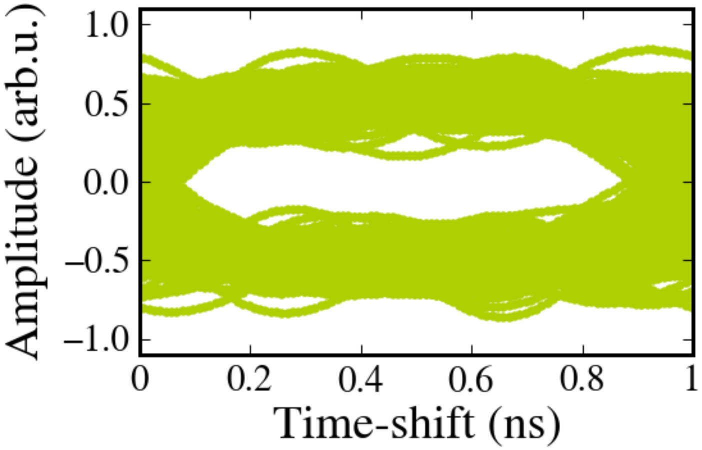
Closed Loop



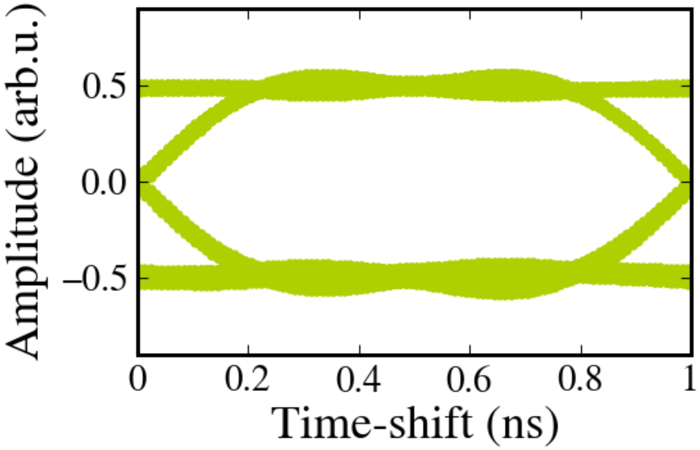


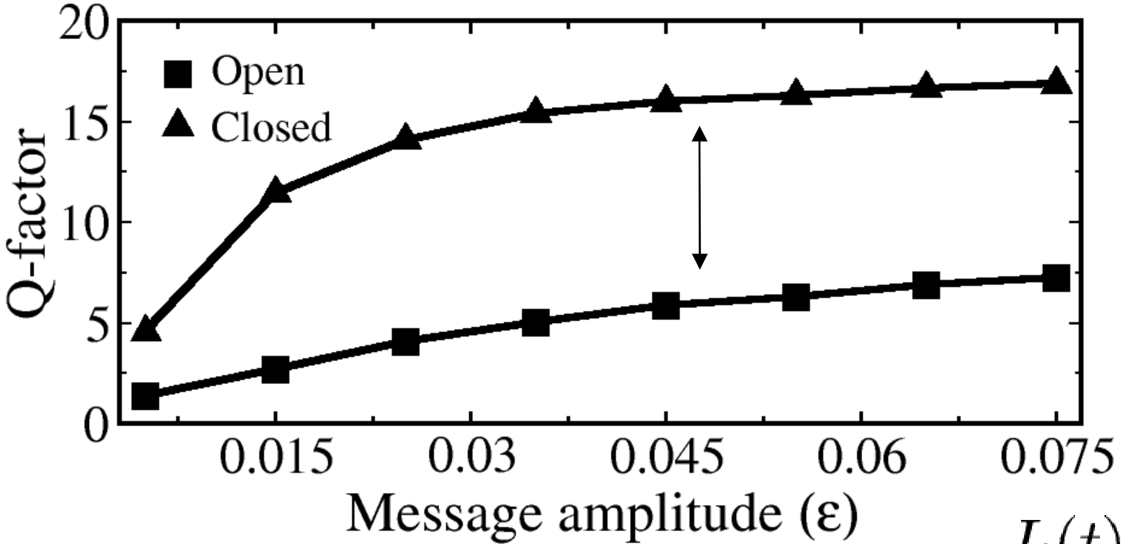
$$P_t(t) = \big(1 - \epsilon\, m(t)\big)\, P_m(t)$$

Open Loop



Closed Loop





$$I_t(t) = (1 + \epsilon m(t))I$$

- Security in the communications connected to the synchronization between emitter and receiver
- Important differences between chaos synchronization and injection locking
- Better chaos-filtering properties of the closed loop receiver
- Higher quality on the extraction of encrypted messages with the closed loop receiver