Semiconductor laser dynamics with two filtered optical feedbacks

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Outline

1. Introduction and motivation for using two filtered optical feedbacks
2. Experimental setup
3. Modeling the dynamics
4. Experimental and numerical results on the frequency of the dynamics
5. Summary
Introduction and Motivation

- Semiconductor lasers have very high material gain → Very sensitive to the external perturbation (optical feedback or optical injection) → Instabilities in the laser dynamics.

- **Different control mechanisms**
  - **Optical delayed feedback**

- Complex nonlinear dynamics:
  - Oscillations death state
  - Periodic behavior
  - Quasiperiodic behavior
  - Chaos

- Control parameters: Feedback strength ($\kappa$), Time-delay ($\tau$) in coupling.

Single filtered optical feedback (FOF)

- A loop between the filter and laser → Produces controlled oscillations in the frequency of the laser light.
- Complex nonlinear dynamics
  - Relaxation oscillations (ROs)
  - Frequency oscillations (FOs) ($\sim$ constant laser intensity)
  - Quasi-periodic behavior
  - Chaos...

Applications: Optical telecommunications, all-optical signal processing, enhancing message security in chaos encryption systems and design of all optical digital gates.

How does the inclusion of the second FOF affect and control the semiconductor laser dynamics?
Schematic of the experimental setup

DL: diode laser; BS: beam splitter; OI: optical isolator; M: mirror; G: glass plate; HWP1, HWP2: half-wave plates; PBS: polarization beam splitter; PDA, PDB, PDC: photodiodes.
A semiconductor laser with two filtered optical feedbacks

\[
\dot{E} = (1 + i\alpha)N(t)E(t) + \kappa_1 F_1(t, \tau_1) + \kappa_2 F_2(t, \tau_2),
\]

\[
T \dot{N} = J_0 - N(t) - (1 + 2N(t)) |E(t)|^2,
\]

\[
\dot{F}_1 = \Lambda_1 E(t - \tau_1) e^{-i\omega_0 \tau_1} + (i\Delta_1 - \Lambda_1) F_1(t),
\]

\[
\dot{F}_2 = \eta \Lambda_2 E(t - \tau_2) e^{-i\omega_0 \tau_2} + (i\Delta_2 - \Lambda_2) F_2(t).
\]

\[
E(t) = \sqrt{I_L(t)} e^{i\phi_L(t)}, \quad F_{1,2}(t) = \sqrt{I_{F_{1,2}}(t)} e^{i\phi_{F_{1,2}}(t)}
\]

\(\tau \rightarrow \) infinite dimensional \(\rightarrow\) analytical study not possible

\(\kappa_1, \kappa_2\): feedback rates \(\Lambda_1, \Lambda_2\): bandwidth (HWHM) of filters

\(\Delta_1, \Delta_2\): detunings between the laser and two filters

\(\tau_1, \tau_2\): time taken by the light to propagate in the two feedback loops

\(\eta\): asymmetry parameter

What are the compound-cavity modes (continuous wave solutions), the so-called external filtered modes (EFMs) of the systems?

Results: Controlled frequency oscillations

- The regime of maximum interest:

\[ \delta \nu_{\text{ECM}} (\sim 75-200 \text{ MHz}) < \Lambda < \nu_{\text{RO}} (4 \text{ GHz}) \]

- FOs using optical feedback from individual cavities

- First cavity

Experimentally measured    Numerically simulated

- Simulation parameters: \( \kappa_1 = 0.015, \tau_1 = 861, \Lambda_1 = 0.012, \Delta_1 = -0.007 \)

- In simulation time \( t \) is scaled by the laser cavity photon life-time (=10 ps for a typical semiconductor laser)
Second cavity

Experimentally measured Numerically simulated

Good match between Experiment and Simulation : − )

Simulation parameters: $\kappa_2 = 0.015$, $\tau_2 = 739$, $\Lambda_2 = 0.012$, $\Delta_2 = -0.007$

Frequency of FOs: $f_{ext2} \sim \frac{1}{\tau_2}$

Filters add a substantial frequency shift of $\sim \frac{1}{\Lambda_{1,2}}$ to the period of FOs.
Dependence of frequency oscillations on relative feedback from the two cavities

**Experimental results** ($f_{\text{ext1}} = 105.6 \text{ MHz}$ and $f_{\text{ext2}} = 121.8 \text{ MHz}$)

**Numerical results** ($\tau_1 = 861$ and $\tau_2 = 739$)

(a) $\kappa_1 = \kappa_2 = 0.0085$  (b) $\kappa_1 = 0.009$, $\kappa_2 = 0.008$  (c) $\kappa_1 = 0.0048$, $\kappa_2 = 0.0122$
The frequency of FOs

\[ f_{\text{ext}} \approx \frac{f_{\text{ext1}} + f_{\text{ext2}}}{2} = 113.8 \text{ MHz} \]

Condition for observing the average between the fundamental frequency of cavity 1 and cavity 2

\[ |f_{\text{ext1}} - f_{\text{ext2}}| < |2f_{\text{ext1}} - f_{\text{ext2}}| < |f_{\text{ext1}} - 2f_{\text{ext2}}| \]

Laser selects the two frequencies whose difference is the smallest and averages between these two frequencies.

The average frequency shifts towards the fundamental frequency of cavity 1 when \( \kappa_1 > \kappa_2 \).

The average frequency shifts towards the fundamental frequency of cavity 2 when \( \kappa_2 > \kappa_1 \).
Average between the fundamental frequency of cavity 2 and second harmonic of cavity 1

Fundamental cavity frequencies: $f_{\text{ext}1} = 75$ MHz and $f_{\text{ext}2} = 131$ MHz

Condition:

\[|2f_{\text{ext}1} - f_{\text{ext}2}| < |f_{\text{ext}1} - f_{\text{ext}2}| < |f_{\text{ext}1} - 2f_{\text{ext}2}|\]

Frequency of FOs

\[f_{\text{ext}} \approx \frac{2f_{\text{ext}1} + f_{\text{ext}2}}{2} = 140.5\text{ MHz}\]
Continued...

- Average between the fundamental frequency of cavity 2 and third harmonic of cavity 1

- Fundamental cavity frequencies: $f_{ext1} = 70.2$ MHz and $f_{ext2} = 189.3$ MHz

- Condition:

$$|3f_{ext1} - f_{ext2}| < |2f_{ext1} - f_{ext2}| < |f_{ext1} - 2f_{ext2}|$$

- Frequency of FOs

$$f_{ext} \approx \frac{3f_{ext1} + f_{ext2}}{2} = 200$$ MHz
FOs in single FOF ($\tau_1 = 1248, \kappa_1 = 0.01, \Lambda_1 = 0.012$ and $\Delta_1 = -0.013$)

- **Fundamental frequency and second harmonic both are present.**

Second FOF is switched on ($\tau_1 = 1248, \tau_2 = 739, \kappa_1 = 0.01, \kappa_2 = 0.0004, \Lambda_1 = \Lambda_2 = 0.012$ and $\Delta_1 = \Delta_2 = -0.013$)

- **The amplitude of fundamental frequency is suppressed while the amplitude of second harmonic becomes larger than that of fundamental frequency.**
Period doubling behavior

- Fundamental cavity frequencies: $f_{\text{ext1}} = 104$ MHz and $f_{\text{ext2}} = 119$ MHz
- Simulation parameters: $\tau_1 = 862$, $\tau_2 = 740$, $\kappa_1 = 0.016$, $\kappa_2 = 0.008$, $\Lambda_1 = \Lambda_2 = 0.01$ and $\Delta_1 = \Delta_2 = -0.007$
- In addition to the oscillations at fundamental frequency a period doubled solution is also found.
Average between period doubled frequency and fundamental frequency

Fundamental cavity frequencies: $f_{\text{ext1}} = 180$ MHz and $f_{\text{ext2}} = 122.4$

Condition:

$$|\frac{1}{2}f_{\text{ext1}} - f_{\text{ext2}}| < |f_{\text{ext1}} - f_{\text{ext2}}| < |2f_{\text{ext1}} - f_{\text{ext2}}|$$

Frequency of FOs

$$f_{\text{ext}} \approx \frac{f_{\text{ext1}}/2 + f_{\text{ext2}}}{2} = 110$$ MHz
Bifurcation analysis: Spectral bifurcation diagram

- A period doubling route to chaos

With time delays \( \tau_1 = 1333, \tau_2 = 793 \), feedback rate \( \kappa_2 = 0.003 \), filter bandwidths \( \Lambda_1 = \Lambda_2 = 0.005 \), detunings \( \Delta_1 = \Delta_2 = -0.007 \), and asymmetry parameter \( \eta = 1 \), the spectral bifurcation diagram of the two-FOF laser as the feedback rate \( \kappa_1 \) is varied: (a) the three dimensional view, and (b) the density map of the combined laser intensity spectra.

*D. Orrell et al., Int. J. Bifurcation and Chaos 13, 3015 (2003)*
Multistability analysis

- Basin of attractors

(a) Basin of attractors in the plane of laser intensity and feedback field intensity initial values. (b) Phase space plot of attractors in the plane of laser and feedback field intensity.

- Simulation parameters: \( \tau_1 = 1082, \tau_2 = 844, \kappa_1 = \kappa_2 = 0.007, \Lambda_1 = \Lambda_2 = 0.012, \Delta_1 = \Delta_2 = -0.007, \) and \( \eta = 1. \)

- Basins of different attractors showing multistability in the system.
In two FOF laser, the introduction of second FOF plays a role in controlling the frequency oscillations of laser light.

The period of oscillations of the frequency of the laser light is determined by the time delays of the two feedback loops, and the frequency corresponding to this period represents the weighted average of cavity 1 and cavity 2.

The average frequency is dependent on the relative feedback from the two cavities and corresponds to the weight between them.

In general, the laser selects the two frequencies whose difference is the smallest and averages between these two frequencies.
The amplitudes of fundamental and second harmonic of single FOF are modified due to the addition of a second FOF, and in particular, by varying the strength of the second feedback, the amplitude of the fundamental frequency is suppressed while the amplitude of the second harmonic becomes larger than that of the fundamental frequency. The ratio of the amplitudes of the second harmonic and the fundamental frequency increases as the feedback ratio $\kappa_2 : \kappa_1$ increases.

- A period doubling route to chaos is found in the two-FOF laser.
- Two-FOF laser exhibits multistability.
- Good agreement between the experiment and simulation is found.

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