Passive Mode-Locking of clockwise and counter-clockwise emission directions in a semiconductor ring laser

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Agenda

1) Background on semiconductor ring laser:
    a) Semiconductor micro-ring
    b) Operating regimes observed
    c) Advantage and drawback of these systems

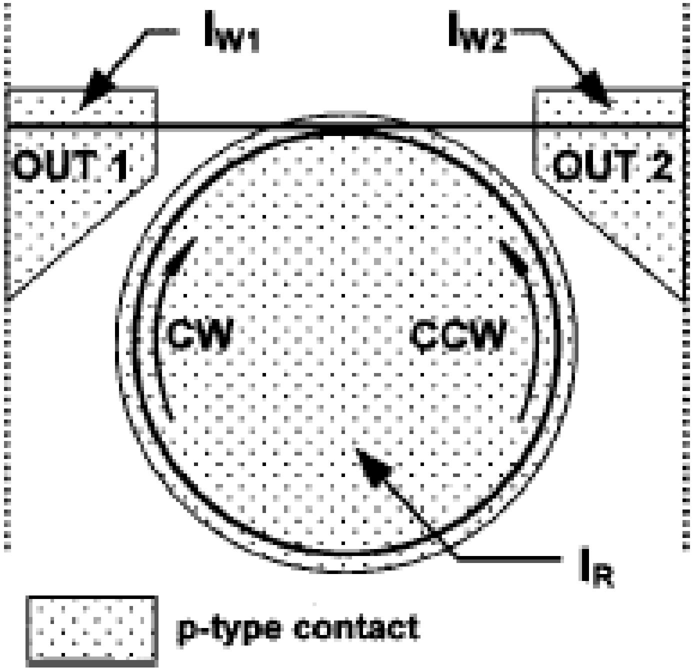
2) Our Experimental System:
    a) Motivation
    b) Configuration

3) Some results
    a) Regime observed - bistability
    b) Operation in class A regime
    c) Mode locked operation

4) Conclusion and Future Direction

Semiconductor Ring Laser

- Semiconductor ring lasers are attractive devices because they can be fabricated without the need for cleaved faced mirror[1] so monolithic integration is easily achievable.



- The circular geometry of the cavity allows a SRL to operate in two possible directions CW mode and CCW mode
- Laser cavity normally consists of a ring-shaped wave-guide
- Layout comprises 1-mm-radius ring cavities evanescent coupled to a straight output wave-guide
- They are single-transverse, single-longitudinal mode

<u>Promising sources in photonics integrated circuits</u>

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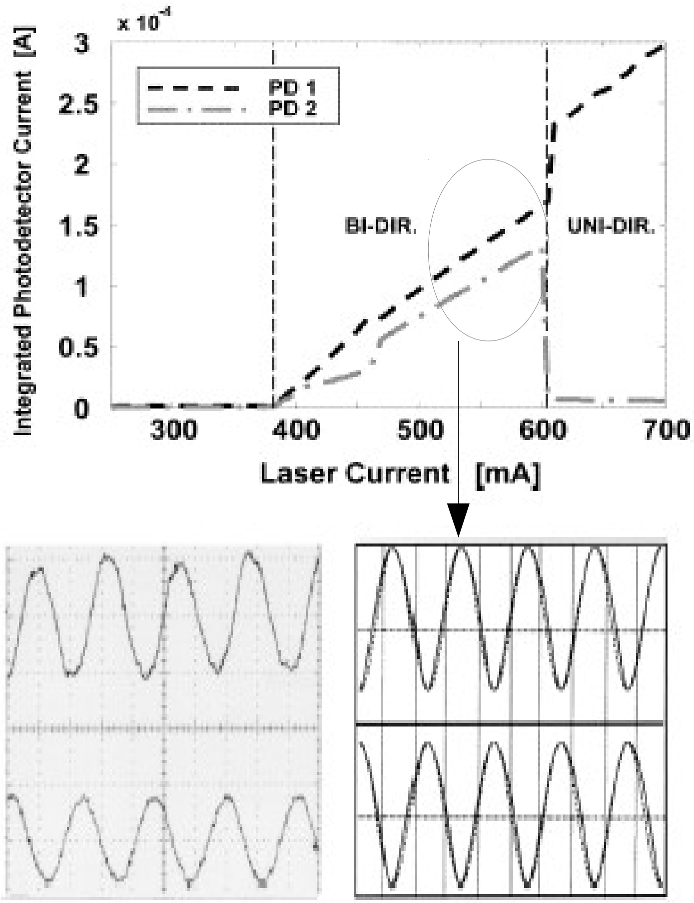
[1]M. Sorel *et al*., "Operating Regimes of GaAs/AlGaAs Semiconductor Ring Lasers: Experiment And Model", IEEE J. Quantum Electr., Vol. **39** No. 10, Oct 2003

Operating Regimes



(a) (b)

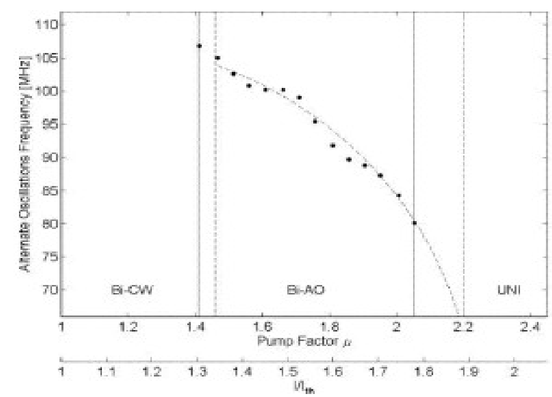
- Three main regimes[1]:

  1) Bidirectional continuous wave where the two modes operate in continuous wave (standing wave)

  2) Bidirectional with alternate oscillations where the intensity of the two modes are modulated by harmonic sinusoidal oscillations

  3) Unidirectional: one of the two mode is suppressed

  - The alternate oscillations are anti correlated between CW and CCW.
  - Frequency of these oscillations is 100 MHz and reduces increasing the pump of the laser.



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[1]M. Sorel *et al*., "Operating Regimes of GaAs/AlGaAs Semiconductor Ring Lasers: Experiment And Model", IEEE J. Quantum Electr., Vol. **39** No. 10, Oct 2003

Explanation of the observed behaviour

- The dynamics observed in these ring lasers are interpreted as follows:

1) Because of the strong cross gain saturation the semiconductor medium tends to select unidirectional operation, however because of the backscattering the pure unidirectional state is not a solution and bidirectional regimes are favoured .

2) The tendency of unidirectional behaviour is then recovered at higher pump level at which non-linear gain imposes a stronger mode selection.

Advantages of these system : Very small, Fast devices, Good candidates for photonics circuits integrations.

Drawback of these system: Due to their compactness, they are not practical for transverse plane studies, Multi-Mode Dynamics.

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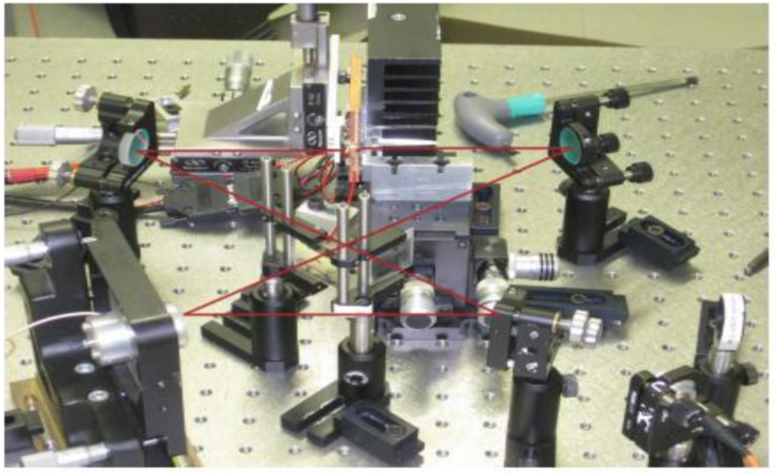
Motivation of our experimental system

- So far has been studied single mode micro-ring system leading to dynamic quite interesting

- What will be the behaviour in Multi-mode system (high Fresnel number – Large cavity) ?

- Our experimental system consist in analyse fast Multi-mode dynamics in Macro-ring laser

<u>Will it be equal to micro-ring ?</u>



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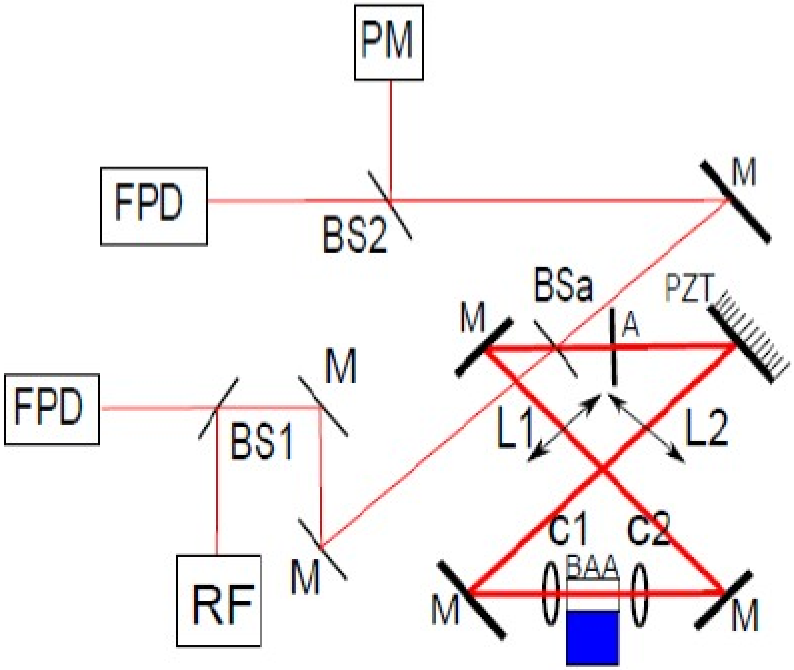
Experimental System



- Broad stripe amplifier Ga-As centred at 980 nm mounted on a C-mount
- Reflectivity at front and rear facet very low 3*10^-4
- Due to high divergence in slow axis cylindrical lenses are used
- The diode has a length of L = 4 mm and stripe width ω = 200 μm, highly Multi mode
- A diaphragm (A) is inserted with minimum aperture 1 mm
- A beam sampler select CW and CCW waves

- Many parameter are accessible in the system also including additional active and passive elements inside the cavity.

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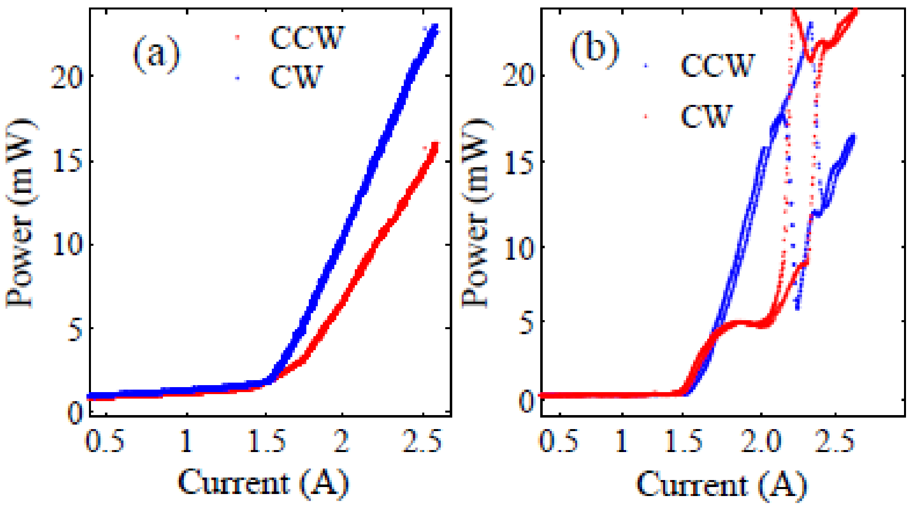
Emitted Power as function of Pump Current



- Both direction of emission have the same threshold current.
- They have different slope, one (CW) is predominant on the other (CCW), depending on alignment.
- Opening and closing the diaphragm
  It is possible to observe bistability, system pass from Fig. (a) to Fig. (b).

- Bistability has been observed in micro-meter sized semiconductor laser, in our system can be manipulated to appear and disappear with a passive element.
- We interpret the bistability as result of CW and CCW competing only when they are spatially constrained.
- The fact that bistability disappear when the Iris is opened and restored with the iris closed indicates that <u>transverse spatial segregation</u> of the two emission directions takes place

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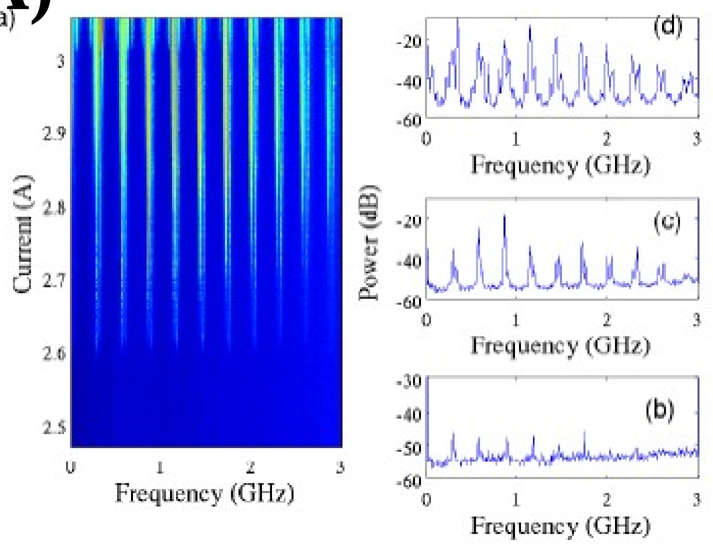
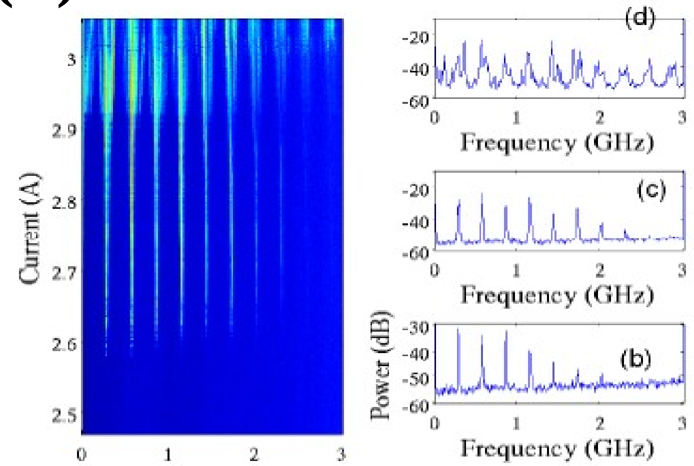
Power Spectrum

(A)



- The power spectrum as function of current with the diaphragm open. Starting from threshold and going up many peaks appear in the power spectra.

(B)



- Fig. (B) shows the power spectrum as function of current with the diaphragm closed.
- New frequencies appear at about 2.9A

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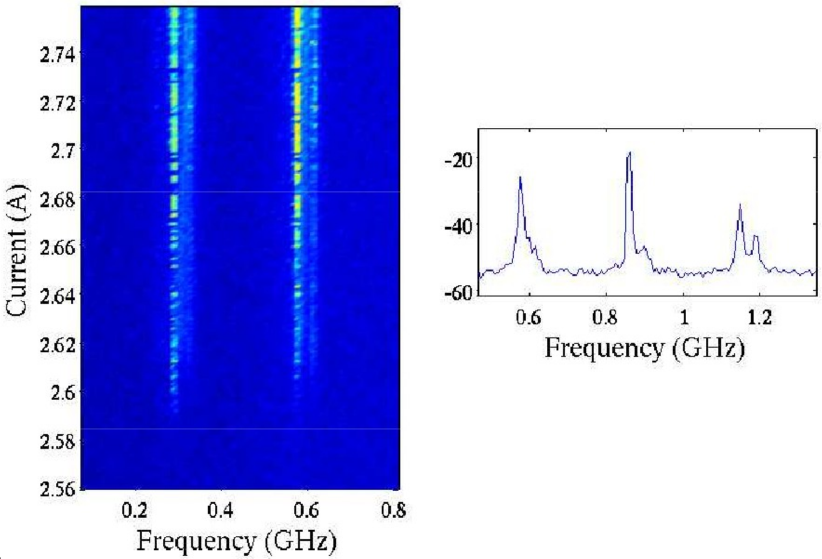
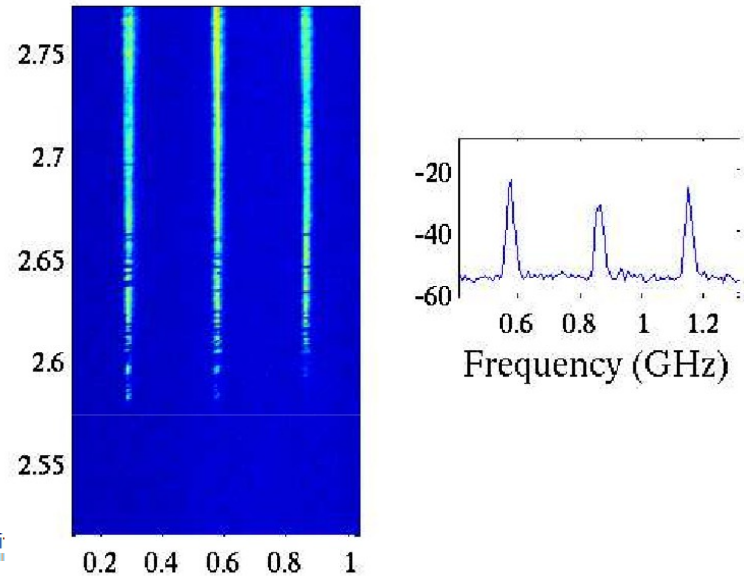
Power Spectrum

(A)



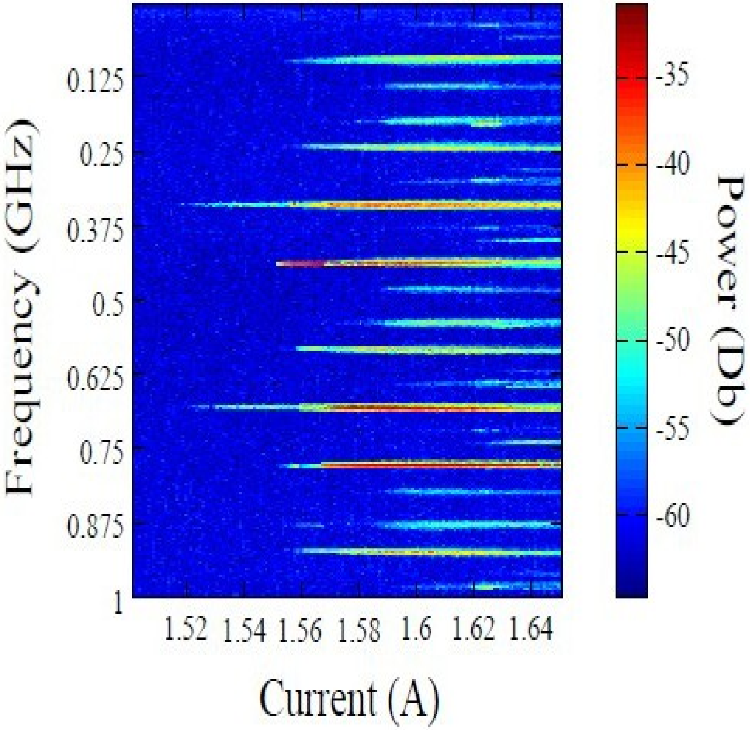
- The power spectrum as function of current with the diaphragm open. Starting from threshold and going up many peaks appear in the power spectra.
- Peaks broaden due to transverse dynamics

(B)

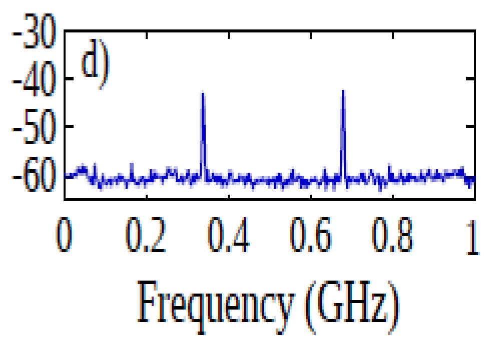


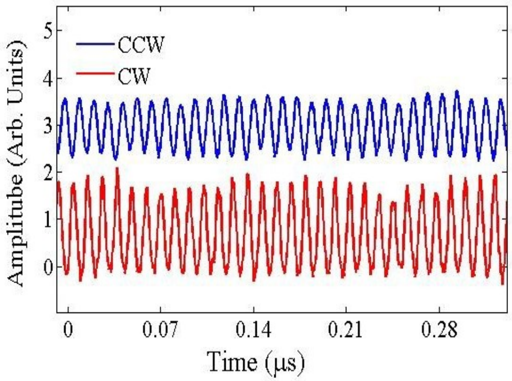
- Fig. (B) shows the power spectrum as function of current with the diaphragm closed.
- No broadening of peaks

Ring laser is class A laser



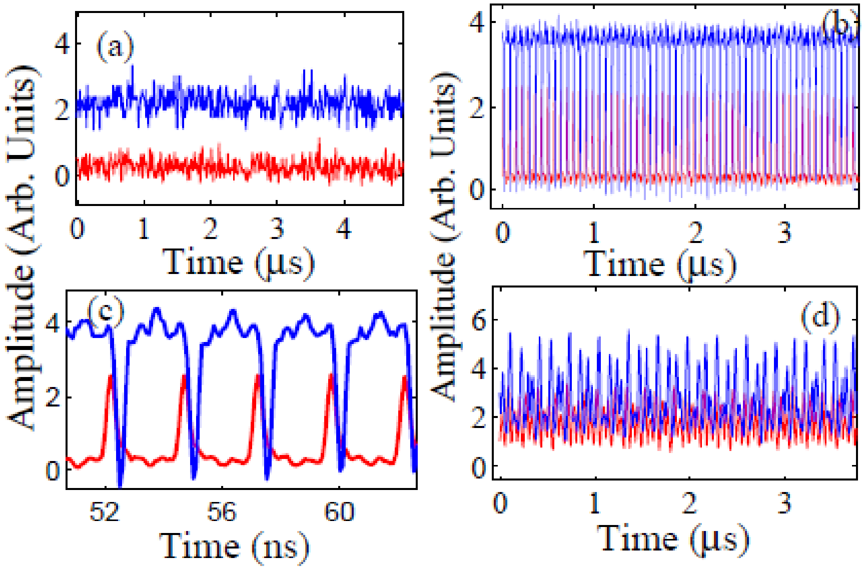
- ➢ Near laser threshold only two peaks are observed corresponding to longitudinal mode beatings.
- ➢ Increasing current many other peaks are observed that indicates low frequency instability (spurious backreflections?)





- ➢ **One important feature is the absence of relaxation oscillations: the semiconductor ring laser is class A laser.**
- ➢ That would be evident as a broad peak whose frequency scales with the square root of the distance from threshold as in any semiconductor laser.
- ➢ Under precise and very sensitive alignment condition and with the help of the possible to achieve a perfect periodic regime.

Passive Mode Locking



- Time traces of the intensities for different current level
- Obtained with no saturable absorber, passive mode locking
- The observed pulse duration is 300 ps at repetition rate of 487 MHz
- The modulation depth is close to 100%
- Total intensity conserved -> phase slip?

- The lag between CW and CCW pulse is due to the fact the output coupler is not in the centre of the cavity but the pulse are superimposed on the active media
- Increasing the pumping current the fixed phase relations between the laser mode breaks resulting in a complex situation as shows in Figure (d)
- The system is passing from Fig (a) to Fig (d) when the diaphragm is open

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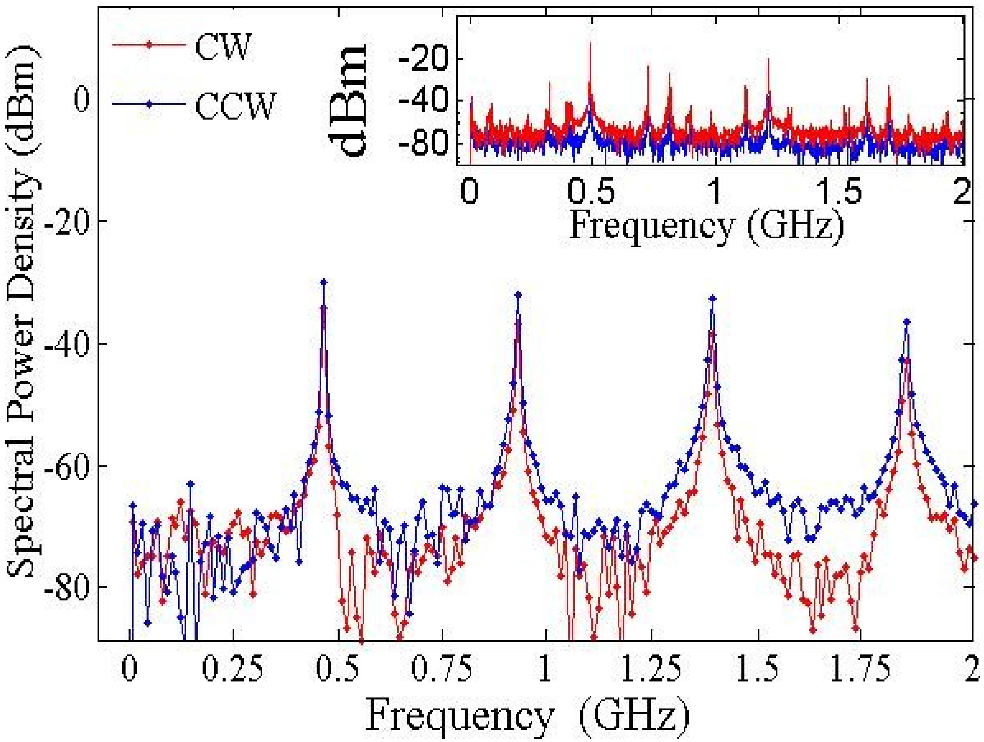
Frequency Domain



- Frequency Spectra of the mode-locked regime

- Inset is the frequency spectra outside mode-locking regime, strongly multi mode, satellite peak

- Our interpretation of this regime of passive mode locking is that is due to competition between CW and CCW interaction when we constrain spatial degress of freedom with the pin-hole and (forcing CW and CCW competition in addition to linear coupling due to backscattering)

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Conclusion

1) A new experimental system is build: a macroscopic semiconductor ring laser

2) The cavity build is a class-A ring semiconductor laser

3) Ring cavity present bistability in LI-curve when CW and CCW are spatially constrained to compete, different behaviour from micro-ring laser

4) Low repetition rate mode locked operation of a macroscopic semiconductor ring laser.

5) Due to its time constants and possibility of unidirectional operation, the device could be highly suitable for the generation of temporal cavity solitons.

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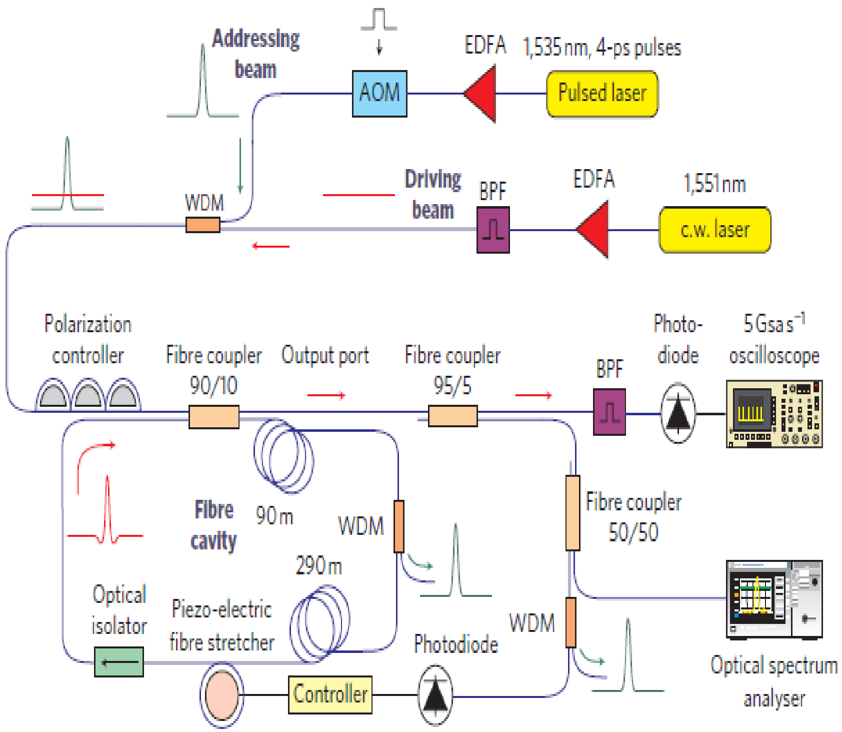
Future Direction - Observation of Temporal Cavity Soliton in Ring Cavity

- Recently Temporal cavity soliton has been discovered for the first time experimentally by[1]
- The experiment is based on a passive ring cavity (380 m) made of standard optical fibre and rely on the instantaneous pure Kerr non-linearity of silica



- The soliton are 4 ps long
- It is important to put an <u>optical isolator</u> because the stability of temporal cavity soliton depends on pure unidirectional emission
- It is a passive system in fibre, it would be possible to do the same in free space with a multi-mode laser?
- http://molosse.org/

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[1] F. Leo *et al* , Nature Photonics **2010.120**