Self– and Cross–Correlation Measurements in Two–Mode Semiconductor Ring Lasers

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ABSTRACT

In this work we present experimental results on the auto–correlation and cross–correlation properties of the two counterpropagating modes of a monolithic semiconductor ring laser. The ring laser can operate in a bidirectional regime where the two modes have equal power, and also in a unidirectional regime where one of the modes is almost suppressed. Auto–correlation measurements, that are carried out using an unbalanced Mach–Zehnder fiber interferometer, allows to determine the coherence length and linewidth of the ring laser. Cross–correlation measurements are carried out using a modified interferometric set–up, and they reveal that the two counterpropagating modes are phase–locked.

Keywords:
Semiconductor ring laser, linewidth measurement, correlation measurement, mode dynamics.

1 INTRODUCTION

Semiconductor ring lasers (SRLs) are attractive devices because they can be fabricated without the need for cleaved facet mirrors, offering the possibility to be monolithically integrated with other optoelectronic devices. SRLs are also interesting because they can support two counterpropagating lasing modes, that give rise to a rich phenomenology of operating regimes and mode dynamics. In particular, SRLs have been demonstrated to operate unidirectionally with the possibility to select the active mode by means of electronic control, and also bidirectionally with an interesting alternate oscillation regime.

Scope of this work is to evaluate the coherence properties of SRLs, as these have not been previously investigated in the literature. We have carried out a thorough experimental study on SRL devices fabricated at the University of Glasgow, that operate on a single transversal and longitudinal mode. These devices are fabricated in GaAs/AlGaAs material, emitting around 870 nm, and have the structure shown in Figure 1. The ring radius is 1 mm, and two integrated photodiodes are fabricated on the output waveguide to monitor the intensity of the two counterpropagating modes. Figure 2 reports the experimental P–I characteristics of a SRL, showing a threshold value of 390 mA. Just above threshold, a bidirectional regime occurs, where the two modes have similar intensities. At higher currents, a unidirectional regime occurs, where one mode is almost completely suppressed, and the other mode doubles its power.

The chosen method for the measurement of the linewidth of the SRL devices is based on an unbalanced Mach–Zehnder optical fiber interferometer. This method was chosen because: i) it gives the measure of the auto–correlation function (i.e., the coherence length and the linewidth) of one specific laser mode, and ii) it allows to measure also the cross–correlation of the two counterpropagating modes in the bidirectional regime.

Experimental results revealed that in the unidirectional regime the linewidth is around 40 MHz, while in the bidirectional regime it is 110 MHz. Cross–correlation measurements showed that the two counterpropagating modes in the bidirectional regimes are phase–locked, and the relative phase value randomly undergoes $\pi$ jumps.

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2 THEORY AND MEASUREMENT PRINCIPLE

The experimental set–up for the measurement of the linewidth/coherence length is shown in Figure 3. Light emitted from both sides of the SRL is butt–coupled to single–mode fibers. One fiber at a time is then connected to the input of the M–Z fiber interferometer, that is composed of two 50%–50% fiber couplers. The first arm of the interferometer includes a polarization controller (PC), and an optical phase modulator fabricated by winding 10 fiber turns around a cylinder piezoceramic transducer (PZT). The PZT is driven by a triangle waveform, to linearly modulate the optical phase. By splicing spans of fiber of variable length in the second arm, the interferometer optical path length difference was increasingly unbalanced.

Figure 1. SEM micrograph showing the structure of the fabricated SRL device

Figure 2. P–I characteristic of the SRL device as measured through the integrated photodiode contacts. The device is kept at 25°C, and the injected current is DC.
The principle of the measurement lies in the fact that a time domain interferometric signal is observed at the interferometer output when the optical phase is modulated. The contrast of this signal is a function of the laser coherence length and of the interferometer arms unbalance.

Assuming a Lorentzian lineshape, the relationship between SRL linewidth (\(\Delta \nu\)), coherence time (\(\tau_c\)), and coherence length (\(L_c\)), is given by:

\[
\nu \Delta \pi = \frac{1}{\tau_c}, \quad \tau_c = \frac{\pi}{\Delta \nu}, \quad L_c = c \tau_c
\]

We define the coherence factor between two e.m. fields, which have a relative time delay \(\tau\), as follows:

\[
\gamma(\tau) = \frac{\langle E_1(t)E_2^*(t-\tau) \rangle}{\langle |E_1|^2|E_2|^2 \rangle}
\]

For a Lorentzian lineshape, we have:

\[
\gamma(\tau) = \exp(-\tau/\tau_c)
\]

If the fiber couplers within the M–Z interferometer have exactly 50%–50% splitting ratio (by using the coherence factor formula for the case where \(E_1\) and \(E_2\) are the same field), the interferometric signal (converted into a photocurrent) is given by:

\[
I_{ph} = I_0 \left[ 1 + \frac{1}{2} \gamma(\tau) \langle \cos \Delta \phi \rangle \right]
\]

We define the contrast factor of the interferometric signal as:

\[
C = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}
\]

As the following relations hold:
Figure 4. Auto–correlation measurements for the SRL device in different regimes. Symbols are measured data; lines are obtained through exponential fitting. Diamonds and solid line: unidirectional regime, mode #1 (strong mode). Triangles and dashed line: unidirectional regime, mode #2 (weak mode). Squares and dash–dotted line: bidirectional regime, mode #1

\[
I_{\text{max}} = I_0 \left[ \frac{1}{2} + \frac{|r(\tau)|}{2} \right], \quad I_{\text{min}} = I_0 \left[ \frac{1}{2} - \frac{|r(\tau)|}{2} \right]
\]

it results:

\[
C = |r(\tau)|
\]

Hence, the contrast \( C \) of the interferometric signal is a function of the interferometer unbalance \( \tau \), and it is equal to the autocorrelation function of the SRL field. From a measurement of the contrast \( C \) for varying delay \( \tau \), the autocorrelation function can be determined, from which the coherence time and linewidth can be easily obtained through a fitting procedure (the underlying hypothesis is that the autocorrelation function decreases exponentially for increasing \( \tau \)). In a practical situation, the actual splitting ratio of the fiber couplers is inessential, as it is always possible to determine the constant of the autocorrelation function through exponential fitting.

3 LINEWIDTH / AUTO–CORRELATION MEASUREMENT

In the experiment, the delay \( \tau \) is varied by repeatedly splicing a fiber span in one of the interferometer arm. As the overall delay cannot be exactly evaluated by measuring in advance the length of the fiber spans to be spliced (especially after a large number of splicings), we use an external cavity tunable laser (also shown in Fig. 3) to measure the actual delay of the interferometer by applying a wavelength sweep of known amplitude, and by measuring the number of interferometric fringes at the output, which is proportional to \( \tau^7 \). This calibration procedure is carried out each time the delay \( \tau \) is varied. Before proceeding with the SRL linewidth measurement, the set–up was tested by measuring a single longitudinal mode Fabry–Perot semiconductor laser, obtaining results in agreement with the linewidth values measured with alternative methods (self–omodyne\(^8\) and self–mixing\(^9\)).
Linewidth measurements have been carried out on the SRL operating in both the bidirectional and the unidirectional regime, at current values very close to the transition between these two regions (i.e., 600 mA). In the unidirectional regime, the main lasing mode was #1 (counterclockwise). However, in this regime, mode #2 (clockwise) was not completely suppressed, and its power was 18 dB below that of the main mode. Hence, in the unidirectional regime, it is interesting to measure separately the linewidth of the two modes, which are in practice both active.

Figure 4 reports the measured values of the contrast as a function of the interferometer arm unbalance (i.e. delay $\tau$ converted into optical pathlength) for both counterpropagating modes when the laser is operating in the so-called “unidirectional” regime, and for only one of the two modes in the bidirectional regime (measurement for the other mode gave identical results). Lines are obtained by fitting the experimental data points with an exponential curve. Calculated values for the coherence length are: $L_c = 2.52$ m (unidirectional, mode #1); $L_c = 2.17$ m (unidirectional, mode #2); $L_c = 0.86$ m (bidirectional). These correspond to the following linewidth values: $\Delta \nu = 37.9$ MHz (unidirectional, mode #1); $\Delta \nu = 44.0$ MHz (unidirectional, mode #2); $\Delta \nu = 111.0$ MHz (bidirectional).

A few comments on the above presented results are worthwhile. The coherence length in the unidirectional regime is larger than in the bidirectional regime. This is reasonable for two reasons:

1. The linewidth of a semiconductor laser is to a good extent inversely proportional to the emitted power (and in our case, this statement shall be interpreted as “inversely proportional to the power of the mode under test). In the unidirectional regime the power for the strong mode (#1) is doubled with respect to the power-per-mode of the bidirectional regime. Hence, the coherence length in the unidirectional regime should be twice the coherence length in the bidirectional regime.

2. From the measurement, the coherence length ratio (unidirectional / bidirectional) is 2.93, which is larger than the expected value. This could be ascribed to the fact that, when two counterpropagating modes are active within the ring cavity, each mode causes an increase in the linewidth of the other mode (with respect to the case of a solitary mode with the same power) through the phase–amplitude coupling mechanism represented by the alpha factor (linewidth enhancement factor). In the SRL laser, the amplitude fluctuations of one mode do influence the phase fluctuations of the other mode.

Interestingly, the coherence length of mode #2 (weak mode) in the unidirectional regime is almost equal to the coherence length of mode #1 (strong mode). This could be surprising at first sight, because the intensities of the two modes differ by as much as 18 dB. However, it happens that the weak mode is actually locked to the strong one. The two modes mutually inject each other symmetrically, but as one of the mode is much stronger than the other, the injection occurs in a sort of master–slave configuration. The coupling between the two counterpropagating modes, that is mainly due to waveguide backscattering, forces the weak mode to lock to the strong one not only in terms of oscillation frequency, but also in terms of phase fluctuations, and hence linewidth.

Figure 5. Experimental set–up used for the measurement of the cross–correlation between the two counterpropagating modes of the SRL in the bidirectional regime.
4 CROSS–CORRELATION MEASUREMENT

The experimental set–up shown in Figure 5 was used to measure the cross–correlation between the two counterpropagating mode of the SRL in the bidirectional regime. The procedure was similar to the one used to determine the auto–correlation, except that the set–up was no longer in a Mach–Zehnder interferometric configuration, but rather the two modes were simply combined via the 50%-50% fiber coupler after they travelled different pathlengths.

At first, we investigated the cross–correlation for $\tau = 0$ (i.e., balanced pathlengths). A clear sinusoidal signal was observed at the interferometer output, thus confirming that the two modes in the bidirectional regime are phase–locked. After some time (typically 5-10 s), a sudden jump in the value of the relative phase may occur, and the modes get locked with a new value of the relative phase, that differs from the previous one by $\pi$. This can be observed in Fig. 6, that reports the time trace of the interferometric signal, acquired by a digital oscilloscope with a long persistence (a few seconds). The trigger instant (i.e. the instant at which the triangle waveform applied to the PZT changes slope) is located at the center of the screen. During this acquisition, a phase jump occurred, and the picture shows two distinct time traces corresponding to different values of the lock–in phase.

Cross–correlation measurements for varying $\tau$ were then carried out, and the result of the measurements is reported in Fig. 7. In this picture, cross–correlation data (diamonds) are plotted along with auto–correlation data previously measured for the bidirectional regime. As it could be expected, the cross–correlation is always smaller than the auto–correlation. From the data in Fig. 7, it is not straightforward to determine the degree of correlation of the two fields. In fact, if the degree of correlation is defined as the ratio of the cross– to the auto– correlation, this parameter shows a dependence on the delay $\tau$. For $\tau = 0$, the degree of correlation is around 0.23, while for larger values of $\tau$ it approaches unity.

5 CONCLUSION

We have reported, for the first time to our knowledge, about experimental investigations on the coherence length of single mode monolithic semiconductor ring lasers. The linewidth of the SRL modes was measured through an unbalanced Mach–Zehnder fiber interferometer in different operating regimes: unidirectional and bidirectional. Cross–correlation measurement have also been carried out, revealing that in the bidirectional regime the two counterpropagating modes are phase–locked.
REFERENCES