Spectral line narrowing in coupled VCSE-laser oscillators for photonic microwave generation

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Abstract

In this work we present a novel technique of narrowing the spectral linewidth of microwave signals generated by heterodyning pairs of VCSELs which form an extended optically coupled cavity and experimentally demonstrate a reduction by as much as a factor of 10^4 – that is, a linewidth narrowed to less than 10 kHz.

1 Introduction

Vertical cavity surface emitting semiconductor lasers (VCSEL) are attractive in several applications, such as optical communication (either long distance fibre systems or short distance optical interconnects), owing to their ease of manufacture and good optical beam and power efficiency. However in applications where more exacting demands are placed on high spectral purity, such as environmental spectroscopy and microwave photonics, the large intrinsic spectral linewidth (circa 100 MHz) of the VCSELs associated with the small laser gain volume presents a serious limitation [Gevorgian *et al.* 1999].

2 Optical line narrowing

During the last decades much research has been performed about different ways of improving the spectral properties of optical and microwave sources, often combining optical/microwave and electrical signal control:

- transferring coherence from a spectrally purer ('master') light source to the source ('slave') to be line-narrowed (so-called injection locking)
- extending the effective cavity length of the source oscillator (optical feedback).

Both optical injection and optical feedback as means of studying and controlling the dynamics of edge-emitting diode lasers has achieved a high level of maturity in recent years. Comprehensive and systematic investigations of the various regimes of injection and stability/chaos are now well established and encompass even high-resolution spectral measurement [Tkach and Chraplyvy 1986, Eriksson and Lindberg 2002]. Corresponding studies in the microwave region date back several decades where attempts at providing more microwave power by including several microwave oscillators in a single cavity required solutions to instabilities in power and frequency associated with multimode behaviour. Phase noise in an array of N coupled microwave oscillators has been shown to be reduced by a factor $1/N$ and parallels have been drawn between studies of chaotic dynamics in coupled oscillators in the optical and microwave regions [Ram *et al.* 2000]. In the present work, a novel way is found of achieving optical line-narrowing in VCSELs. Studies have commenced more recently than for edge-emitting diode lasers.

In the present work, a novel way is found of achieving optical line-narrowing in VCSELs. Studies have commenced more recently than for edge-emitting diode lasers. The intensity and phase noise spectra of isolated VCSELs are well understood, particularly the relative large intrinsic spectral linewidth (ranging from tens to one hundred MHz for different laser powers) [Agrawal and Gray 1991].

Chang *et al.* [2002] report that VCSEL-VCSEL injection locking resulted in improvement in the signal transmission performance using an L-band VCSEL modulated directly at 2.5 Gb/s owing to an apparent reduction in laser chirp. Linewidth narrowing by optical feedback by reflection of light from a VCSEL has been investigated by Chung and Lee [1991] and by Dowd *et al.* [1997] - the latter with a fibre-loop mirror with high spectral resolution using optical heterodyning with a second VCSEL demonstrated line-widths as narrow as 190 kHz. In an extended cavity version – the so-called VECSEL – of vertical cavity, surface-emitting laser, linewidths of just 3 kHz using locking to an external resonator have been reported [Abrams *et al.* 2003].

3 Optical feedback and locking and line-narrowing

Optical feedback as a means of narrowing the linewidth of edge-emitting diode lasers has been extensively studied both experimentally and theoretically for a number of different reflectors, such as a simple mirror, diffraction grating as well as a high-finesse optical interferometer such as a Fabry-Pérot cavity [Li and Telle 1989].

A model to describe spectral line-narrowing of heterodyning pairs of VCSELs which form an extended optically coupled cavity is in terms of a Fabry-Pérot interferometer as formed between one facet mirror of each VCSEL. Line-narrowing in this case can be explained in terms of extending the length (very) short cavity of a VCSEL (typically about 1 μm) to the large (L, typically 80 cm) distance between the two VCSELs and a longer photon lifetime.

The effective reflectivity of such a coupled cavity can be calculated using scattering theory [Coldren and Corzine 1995]:

$$r_{eff} = r_2 + \frac{t_2^{\,2} r_3 e^{-j2\beta L_p}}{1 + r_2 r_3 e^{-j2\beta L_P}} ,$$

where factor $2j\beta L_P = \omega\tau_0$ represents the roundtrip phase of the external cavity of length L_p, r_2 and r_3 are the reflection coefficients of the laser facets.

A calculated value of the total change in lasing frequency $\Delta\omega = \omega - \omega_0$ can be used to obtain linewidth narrowing factor $\eta = \left(\frac{d\omega_0}{d\omega}\right)$. Multiple solutions exist for $\sqrt{1-\alpha^2} k_f \tau_0 > 1$, where α is the linewidth enhancement factor (typically 5) and k_f is the optical feedback rate, which is confirmed experimentally.

In order to compare the extended cavity model [Coldren and Corzine 1995] with that of Li and Telle [1989], we have calculated linewidth narrowing factor as a function of reflection coefficients of the mirror facet of the VCSEL (figure 1) upon reflection from a mirror of 99% reflectivity placed at a distance of 80 cm from the first VCSEL

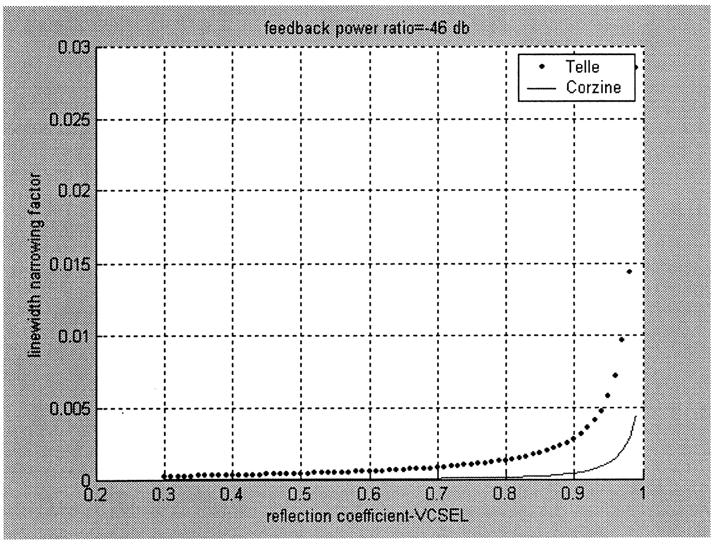

figure 1 linewidth narrowing factor *vs* reflection coefficient for an optically extended cavity

4 Experiment

To investigate the narrowing of the spectral linewidth of microwave signals generated by heterodyning pairs of VCSELs which form an extended optically coupled cavity, the following experimental arrangement was set up. Laser light from each VCSEL (wavelength 850 nm, optical power 200 μW, Ulm Photonics GmbH) was reflected by a mirror and a beam-splitter on to the other VCSEL in order to form an extended optically coupled cavity. The beam-splitter (nominally 50:50) allowed light from both VCSELs to be passed to two spectrometers: a scanning confocal interferometer (free spectral range 1.5 GHz, finesse 200) and a fast photodetector (avalanche photodiode) combined with an electrical spectrum analyser (3dB-bandwidth about 2 GHz). The corresponding heterodyne beat spectrum obtained thus with the fast photodiode and electrical spectrum analyser between two coupled VCSELs is shown in figure 2. The single, 150 MHz broad peak of an isolated VCSEL is now replaced by a comb of narrow peaks spaced by the free spectral range (180 MHz) of the extended cavity between the VCSELs (length L = 80 cm).

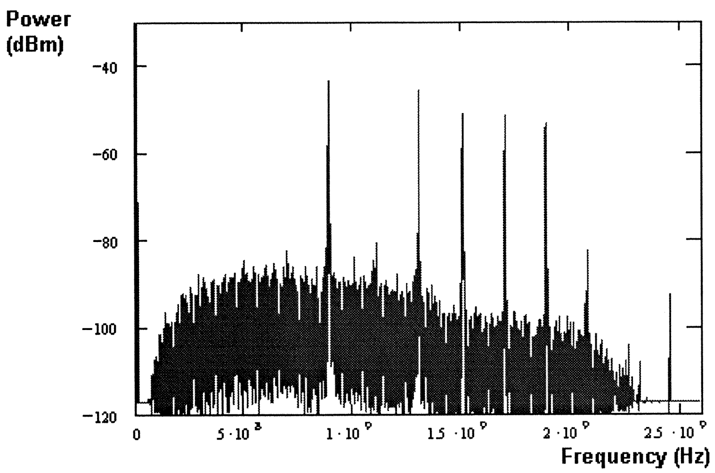

Figure 2. Heterodyne spectrum of a pair of optically coupled VCSELs (180 MHz is the free spectral range of the coupled cavity) (*RBW* = 1MHz, *SWT* = 50 ms, single sweep)

A higher resolution spectral scan of one of the peaks in the heterodyne beat spectrum reveals a 3 dB linewidth of less than 10 kHz (limited by the resolution bandwidth (*RBW*) of the electrical spectrum Analyser).

Repeated scans of this high-resolution spectrum reveals some frequency fluctuations of amplitude several MHz for times longer than 50 ms. These fluctuations are attributed to acoustic vibrations in the distance between the coupled VCSELs.
This set-up for photonic generation of high spectral purity microwaves is a relatively simple arrangement of a pair of optically coupled VCSELs based on readily available commercial products. In order to refine further this microwave photonic source a number of additions to the set-up are planned.

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