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Phase-Locked Mutually Coupled 1.3 μM Quantum-Dot Lasers

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Phase-locked mutually coupled 1.3 μm quantum-dot lasers

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Fabry-Perot InAs quantum-dot lasers grown on GaAs substrates are mutually coupled with a delay of several nanoseconds. Stable phase-locked output with narrow linewidth is obtained when the frequency detuning between the two lasers is less than 4 GHz. This simple locking scheme could find application in a variety of photonics applications.

OCIS codes: 030.1640, 060.1660, 140.3520, 140.5960.

1. Introduction

Phase-locked optical sources either in array form or as discrete sources have a significant number of emerging technological applications in communications, display and materials processing. Where possible, semiconductor lasers are preferred to gas and optically pumped solid-state emitters due to their small size, efficiency, reliability, potential low-cost and high response speeds. An example of the advantages of semiconductor sources can be found in the area of phased-array antennae for free-space communications which seek to displace actuated bulk optics and simple sources. Phased-arrays are a common technique in the microwave regime for serially addressing separate receivers, tracking mobile receivers or compensating for atmospheric disturbances. Optical phased-arrays would have significant size, speed, reliability and weight advantages over moving bulk optics, of particular importance to airborne systems. Other applications of phase-locked semiconductor sources would include beam combining for fibre laser pumping, for non-linear conversion and for beam working distance extension. Unfortunately, the generation of phase locking between semiconductor lasers has proven troublesome, essentially because of the non-linear dynamics generated when introducing delay or direct coupling in lasers with a large phase-amplitude coupling (α-factor)and underdamped relaxation oscillations. These non-linearities have led to extensive study of systems such as delayed optical feedback [1], the laser in master-slave configuration [2] and two or more mutually coupled semiconductor lasers with delay [3]. Most studies have focused on the complex dynamics typically generated by the above configurations, and in one notable example [4] on the potential exploitation of chaotic dynamics for the encryption of a communications channel.

Quantum-dot (QD) lasers were developed with the ambition of narrowing and making symmetric the semiconductor gain linewidth, with attendent improvements in modulation speeds, efficiency and a reduction in the α-factor. It has been previously reported that InAs/GaAs QD lasers, in addition to regions of complex dynamics, display regions of stability in configurations that would be chaotic in quantum-well (QW) lasers [5,6]. In particular, it was shown that a QD laser could suffer 15-20 dB more external optical feedback than a QW laser before entering coherence collapse [7], and that in the master-slave configuration the unstable dynamics were restricted to a small region on one unlocking boundary [5]. There are two main reasons why QD lasers are able to stably run under adverse conditions and display dynamical states that are typically obscured by chaos in other semiconductor lasers: firstly the α-factor in the QD devices is reasonably low [8] and secondly the relaxation oscillation is highly damped [9–11]. The stability of the delayed feedback and master-slave configurations using QD lasers suggests that the relatively simple method of mutual coupling could generate stable phase-locked output over substantial parameter ranges. In this paper, we report for the first time (to our knowledge) stable phase-locked operation in mutually delay-coupled QD lasers, and demonstrate narrow linewidths with significant tolerance to detuning.

2. Device details

The laser structure was grown on Si-doped (100) GaAs substrate by molecular beam epitaxy (MBE). The active region consisted of six stacked InAs/$In_{0.18}Ga_{0.82}As$ QD layers separated by five 40 nm-thick GaAs electronic barriers and embedded between two 55 nm-thick GaAs spacers. The 2.8 monolayers of InAs, the $In_{0.18}Ga_{0.82}As$ and the first 5 nm-thick GaAs barrier were grown at low temperature and the remaining 35 nm of GaAs barrier were grown at high temperature (600 ^{o}C). More details concerning the growth can be found in [12]. On an uncapped sample, the QD density was measured by atomic force microscopy (AFM) as 3x10^{10} cm^{-2}. The active region was embedded in two $Al_{0.7}Ga_{0.3}As$ cladding layers. The n-type and p-type layers were 1.5 and 1.3 μm-thick respectively. The structure was finally capped by a 300 nm p+-GaAs layer. The doping level of the p-type layers was decreased from the contact layer to the undoped active region, with a doping range varying from 3x10^{19} cm^{-3} to 4x10^{17} cm^{-3}. Narrow stripe ridge waveguides were formed by optical lithography followed by selective wet chemical etching, which was stopped above the active region. Thin silicon oxide was then deposited by plasma-enhanced chemical-vapour deposition in order to open a contact window over the narrow ridges through the dry etching of the oxide. Ti/Au p-type contact was thermally deposited on the topmost layer. Then the substrate was thinned down to around 100 μm and finally n-type metal AuGe/Ni/Au was deposited on the wafer backside. Laser cavities with different lengths were cleaved and no coatings were applied on the facets. These devices have demonstrated high modal gains [13] allowing short uncoated cavities with high free spectral ranges.

3. Experimental arrangement

Two QD lasers, one 600 μm long and one 1 mm long of ridge-widths 2.5 μm, were mounted on temperature controlled stages that gave optical access to both laser facets. The wavelength of one mode of one laser (QDL1) was measured with an optical spectrum analyser and chosen as a reference wavelength. The temperature and injection current of the second laser (QDL2) were then varied so that the wavelength of one of its modes matched the reference wavelength. The laser outputs from the facets facing one another with approximately 30 cm separation were collimated in free-space and coupled to one another. The laser outputs from the non-facing facets were passed through optical isolators and used to analyse the laser characteristics. The mutual coupling caused the devices to emit a common spectrum. The free running spectra (Fig. 2(a)) were modified so that only the modes common to both were permitted as shown on Fig. 2(b). For the 1 mm device, this meant that every fifth mode was allowed in the coupled configuration, for the 600 μm device, every third mode lased. The side-mode suppression of modes adjacent to shared modes could be used to optimise the laser detuning, when this was done the relative suppression of non-common modes was on the order of 30 dB. The total laser intensities were coupled to high-frequency photodiodes and examined on an electrical spectrum analyser (ESA) and an oscilloscope. No intensity fluctuations were observed on either instrument. The laser output was combined with a tunable laser source using a fibre coupler and the beat tone examined on the ESA. The linewidth of an individual mode was 4 MHz (significantly narrower than the 25 MHz linewidth measured when the mutual coupling was removed) without any conspicuous noise peaks or bands. These multi-longitudinal mode results are greatly at variance with the chaotic QW laser dynamics found in comparable configurations, though they are insufficient to demonstrate phase-locking.

To address the issue of phase-locking, the separation between the two lasers was increased to approximately 1 m to accomodate a blazed grating with 1200 lines cm^{-1} as shown in Fig. 1. The grating resolution was sufficient to induce single-mode emission from the two lasers with a side-mode suppression ratio of 37 dB (Fig. 2(c)). This optical arrangement however rendered an estimation of the coupling strength between the two lasers difficult, and a detailed study of the effect of coupling strength will be carried out in a future experiment. The linewidth was again measured using the tunable laser source and ESA, and was as low as 2 MHz (Fig. 2(d)), the extra narrowing a consequence of the increased photon lifetime and the absence of mode-partition noise. The fibre coupled outputs of the two lasers were collimated in free-space and interfered on a video camera. The interference fringes shown in Fig. 3(a) are high contrast, indicating good phase locked operation. The single-mode laser output was again coupled to a high-speed photodetector, and the time-trace and intensity spectrum examined on an oscilloscope and ESA respectively. The deep intensity fluctuations of mutually coupled QW lasers are again absent and no increase in laser relative intensity noise was observed.

The tolerance of the phase-locked state to detuning between the laser modes is critical to potential technological exploitation of this effect. The mutual coupling between the lasers was removed and one of the free-running laser modes was beaten with the tunable laser source. The beating frequency was recorded as a function of laser injection current, where the dominant effect will be Joule heating of the device. The coupling between the lasers was restored and the stable range of injection current recorded which corresponded to approximately 4 GHz when each laser was operated at twice threshold current. Outside this stable detuning range large amplitude instabilities could be observed though their description is outside the scope of this work. This stable detuning range is comparable to those of the master-slave configuration for similar QD lasers, where the coupling rate is on the order of 30%.

4. Conclusion

We have carried out in this work the first study, to our knowledge, of mutual coupling in QD lasers of InAs/GaAs at 1.3 μm. These devices display uniquely stable dynamics when mutually coupled as a consequence of the highly damped relaxation oscillations typical of this material system and the relatively low α-factors. This characteristic offers the possibility of manipulating the output spectrum, for example by reducing the density of viable modes or by narrowing the laser linewidths. Additionally, novel photonic devices such as coherent arrays of devices using simple coupling may emerge for applications in communications, optical pumping and optical machining.

Acknowledgments

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List of Figures

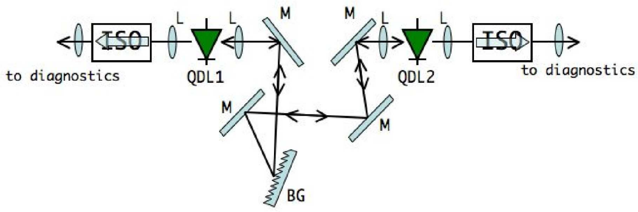

Fig. 1. Experimental arrangement for investigating the dynamics of bi-directionally coupled QD-FP lasers, QDL1 and QDL2. The blazed grating BG is included to ensure single mode operation. Optical isolators (ISO) prevent external reflections from perturbing the system.

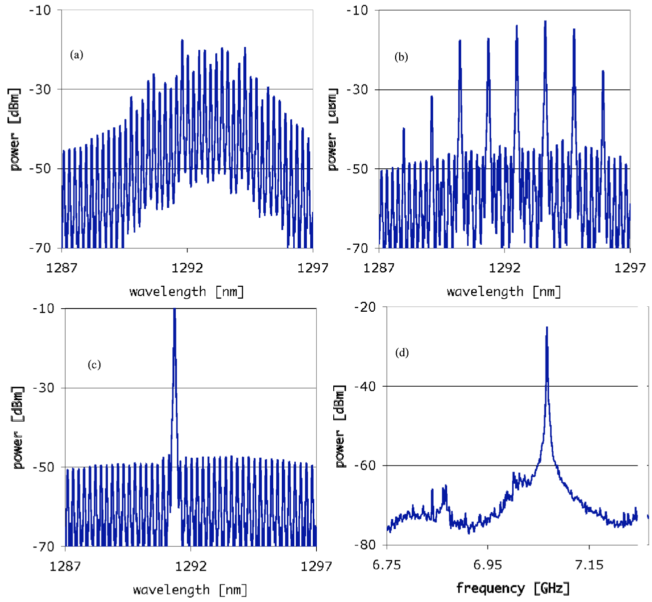

Fig. 2. Optical spectra of 1 mm QD-FP laser running at twice threshold current. (a): free-running laser. (b): coupled directly to 600 μm QD-FP laser. (c): coupled to 600 μm QD-FP laser via diffraction grating to select a single mode. (d): Mixing signal of mutually coupled laser with narrow linewidth tunable laser. QD laser linewidth ∼2 MHz. Free running QD laser linewidth ∼25 MHz. The laser separation is 30 cm for (b) and ∼1 m for (c) and (d).

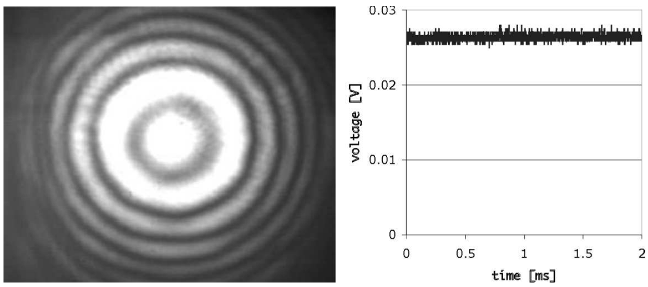

Fig. 3. Left: Fringes produced by interfering two mutually coupled, 1.3 m separated quantum dot lasers. The phase coherence between the two lasers is evident in the high visibility of the fringes generated. Right: oscilloscope trace with 1.5 GHz bandwidth of a 1 mm long QD-FP laser coupled to 600 μm long QD-FP laser, 1.3 m distant.