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Frequency Dependence of Phase Difference between Synchronised Self-pulsating Laser Emission and Injected Periodic Signals

A. Egan
Trinity College Dublin

G. O'Gorman
Trinity College Dublin

P. Rees
Trinity College Dublin

See next page for additional authors

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Authors
A. Egan, G. O'Gorman, P. Rees, Gerald Farrell, Joe Hegarty, and P. Phelan

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Frequency dependence of phase between synchronised self-pulsating laser emission and injected periodic electrical signals

A. Egan, J. O'Gorman, P. Rees, G. Farrell, J. Hegarty and P. Phelan

Indexing terms: Semiconductor junction lasers, Clock recovery, Injection locked lasers

The authors show by experiment and calculation that, for self-pulsating laser diodes synchronised to external electrical signals, a phase shift exists between the applied signal and the laser output. The authors then show that this phase shift depends on the frequency difference between these signals and on the applied signal amplitude.

Introduction: Electro-optical and all-optical synchronisation have important applications in communications systems [1]. An understanding of the factors that affect synchronisation in these devices is important since self-pulsating lasers may play an important role as functional elements in transparent transmission systems. Timing extraction and optical synchronisation of external signals with the emission from self-pulsating (SP) laser diodes (LD) have already been demonstrated [2, 3]. A crucial issue for timing applications, which, until now, has not been addressed, is the fidelity of the phase relationship between the extracted clock and the applied signal. We have experimentally observed for the first time that a phase difference exists between the input electrical signal and the output optical signal of a synchronised SP LD and that it depends on the free-running LD self-pulsation frequency. Numerical simulation of laser synchronisation yields good agreement with experiment.

Results and discussion: The SP LD used is a two section Fabry-Perot device that self-pulsates when one section is DC biased above threshold (gain section) using a constant current source and the other (absorber) section is DC biased below threshold using a constant voltage source [3]. The occurrence of controllable self-pulsation in such twin-section devices is well established and is explained on the basis of standard saturable absorption models [4]. This standard model states that self-pulsation occurs if, under the appropriate laser operating conditions and above threshold, the absorption in the absorber section saturates before laser gain. The laser emits a giant, short pulse that switches the carrier density below threshold. The laser gain then recovers on a time scale of about the inverse of the relaxation oscillation frequency at which stage the laser again emits a pulse. The free-running self-pulsation frequency (f_{SP}) of the laser emission can be controlled by varying the bias applied to either section and in this case it is controlled by varying the absorber voltage.

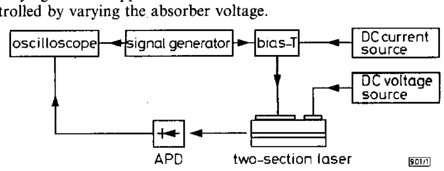

Fig. 1 *Experimental setup*

The Fabry-Perot bulk active region laser is temperature stabilised to 0.1°C. The APD has a bandwidth greater than 3.5GHz.

Fig. 1 shows the experimental setup. The laser is maintained at a constant temperature of 15.7°C. The gain section of the SP laser is biased at 95mA and when the absorber section is biased at ~0.257V the laser self-pulsates at a frequency f_{SP} = 1300MHz. A sinusoidal input electrical signal is applied to the laser gain section in addition to the normal DC biases via a bias T. The laser emission is monitored in the time domain using an avalanche photodiode and a sampling oscilloscope that is triggered by a portion of the applied signal. The RF power spectrum of the self-pulsation is also monitored to measure f_{SP} and to verify that the laser self-pulsation has locked on to the applied signal. When synchronisation is achieved, the relative phase shift between the input signal at a fixed frequency and the emitted laser pulses is measured on the oscilloscope. Its behaviour is also measured when f_{SP} is varied by changing the bias voltage applied to the laser absorber section.

The phase offset variation between the LD SP and the input electrical signal is shown for two different applied electrical signal levels in Fig. 2 (the higher level corresponds to a modulation voltage of 224mV while the lower level is 3dB less than this). For an applied RF signal frequency of f_{IN} = 1300MHz, $\Delta\Phi_D$ is the measured phase difference between the sampling scope trigger signal and the detected pulsation and is plotted relative to the phase difference measured when $f_{SP} = f_{IN}$. Each data point is the average of a number of measurements of $\Delta\Phi_D$ taken for the same value of f_{SP}. The total variation in phase shift for each electrical input level is ~0.61π rad. We note that the applied signal level is sufficient to achieve synchronisation but insufficient for the observed effect to be a result of the applied signal modulating the laser.

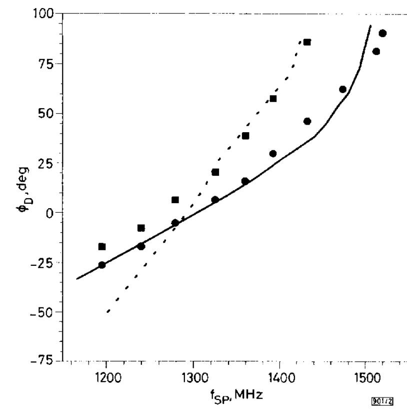

Fig. 2 *Variation in the phase difference, $\Delta\Phi_D$, between the applied electrical signal and the laser output pulsation relative to the phase difference at f_{SP} = 1300MHz, as the free-running self-pulsation frequency varies*

Note that the phase difference of $\Delta\Phi_D$ = 0° does not necessarily correspond to an absolute phase difference of 0°
- ● experimental results, large applied signal
- —— theoretical prediction, large applied signal
- ■ experimental results, small applied signal (3dB less than ●)
- – – – theoretical prediction, small applied signal

The existence of a phase shift between the applied electrical signal and the laser has not previously been reported or discussed. Moreover, the dependence of this phase shift on f_{SP} and on the applied signal level has important consequences for systems using these devices for clock extraction or distribution. To determine the origin of this behaviour we have simulated the synchronisation process in self-pulsating lasers.

Fig. 2 also shows the result of a numerical simulation using a standard singlemode rate equation model. The model is based on three rate equations for the carrier and photon density temporal evolution in the laser [5, 6] describing the carrier dynamics in the gain section, the carrier dynamics in the absorber section and the mean photon density in the combined laser cavity. We note that in each of the carrier rate equations the spontaneous and stimulated emission terms depend only on the photon density in the relevant section. The mean photon density in the cavity is a weighted average of the photon densities in both cavities, with the weighting factors depending on the losses and gains in each section and on their lengths [5, 6]. The output power from the laser is proportional to the mean photon density. Simulations of the synchronisation process when a sinusoidal electrical signal is applied to the laser gain section are carried out and the variation in the phase difference between the input and output signals is determined as f_{SP} varies. The results of these calculations are plotted with the experimental results in Fig. 2. For values of f_{SP} above 1300MHz, agreement between the theoretical curves and experimental data is excellent. The calculations also lead to an accurate prediction of the upper frequency limit to the synchronisation range. For values of f_{SP} below 1300MHz, the agreement is not as good for the low signal level as for the high signal level, a result that is not fully understood but is being investigated. Nevertheless, the agreement between calculation and experiment is excellent considering the simplicity of the model and the fact that standard parameters are used in the calculations: literature values have been used for standard parameters [5].

Formerly, it has been assumed that the signals synchronise with zero phase difference when electro-optical or all-optical synchronisation occurs in an SP LD, i.e. the emission of an optical pulse coincides with the presence of an electrical pulse in the laser [1]. Contrary to this, our results show that an absolute phase difference exists between the applied signal and the pulsation, i.e. frequency synchronisation does not automatically imply phase synchronisation. Our simulations show that the signal applied to the laser synchronises the pulsating emission by perturbing the carrier density and seeding the emitted optical pulse. This interaction results in the observed phase shift.

The phase dependence on the frequency difference between the applied signal and the LD self-pulsation has important consequences for communication systems using SP LDs for clock extraction. Our results show that it is not simply enough to achieve synchronisation between an external signal and an SP LD. The observed frequency dependent nature of the phase shift shows that all synchronised states are not the same, at least as far as phase is concerned. In some cases, this phase variation may be a desirable effect, for example, in fine tuning the clock delay in clock extraction systems. In other cases, it may be preferable if the effect is minimised. Consequently, an understanding of the origin of this phase shift and its behaviour is necessary if it is to be exploited. Indeed it may be possible to enhance or diminish the total phase variation over the synchronisation range, according to the requirements of a particular application.

Conclusions: We have observed and explained a significant new aspect of electro-optical synchronisation and clock extraction using SP LDs, which has not been fully appreciated previously. We have shown that when an SP LD synchronises to an external electrical signal, the phase difference between the electrical input and the laser emission depends on the free running SP frequency. Modelling of this effect, using a two section singlemode laser rate equation model, has yielded good agreement with the experimental results. While it may be expedient to minimise this phase variation for some applications, it may also be possible to exploit it for fine tuning of the clock delay in clock extraction systems. In both cases, our results are essential for understanding and controlling this important new phenomenon.

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A. Egan, J. O'Gorman, P. Rees and J. Hegarty (*Physics Department, Trinity College, Dublin 2, Ireland*)

G. Farrell (*Electronics and Communications Engineering Dept., Dublin Institute of Technology, Kevin Street, Dublin 8, Ireland*)

P. Phelan (*Opto-electronica, INESC, Rua José Falcao 110, 4000 Porto, Portugal*)

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High temperature characteristic T_0 and low threshold current density of 1.3μm InAsP/InGaP/InP compensated strain multiquantum well structure lasers

A. Ougazzaden, A. Mircea and C. Kazmierski

Indexing terms: Chemical vapour deposition, Semiconductor junction lasers

A high device quality material consisting of 10 compensated strained quantum well InAsP/InGaP structures was grown by MOCVD at atmospheric pressure. The estimated threshold current density for an infinite cavity length was 130A/cm² per well. A high characteristic temperature of 117K was obtained. To the authors' knowledge, this is the highest value for as-cleaved lasers at 1.3μm on InP substrates.

High temperature operation with a low threshold current, a high output power and no Peltier cooler are the main requirements for 1.3μm lasers used in local networks. It has been reported that the structure with strained InAsP wells and lattice-matched InGaAsP barriers is very promising because of its large conduction-band offset (70%) [1]. However, the high strain needed in the wells in this system material (~1.4% at 1.3μm wavelength) reduces the critical layer thickness to a small number of wells, usually less than five. However, a thick active layer, with a large number of wells, is very desirable for several purposes. For instance, good optical confinement together with favourable carrier transport mechanisms, and increased characteristic temperature.

In this Letter, we report for the first time a laser structure at 1.3μm based on compensated strain InAsP/InGaP material on an InP substate. High device quality material has been grown. 1.3μm lasers have exhibited a low threshold current density of 130A/cm² per well and a high characteristic temperature T_0 of 117K.

The growth was performed by MOCVD at atmospheric pressure. TMI and TMGa were used as sources of III elements and AsH_3 and PH_3 as sources for V elements. The structure consists of 10 InAsP compressive wells (1.7%) of 7nm thickness embedded between InGaP tensile barriers (–1.4%) of 5nm thickness. To increase the carrier injection efficiency from the InP cladding layer to the wells, the composition of the InGaP barriers is chosen with a bandgap (1.33eV) lower than that of InP. In addition, the InGaP material did not play only a mechanical role, i.e to compensate for the strain of the well, but improved also the electron confinement in the wells, which is the main requirement for operation at high temperature. The barrier height in the conduction band in this case is 212meV instead of 110meV when the lattice matched InGaAsP barriers at 1.1μm wavelength are used.

The material quality depends largely on the interface nature between the wells and the barriers. When the wells and barriers are grown on top of each other, the satellite peaks of the X-ray diffraction spectrum are very broad compared with the simulated results (Fig. 1(i)). The origin of this broadening is underlined by TEM [2] where lateral thickness undulations are observed. On the other hand, if a very thin layer of InP with just two monolayers is inserted between the well and barrier, the lateral thickness undula-