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

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


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The authors show by experiment and calculation that, for self-pulsating laser diodes synchronized to external electrical signals, a phase shift exists between the input 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.

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 -0.25V the laser self-pulsates at a frequency \(f_{SP} = 1300\)MHz. A sinusoidal input electrical signal is applied to the laser gain section in addition to the normal DC bias 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 measured to monitor \(f_{SP}\) 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 \(f_{SP} = 1300\)MHz, \(\Delta \phi_{LD}\) 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 \(f_{SP} = f_{SP}\). Each data point is the average of a number of measurements of \(\Delta \phi_{LD}\) taken for the same value of \(f_{SP}\). The total variation in phase shift for each electrical input level is -0.61 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. 1 Experimental setup](image)

![Fig. 2 Variation in the phase difference, \(\Delta \phi_{LD}\), between the applied electrical signal and the laser output pulsation relative to the phase difference of \(f_{SP} = 1300\)MHz, as the free-running self-pulsation frequency varies](image)
We have shown that when an SP LD synchronises to an external electrical signal, the phase difference between the electrical input and the laser output is determined by the phase of the electrical signal and the phase of the laser. The observed frequency dependent nature of the phase shift shows that all synchronised states are not the same, at least as far as the 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 phase 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. Contrary to this, our results show that an absolute phase difference exists between the applied signal and the pulseation, 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. For 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 the synchronised states are not the same, at least as far as the 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 possible to exploit 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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