AIP | Applied Physics Letters

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Citation: Applied Physics Letters **68**, 3534 (1996); doi: 10.1063/1.116521
View online: http://dx.doi.org/10.1063/1.116521
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/68/25?ver=pdfcov
Published by the AIP Publishing

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# All-optical synchronization of self-pulsating laser diodes

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(Received 6 December 1995; accepted for publication 15 April 1996)

We examine the behavior of self-pulsating laser diodes when injected with periodic optical signals. We experimentally and theoretically investigate the phase difference between the injected optical signal and the synchronized self-pulsating laser diode emission. We explore the phase difference dependence on detuning between the laser free-running self-pulsation frequency and the applied signal frequency, and on the injected signal power. The determined sensitive dependence of the phase difference on these factors has important consequences when self-pulsating lasers are used as optical signal processing elements in all-optical communication networks, where such sensitivity may lead to timing problems. © *1996 American Institute of Physics.* [S0003-6951(96)02625-3]

The physics of nonlinear oscillators interacting with applied signals is a problem that has long been of intense interest.[1–4] Laser diodes are particularly appropriate for investigating such phenomena as they are a relatively well understood model system for studying nonlinear dynamics and there is fundamental interest in understanding active nonlinear optical system behavior when perturbed by incident optical signals.[5] A less esoteric, but nonetheless urgent, applied interest in these matters is driven by telecommunications as the increasing sophistication of high bandwidth fiber optic networks will ultimately demand high speed optically transparent systems. While existing networks are not yet all-optical and contain electronic elements that carry out specific functions such as routing and switching, it is becoming increasingly apparent that such electro-optical conversions will place severe limitations on the bandwidth of future networks. All-optical networks hold the key to communications that will be high-speed, high-volume, and more widespread than ever before, especially given the market driven constraints of effective utilization of the installed infrastructural base. Given these demands and constraints, all-optical alternatives are being sought to many functions currently performed by electronic devices in communication networks. Selection and development of these all-optical networks requires understanding of the interaction of light with active optical media; for example, in wavelength division multiplexing using semiconductor optical amplifiers[6] and in signal processing using self-pulsating laser diodes (SP LDs).[7] In this letter, we examine the behavior of self-pulsating compact disk (CD) laser diodes when synchronized to externally injected optical signals. We examine the mechanism by which optical synchronization occurs and show how our numerical and experimental results can be explained on the basis of this mechanism. Calculations are found to be in excellent agreement with experimental results.

SP LDs using complex, multisection devices have been shown to carry out function such as all-optical synchronization and clock extraction at high speeds.[7,8] However, future low cost networks may require simpler structures with which to implement such functions. Laser diodes used for CD readout are designed to self-pulsate in order to reduce the deleterious effects of optical feedback on readout noise. Their low cost has already made CD lasers the emitter of choice for low cost data communications/interconnect applications, in which their low coherence reduces the effects of modal noise on transmission. Previously, the behavior of electro-optically synchronized SP multisection and CD laser diodes has been extensively investigated.[9–11] However, for transparent optical systems all-optical synchronization is of greater importance and is the subject of this letter.

Figure 1 shows the experimental setup. The CD laser to be synchronized (the slave) and the laser (the master) that provides the optical input to the slave are each a Sharp LT022. The master is electro-optically synchronized by application of a sinusoidal rf signal with a frequency of $\nu_{app} = 2$ GHz. The master laser synchronization is verified by monitoring its emission using an avalanche photodiode connected to a rf spectrum analyzer. Synchronization implies that the master laser optical output has a well-defined phase relationship with the signal generator output. The optical output from the master is coupled to the slave via an optical isolator, providing greater than 46 dB isolation. The slave laser emission is detected with a *p*-*i*-*n* photodiode, whose output is split: one portion is passed to a rf spectrum analyzer, to determine whether or not synchronization of the slave to the master has taken place, while the other portion is passed to an oscilloscope, which is triggered by the signal generator. If either the free-running SP frequency of the slave or the injected signal power are changed, the trace displayed on the oscilloscope shifts in time, and a change in the relative phase difference between the slave laser emission and the signal generator output can be measured, giving a measure of the relative phase difference, $\Delta\phi_D$, between the optical outputs of the master and slave. Note that this technique does not measure the absolute phase difference between the two signals.

Figure 2 shows $\Delta\phi_D$ for a number of injected power levels. For each set of data, $\Delta\phi_D$ is expressed relative to the phase difference at a frequency of $\nu_{fr} = \nu_{app}$, and the synchronization range shows a sharp cutoff at this point. The total phase range in Fig. 2 is about 100°, which is similar to the range reported for electro-optical synchronization of a two section SP LD.[10]

In order to understand these results we have carried out numerical modeling of the optical synchronization of a CD

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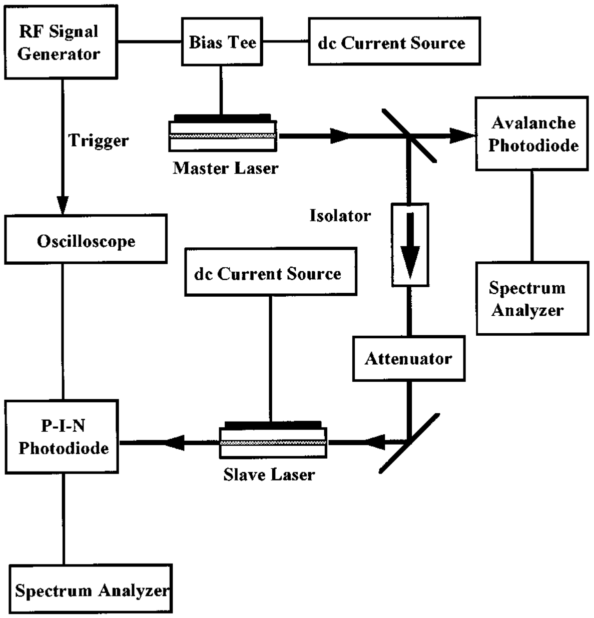

FIG. 1. Experimental setup used to measure the dependence of the phase difference between the optical input and the output for a synchronized self-pulsating CD laser on the free-running SP frequency and the input signal power. The master laser emission is injected into the slave laser and synchronizes it.

laser. SP in laser diodes is explained on the basis of saturable absorption models.[12–16] CD laser saturable absorption arises because the optical mode extends beyond the central region of the laser to overlap the umpumped region parallel and adjacent to the active region. The photon and carrier dynamics of these lasers can be described by three rate equations; one each for the carrier density in the active and parallel regions, and one for the mean photon density in the cavity. Such a model has been described by Yamada[17] and the calculations presented in this letter are based on this model. The parameters used in the rate equations are also taken from Yamada.[17]

We model synchronization of a CD laser using Yamada's model with the modification of the photon rate equation to

$$\frac{dS}{dt}=\nu_{gp}[\Gamma_1 g(n_1)-\Gamma_2 \alpha(n_2)-\alpha_0]S+\beta B n_1^2+S_{app}(t), \qquad (1)$$

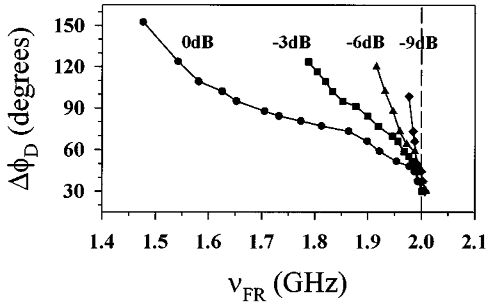

FIG. 2. Experimentally determined dependence of phase difference between optical input and output on free-running SP frequency and injected optical power. The labels signify the injected power level and are expressed relative to the 0 dB level ($\nu_{app}=2$ GHz).

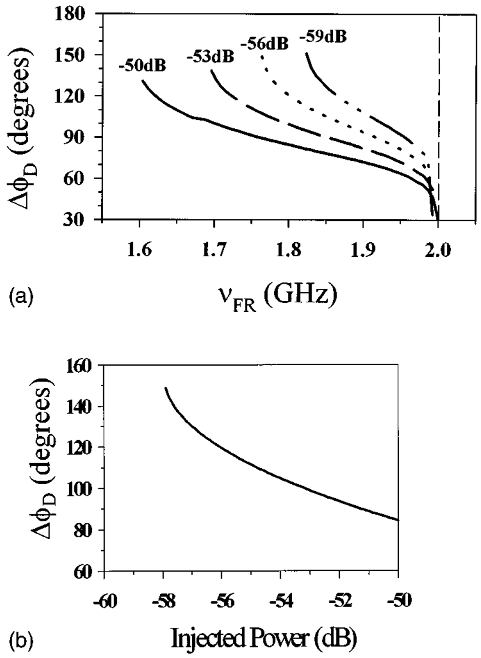

FIG. 3. Calculated dependence of relative phase difference between injected optical signal and laser output on (a) free-running SP frequency of a synchronized CD laser and (b) injected signal power. The labels in (a) refer to the injected signal power and $\nu_{app}=2$ GHz. $\nu_{fr}=1.8$ GHz in (b).

where all symbols have their usual meanings and the last term represents the applied optical signal. Spectral detuning effects are neglected in the model. While spectral detuning will obviously affect the coupling between the master and slave lasers, it has been shown that injection locking is not required for all-optical synchronization and these systems can be used for synchronization/clock extraction with wavelength changing.[18] For simplicity, the simulated optical signal is treated as a train of rectangular pulses with a duty cycle of 10% and a frequency of $\nu_{app}=2$ GHz. The laser dc bias is varied so as to vary $\nu_{fr}$ around 2 GHz. Synchronization occurs when the injection of the optical signal causes the slave laser SP frequency to shift to 2 GHz. The phase difference between the optical input and output is then determined, where this is defined as the phase difference between the rising edge of the applied optical pulse and the peak of the next output optical pulse, i.e., the output pulse leads the input pulse.

Figure 3(a) shows the calculated dependence of the phase difference on $\nu_{fr}$ and injected power level. All power levels are expressed relative to the laser output power when $\nu_{fr}=2$ GHz and 100% coupling of the injected signal to the lasing mode is assumed. It can be seen that the total phase range in each case is about 90°, which compares well with the phase range in the experimental results of Fig. 1. The agreement in the trend of phase shift with detuning and incident power between the two figures is excellent. For SP LDs synchronized to applied electrical signals, synchronization occurs for both positive and negative detuning of $\nu_{app}$ from $\nu_{fr}$.[11] Both experiment and calculation show that this is not the case for optically injected signals. Figure 3(b) shows the dependence of $\Delta\phi_D$ on injected power for $\nu_{fr}=1.8$ GHz. Clearly the variation of $\Delta\phi_D$ with power is greatest for low powers. We note that no attempt has been

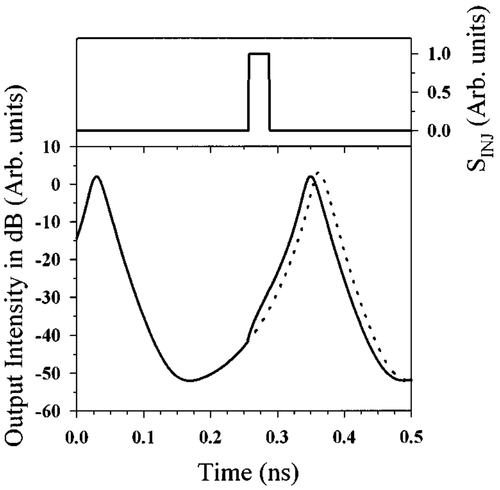

FIG. 4. Calculated temporal evolution of normalized injected light intensity, $S_{\mathrm{INJ}}$, and logarithm of output light intensity from a CD laser. The free-running SP frequency of the laser is 1.92 GHz and the injected optical signal frequency is 2 GHz. The dotted line in the lower plot represents the evolution of the optical output in the absence of the injected signal.

made to fit the calculated results to experiment. Nevertheless, the agreement in trend between experiment and calculation is excellent. The residual discrepancies perhaps arise from the fact that the CD laser emission is multimode while our model is single mode.

To better understand these results, we show in Fig. 4 the calculated synchronizing effect when an optical pulse train with a repetition frequency of $\nu_{app} > \nu_{fr}$ is injected into a SP LD. The incident signal frequency is $\nu_{app} = 2$ GHz and the pulse width is 40 ps (approximately the same width as the CD laser pulses), while the CD laser free-running SP frequency is $\nu_{fr} = 1.92$ GHz. The injected power is approximately $-55$ dB. The upper plot in Fig. 4 shows the injected optical pulse while the lower, semilogarithmic plot show the laser emission. The figure illustrates how the injected optical signal modifies the emission time of the next output laser pulse, i.e., the mechanism by which optical synchronization occurs. The dotted line represents the evolution of the laser emission in the absence of the injected signal. It is clear that the injected optical pulse hastens the occurrence of the next laser pulse by increasing the photon density rate of change in the cavity for the injected pulse duration, thereby decreasing the period between the output pulses and increasing the laser SP frequency from $\nu_{fr}$ to $\nu_{app}$. At low injected power levels there is no mechanism to allow the injected optical pulse to delay the emission of the next laser pulse; hence the extreme asymmetry of the synchronization range. (At higher power levels this is not the case.)

An understanding of the mechanism of optical synchronization allows us to explain why $\Delta\phi_D$ depends on $\nu_{fr}$ and injected signal power. The laser cavity photon density evolution is clearly nonlinear between the emission of optical pulses. Consequently, the effect of the injected optical pulse on the photon density in the cavity depends on the photon density rate of change at the time of injection, and hence on the phase difference with respect to the next output laser pulse. When $\nu_{fr}$ changes, the input synchronizing pulses must interact at a different value of $\Delta\phi_D$ in order to appropriately modify the emission time of the next output optical pulse and change the SP frequency from $\nu_{fr}$ to $\nu_{app}$. $\Delta\phi_D$ depends on the injected power level since this parameter also defined how much the injected optical pulse modifies the photon density evolution.

The master/slave SP frequency detuning dependence and the incident power dependence of $\Delta\phi_D$, are clearly significant for timing applications that utilize synchronized SP LDs in all-optical communication networks. In previous works, utilizing more complex multisection SP LDs it has been suggested that when all-optical synchronization takes place the pulse emitted by the slave coincides with the injected synchronizing pulse.[19] While our investigations concern CD laser diodes we expect that these results are applicable to all SP LDs containing saturable absorbers. Our results have clearly shown that a simple temporal coincidence of the injected optical pulses and output laser pulses cannot be assumed. Of particular practical importance is the dependence of $\Delta\phi_D$ on the injected signal power. In optical communication systems, data or clock signals may travel from one element in the system to another along different routes and thereby suffer different levels of attenuation along these routes. Under such circumstances the injected signal power to the SP LD will vary and the result will be a stochastic phase difference between the injected signal and the output signal from the laser. Such a situation would cause tremendous difficulties in clock extraction and timing. Since the phase variation with power is less for higher injected powers, the problem can only be minimized by requiring very high power arriving at switching nodes.

We acknowledge insightful discussions with Gerry Farrell. This work was supported by the Commission of the European Communities under a Human Capital and Mobility Network, Contract CHRX-CT94-0594 (administered by France Teecom). P. Rees is supported by the Commission of the EC under the Human Capital Mobility Research Training Program.

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