Optical injection locking and phase-lock loop combined systems

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Optical injection locking and optical phase-lock loops have been used for laser synchronization. The use of a combined optical injection locking and phase-lock loop system is proposed here. We have taken into account the modification of the slave laser phase response induced by the injection locking to calculated the phase-error signal spectrum and the phase-error variance for an optical injection locking and phase-lock system. They show that this system presents both a wide locking range, given by the optical injection locking action, and a low phase error for low frequencies, given by the optical phase-lock loop action. These results can improve the system tracking capability and decrease the final phase-error variance compared with those in isolated systems.

Optical injection locking (OIL) and optical phase-lock loops (OPLL's) are two methods of obtaining laser synchronization, with a wide range of applications.[1] In communications, they are used to provide a synchronous optical local oscillator in coherent detection and pure optical carriers for dense optical frequency-multiplexed systems.[2] They can provide sensitive phase demodulation for optical sensors and communication systems.[3] Synchronized multiple coherently combined lasers[4] are used for generation of optical pulses,[5] and these methods are also used for microwave signal generation[6] for beam-forming networks in phased-array antennas.[7]

Synchronization of narrow-linewidth lasers, such as Nd:YAG lasers,[3] can be made with OPLL's. However, this technique becomes complicated when semiconductor lasers are used, because of their wide linewidth. One solution, to reduce the lasers linewidth with, for example, external cavities,[8] presents mechanical stability problems. Another solution is to increase the OPLL loop bandwidth to compensate for the wider phase noise spectrum. The main factor limiting the loop bandwidth is the loop propagation delay time T_d.[9] First, a homodyne OPLL was built with $T_d = 1$ ns, resulting in a phase-error variance σ^2 of 0.15 rad^2 and a 134-MHz loop bandwidth.[10] A heterodyne experiment was made with $T_d = 3$ ns, $\sigma^2 = 1.02$ rad^2, and a 20-MHz loop bandwidth limited by the narrow phase response of the lasers used.[11] This problem was solved in a third experiment by use of multisection laser diodes, with which a 180-MHz loop bandwidth and $\sigma^2 = 0.04$ rad^2 with $T_d = 0.4$ ns were achieved.[6] However, only the integration of such systems can make OPLL's commercially available.

OIL systems can also provide a phase lock with the complexity involved in building an OPLL, with a wide locking range. Experiments show that locking ranges of the order of gigahertz are achievable.[12] However, OIL systems cannot follow long-term drifts of the master laser, as they present nonzero steady-state error. We propose here a new system made by the combination of optical injection and the phase-lock loop (OIPLL) as an option to increase the locking bandwidth, to reduce the phase-error variance, and to reduce the zero-frequency phase error, in relation to those of isolated OIL and OPLL systems.

Figure 1 is a block diagram of a homodyne OIPLL system. The signal from the master laser is divided into two paths: one is injected into the slave laser cavity and the other is mixed with the signal from the slave laser on a photodetector surface. The photodetector works as a phase detector that will produce a phase-error signal proportional to the phase difference between the master and slave laser signals. This error signal is used to change the slave laser current after it passes through an appropriate loop filter. The idea is to phase lock the slave laser to the master laser through injection locking and use the phase-lock loop to minimize the phase error.

In the OIL case, phase locking is achieved directly by the injected optical signal from the master laser, which stimulates the emission in the slave laser waveguide to be in phase with the injected signal.[12] The spectral density of the phase error caused by the phase noise from master and slave lasers is given by[13]

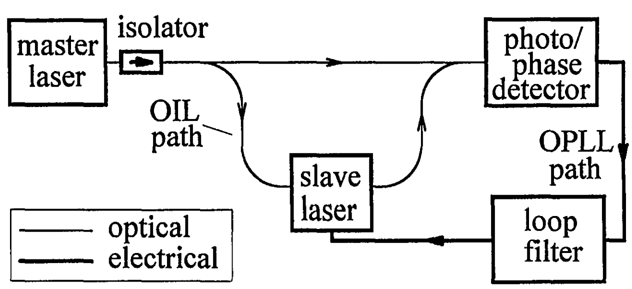

Fig. 1. Block diagram of a homodyne OIPLL system.

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$$S_i(\omega) = \frac{\omega^2}{\omega^2 + \omega_c^2}[S_m(\omega) + S_s(\omega)], \tag{1}$$

where ω is the phase-error signal angular frequency and $S_m(\omega)$ and $S_s(\omega)$ are the phase noise spectral densities of the free-running master and slave lasers, given by

$$S_m(\omega) = \frac{\Delta\omega_m}{\omega^2}, \qquad S_s(\omega) = \frac{\Delta\omega_s}{\omega^2}, \tag{2}$$

with $\Delta\omega_m$ and $\Delta\omega_s$ the master and slave laser free-running cw linewidths. Note that these equations can be considered valid for frequencies well below the laser's photon-carrier relaxation frequency (adiabatic linewidth approximation). The 3-dB cutoff frequency, ω_c, is given by

$$\omega_c(\theta) = \frac{\partial\delta\omega(\theta)}{\partial\theta}. \tag{3}$$

θ is the stationary value of the phase detuning and $\delta\omega(\theta)$ is the slave laser detuning, which is the difference between the optical frequency of the master and that of the slave laser, given by

$$\delta\omega(\theta) = \rho(\sin\theta - \alpha\cos\theta), \tag{4}$$

where α is the amplitude-phase coupling between intensity and phase fluctuations and the factor ρ is given by

$$\rho = \frac{1}{2L} v_g\sqrt{\eta(P_m/P_l)}. \tag{5}$$

Here L is the length of the slave laser cavity, v_g is the group velocity, η is the fraction of the incident light coupled to the lasing mode, P_m is the master laser power, and P_l is the slave laser power. The locking range bandwidth is given by[14]

$$L_R = \rho\sqrt{1 + \alpha^2}. \tag{6}$$

Note that the locking range is not symmetric[14,15] for Fabry–Perot lasers, which means that this value of L_R is valid for locking from only one side of the frequency spectrum. However, it can be considered symmetric when distributed-feedback lasers are used. In the OIPLL case, when the OPLL path is added, the spectrum of the phase-error signal becomes

$$S_e(\omega) = S_i(\omega)|1 - H(\omega)|^2 + S_{sn}(\omega)|H(\omega)|^2, \tag{7}$$

where $S_{sn}(\omega)$ is the phase noise spectrum that results from shot noise and $H(\omega)$ is the closed-loop transfer function, given by

$$H(\omega) = \frac{kF(\omega)H_\varphi(\omega)\exp(-j\omega T_d)}{1 + kF(\omega)H_\varphi(\omega)\exp(-j\omega T_d)}. \tag{8}$$

Here k is the loop gain, T_d is the total loop delay time, and $F(\omega)$ is the loop filter transfer function. The loop filter transfer function for a second-order loop is given by

$$F(\omega) = \frac{j\omega T_2 + 1}{j\omega T_1}, \tag{9}$$

where T_1 and T_2 are the loop filter constants. The critical conditions for the OPLL stability are calculated as shown by Grant *et al.*[16]

$H_\varphi(\omega)$ is the phase-modulation response of the slave laser. It is a crucial parameter that can limit the performance of the OPLL section.[11] The presence of injection locking can modify the phase-modulation response of the slave laser.[17] Generally speaking, a frequency variation of the output signal of a free-running laser is proportional to a current variation applied to it, for low modulation frequencies. However, when the laser is injection locked, a variation of current (within the locking range) leads to a variation of the output signal phase, modifying the phase difference between the slave and master optical signals. This modification of the slave laser phase response induced by the presence of injection locking can seriously affect the performance of the OPLL part of the system.

When the slave laser is injection locked, it presents a phase-modulation response given by (for a saturated gain single-section semiconductor laser)[18]

$$H_\varphi(\omega) = \frac{1}{e}\,\frac{(EK + ED - BC + j\omega E)}{L(\omega)}, \tag{10}$$

where the variables A, B, D, E, F, H, K and $L(\omega)$ are defined as[18] $A = 2P_s\rho\sin\theta$, $B = G_nP_s$, $C = (\rho/2P_s)\sin\theta$, $D = \rho\cos\theta$, $E = \alpha G_n/2$, $F = G_o + G_pP_s$, $H = G_nP_s + 1/T_e$, $K = (n_{sp}G_s/P_s) - G_pP_s$, and

$$\begin{aligned} L(\omega) = {} & [FAE + FBD + HKD + HD^2 \\ & + HAC - \omega^2(H + 2D + K)] \\ & + j\omega(FB + 2HD + HK \\ & + KD + D^2 + AC - \omega^2), \end{aligned}$$

where P_s is the number of photons in the slave laser cavity, n_{sp} is the spontaneous emission factor, G_s is the slave laser gain, G_n is the differential gain, G_o is the stationary value of the gain, G_p represents the spectral hole burning, and T_e is the excited carrier lifetime. The phase-error variance can be calculated by

$$\sigma^2 = \int_0^\infty S_e(\omega)\mathrm{d}\omega. \tag{11}$$

Figure 2 shows the spectrum of the phase error $S_e(\omega)$ for the following cases: free running, OIL only, OPLL only, and OIPLL. The master laser is assumed to present a relatively narrower linewidth (1 MHz) compared with the slave laser linewidth (70 MHz), which is considered to be a GaAs/AlGaAs CSP laser (Hitachi HLP1400) with 2 mW of output power. It is assumed that the path length between the slave laser and the photodetector is adjusted for

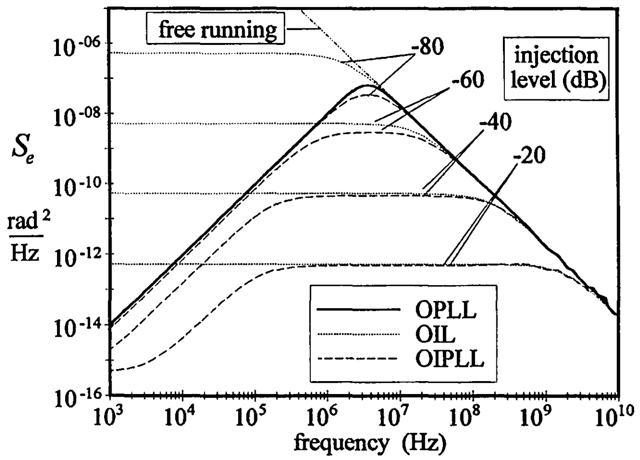

Fig. 2. Phase-error spectrum S_e for OPLL, OIL, and OIPLL for injection rates of −20, −40, −60, and −80 dB.

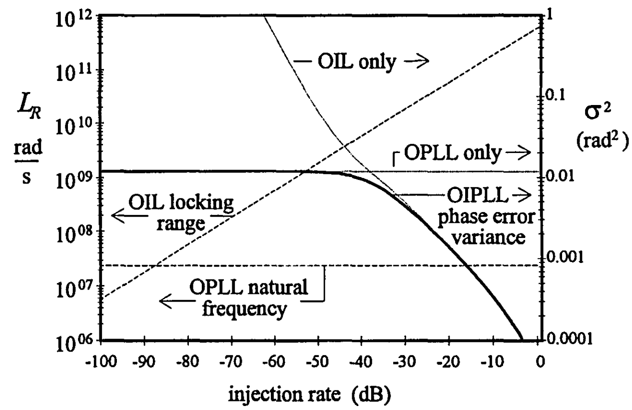

Fig. 3. OIL locking range and OPLL natural frequency (left-hand scale) and phase-error variance for OIL, OPLL, and OIPLL systems (right-hand scale) as functions of the injection rate.

$\theta = 0$. The values for the constants used are $\lambda = 830$ nm, $L = 300$ μm, $\alpha = 5$, $n_{sp} = 2.6$, $T_e = 2.2$ ns, $G_n = 5750$ s^{-1}, $G_o = 1.67 \times 10^{12}$ s^{-1}, $G_p = 5460$ s^{-1}, $G_s = 7.7 \times 10^{11}$ s^{-1}, $k = 1.74 \times 10^5$, $T_d = 1$ ns, $T_1 = 0.32$ ns, and $T_2 = 60$ ns. A loop gain margin of 30 dB from the critical value and a damping factor of 0.707 are used in the OPLL part to ensure the system's stability. The change of the slave laser phase response as a result of the presence of injection locking may relax the stability conditions of the OPLL mechanism. This makes it possible for us to improve its performance by adjusting the loop parameters, with the risk of oscillations in the case of a momentarily lack of optical injection.

From Fig. 2 it can be seen that the addition of the OPLL circuit to the OIL system reduces the low-frequency phase error, tending to reduce the zero-frequency phase noise to shot-noise levels. The effect of adding an OIL system to an OPLL system is to decrease the amount of phase error for the frequencies in which the residual phase noise of the OPLL is greater than that of the OIL.

Figure 3 shows the phase-error variance of the combined system for a bandwidth of 10 GHz. For low values of injection (below −50 dB), the phase-error variance is close to the OPLL value without injection locking. For high values of injection (above −25 dB), the action of the OIL becomes dominant, and the system behaves as injection locked only. A linearized model of the phase detector was adopted in these calculations. However, if a sinusoidal phase detector is used, the performance of the OPLL becomes compromised as a result of the effect of cycle slips. In this case, the action of the OPLL would be negligible for phase-error variances greater than 1 rad^2. Figure 3 also compares the injection-locking range as a function of the injection rate to the OPLL natural frequency. The locking range of an OPLL is assumed here to be very close to the loop natural frequency (23.4 Mrad/s in this example). Note that the natural frequency cannot be defined for the OIPLL system, as it is no longer a second-order system. The injection-locking range is greater than the OPLL natural frequency for injection rates above −88 dB, in this example.

The OIPLL system can provide both the wide locking range of an OIL system and the weak low-frequency phase error of an OPLL system. The tracking capability of the combined system can be improved in relation to that of the isolated OIL and OPLL systems, as long-term fluctuations can be compensated for electrically by the OPLL path and the faster fluctuations can be followed by the OIL path.

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