Comparison Between First-Order and Second-Order Optical Phase-Lock Loops

R. T. Ramos and A. J. Seeds, *Senior Member, IEEE*

Abstract—**A comparison between the performance of modified first-order and second-order optical phase-lock loops (OPLL's) is made, revealing that the modified first-order loop offers better performance when long loop delay time is present and a wide bandwidth loop filter is used. The introduction of a 10 dB gain margin from the critical gain can be used to keep the damping close to that expected when the delay time is negligible. If OPLL design is optimized for this gain margin and 5 MHz linewidth lasers are used, the increase in the phase-error variance with delay time is 54 rad$^2/\mu$s for a modified first-order and 80 rad$^2/\mu$s for a second-order loop, confirming that modified first-order loops are less sensitive to loop delay.**

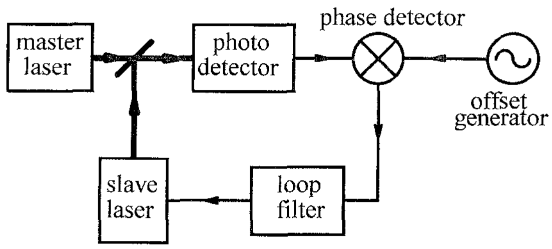

Fig. 1. Block diagram of an heterodyne optical phase-lock loop.

OPTICAL Phase-Lock Loops (OPLL's) have been studied as a way of generating microwave signals for Optical Beam Forming Networks (OBFN's) for phased array antennas [1], when a large number of elements would make advantageous the use of an optical fiber distribution network. Experiments have demonstrated the feasibility of this approach at microwave frequencies [2], [3], and the technique can be extended to the millimeter-wave range.

Fig. 1 shows the block diagram of an heterodyne OPLL. The slave laser is controlled by the loop to oscillate at an optical frequency different from the master laser by the frequency of the offset generator. In the case of an OBFN, the microwave signal is reproduced at each element of the antenna array by the heterodyne of the two optical signals after transmission through a fiber network. The OPLL performance is given by its ability to eliminate the phase-error in the heterodyne signal, introduced mainly by the phase noise from the lasers used. When semiconductor lasers are used, as preferred for practical systems, this phase noise can make the linewidth of the microwave signal generated of the order of MHz in the free-running case.

Two kinds of loops are studied here: The modified first-order loop and the second-order loop. The loop filter transfer functions for the modified first-order loop and the second-order loop are respectively:

$$F_1(s) = \frac{1}{sT_1 + 1} \quad \text{and} \quad F_2(s) = \frac{1 + sT_2}{sT_3}. \tag{1}$$

Manuscript received August 24, 1993.

R. T. Ramos is with the École Nationale Supérieure des Télécommunications, Dépt Communications, 75634 Paris, cedex 13, France.

A. J. Seeds is with the Dept. of Electronic Engineering, University College London, Torrington Place, London, WC1E 7JE, UK.

IEEE Log Number 9214717.

The closed loop transfer function is then given by:

$$H(s) = \frac{kF(s)e^{-sT_d}}{s + kF(s)e^{-sT_d}} \tag{2}$$

where T_1 and T_2 are time constants, k is the loop gain, T_d is the loop propagation delay time and $s = j2\pi f$. The spectrum of the phase-error signal $S_e(f)$ can be calculated from [4]:

$$S_e(f) = \left[\frac{\delta f_m + \delta f_s}{2\pi f^2}\right][|1 - H(j2\pi f)|]^2 + \left[\frac{e}{2RP_s}\right][|H(j2\pi f)|]^2 \tag{3}$$

where δf_m and δf_s are the FWHM linewidth of the master and slave lasers, respectively, R is the photodetector responsivity and P_s is the slave laser power. The phase-error variance is given by:

$$\sigma^2 = \int_0^\infty S_e(f)df. \tag{4}$$

Figs. 2 and 3 show the spectral density of the phase-error signal for a modified first-order loop and a second-order loop using several values of loop gain. Representative values of loop delay time and laser linewidths of 3 ns and 2.5 MHz were assumed. A stability study was made, and the critical loop gain was calculated for each case. When values of gain close to the critical gain are used, the phase-error spectrum presents a peak at the loop natural frequency and the loop tends to oscillate. The critical gain is calculated here as in [4] ($k_{cr1} = 478 \times 10^6 s^{-1}$) for the modified first-order loop and as in [5] ($k_{cr2}/T_3 = 6 \times 10^{16} s^{-2}$) for the second-order loop. The loop filter cut-off frequency for the modified first-order loop is assumed to be 500 MHz (T_1 = 318ps), and the value of T_2 is optimized for each value of gain to keep the system stable (T_2 =5.74, 7, 8.1, and 10 ns when the gain is 0, 1.76, 3, and 10

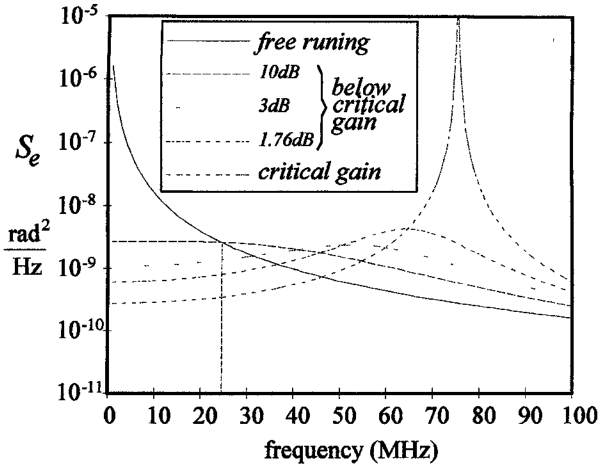

Fig. 2. Spectrum of the phase-error signal S_e for a modified first-order loop for several values of loop gain.

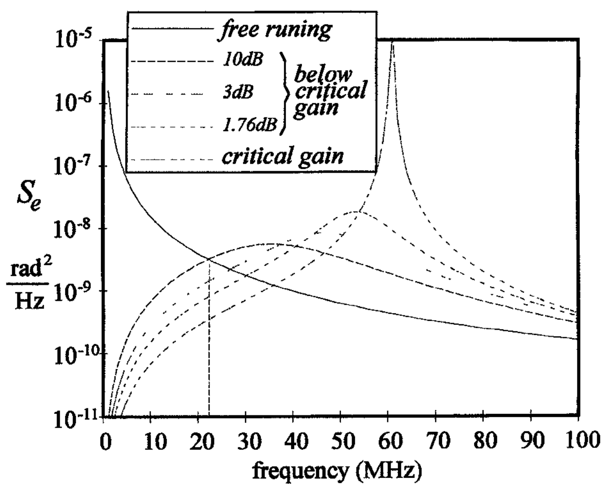

Fig. 3. Spectrum of the phase-error signal S_e for a second-order loop for several values of loop gain.

dB below critical). This modeling does not take into account the non-uniform frequency response of loop components such as the phase detector and the slave laser FM response, which would modify the spectrum in Figs. 2 and 3 [2].

Note that the loop damping factor cannot be defined for a loop with significant delay, as it cannot be seen as a second-order system. A reduction of 10 dB from the critical gain value introduces a gain margin and makes the actual damping to be closer to the calculated value when the effect of the loop delay time is not taken into account. In the case of Figs. 3 and 4, this value is set at $1/\sqrt{2}$.

The OPLL bandwidth is given by the point where the spectrum of the residual phase noise presents the same value as the one for the free-running case [6]. The gain margin could be reduced to 3 dB to increase the loop bandwidth, which would decrease the actual system damping. For the modified first-order loop, this gain margin reduction to 3 dB could reduce the zero frequency phase-error without significant change in the value of phase-error variance.

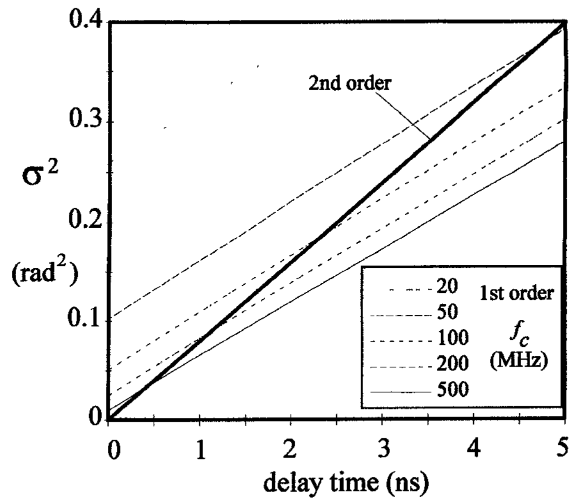

Fig. 4. Phase-error variance σ^2 of a modified first-order loop for several values of loop filter cut-off frequency and of a second-order loop as function of the loop delay time.

Fig. 4 shows the phase-error variance for a modified first-order loop and second-order loop as a function of delay time. A summed linewidth of 5 MHz and gain 10 dB below critical are used for each point. It can be seen that the slope of the line corresponding to a second-order loop ($\sim$ 80 rad$^2/\mu$s) is steeper than that for a modified first-order loop ($\sim$ 54 rad$^2/\mu$s) indicating that second-order loops are more sensitive to delay time than modified first-order loops. This can make the use of modified first-order loops preferable in systems with long delay time. However, for short delay times, a modified first-order loop would have to contain a very wide bandwidth filter in order to present a reasonable performance. This is not always practical as other loop components can also limit the open loop bandwidth.

To conclude, a reduction of 10 dB from the critical gain value introduces a gain margin and assures a damping close to that expected if the loop delay time was negligible. A gain margin reduction to 3 dB can be used for a modified first-order loop to increase the system bandwidth and decrease the zero frequency error without significant change in the total phase-error variance.

Second-order loops can present better performance than modified first-order loops for small loop delays. However, mechanical constraints result in having significant loop delay time. In such systems, the modified first-order loop can offer reduced phase-error variance. For a representative loop having a 10 dB gain margin and 5 MHz summed linewidth lasers, the increase rate of the phase-error variance with loop delay time is ($\sim$ 54 rad$^2/\mu$s) for a modified first-order and ($\sim$ 80 rad$^2/\mu$s) for a second-order loop, confirming that modified first-order loops are less sensitive to loop delay. This makes modified first-order loops a better option for long delay time systems with wide linewidth lasers. The use of the design techniques described here should bring semiconductor laser-based coherent-beam forming networks closer to commercial implementation.

REFERENCES

[1] U. Gliese, E. L. Christensen, and K. E. Stubkjær, "Laser linewidth requirements and improvements for coherent optical beam forming networks in satellites," *J. Lightwave Technol.*, vol 9, pp. 779–790, June 1991

[2] R. T. Ramos and A. J. Seeds, "Fast heterodyne optical phase-lock loop using double quantum well laser diodes," *Electron. Lett.*, vol. 28, pp. 82–83, 1992.

[3] U. Gliese, T. N. Nilsen, M. Bruun, E. L. Christensen, K. E. Stubkjær, S. Lindgren, B Broberg, "A wide heterodyne optical phase-lock loop for generation of 3–18GHz Microwave carriers," *IEEE Photon. Technol. Lett.*, vol. 4, pp. 936–938, Aug. 1992.

[4] R. T. Ramos and A. J. Seeds, "Delay, linewidth and bandwidth limitations in optical phase-locked loop design," *Electron. Lett.*, vol 26, pp. 389–391, 1990.

[5] M. A. Grant, W. C. Michie and M. J. Fletcher, "The performance of optical phase locked loops in the presence of nonnegligible loop propagation delay," *J. Lightwave Technol.*, vol. 5, pp. 592–597, 1987.

[6] M. Kourogi, C.H Shin, M Ohtsu, "A 134 MHz bandwidth homodyne optical phase-locked-loop of semiconductor laser diodes," *IEEE Poton. Technol. Lett.*, vol. 3, pp. 270–272, 1991.