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Coherent Optical Generation of a 6 GHz Microwave Signal with Directly Phase Locked Semiconductor DFB Lasers

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Abstract

Experimental results of a wideband heterodyne second order optical phase locked loop with 1.5 μm semiconductor lasers are presented. The loop has a bandwidth of 180 MHz, a gain of 181 dBHz and a propagation delay of only 400 ps. A beat signal of 8 MHz linewidth is phase locked to become a replica of a microwave reference source close to carrier with a noise level of -125 dBc/Hz. The total phase variance of the locked carrier is 0.04 rad^2 and carriers can be generated in a continuous range from 3 to 18 GHz. The loop reliability is excellent with an average time to cycle slip of 10^{11} seconds and an acquisition range of 640 MHz.

I. Introduction

Optical generation, distribution and signal processing of microwave signals have become increasingly interesting since many signal processing tasks are performed much more efficiently in the optical domain. Examples of applications are optical transmission of microwave signals, optical control of microwave devices, and optical beam forming for phased array antennas in microwave communication systems [1].

To be able to take full advantage of the optical signal processing capabilities, it is often necessary to generate the microwave carriers with coherent optical methods. Naturally, the hereby generated carriers must comply with the noise requirements of the microwave systems, in which they are to be used. Such carriers can be generated with a narrow band heterodyne optical phase locked loop (OPLL) based on either solid state lasers, such as the Nd:YAG [2], or semiconductor lasers with external cavities [3], [4] or with negative electrical feedback [5]. The use of semiconductor lasers without external linewidth narrowing arrangements would, however, be much more attractive due to compactness and potential for monolithic opto-electronic integration.

A major drawback of semiconductor lasers is phase noise which must be reduced significantly. For this purpose, a wideband OPLL can be very efficient if properly designed [1]. Until now, only two wideband quasi first order OPLLs with 830 nm semiconductor lasers have been reported; one homodyne exhibiting a total phase variance of 0.15 rad^2 [6] and one 5-7 GHz heterodyne exhibiting a total phase variance of 1.02 rad^2 [7]. Theoretical calculations, however, show that the required phase noise performance cannot be achieved from first order loops with realizable bandwidths [1]. In this paper, we present the experimental results of a 3-18 GHz heterodyne wideband high gain second order OPLL implemented with 1.5 μm DFB lasers without external cavities or electrical feedback for linewidth narrowing. As will be shown, the generated microwave carrier is highly stable and fulfills the phase noise requirements of existing QPSK/DQPSK microwave telecommunication systems. Furthermore, the loop operation is sufficiently stable for practical applications.

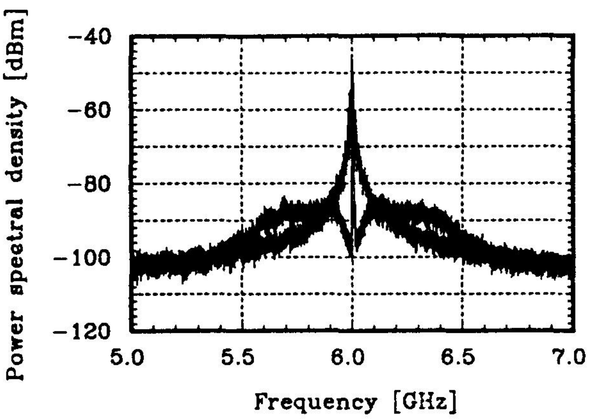


Figure 2: Power spectral density of the carrier at 6 GHz for both free running and phase locked lasers (as measured with RB = 3 MHz, VB = 100 kHz).

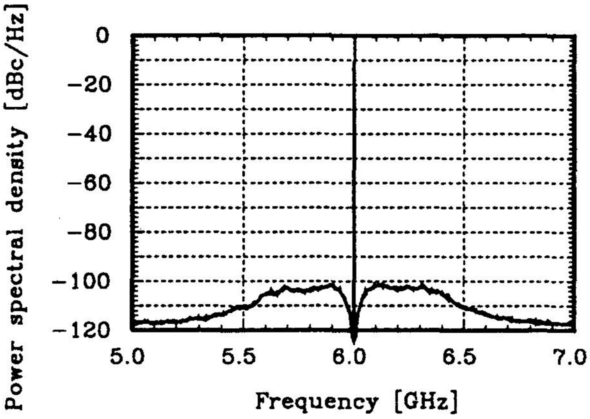


Figure 3: Measured power spectral density of the phase locked carrier at 6 GHz.

efficiency of 0.015 A/V of mixer input voltage to laser current. The loop filter following the mixer is a passive lowpass filter with phase lead correction. Due to the requirement of a low loop propagation delay, additional amplifier stages cannot be inserted neither before nor after the mixer to obtain the required loop gain. Instead, it is provided by the use of a CCO-laser with a uniform FM-response having a high FM-sensitivity of 2.5 GHz/mA. For this purpose the three-electrode DFB laser has proved very advantageous [9].

The principle of the OPLL operation is as follows: The beat signal of the two semiconductor lasers is compared to the signal from a microwave reference oscillator with a phase noise a little lower than required for the generated carrier (a HP synthesizer is used in the experiment). The resulting phase difference signal is fed back to the CCO-laser which is thus forced to track the Tx-laser. This causes a significant reduction of the phase noise of the optically generated microwave carrier. The power spectral density of the carrier is measured with a lightwave analyzer, and a Fabry-Perot interferometer is used to monitor the OPLL modulation of the CCO-laser during acquisition.

III. Results

As shown in Fig. 2, the action of the OPLL is to change the Lorentz-shaped 8 MHz linewidth beat spectrum of the free running lasers to a phase locked beat spectrum. Close to carrier, the phase locked spectrum corresponds exactly to the shape of the microwave reference oscillator, i.e., sub-Hertz linewidth. In Fig. 3, the power spectral density of the beat signal between the phase locked lasers is shown for a 6 GHz carrier frequency where the loop has its optimum performance. It is seen that the noise level is as low as -125 dBc/Hz close to the carrier and less than -102 dBc/Hz at all carrier offsets.

The measured phase fluctuation spectrum of the phase locked 6 GHz carrier is shown in Fig. 4. Due to the long sweep time required for the measurement, it is not possible to perform a comparative measurement of the 8 MHz linewidth free running signal. A calculated curve based on laser linewidth measurements is, therefore, shown for comparison. The total phase variance, $(\sigma_\phi)^2$, is found by integration of the phase fluctuation spectrum from zero to 1 GHz. The upper

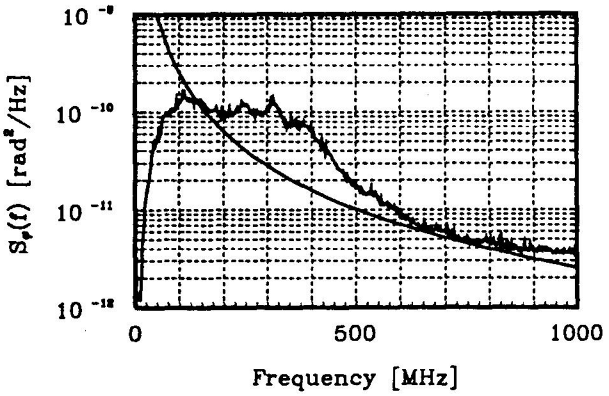


Figure 4: Measured phase fluctuation spectrum of the phase locked microwave carrier together with a curve representing the free running 8 MHz linewidth signal.

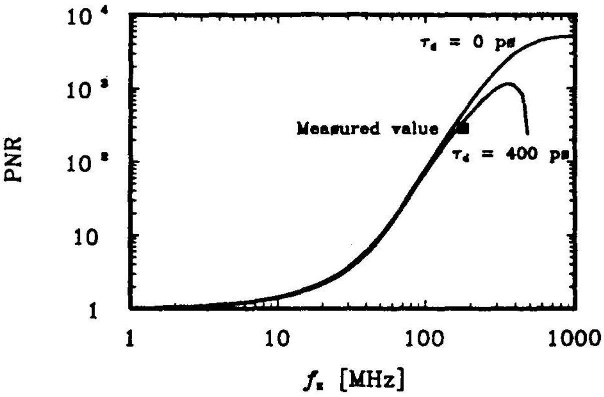


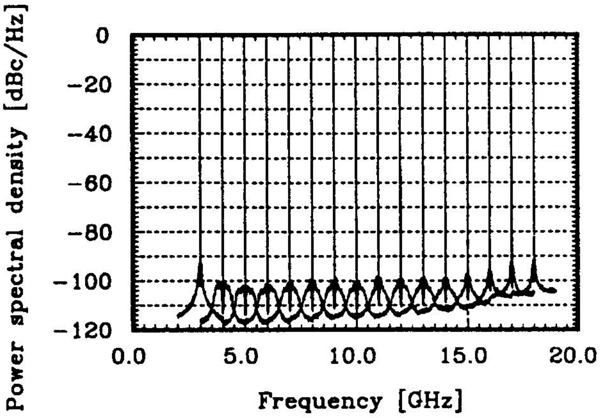
Figure 5: Phase noise reduction after receiver filtering in a 131 Mbit/s DQPSK system as a function of loop bandwidth. The results are for a second order OPLL with a loop gain of 181 dBHz, a damping coefficient, ζ, of 0.707 and the loop propagation delay as parameter.

limit of 1 GHz may be used as a good approximation to infinity due to the relatively lower noise content at high frequencies. The total phase variance is 0.04 rad^2 ($\sigma_\phi = 12°$) and represents the lowest value reported for phase locked semiconductor lasers to date.

In existing 131 Mbit/s QPSK/DQPSK microwave telecommunication systems the carrier is filtered in the receiver before demodulation and the phase noise is consequently lowered by the receiver filter [1]. For the generated carrier with $\sigma_\phi = 12°$, the expected values of σ_ϕ and $\sigma_{\Delta\phi}$ are only 1.4° and 2.4°, respectively. The values are below the required value of 2.8° in both cases, and the generated microwave carrier can thus be used in existing QPSK/DQPSK microwave telecommunication systems with bit rates of up to 131 Mbit/s.

A good measure for the OPLL performance is the phase noise reduction, PNR, of the differential phase noise after receiver filtering as defined in [1]. The PNR is given as the ratio between the differential phase variance in the free running state and in the locked state. For a 131 Mbit/s system we find a differential phase variance, $(\sigma_{\Delta\phi})^2$, of 0.51 rad^2 in the free running state [1], while it is 0.0018 rad^2 ($\sigma_{\Delta\phi} = 2.4°$) in the locked state, so the PNR is 284. In Fig. 5, the calculated PNR is depicted as a function of the loop bandwidth together with the experimental value which is found to be in excellent agreement with the theoretical prediction.

Due to the broad bandwidth of the microwave components, the OPLL can operate over a continuous carrier frequency range from 3 to 18 GHz. This is shown in Fig. 6 where the power spectral density of the phase locked carrier is shown as a function of the carrier frequency in steps of 1 GHz. The loop performance versus carrier frequency is shown in Fig. 7 where the percentage of total signal power locked in the carrier peak is depicted. For the 6 GHz carrier as much as 97.7 % of the total power is locked in the carrier peak. This agrees well with the measured total phase variance of 0.04 rad^2. Slight performance degradation occurs at the other carrier frequencies due to small variations of the transfer function of the microwave components (especially that of the mixer). It is, however, seen that more than 96 % of the total signal power is locked in the carrier peak for carriers in the frequency range from 4 to 15 GHz and more than



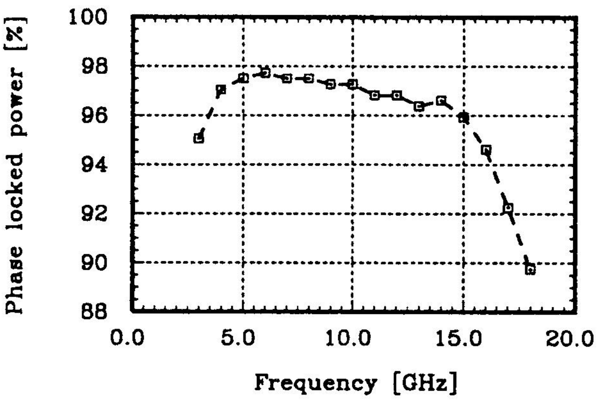


Figure 6: Power spectral density of the phase locked carrier in the range from 3 to 18 GHz.

Figure 7: Percent of total signal power locked in the carrier peak versus carrier frequency.

90 % for all the carriers in the range from 3 to 18 GHz. This is the largest range of highly stable microwave carriers ever reported for an OPLL with semiconductor lasers. The range could be further extended provided that microwave components (frontend and mixer) with a broader bandwidth are available.

Another very important property of our OPLL is its fine stability which is due to the large bandwidth and high gain. An acquisition range of 640 MHz has been measured and is in very good agreement with the theoretically expected value of 647 MHz. From the measured loop parameters, the average time to cycle slip, T_{av}, is 10^{11} seconds. This yields a probability of less than 0.3 % for one cycle slip within 10 years.

IV. Conclusion

In conclusion, experimental results for a highly efficient 3-18 GHz heterodyne OPLL have been presented. The results represent, to our knowledge, the best reported for wideband OPLLs. Furthermore, an excellent agreement between the theoretically predicted and the experimentally obtained results confirms the predicted phase noise reduction capabilities of extremely wideband OPLLs.

The results clearly demonstrate the feasibility of optical generation of microwave carriers with moderate linewidth semiconductor lasers. The carriers are sufficiently phase stable for application in existing microwave telecommunication systems.

Compared to optical generation of microwave carriers with narrow band OPLLs based on Nd:YAG lasers, this method has the inherent advantage of possible future monolithic optoelectronic integration. This is a very important issue for practical applications, especially in satellite systems but also in optical communication systems. Integration will further decrease the loop propagation delay and carriers for future Gbit/s systems can thereby be obtained.

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