Phase locking of a frequency agile laser

Vincent Crozatier, a) Guillaume Gorji, Fabien Bretenaker, Jean-Louis Le Gouët, and Ivan Loriger b)
Laboratoire Aimé Cotton, CNRS, Université Paris Sud, Bâtiment 505, 91405 Orsay Cedex, France
Claude Gagnon and Eric Ducloy
NetTest/Anritsu, 24 rue Emile Baudot, 91120 Palaiseau, France

(Received 11 October 2006; accepted 28 November 2006; published online 28 December 2006)

The authors report on the development and phase locking of a frequency agile laser. The use of a simple unbalanced Mach-Zehnder interferometer together with a wideband phase-locked loop permits to control very fast frequency chirps (up to 3 GHz in 5 µs) with an excellent precision (frequency error less than 100 kHz). The servolop could be applied to many tunable lasers. © 2006 American Institute of Physics. [DOI: 10.1063/1.2424659]

Lasers exhibiting high spectral purity and stability, together with fast, linear, and precise tunability, are key to many applications, e.g., laser spectroscopy, 1 coherent manipulation of atoms and molecules, 2 optical frequency domain reflectometry and laser radar, 3 or wideband optical coherent processing. 4,5

High spectral purity can be achieved through active stabilization on frequency references such as high finesse cavities 6 or atomic absorption lines. 7 However, these stabilization schemes do not permit laser frequency sweeps. Self-heterodyning schemes, using (fiber-based) Mach-Zehnder or Michelson interferometers, are easy to implement and can provide error signals for fixed frequency, 8,9 as well as frequency chirped lasers. 10,11 Servolop control of frequency chirped laser using self-heterodyning was initiated by Greiner et al. 10 However, the conception of this loop severely limited its bandwidth, hence its performances. In this letter, we present a very simple and versatile phase-locked loop (PLL) based on self-heterodyning that allows us to produce very fast and highly coherent laser chirps as well as fixed-frequency laser stabilization. The demonstration is performed with an extended-cavity diode laser but the same loop could be applied to virtually any tunable laser.

The experimental apparatus is described in Fig. 1. We consider a laser whose frequency is linearly scanned with a chirp rate r. The laser instantaneous frequency v(t) can be expressed as

\[ v(t) = v_0 + rt + \epsilon(t), \]

where \( v_0 \) is the quiescent laser frequency, and \( \epsilon(t) \) represents noises affecting the laser frequency while it is chirped. The laser output is connected to an unbalanced Mach-Zehnder interferometer (UMZI), whose long arm introduces a propagation delay \( T_d \).

At the interferometer output the laser instantaneous frequencies \( v(t) \) and \( v(t-T_d) \) are recombined, and a beat signal

\[ I_b(t) = I_0 \cos(2\pi f_0 t + \psi + 2\pi \int_{t-T_d}^{t} \epsilon(t') dt') \]

can be detected. \( I_0 \) is the beat note amplitude, \( f_0 = rT_d + f_0 \) the beat frequency with \( f_0 \) the driving frequency of the optional acousto-optic modulator (AOM), and \( \psi \) a constant phase term.

The beat signal phase noise is related to the laser frequency (or phase) errors. Through spectral analysis of such a beat note one can identify the stochastic or deterministic noises that affect the laser frequency during the chirp. 11 If we consider that the propagation delay \( T_d \) is small as compared to the typical variation time scale of \( \epsilon(t) \), Eq. (2) can be developed as

\[ I_b(t) = I_0 \cos(2\pi f_0 t + \psi + 2\pi T_d \epsilon(t)). \]

In order to extract \( \epsilon(t) \), one can for instance mix the beat note signal with a reference local oscillator (LO), whose frequency matches \( f_b \). This demodulation process creates an error signal \( \epsilon(t) \) directly proportional to \( \epsilon(t) \). This signal can further be filtered to provide a correction signal \( c(t) \) to apply to the laser. The errors \( \epsilon(t) \) are compensated for and the laser frequency follows precisely a linear chirp. This system is comparable to an electronic PLL, where the voltage-controlled oscillator consists of the ensemble laser+UMZI.

However, the UMZI and its propagation delay \( T_d \) induce important effects. One can show that the UMZI exhibits a transfer function \( H(f)=1-\exp(-2\pi fT_d) \). This function is unusual as it mixes a linear phase dispersion together with a sine amplitude response. The latter is equivalent at low frequency to a derivative response and can be compensated for electronically. But the phase dispersion associated with the delay \( T_d \) has a drastic impact that obviously limits the loop bandwidth to \( \sim T_d^{-1} \). On the other hand, a long propagation delay improves the chirp measurement sensitivity. 11

This stabilization scheme was implemented with a homemade frequency agile laser (see Fig. 1). The laser is an extended-cavity diode laser (ECDL) in the Littrow configuration with a prism-shaped electro-optic (EO) crystal inserted

---

a) Electronic mail: vincent.crozatier@labc.cnrs.fr
b) Electronic mail: ivan.loriger@labc.cnrs.fr

FIG. 1. Experimental setup: LD: laser diode; EO: electro-optic crystal; VRG: voltage ramp generator; PD: photodiode; LO: local oscillator; AO: optional acousto-optic modulator; \( \epsilon(t) \): error signal; \( c(t) \): correction signal.
in the cavity for fast frequency tuning. The laser emits around 1.5 μm. Light emitted by the rear facet of the laser diode is coupled into a single mode fiber.

A power of 5 mW is delivered for a 100 mA driving current. The side mode suppression ratio measured with a Fabry-Pérot is 40 dB.

The laser coherence time is measured with a self-heterodyning method using the setup of Fig. 1 with an UMZI of 48 μs time delay and an AOM at 80 MHz. It evolves linearly with the output power of the laser, reaching 180 μs at 5 mW, which corresponds to a 2 kHz emission linewidth.

We also evaluate the laser frequency stability. The power spectral density (PSD) of the laser frequency noise is measured with the setup of Fig. 1 and the method suggested in Ref. 11, with an UMZI with a short time delay of 250 ns and the AOM at 80 MHz. The noise spectrum is presented in Fig. 2. One can see a quasi-1/f technical noise on a 200 kHz bandwidth plus some strong peaks. The standard deviation associated with this noise in a 3–500 kHz integration band is only 12 kHz. Over hours, the wavelength drifts less than 1 pm, thanks to a thermal regulation of the laser cavity. The spectral characteristics of this ECDL are intrinsically good for coherent processing.

As for frequency tuning, the EO scale factor is 8.55 MHz/V. Applying 1 kV voltage ramps on the EO crystal, the laser frequency is linearly scanned over 8.5 GHz, i.e., more than three free spectral ranges of the laser cavity. The laser wavelength can also be tuned over ~70 nm by rotating the grating. Thanks to the megahertz-wide modulation bandwidth of the EO crystal, one can perform very fast frequency scans, up to 3 GHz in 5 μs, limited by our high voltage amplifier. Optical coherent processing applications require such chirp rates, with an excellent precision. The chirps directly provided by the laser are not precise enough, as technical noises and parasitic modulations are superimposed to the chirp. This is why we decided to servocontrol the chirps. We then resort to the setup of Fig. 1 where the AOM is not used.

As discussed above, the choice of \( T_d \) lies in a trade-off between the precision on the chirp and the maximum loop bandwidth. Looking for a loop bandwidth of a few megahertz we actually chose \( T_d=250 \) ns, which corresponds to a 60 m long optical fiber. The beat note signal generated at the UMZI output is detected by a photodiode and then amplified and mixed with a reference LO provided by a rf synthesizer. The signal-to-noise ratio at the mixer input is limited to 18 dB by the photodiode. The mixer output is low-pass filtered at 25 MHz in order to keep only the baseband demodulated signal. The loop filter consists of a proportional integrator with a cut-off frequency of 725 kHz. The loop bandwidth is 2.5 MHz, mainly limited by the UMZI transfer function which conditions the loop design.

Figure 3 shows the data obtained when the laser frequency is scanned over 3 GHz in 50 μs. In (a) one can see the spectrum of the beat note detected at the interferometer output. If the chirp were perfectly linear, one would have a Fourier-transform-limited peak. This is the case when the servoloop is closed as the beat note peak full width at half maximum is 20 kHz, limited by the 50 μs long chirp. In comparison, the beat note peak is enlarged by technical noise on hundreds of kilohertz in open-loop regime.

In order to extract the laser frequency error during the chirp, one resorts to the error signal [see Fig. 3(b)]. As expressed in Eq. (3), the beat note phase is a linear function of the error \( e(t) \). When the loop is open, the phase error is several times \( \pi \). Therefore, the laser frequency deviation from a linear chirp in Fig. 3(b) is about 10 MHz. With the chirp stabilization, the phase remains around 0. The standard deviation associated with this signal is 0.1 rad, which corresponds to a frequency error of 65 kHz. The error is then reduced by more than two orders of magnitude. One can also see the fast locking of the loop. For a frequency offset between the beat note and the LO of less than 100 kHz, the locking occurs in less than 1 μs.

When the laser frequency is swept over 3 GHz in 20 μs, one records the beat note spectrum of Fig. 3(c). The beat note is strongly modulated by piezoelectric resonances of the EO crystal, located at 155 and 625 kHz. This spectrum spreads over 5 MHz, exhibiting harmonics of the resonance frequencies and intermodulation frequencies. Using standard frequency modulation theory, one can extract peak-to-peak amplitudes of the frequency modulation of 3 MHz at 625 kHz and 1 MHz at 155 kHz. When the loop is closed, the modulation amplitudes are suppressed by one order of magnitude and contained within 100 kHz. Except for residual modulations caused by the piezoelectric resonances of
the EO crystal, the noise floor of the beat note is rejected by more than 30 dB in a ±2.5 MHz range around the carrier.

The loop suppresses efficiently frequency noises that affect the chirps, as demonstrated above and by coherent optical experiments. It can also be used to stabilize the laser frequency under fixed-frequency operation. In that case the AOM is necessary to produce a beat note at the UMZI output. We performed this experiment with an AOM driven at 80 MHz. Figure 2 shows experimental results. With the loop closed, the noise level is reduced by more than one order of magnitude before reaching the white noise level around 300 kHz. The integrated noise power in a 3–500 kHz band is lowered by a factor of 16, reducing the standard deviation from 12 to 3 kHz.

We then added a second integration stage in our loop filter (integration bandwidth of 1–150 kHz). The noise level is further reduced between 30 and 500 kHz. More precisely, large noise around 60 kHz is completely annihilated while it remained with a single integration stage. The integrated noise power is reduced by a factor of 35 as compared to the open-loop case, and the standard deviation is as low as 2 kHz in the 3–500 kHz integration bandwidth. Let us point out that since the UMZI is equivalent to a derivator, the second integrator actually provides the equivalent of a second order PLL. This allows, in particular, the loop to better correct for frequency offset.

In conclusion, we introduced the phase locking of a rapidly chirped laser. The system simply uses an unbalanced fibered Mach-Zehnder interferometer that provides a beat note whose frequency is proportional to the laser chirp rate. This frequency can then be phase locked to a reference local oscillator, using standard PLL design. The effect of this servocycle is a great enhancement of the chirp precision. The loop can also be used for fixed-frequency operation. Actually, if the local oscillator were a digital arbitrary wave form generator, the system could also produce nonlinear frequency chirps. We believe that improvement of the detection signal-to-noise ratio could greatly enhance the loop performance. Because of its simplicity and its megahertz-bandwidth capability, the loop can be applied to many tunable lasers.

This work was partly supported by the AC Nanosciences LASCOH program.

---