Active stabilization of a rapidly chirped laser by an optoelectronic digital servo-loop control

G. Gorju, A. Jucha, A. Jain, V. Crozatier, I. Lorgeré, J.-L. Le Gouët, and F. Bretenaker
Laboratoire Aimé Cotton, CNRS, Université Paris Sud, Bâtiment 505, 91405 Orsay Cedex, France

M. Colice
Department of Electrical and Computer Engineering, University of Colorado, Boulder, Colorado 80309, USA

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We propose and demonstrate a novel active stabilization scheme for wide and fast frequency chirps. The system measures the laser instantaneous frequency deviation from a perfectly linear chirp, thanks to a digital phase detection process, and provides an error signal that is used to servo-loop control the chirped laser. This way, the frequency errors affecting a laser scan over 10 GHz on the millisecond timescale are drastically reduced below 100 kHz. This active optoelectronic digital servo-loop control opens new and interesting perspectives in fields where rapidly chirped lasers are crucial. © 2007 Optical Society of America

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Monomode laser sources with fast frequency chirping capabilities are crucial in several fields, including optical processing of RF signals, reflectometry, lidar, and coherent manipulation of atoms. All these domains need fast and mode-hop-free frequency scans through a broad spectral range with high spectral purity. For example, in optical RF signal processing using rare-earth-ion doped crystal, one aims at analyzing RF signals over a 10 GHz bandwidth with MHz resolution. A demonstrated architecture consists of engraving the optically carried RF signals to be analyzed in the populations of the rare-earth ions by spectral hole burning (SHB) and to read the resulting spectrum with a chirped laser. For such an application, broad and fast frequency scans (typically 10 GHz in 1 ms) with high linearity and reproducibility are mandatory to preserve the spectrum analyzer resolution and precision of 1 MHz. This means that the frequency deviation from a perfect linear chirp has to be much lower than 1 MHz when integrated over the whole chirp bandwidth. Until now, the spectral purity and precision of the frequency chirps were limiting factors for several of the cited applications. Thus, the development of a new system to precisely control and stabilize chirping lasers is a difficult but necessary endeavor for successful applications.

Usual laser frequency stabilization techniques deal with fixed frequency lasers. They typically use electronic feedback to minimize the laser frequency mismatch from a highly stabilized Fabry–Perot cavity or an absolute atomic absorption line. Since they use fixed references, they cannot be used for our applications employing lasers chirped over a broad spectral range. To precisely control a fast laser chirp, the laser's instantaneous frequency has to be measured in the whole relevant bandwidth. Path difference interferometers have shown their capabilities of finely characterizing laser frequency noises and provide an error signal for fixed-frequency and chirped lasers. However, the system developed by Greiner et al. is efficient for suppressing only some superimposed modulations but does not permit one to cancel all sources of frequency deviations in the relevant bandwidth. The sigmometer presented by Jun-car and Pinard is not adapted for fast chirping capabilities. In this Letter we present a new and efficient scheme for stabilizing fast and continuous laser frequency scans without stabilizing the center frequency. It uses a phase detection process via optical quadrature signals and a simple digital algorithm. This very versatile method does not need any postprocessing techniques and can be used to drastically reduce the frequency errors of any kind of laser chirped around a given frequency. The effects of this active stabilization in a SHB experiment are described.

The experimental setup used to stabilize the chirped laser is presented in Fig. 1. For this experiment, the laser under test is an external cavity diode laser closed by a grating in Littrow configuration. This laser is used for SHB experiments with Tm3+:YAG ions at 793 nm. It contains a prismatic LiTaO3 electro-optic crystal that turns the laser into an optical voltage-controlled oscillator characterized by a scale factor $K=12.5$ MHz/V. We chirp the laser by applying voltage ramps to the electro-optic crystal.
frequency by applying a linear high-voltage ramp on the electro-optic crystal. Thus the instantaneous frequency of the laser under investigation can be expressed as \( \nu(t) = \nu_0 + rt + \delta \nu(t) \), where \( \nu_0 \) is the average optical frequency, \( r \) is the chirp rate, and \( \delta \nu(t) \) represents the frequency errors. These errors can be measured thanks to an unbalanced interferometer.\(^1\) Because of the propagation delay, the error will be detected after a time \( \tau_d \). Consequently, if \( \tau_d \) is longer than the error variation time scale, the correction will be applied too late after the error happens. On the other hand, the longer the time delay, the better the chirp measurement precision. As already demonstrated,\(^1\) a time delay of \( \tau_d = 30.7 \) ns is sufficient to characterize frequency errors smaller than 1 MHz on a bandwidth of a few hundreds of kHz. To build our interferometer we use a 50/50 fiber coupler followed by two different lengths of fiber to create the delay \( \tau_d \) between the two arms of the interferometer. The two beams are then recombined in free space by a beam splitter. The beat note phase detected at the interferometer output can be expressed\(^1\) as \( 2 \pi f_{bd} t + \phi_0 + \Psi(t) \), where \( f_{bd} = r \tau_d \), \( \phi_0 \) is a constant term and \( \Psi(t) = 2 \pi \tau_d \delta \nu(t) \). It contains the frequency errors occurring during the chirp. This phase can be unambiguously extracted, provided that we detect two signals in quadrature at the output of the interferometer.\(^\text{11} \) The whole interferometer is built using polarization-maintaining panda fiber with a 20 dB polarization extinction ratio and a beam length around 1.5 mm. The desired phase difference of \( \pi / 2 \) between the two channels is obtained by manually tuning the orientations of different wave plates at the outputs of the fibers, together with two crossed polarizers in front of the two photodetectors as pictured in Fig. 1. Thus two beat notes in quadrature are detected with two photodetectors of bandwidth 80 Hz–400 kHz with variable gain to equalize the signal amplitudes \( I_0 \). The two detected signals are

\[
\begin{align*}
I_c(t) &= I_0 \cos[2 \pi f_{bd} t + \phi_0 + \Psi(t)], \\
I_s(t) &= I_0 \sin[2 \pi f_{bd} t + \phi_0 + \Psi(t)].
\end{align*}
\]

To measure the phase term related to the frequency errors we use a homemade digital processing unit. It is composed of standard 8 bit converters and a field programmable gate array with a sampling rate of 1 MHz. A digital algorithm makes simple operations with two reference signals, \( \cos(2 \pi f_{bd} t + \phi_0) \) and \( \sin(2 \pi f_{bd} t + \phi_0) \), previously stored in the field programmable gate array memory thanks to a microcontroller driven by a computer. This digital phase detection process leads to an error signal according to

\[
e(t) = I_s(t) \sin(2 \pi f_{bd} t + \phi_0) - I_c(t) \cos(2 \pi f_{bd} t + \phi_0)
\]

\[
= I_0 \sin[2 \pi \tau_d \delta \nu(t)].
\]

\( e(t) \) behaves as a sine wave as a function of the laser frequency error with a period given by \( 1/\tau_d \) (30 MHz). One can deduce the frequency noise power spectral density (PSD) from a simple spectral study of \( \arcsin[e(t)] \). Reaching a precision better than 100 kHz requires that the phase of \( e(t) \) be measured with a precision better than \( \pi / 50 \), thus justifying our use of 8 bit components. To reduce thermal and acoustic noise, we locate our interferometer in a compact and thick box.\(^1\) Using a stabilized fixed-frequency laser, we measured the interferometer noise. It corresponds to a maximum fluctuation of 4 kHz in 1 ms for our laser frequency. Finally, a careful adjustment of the quadrature phases must be performed to minimize a superimposed beat note at frequency \( 2 f_{bd} \). The cancellation of this undesired signal certifies the optimum system adjustment.

Once the loop is closed, we expect the frequency error \( \delta \nu(t) \) to remain small compared with \( 1/\tau_d \), leading to \( e(t) = I_0 \pi \tau_d \delta \nu(t) \). Thus \( e(t) \) is directly proportional to the laser frequency errors, and a simple spectral study leads to frequency noise PSD. This signal can be used after filtering as a correction voltage to apply on the electro-optic crystal. The loop filter consists of a proportional integrator (cutoff frequency at 150 kHz). Because of the sampling frequency, the efficient bandwidth of the servo-loop is limited to 500 kHz.

Figure 2 shows different results obtained when the laser frequency is scanned over 10 GHz in 4 ms. To extract the laser frequency error during the chirp, we measure the error signal given by the digital processing unit [see Fig. 2(a)]. The gray curve represents the error signal when we scan the laser frequency with the loop open. As predicted by Eq. (2), each time the laser frequency deviation from a perfectly linear chirp reaches 30 MHz, the phase of \( e(t) \) skips by \( 2 \pi \).\(^1\) Thus for a frequency scan of 10 GHz in 4 ms, an error of more than 100 MHz can be observed. The black curve of Fig. 2(a) represents the error signal when the loop is closed. As predicted, \( e(t) \) remains around zero. By calculating the standard deviation of \( e(t) \) (over the full signal bandwidth), one can estimate the remaining error to be around 100 kHz. The error is thus reduced by 3 orders of magnitude.

As presented in Ref. 14, the spectral purity degradation of a chirped laser is mainly due to technical noises. To compare these noises with and without the
stabilization, we resort to laser frequency noise PSD measurements. The spectra are presented in Fig. 2(b). When the loop is open, one can see a quasi 1/f technical noise on a 150 kHz bandwidth. The standard deviation associated with this noise in a 0.25–150 kHz integration band is about 2 MHz. With the loop closed, the technical noise is drastically reduced before reaching the white noise level. The integrated noise in a 0.25–150 kHz bandwidth is then reduced by a factor of 35, reducing the error to 56 kHz. The white noise limitation level is mainly due to the quantification noise of our 8 bit converters and could be improved by increasing the number of bits. Because the laser’s relative intensity noise is about –120 dB/Hz over a 0.25–500 kHz bandwidth, it hardly affects the PSD measurement.

One can ultimately test the chirp spectral purity with a Fourier analysis of the signals delivered by the interferometer as suggested in Ref. 14. In the inset of Fig. 2(b), we see the beat note spectra detected at the interferometer output with and without stabilization. If the chirp were perfectly linear, one would have a Fourier transform limited beat note width. This is the case when the servo-loop is closed. As we use a rectangular window for the Fourier analysis, one can see a perfect cardinal sine spectrum shape with a FWHM of 250 Hz. In comparison, the beat note spectrum when the loop is open is enlarged and distorted by the different noises affecting the frequency of our laser.

The influence of the active stabilization process on a SHB experiment is presented in Fig. 3. The experiment consists of exposing a Tm3+:YAG crystal (cooled at 5 K) to our external cavity diode laser operating at fixed frequency. Thus, a spectral hole is engraved in the inhomogeneous bandwidth of the crystal. The hole width is ultimately limited by the homogeneous linewidth (Γh) of the crystal (150 kHz; see Refs. 1–3). Then by simply measuring the SHB crystal transmission with our external cavity diode laser scanned over the absorption profile, we can measure the spectral feature that was previously engraved. This experimental process is often used in optical processing of RF spectral signals.1–3 The spectral feature has been engraved by an optical beam presenting a waist of 500 μm and an optical power of 800 μW during 700 μs. The reading is performed 2.2 ms later with an optical power increased to 1 mW. Figures 3(a) and 3(b) correspond to 5 GHz (10 GHz) broad frequency scans performed in 4 ms. When the altered absorption profile is read with a frequency scan of 5 GHz in 4 ms (10 GHz) the spectral feature exhibits a linewidth of 2.2 MHz (3.25 MHz) and a linewidth of 1.1 MHz (1.2 MHz) when the loop is open and closed, respectively. The spectral linewidths obtained when the loop is on (~1 MHz) are still larger than the absolute limit given by Γh because of the engraving laser’s frequency jitter contribution. However, as the closed loop system has a spectral purity much better than 1 MHz, the readout shows the behavior discussed in Ref. 15. Indeed, one can see the expected ringing in the detected signal.

In summary, we have proposed and experimentally investigated an active optoelectronic digital servo-loop control. We have shown that, for a laser scan over 10 GHz in 4 ms, the remaining frequency error from a perfect linear chirp is below 100 kHz (compared with 100 MHz with the loop open). By improving the chirp spectral purity, this system will open unexplored perspectives in optical signal processing of RF signals. Moreover, with the ease and the versatility of the system, it can be possible to stabilize the nonlinear frequency chirp, expanding the application range of such laser sources.

G. Gorju’s e-mail address is guillaume.gorju@luc-psud.fr.

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