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Ultralow-frequency-noise stabilization of a laser by locking to an optical fiber-delay line

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We report the frequency stabilization of an erbium-doped fiber distributed-feedback laser using an all-fiber-based Michelson interferometer of large arm imbalance. The interferometer uses a 1 km SMF-28 optical fiber spool and an acousto-optic modulator allowing heterodyne detection. The frequency-noise power spectral density is reduced by more than 40 dB for Fourier frequencies ranging from 1 Hz to 10 kHz, corresponding to a level well below 1 $\mathrm{Hz}^2/\mathrm{Hz}$ over the entire range; it reaches 10^{-2} $\mathrm{Hz}^2/\mathrm{Hz}$ at 1 kHz. Between 40 Hz and 30 kHz, the frequency noise is shown to be comparable to the one obtained by Pound–Drever–Hall locking to a high-finesse Fabry–Perot cavity. Locking to a fiber delay line could consequently represent a reliable, simple, and compact alternative to cavity stabilization for short-term linewidth reduction.

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Very-low-frequency-noise lasers are important tools for many applications, such as high-resolution spectroscopy, optical atomic clock local oscillators, interferometric sensors (including gravitational-wave detection), and coherent optical communications systems. Erbium-doped fiber distributed-feedback lasers (DFB EDFL) near 1550 nm typically exhibit optical linewidths in the range of 1–10 kHz and a frequency-noise power spectral density (PSD) dominated by $1/f$ component. Although narrower than the diode laser linewidth, these performances are still insufficient for many of these applications.

Stabilization of laser frequency over a very long term is achieved by comparing it to an atomic or molecular absorption line reference frequency. However, this method generally does not provide fast frequency-noise reduction. The linewidth of lasers is then usually reduced by locking to an ultrastable optical cavity, using the Pound–Drever–Hall method [1–3]. It led to fractional frequency instability lower than 10^{-15} for 1 s averaging times and subhertz linewidth [4]. But this scheme requires fine alignment of free-space optical components, tight polarization adjustment, and spatial mode matching. Moreover, high-finesse cavities are relatively expensive, bulky, and fragile devices. Finally, to avoid air-index fluctuations and improve the thermal control and stability, the cavity has to be housed in a high vacuum enclosure with thermal radiation shielding.

Another approach of the frequency-noise reduction with a length etalon is to use a two-arm (Michelson or Mach–Zehnder) interferometer to measure the frequency fluctuations during a fixed time delay [5,6]. This method requires a relatively large arm imbalance to obtain a sufficient frequency-discriminator sensitivity. Indeed, to have with a Michelson interferometer the quality factor of a 10 cm Fabry–Perot cavity of finesse 330000, the arm imbalance has to be as long as 10 km. Optical fiber is an excellent material to achieve such a large path imbalance. This can lead to a largely lighter, more compact, and cheaper device than the low thermal expansion (ULE) high-finesse Fabry–Perot cavity. In addition, a frequency shifter can be inserted in one arm of the interferometer, and consequently the Pound–Drever–Hall system can be replaced by a simple heterodyne detection scheme as detailed below. Contrary to Fabry–Perot cavity locking, the stabilized output frequency is not limited to a discrete set of values and can be continuously tuned via a phase shift on one of the interferometer arms.

For Fourier frequencies where the loop gain is high, the stabilized-laser relative frequency noise $\delta\nu(f)/\nu_0$ equals the etalon optical length relative fluctuations $\delta L(f)/L_0$, which consequently has to be as low as possible. Ultrastable Fabry–Perot cavities use a low-thermal expansion material spacer and have to be well protected from environmental perturbations, using vacuum enclosures and seismic isolation provided by modern antivibration platforms. Their stability is ultimately limited by fundamental thermodynamics fluctuations in mirrors, substrates, and coatings [7]. The optical length of fibers is also sensitive to acoustical, mechanical, and thermal perturbations. These perturbations are generally very low for Fourier frequencies above 1 kHz but can significantly degrade the frequency noise of the locked laser at low frequencies. The optical fiber must consequently be placed into an enclosure to isolate it from external fluctuations. If noise sources are spatially uncorrelated, $\delta L(f)/L_0$ scales as $1/L_0^{1/2}$ and then decreases with a longer fiber. Finally, refractive index thermodynamic fluctuations in the fiber set a fundamental limit on the stabilized laser frequency noise [8]. This limit can be pushed down by extending the fiber length. However, this will lower the discriminator bandwidth. This can be partially overcome by designing sophisticated loop filter controllers [9].

The first frequency stabilization experiment of a laser onto a fiber spool used a Mach–Zehnder interferometer (MZI), with phase modulation into one arm, to stabilize a He–Ne laser. Corrections were applied via a Piezoelectric Transduce-(PZT) stretcher. It led to a 5 kHz linewidth on 1 s [5]. Cranch stabilized a DFB EDFL onto a 100 m path imbalance MZI using homodyne electronics and a PZT actuator, reaching about 2 $\mathrm{Hz}^2/\mathrm{Hz}$ at 1 kHz [6]. This method was also applied to diode lasers with all-fibered interferometers using homodyne detection leading to 10^2 $\mathrm{Hz}^2/\mathrm{Hz}$ at 10 kHz [10]. Extension of the control bandwidth using a sophisticated controller design was achieved with a 10 km arm imbalance Michelson interferometer [9]. Recently, frequency-noise reduction of a DFB EDFL was reported to reach 4 $\mathrm{Hz}^2/\mathrm{Hz}$ at 80 Hz [11]. The setup is based on a 110 m arm imbalance, all-fibered, Michelson interferometer in vacuum with advanced seismic isolation and homodyne detection.

We present here a system using an all-fibered 2 km imbalance Michelson interferometer with heterodyne detection. Figure 1 shows the scheme of the laser-frequency stabilization system. The main component of the system is the frequency-shifted fibered Michelson interferometer. The input optical wave is split between the two arms by a 50/50 fiber coupler. The first arm of the coupler is directly connected to a Faraday mirror; the second arm is connected to a 1 km spool of standard SMF-28 fiber followed by an acousto-optic frequency shifter and a Faraday mirror. The Faraday rotator mirror guarantees that in a retracing fiber-optic link the output state of polarization is orthogonal to the entrance state; consequently, the two waves in the output port of the Michelson interferometer have always the same state of polarization and lead to a maximum beat-note signal amplitude without requiring any polarization controller. The fiber spool is placed into a ring-shaped aluminum box, and the interferometer is placed inside a thick aluminum box, recovered by a thermal isolating thermoplastic film, which is set onto a compact seismic ($310\times310\times170$ mm) vibration isolation platform. The entire experiment is covered by an acoustic isolation box of volume ≈ 0.125 m^3.

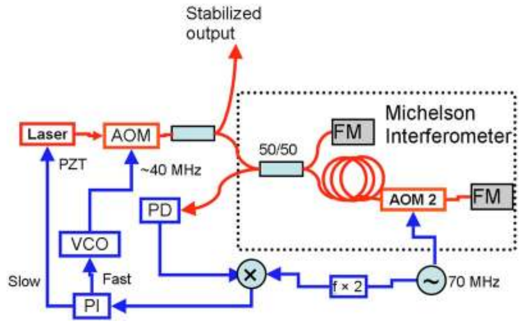

Fig. 1. (Color online) Scheme of the laser frequency-noise-reduction system: AOM, acousto-optic modulator; PD, photodiode; VCO, voltage-controlled oscillator; PI, proportional-integrator filter; FM, Faraday mirror.

The frequency-shift fibered Michelson interferometer acts as an optical frequency (ν_{opt}) to rf phase (ϕ_{err}) converter with transfer function $\phi_{err}(f)/\nu_{opt}(f) = H_{Mich}(f) = [1 - e^{-i2\pi f\tau}]/if$ (rad/Hz), where τ is the fiber double-pass delay time and f is the Fourier frequency. For $f \ll 1/\tau$, $H_{Mich}(f) \approx 2\pi\tau$. The interferometer is seeded with 200 μW, and the total double-pass optical power losses in the long arm containing the fibered AOM at 70 MHz are about 6 dB. The optical power photodetected at the output port of the interferometer then contains an rf carrier at $2f_{AOM}$, phase modulated by ϕ_{err}, which is downconverted by an rf mixer driven by the frequency-doubled output of a low-noise reference oscillator at 70 MHz. This provides a low-frequency error signal proportional to $\phi_{err} + \Delta\theta_{RF}$, where $\Delta\theta_{RF}$ is the local oscillator phase shift. The error signal is amplified, filtered, and converted into optical frequency correction using an AOM operating at 40 MHz, which is driven by a high-modulation-bandwidth voltage-controlled oscillator for fast correction and a piezoelectric element controlling the fiber-laser cavity length for drift compensation. The correction bandwidth ($\sim$100 kHz) is limited by the round-trip delay in the fiber interferometer. The laser source is a single-longitudinal-mode Er^{3+}-doped fiber Bragg grating laser with an emission wavelength of 1542 nm and a maximum output power of 100 mW. The free-running laser-frequency noise is dominated by a flicker component with 10^4 $\mathrm{Hz}^2/\mathrm{Hz}$ at 100 Hz as shown in Fig. 2.

The frequency-noise PSD of the fiber-stabilized laser is measured by comparison with a high-finesse Fabry–Perot cavity-stabilized laser described in [12]. The rf beat-note signal is downconverted to 700 kHz by a low-phase-noise synthesizer then frequency-to-voltage converted and analyzed using a fast Fourier transform analyzer after removing a linear drift of the order of 1 kHz/s. Results are shown in Fig. 2. With the antivibration platform, the frequency-noise reduction is larger than 40 dB between 1 Hz and 10 kHz, and the frequency noise PSD is (notwith-

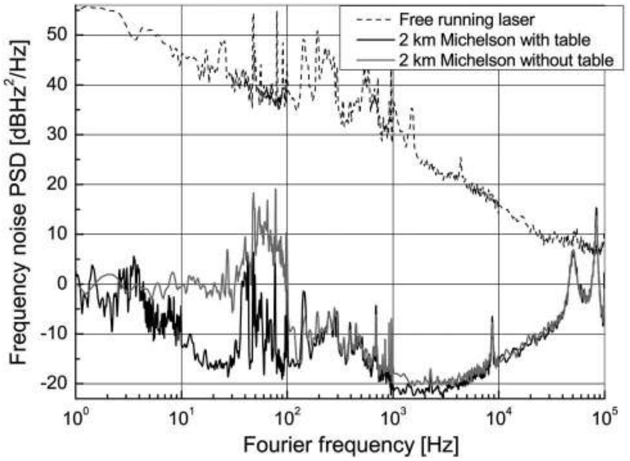

Fig. 2. Frequency-noise power spectral density versus Fourier frequency of the free-running laser (dashed curve) and laser stabilized on a 2 km imbalance Michelson interferometer with (dark curve) and without (gray curve) a passive antivibration table.

standing several peaks) below 1 $\mathrm{Hz}^2/\mathrm{Hz}$ in the same range. Effect of the antivibration table is notable between 5 Hz and 100 Hz; however, even without table the noise reduction is better than 30 dB. In Fig. 3 is plotted the measured frequency noise of the fiber-stabilized laser together with the cavity-stabilized reference-laser frequency noise. For Fourier frequencies between 40 Hz and 30 kHz the measurement is limited by the reference-laser frequency noise and is therefore an upper limit of the fiber-stabilized laser noise. A lower limit is also plotted in Fig. 3, set by the thermodynamic noise derived from [8] up to 10 kHz and the in-loop noise derived from the error signal fluctuations above that frequency. Below 40 Hz the measured frequency noise is dominated by the fiber-delay-line optical length fluctuations.

The optical spectrum was numerically derived by fast Fourier transform of the autocorrelation function computed from the frequency-noise PSD measured from 100 mHz to 100 kHz. A measurement time was taken into account corresponding to a first-order filter of the frequency-noise PSD. The 3 dB linewidth of the optical spectrum is 8 Hz for 1 s measurement time. When the isolation platform is deactivated the linewidth rises to 17 Hz for the same measurement time. For comparison, the linewidth of the free-running laser is 8 kHz.

In conclusion, we have demonstrated that an all-fibered frequency-shift Michelson interferometer can be used to reduce the frequency noise of a fiber laser to a level comparable to a high-finesse Fabry–Perot stabilized laser for Fourier frequencies ranging from 40 Hz to 30 kHz. This is several orders of magnitude better than previous results of laser stabilization using fiber-delay lines. This improvement is most likely due to the use of rf heterodyne detection at a frequency where technical issues such as laser intensity noise and detection noise are totally negligible. This method now constitutes an interesting alternative to cavity locking for applications where this frequency range is relevant. It has the great advantage to provide a fibered system without any optical alignment or polarization adjustment. It is therefore intrinsically more compact, light, and flexible than cavity-based systems. For Fourier frequencies below 40 Hz, our system is presumably limited by thermal fluctuations and mechanical vibrations, which can certainly be improved. The interferometer could, for instance, be installed in a temperature-stabilized vacuum tank with several thermal shields. In addition, a fiber of lower thermal sensitivity could be used like specifically designed photonic-crystal fibers [13] or liquid-crystal polymer coatings [14]. The ultimate limits of this system are still an open question.

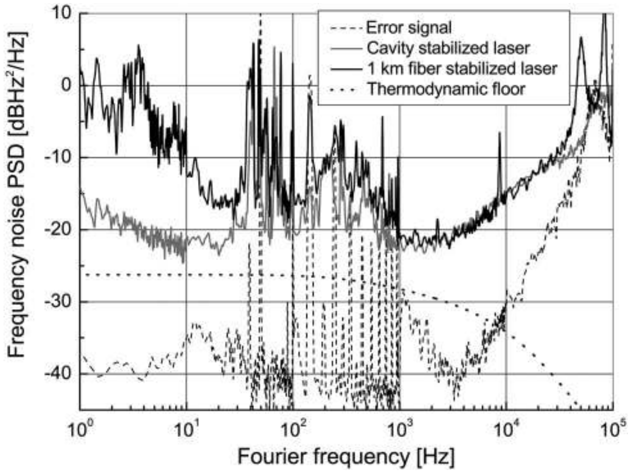

Fig. 3. Frequency-noise power spectral density versus Fourier frequency of the laser stabilized on a 2 km imbalance Michelson interferometer with an antivibration table (dark curve), a reference laser (gray curve), an error signal converted into frequency noise (dashed curve), and a thermodynamic noise floor (dotted curve).

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