Tunable laser with linewidth suppression for optical frequency standards working in telecommunication bands

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Abstract

In this work we present a laser source working in telecommunication wavelength band useful for construction of an optical frequency standard at 1540 nm. These standards are usually defined through a saturated absorption spectroscopy technique where acetylene gas is used as the absorption medium. Because the linewidth of absorption lines of acetylene are very narrow (several hundred kHz) it needs the laser with linewidth below the level of several kHz. We present a single-mode laser diode with a planar lightwave circuit (PLC) that includes a Bragg grating as the primary laser source. It has mode hop free tunable range up to 5 GHz of optical frequency at the operational wavelength 1540.577 nm. The linewidth of the laser is better than 3 kHz for short term period. But the laser absolute frequency is influenced by a flicker noise that could be suppressed. We used unbalanced Michelson fiber interferometer with 1 km long arm to suppress frequency noise of the laser. We provided the signal processing with PID servo loop with the laser current control. We suppressed the noise around the laser linewidth by -60 dB up to 33 kHz of Fourier frequency. The noise properties of the stabilized laser have promising stability for the optical frequency standard using an acetylene saturated absorption technique as a reference.

1. Introduction

Generation of the length etalons and measurement of length of passive Fabry-Perot cavities (FPC) [1,2] or their displacement [3,4] is limited by vibration of mirrors, thermal fluctuations, speed of lock-loops and by the noise and by the linewidth of the laser source. To lock the laser to the FPC by either derivative technique [5] or Pound-Drever-Hall technique [6] the linewidth of the laser should be narrower than the linewidth of the passive FPC modes. The typical external laser cavity has plan-concave configuration with mirror distance of 100 mm. Finesse of the cavity is usually over 2000 and in atomic clock applications can achieve up to 100000s. Linewidth of the typical cavity then reaches less than kHz and MHz, respectively, which corresponds from pm to nm uncertainty in the cavity length. The measurement of the displacement of the Fabry-Perot cavities should be made by the tunable lasers with sub-kHz to sub-MHz linewidth and an optical reference should be of the same or better linewidth [7,8].

The difference beat frequency between the optical reference standard and the tunable laser is limited by the photodetector and counter to only 20 GHz. The typical standards He-Ne lasers and Nd-YAG standards with iodine gas absorption cell can achieve 10^{-13} [9] stability but the PZT tuning range of tunable lasers limits the tunability only to 1 GHz.

The typical diode lasers have larger tunability but the linewidth of 30 MHz. The Distributed FeedBack lasers (DFB) [10] can achieve roughly about 1 MHz linewidth corresponding to 10^{-8} of relative uncertainty. Better linewidth can be achieved for external cavity laser (ECL) diodes based on DFB lasers and grating [11] but these complex laser systems may be quite robust and sensitive to alignment, introducing power losses. The state-of-the-art ECLs include planar lightwave circuit (PLC) with the fiber Bragg grating and reach the linewidth under 3 kHz [12] but their tunability is limited only 20 pm or 5 GHz. Further improvement of relative uncertainty can be achieved by laser frequency noise suppression. The frequency noise suppression can be achieved by locking and stabilization of the laser by a saturation absorption spectroscopy to iodine [7] or acetylene [13] gas cell. Another approach is to use an ultrastable cavity from very low expansion material such as ULE [14] or Zerodur [3].

The technique of the suppression of the laser linewidth by the stabilization to a high finesse FPC limits the tunability of the laser. The use of tunable cavities with complicated locking scheme could be easily surpassed by the use of unbalanced fiber Michelson interferometer (UFMI) and a servo-loop control working as frequency noise discriminator [15].

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2. The technique of laser noise suppression

Method of stabilization and narrowing the laser linewidth on the UFMI is based on the fact that the light coming into the longer arm of UFMI is sufficiently delayed. One arm of the interferometer is usually much longer ($L_1 \sim 1$ km) and the second one is usually negligible ($L_2 \sim 1$ m). The light going through the long arm is then delayed by the $\tau_1 = n \cdot L_1 / c \approx 5.4 \mu s$ whereas the light in the short arm is almost without any delay $\tau_2 = n \cdot L_2 / c \approx 5 ns$. The principle of the method is farther described in ref. [15]

The method was applied on the ECL laser with PLC (ORION module) by Redfern Integrated Optics, Inc. working at central wavelength 1540.577 nm with 3 kHz linewidth. It has the modulation bandwidth up to 100 MHz at the speed of 10 kHz for 3.65 V sweep voltage. The experimental set-up is shown in Fig. 1. The optical part consists of heterodyne UFMI, photodetector (PD) and the laser. The ORION module laser was coupled to PM fiber through the APC connector to the 90/10 splitter. The 10% of optical power is used and coupled to the UFMI.

Longer arm of that interferometer includes the acousto-optic modulator (AOM) and 1 km long spool. Both UFMI arms have been ended by Faraday Mirror (FM). The light in the long arm is shifted by the frequency of 80 MHz on AOM each time it travels through resulting in the signal of 160 MHz at the PD. This signal includes the noise of the laser and the noise of the interferometer. The AOM is driven by fixed frequency of 80 MHz generated by Direct Digital Synthesizer (DDS) referenced to the 10 MHz clock signal [16].

All fibers are single mode (SMF-28) except the polarization maintaining (PM) fiber at the laser source. The fiber of the spool and in the interferometer had 250 µm in diameter secondary protective layer to reduce the influence of external vibrations. Some set-up fibers have another protective fiber coating up to 900 µm. The interferometric part of the set-up is placed and fixed inside the aluminum box with FC/APC connectors to avoid an additional source of noise from the fibers in the interferometer.

Laser servo loop consists of 10 MHz radiofrequency clock's reference signal [16] that controls the Direct Digital Synthesizer (DDS) frequency and works as a reference to the digital rf synthesizer. Rf signal coming from the PD consists of the 160 MHz carrier frequency and frequency noise of the laser. This signal is divided by factor of 5 producing the signal of 32 MHz frequency with the phase noise and rf frequency noise of the laser divided by factor of 5. The measurement of the signal is provided by phase noise measurement set (5120A Symmetricom) at 10 MHz.

Fourier Transform signal measurement is provided by signal analyzer (3561A Hewlett-Packard) at DC level whereas the measured signal was divided 1/5 and mixed with 32 MHz reference signal from the synthesizer and analyzed on HP 3561A referenced to the same 10 MHz reference signal. This signal is sent to PID controller with only proportional (P) and double stage integral (I_1 and I_2) components involved in the servo loop. PID output signal was sent to the laser current control and therefore the laser frequency was controlled.

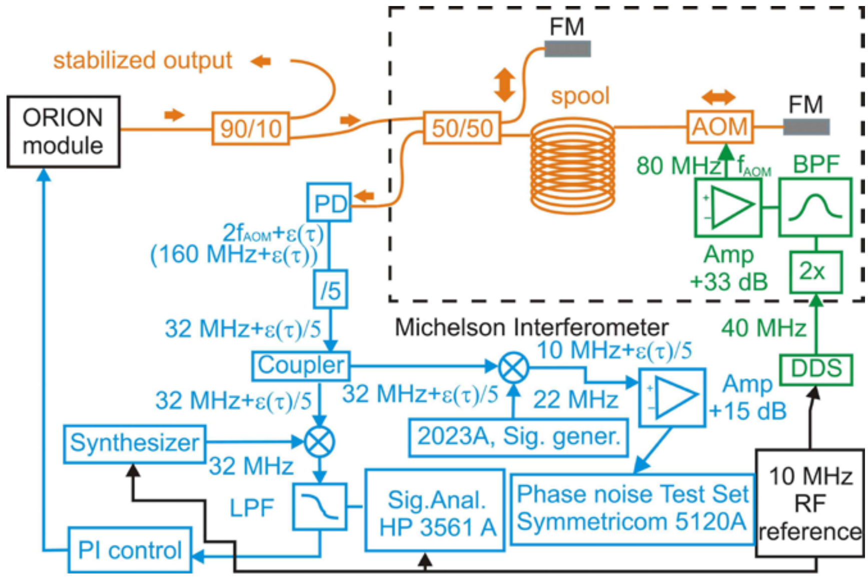

Fig. 1. Set-up to the laser noise suppression with an unbalanced fiber Michelson interferometer. The set-up consists of optical (fiber) parts with ORION laser module, FM - Faraday mirror and 1-km long fiber spool. Laser frequency is controlled via PI controller and electronics servo-loop from the heterodyne beat measurement on photodetector - PD.

3. Experimental results

First we measured the free running laser (green line in Fig. 2). The recorded data includes mainly 50 Hz electrical noise and decrease from relative spectral density to the carrier of -30 dB at 1 Hz to -80 dB at 100 kHz representing the cut-off frequency of the UFMI. Then the P and I_1 parts were applied to suppress the noise of the laser by the use of UFMI (blue line in Fig. 2). The integrator I_1 had limited bandwidth cut-off at 100 Hz. Therefore, we applied an additional integrator I_2 to cover higher frequency bandwidth of the laser frequency noise (red line in Fig. 2). All of records show the 50 Hz signal representing the noise from the electrical power supply. The use of the noise suppression method ($P+I_1+I_2$ involved) leads to the stronger dissipation of the Fourier frequency spectrum of the laser to higher frequencies with very low noise around the frequency carrier. There are visible $1/f$ flicker frequency noise peaks in the frequency range 10^4-10^5 Hz in Fig. 2. The laser noise around and within the laser linewidth was suppressed by -60 dB at all frequencies up to 33 kHz. This frequency is the limit controlled by the bandwidth of the laser electronic control circuit. The carrier frequency of the laser was stabilized using the unbalanced heterodyne fiber interferometer while the tunability range of the laser stayed untouched.

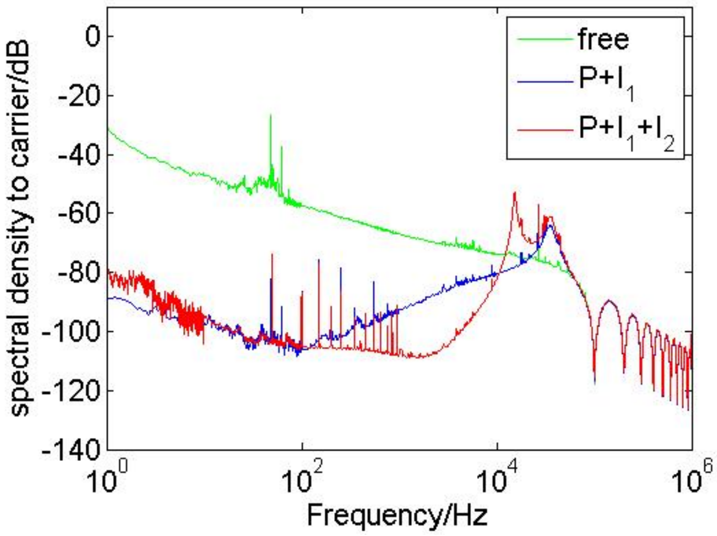

Fig. 2. Measurement of suppression of the frequency noise of the laser module ORION. P is the proportional, I_1 is the low frequency bandwidth integrator and I_2 is higher frequency integrator of the servo loop controller.

4. Conclusion

We presented and experimentally demonstrated frequency noise suppression of the ORION laser module working at 1540.577 nm wavelength. We used the unbalanced hetorodyne fiber Michelson interferometer with the servo loop controller as the noise discriminator. The noise suppression was done by fast modulation of the injection current of the ORION laser module. The free running regime of the laser module has been compared to the frequency noise suppression by the proportional and double stage integral servo loop controller with low-frequency and high- frequency bandwidth. The laser noise around and within the laser linewidth was suppressed by -60 dB at up to the Fourier frequency of 33 kHz while the tunability range stayed untouched.

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