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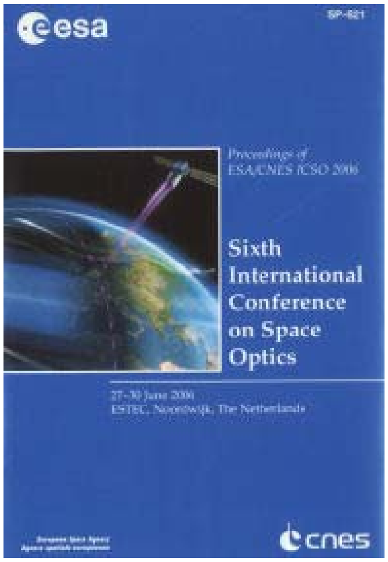

High performances frequency-stabilized semiconductor laser metrology sources for space-borne spectrometers

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HIGH PERFORMANCES FREQUENCY-STABILIZED SEMICONDUCTOR LASER METROLOGY SOURCES FOR SPACE-BORNE SPECTROMETERS

C. Latrasse, F. Pelletier, A. Doyle, S. Savard, A. Babin,
F. Costin, A. Biron, J.-F. Cliche, M. Allard and M. Têtu.

TeraXion, 2716 Einstein, Québec, Canada, G1P 4S8

1. ABSTRACT

In a project with the Canadian Space Agency (CSA), we have developed prototypes of 1.55 µm frequency-stabilized lasers for space applications. These lasers can be used as metrology sources for internal calibration of spectrometers such as the Cross-track Infrared Sounder (CrIS). Our prototypes include a 1552 nm DFB laser frequency-locked to $H^{13}CN$ using external phase modulation. The prototypes feature high quality characteristics such as CW output power of 8 mW and a narrow linewidth of 1.5 MHz. The frequency of the laser is known to a few ppm. The frequency stability levels at 10^{-10} between 30 and 10 000 s. The relative intensity noise (RIN) falls from -100 to -140 dBc/Hz between 1 Hz and 10 kHz, and levels at -140 dBc/Hz between 10 kHz and 1 MHz. Further improvement to reduce the linewidth to a few kHz can be provided using an all-fiber interferometer and correction of the laser injection current accordingly.

2. INTRODUCTION

Some future satellite experiments will require on-board high precision and high reliability spectral calibration optical reference. For that purpose, semiconductor lasers frequency-locked or frequency-calibrated against molecular resonances are very interesting candidates. They are particularly interesting if their operation wavelength is within the optical telecommunication bands since already Telcordia qualified components are commercially available from many suppliers. When frequency-locked, these lasers deliver an optical signal at a frequency that can be specified with great precision and high stability. They are also very reproducible and are traceable to international standards. They can find application for instance as metrology sources for internal calibration of spectrometers for Earth Observation experiments.

In collaboration with CSA and ABB, TeraXion is pursuing the development of a space qualified laser reference in the 1.55 µm range to be used within Fourier Transform Infrared (FTIR) spectrometers. In this project, we have developed two prototypes comprising a semiconductor laser frequency locked to a HCN absorption line at 1552 nm. We report in this paper on the technique selected for interrogating the resonance line and locking the laser frequency, on the design considerations for space qualification and on the results obtained during performance assessment. Finally, a possible performance added value by narrowing the laser emission linewidth is introduced.

3. STABILIZATION TECHNIQUE

Our prototypes are based on 1552 nm DFB lasers from the telecommunications industry. To guarantee a high frequency stability, these lasers are frequency-locked to the P(14) absorption line of $H^{13}CN$. Molecular lines have proved to provide high stability frequency references with low sensitivity to environmental parameters [1]. For the frequency locking, we use external phase modulation as presented in Fig. 1. This technique consists in generating sidebands on each side of the laser optical carrier to probe the absorption line [2, 3]. This is performed using a commercial pigtailed phase modulator driven by a voltage controlled oscillator (VCO). Using a RF mixer and comparing the VCO signal with that of the photodetector after the $H^{13}CN$ cell, we obtain an error signal that is fed back to the DFB current driver. In this way, the laser is locked at the bottom of the absorption line while keeping a CW optical output. Such a frequency locking technique is known to provide high performances for the stability frequency.

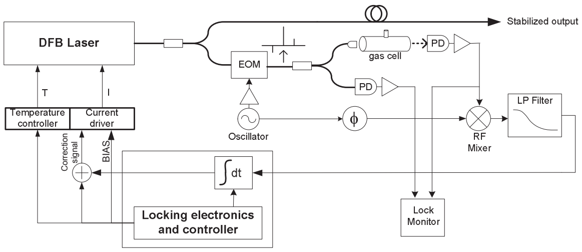

Fig. 1. Schematics of the frequency-locked standard.

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4. PROTOTYPE DESIGN

Due to the harsh environment, space qualification is necessary to provide frequency-locked lasers that will maintain good characteristics for many years. In a first step toward a space qualification design, we have focused on the optical sub-assembly. In this scope, we have chosen pigtailed optical components such as the laser source, the optical coupler, the phase modulator and the pigtailed photodetector. These components are issued from the telecommunication industry and they are known to be Telcordia qualified. Therefore, they are good candidates to go through space qualification. Fig. 2 shows the optical module (dimensions 70 x 185 x 35 mm).

Fig. 2. The optical module

The optical module is driven by an independant electronics board that integrates a temperature controller and a current source for the DFB laser, a RF driver for the phase modulator, a demodulation section to generate an error signal and a loop filter. It also includes a microcontroller that controls the different sections of the electronics board allowing the launch of an automatic locking procedure at power up of the prototype. The microcontroller also allows monitoring the levels of different signals such as the laser temperature and injection current, the absorption depth through the use of DAC/ADC.

5. TECHNICAL CHARACTERISTICS

We have built two units of the frequency-locked lasers. These prototypes feature high quality characteristics as is detailed below. The CW optical power is delivered over a PM fiber output and is up to 8 mW. The linewidth has been measured using the self-heterodyne technique. A typical self-heterodyne spectrum is shown on Fig. 3. A numerical fit with a Voigt profile was performed on the data (black line): the lorentzian contribution to the beat note is typically 1 MHz while the Gaussian contribution is about 2.9 MHz. From these values, we can estimate the 3-dB linewidth of the frequency-locked laser to 1.7 MHz.

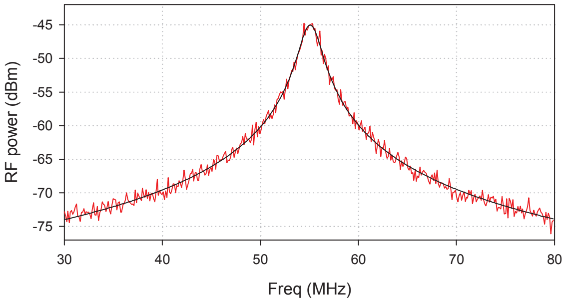

Fig. 3. Self-heterodyne beat note of the frequency-locked DFB laser.

The absolute frequency of the locked lasers has been measured with a EXFO wavelength meter WA1500 over 41 hours as presented in Fig. 4 for prototype #1. We obtain an absolute frequency of 193 049.51 ± 0.02 GHz (or 1552.9304 ± 0.0002 nm) for both prototypes, and it is limited by the wavelength meter. This is in good accordance with the $H^{13}CN$ P(14) value tabulated by the NIST [4] , i.e. 1552.931 ± 0.003 nm.

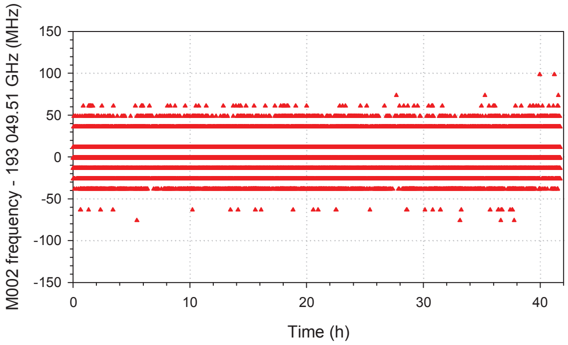

Fig. 4 Frequency of the frequency-locked laser over 41 hours.

The frequency stability has been measured by beating the two prototypes together. An acousto-optic shifter at 55 MHz is used on one of the prototypes to shift the beat frequency away from zero. The beat note evolution is presented in Fig. 5 under free-running (red curve) and locked (blue curve) conditions for a sampling period of the frequency counter of 10 s. We observe a dramatic improvement of the frequency stability, as the beat note fluctuations are reduced to sub-MHz levels.

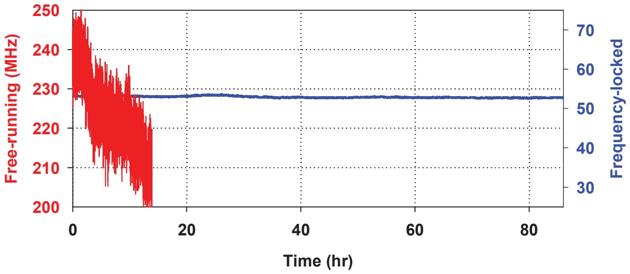

Fig. 5. Relative intensity noise of the frequency-locked DFB laser.

The corresponding stability is presented in Fig. 6 in terms of Allan standard deviation. We observe the effect of the frequency locking to the molecular line for averaging times greater than 100 ms, which is related to the bandwidth of the locking loop. The stability reaches levels at 10^{-10} between 30 and 10 000 s which is typical of the frequency-locking technique used here. This represents an improvement of two orders of magnitude over the free-running stability.

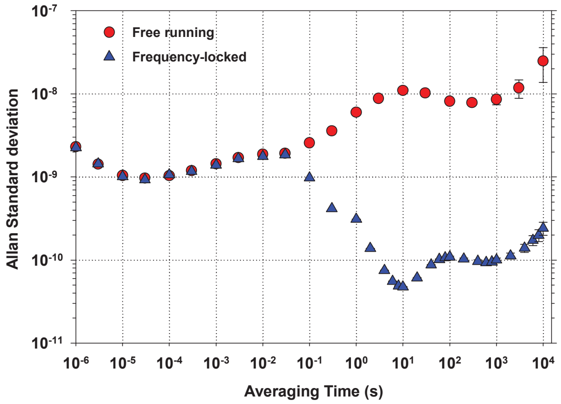

Fig. 6. Allan standard deviation for free-running and frequency-locked lasers.

The relative intensity noise has been measured on both prototypes between 1 Hz and 10 GHz. (Fig. 7). We obtain a decrease of the RIN from -100 to -140 dBc/Hz between 1 Hz and 10 kHz with a 1/f dependency, and then a level below -140 dBc/Hz between 10 kHz and 10 GHz. However, in this frequency range, we are limited by our measurement setup.

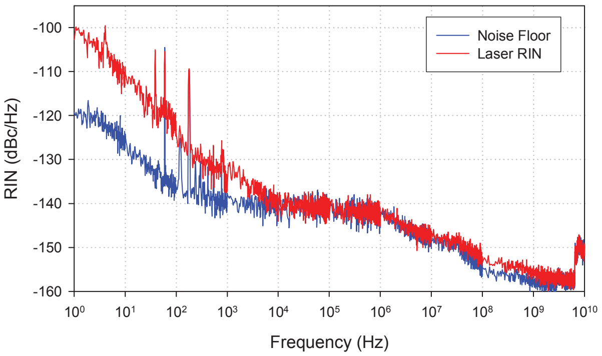

Fig. 7. Laser RIN and noise floor of the measurement system.

At this point, the two prototypes of frequency-stabilized lasers present excellent performances to be used as metrology sources in space instrumentation. However, they have to go through a space qualification in order to confirm that these performances will be maintained while the stabilized sources are submitted to various stress present in a space environment. For this, we are planning to run several tests including different cycling (temperature, vacuum and vibration) together with outgasing and radiation testing. After each test, the performances of the prototypes will be verified.

6. FURTHER IMPROVEMENTS: LASER LINE NARROWING

Space applications can require laser sources with a high degree of coherence and low phase noise. To further improve the above HCN frequency-stabilized light source, we are working on the realization of ultra-narrow laser sources by reducing the linewidth of standard DFB sources under the kilohertz level. The linewidth narrowing is done by means of an electronic feedback loop [5].

The principle of operation of the linewidth reduction system is schematized in Fig. 8. The optical output of the laser, a DFB type semiconductor laser in the present case, is sent to a frequency discriminator. The frequency discriminator converts the laser frequency fluctuations into power variations. A comparison of these power variations with a reference power level allows the generation of an error signal. A loop filter generates a correction signal that is applied to the injection current of the laser. When the feedback loop is activated, the frequency of the laser will track the frequency of the optical frequency discriminator within the bandwidth of that locking loop.

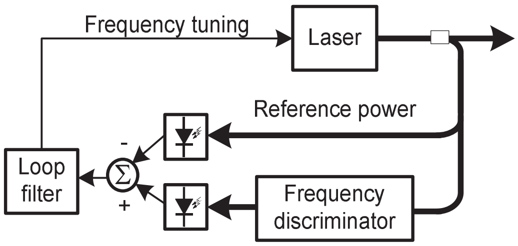

Fig. 8: Electronic feedback based linewidth reduction system.

It is thus mandatory to select the appropriate frequency discriminator. The latter must have lower frequency noise than the laser in the locking bandwidth but also provides a suitable frequency-to-power conversion.

The effect of a linewidth narrowing system, acting on a DFB semiconductor laser (SCL), is analysed through the power spectral density (PSD) of frequency noise. Fig. 9 compares the PSD of frequency noise of the sole laser (Free-Running SCL) and the laser with applied electronic feedback (Narrow Linewidth SCL).

The PSD of frequency noise of the free-running SCL shows 1/f frequency noise behaviour from 1 Hz up to 100 kHz followed by a white noise plateau. When the linewidth reduction system is activated, the SCL frequency noise is considerably reduced (up to 40 dB) in the frequency range up to 100 kHz. After 100 kHz, the noise increases to reach the white noise plateau of the free-running laser at 1 MHz. This feature is a consequence of the 1 MHz locking bandwidth of the frequency locking loop. A greater bandwidth would allow noise reduction at higher frequencies.

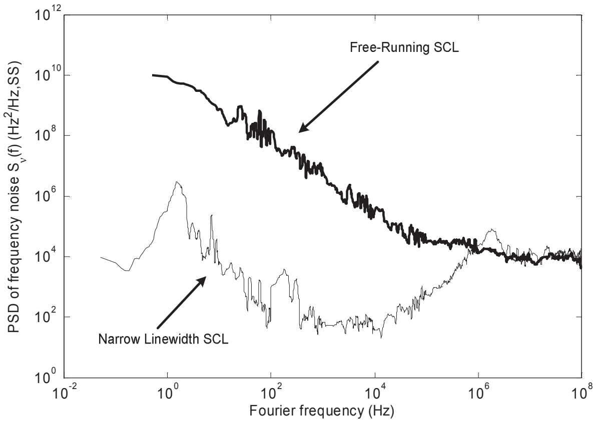

Fig. 9: PSD of frequency noise comparing the free-running SCL and the narrow linewidth SCL.

The consequence of the frequency noise reduction shown above is many-fold. For instance, the laser coherence length (at 50% coherence level) is increased from 145 m in fiber, up to 45 km when the linewidth reduction system is activated. These theoretical results have been qualitatively confirmed by analyzing the moving fringes at the output of unbalanced interferometers [5].

The frequency noise reduction also impacts on the laser lineshape, reducing the laser linewidth from 500 kHz to below the kilohertz level. Fig. 10 compares the lineshape of the free-running SCL and the narrow linewidth SCL measured in a self-heterodyne setup. The optical path difference (OPD) in the unbalanced fiber interferometer is 25 km. The results in Fig. 10 demonstrate the ability of the linewidth reduction system to decrease the laser linewidth. The measurement setup limits the measurable linewidth to 1 kHz.

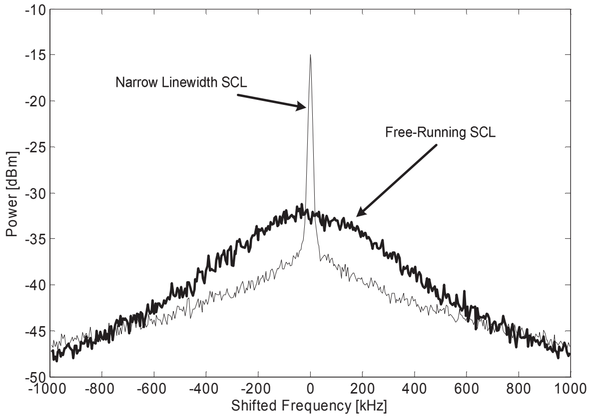

Fig. 10: Self-Heterodyne lineshape measurement comparing the Free-Running SCL and the Narrow Linewidth SCL. The interferometer OPD corresponds to 25 km in fiber.

7. CONCLUSION

We have built two prototypes of frequency-locked lasers to be used as metrology source for FTIR spectrometers. The performances of these units are within the best obtained for this type of optical frequency standards, i.e. a laser is frequency-locked on a molecular absorption line using linear absorption spectroscopy technique based on the Drever-Pound-Hall method. The laser useful output is a CW signal at 1552.93 nm delivering a power of 8 mW. The accuracy of the output frequency is better than 0.2 pm (20 MHz) and its stability is at 1.5 x 10^{-10} for averaging time between 3 sec and 3 x 10^3 s. The optical module of these lasers was designed to be space-qualifiable and all the materials are selected to meet space out-gassing standards for space applications. In order to improve upon the performance of this laser system, work has also been undertaken to narrow the emission linewidth of the laser by external electrical feedback. Preliminary results show a reduction of the 3 dB linewidth from 500 kHz to below 1 kHz for measurement time of the order of 1 ms.

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