Compact silicon photonics-based laser modules for FM-CW LIDAR and RFOG

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ABSTRACT

Narrow-linewidth semiconductor lasers, micro-optics, silicon photonics (SiP), low noise electronics and high-density packaging are key elements for the development of compact high-end light sources for sensing.

A laser module for the interrogation of an RFOG (Resonant Fiber-Optic Gyroscope) includes three distributed feedback lasers coupled with micro-lenses to a multi-component SiP chip that performs beat note detection and several other functions. The lasers and SiP chip are packaged in a 2.6 cm^3 multi-layer ceramic package, a 4x volume reduction over a first generation module. The package interfaces with 92 electrical pins and two fiber pigtails, one carrying the signals from a master and slave lasers, another carrying that from a second slave laser. The complete laser source including electronics is 60 mm in diameter and 23 mm in height, a 10x volume improvement over a previous version. The master laser can be locked to the RFOG resonator with a loop bandwidth greater than 1 MHz. The slave lasers are offset frequency locked to the master laser with loop bandwidths greater than 100 MHz. This high performance source is compact, automated, robust, and remains locked for days.

A lighter version of this laser module for FM-CW LIDAR applications produces an output optical frequency that varies linearly as a function of the electrical drive. A triangular modulation at 100 kHz with a greater than 1 GHz amplitude has been demonstrated with a linearity noise near 1 MHz as measured through a 150 m unbalanced interferometer.

Keywords: Silicon photonics, laser stabilization, Pound-Drever-Hall method, optical phase-locked loop, resonance tracking, fiber resonator, optical sensing, FM-CW lidar

1. INTRODUCTION

Monitoring the variation of an optical path under the action of a measurand affords the highest sensitivity achievable through optical sensing. The most striking achievement of this approach has been the detection of gravitational waves generated by merging black holes[1]. The change in optical path takes place within an interferometer converting it into an intensity variation detectable by a photodiode. Rather than measuring intensity fluctuations resulting from an applied measurand, one may monitor the optical frequency change required to equalize the intensity reflected or transmitted by the interferometer. In either case, the achievable sensitivity is proportional to the narrowness of the interferometric spectral feature interacting with the sensing light. Monitoring the shift of a narrow spectral feature under the action of a measurand requires a narrow linewidth optical source and high quality control electronics. Furthermore, the monitoring of rapidly evolving phenomena requires electronics with sufficient bandwidth for tracking. A Pound-Drever-Hall (PDH) locking loop can achieve both objectives, i.e. tracking a narrow spectral feature with a bandwidth in the MHz range[2]. Finally, some sensing applications require tracking the frequency difference between two narrow spectral features[3], a first feature acting as a sensor and a second one as a reference. Such differential sensing requires controlling the frequency difference between two lasers precisely. An optical phase-locked loop (OPLL) locks in phase two laser signals at a fixed or tunable frequency offset. Applications that can benefit from PDH and OPLL locking loops include biosensing[4], temperature, pressure, acoustics or strain sensing[5], and resonant fiber optic rotation sensing[6-9].

A first version of an optical source for sensing included a low-noise, high-bandwidth PDH loop for locking a master semiconductor laser to an optical interferometer as well as low-noise, high-bandwidth OPLL loops to lock three slave semiconductor lasers to the master laser[10]. Each semiconductor laser was encapsulated individually in a butterfly package, whereas a silicon photonic (SiP) chip including passive optical components and photodiodes controlled the four lasers[10].

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Further integration was realized by encapsulating unpackaged semiconductor lasers on a common substrate with a SiP chip comprising active and passive components[11]. Other than a reduction in size, this allowed a sizable increase in the bandwidth of the OPLL loops by shortening optical and electrical paths. The SiP chip carried more functionalities such as the PDH modulation of the master laser, power monitoring and variable optical attenuation for control of the optical output power.

Yet another version of a high-end laser source for sensing is presented, wherein micro-optics and high-density packaging further improve compactness. The construction of this new source is discussed in section 2 and experimental results are presented in section 3. A lighter version of this laser module provides a linear output optical frequency as required by FM-CW lidar applications and is discussed in section 4.

2. LASER SYSTEM DESCRIPTION

2.1 Semiconductor lasers

The laser module for sensing includes custom distributed feedback (DFB) lasers developed in collaboration with the National Research Council Canada. These lasers emit around 1550 nm and display a low frequency noise with an intrinsic linewidth smaller than 10 kHz. Furthermore, they provide a nearly flat frequency modulation (FM) response up to frequencies greater than 100 MHz as shown in Figure 1, which compares the FM response of TeraXion's laser to that of a commercial DFB laser. The FM response of the standard DFB laser dips at frequencies well below 1 MHz and presents a phase inversion that precludes an efficient frequency noise reduction by means of an electronic feedback.

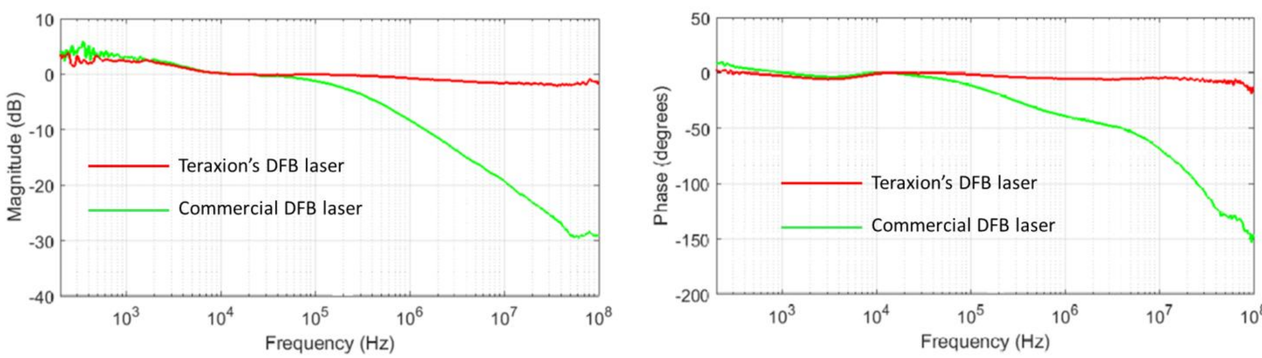

Figure 1. Comparison of the FM response of TeraXion's custom DFB laser to that of a commercial DFB laser

2.2 Frequency noise management

The high level of spontaneous emission and the index of refraction dependence on the carrier density result in a sizable frequency noise even in Teraxion's custom DFB lasers. Locking the laser to a passive optical resonator can reduce this frequency noise markedly. In the present instance, the master laser is locked to the side of the reflectivity spectrum of a narrow band (340 MHz) fiber Bragg grating (FBG) used as a frequency discriminator. The intensity fluctuations of light reflected by the FBG are detected and a feedback signal is generated and applied to the master laser.

The master laser can also be locked to an external optical resonator, such as a Sagnac interferometer in the case of a RFOG (Resonant Fiber-Optic Gyroscope), with a PDH loop. The basic configuration of a PDH loop was presented in reference [11]. Light from the master laser is phase-modulated before being reflected by the external resonator and detected with a photodiode. The photodetection signal is mixed with the RF wave driving the phase modulator to produce a correction signal that is fed to the laser to tune its optical frequency. The correction signal stabilizes when the laser is in anti-resonance with the optical resonator, i.e. perfectly aligned with a maximum reflectivity peak.

The optical resonator to which the master laser is locked can be used for sensing as well. In this case, slave lasers tuned independently from the master laser interrogate the interferometer for sensing purposes. For example, in a RFOG used for inertial sensing, rotation creates a differentiation of the resonance peaks for light propagating clockwise and counterclockwise within the optical fiber loop[6-7]. The beat frequency of two slave lasers counter propagating within the fiber loop and tuned independently to track each a resonance peak is then proportional to the rotation rate of the fiber loop. High sensitivity sensing is afforded when both slave lasers carry the same frequency noise, which then subtracts when the lasers beat together. This condition is obtained by locking each slave laser to the master laser with an OPLL loop as discussed in reference [11]. The slave lasers then share a common frequency noise equal to that of the master laser over a bandwidth limited by the OPLL bandwidth.

In order for this phase-locking to occur, the wavelengths of emission of the master and slave lasers must be close enough from one another. These wavelengths are brought within a few picometers from one another by adjusting the temperature and the DC drive current of the lasers. The present system comprises two slave lasers that are phase-locked to a master laser.

2.3 System configuration

The main elements of the laser module are presented schematically in Figure 2. In order to improve compactness and performance, optical components are mounted in a multi-layer ceramic package. This core package includes a master laser (ML) and two slave lasers (SL1 and SL2) mounted on thermo-electric coolers (TECs) to keep their wavelengths of emission in sufficient proximity to ensure proper operation of the OPLL loops. The output beam from each laser is collimated by a microlens, then goes through an isolator (ISO) to minimize detrimental light reflection towards the laser, and is finally focused by a second microlens in a SiP chip. Electrical connections between the ceramic package and the TECs, lasers and SiP chip are achieved by wire bonds. Further details can be found in reference [11], the main difference between the current system and a previous one being the addition of a FBG as a frequency discriminator to further reduce the frequency noise of the master laser. Figure 3 highlights the micro-optical components used to couple the master laser to the FBG. An optical tower diverts 30% of the laser power towards the FBG, whereas a polarizing beam splitter and a Faraday rotator redirect light reflected by the FBG towards a photodiode (PD).

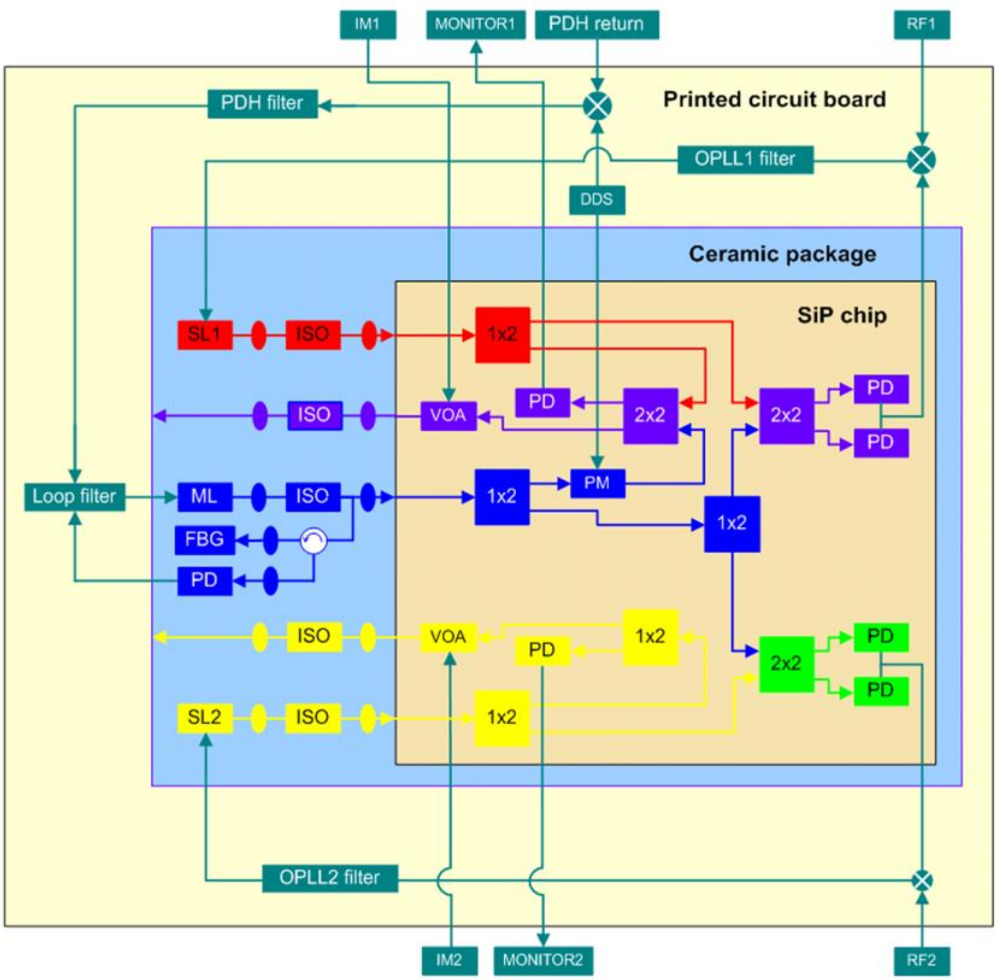

Figure 2. General configuration of the multi laser source

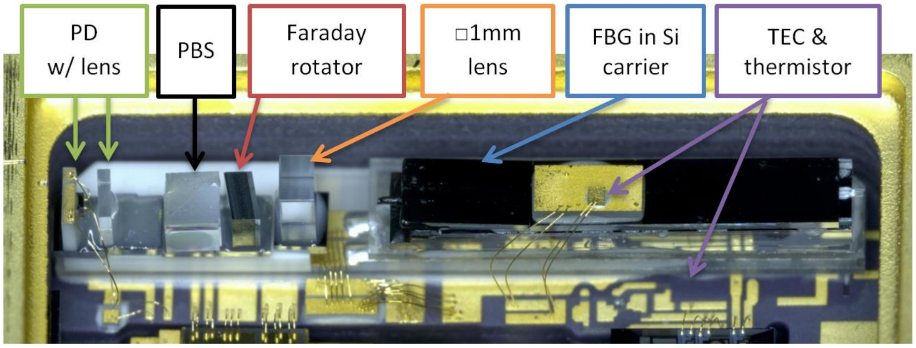

Figure 3. Coupling of the master laser to a fiber Bragg grating (PD: photodiode)

The core package, shown in Figure 4, contains the lasers, the FBG and a 3 mm x 16 mm SiP chip. It covers an area of 18.3 mm x 24.5 mm. It is interfaced with 92 electrical pins and two fiber pigtails. The pins are soldered to a printed circuit board (PCB) featuring a micro-processor that controls and monitors the system to ensure stable operation over fluctuating environmental conditions. One fiber pigtail carries light from the master laser and a slave laser, while another carries light from the second slave laser. This configuration allows locking the master laser to an optical resonator and to interrogate the same resonator with the slave lasers for differential sensing. The complete laser source including electronics is 60 mm in diameter and 23 mm in height, a 10x volume reduction over a previous version[11].

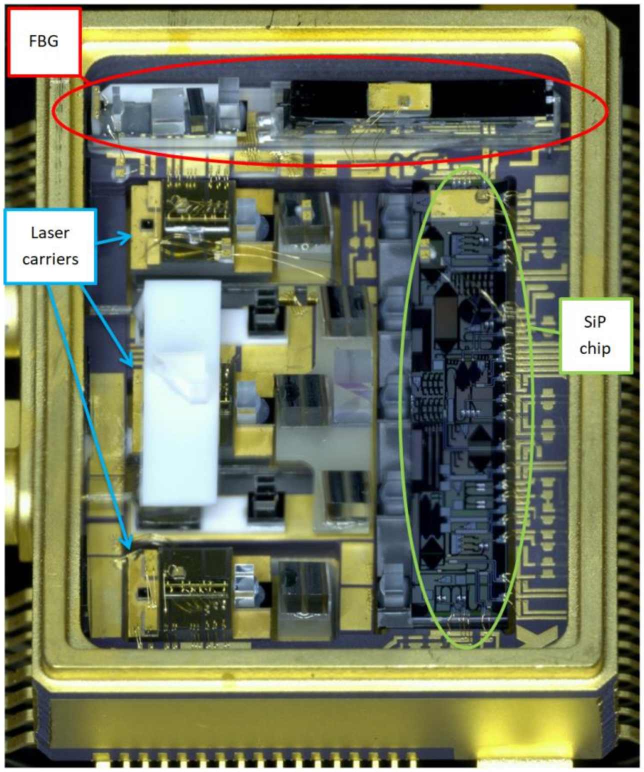

Figure 4. Core package including three lasers, the FBG frequency discriminator and a SiP chip

The multi laser source does not include an optical input. As illustrated in Figure 5, the photodiode required to close the PDH loop is located on a separate printed circuit board that communicates with the main one through a coaxial cable. The RF reference signals (RF1, RF2) that determine the frequency offset between the master laser and the phase-locked slave lasers are provided as inputs.

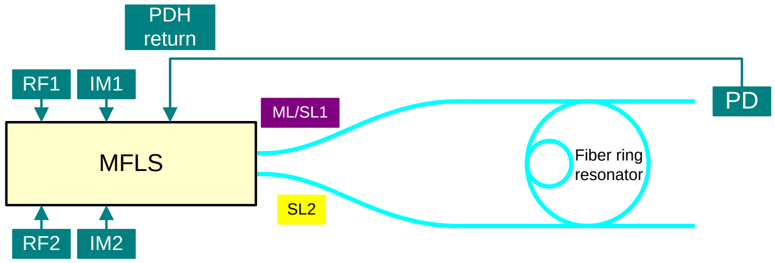

Figure 5. Interrogation of a fiber ring resonator

3. RESULTS IN RFOG CONFIGURATION

A multi laser source as described was built and characterized. All desired functionalities were demonstrated successfully. Performances were improved relatively to those of a previous version[11], notwithstanding the higher packaging density of the current version. The master laser can be locked to an RFOG resonator with a loop bandwidth greater than 1 MHz. The slave lasers are offset frequency locked to the master laser with loop bandwidths greater than 100 MHz. This high performance source is compact, automated, robust, and remains locked for days.

Figure 6 presents measurements of power spectral densities of frequency noise (PSDFN) performed on the laser source. The intrinsic frequency noise of Teraxion's DFB lasers is as low as 2000 Hz^2/Hz at high frequencies corresponding to a Lorentzian linewidth of 6.3 kHz. Locking the master laser to the FBG frequency discriminator reduces the frequency noise markedly, up to frequencies of 30 MHz. The yellow curve on the graph also highlights the successful subtraction of the frequency noises of the master laser and a slave laser resulting from their phase locking with an OPLL. The PSDFN of the beat signal between the master laser and the second slave laser generated within the SiP chip stands at 10^{-1} Hz^2/Hz at 1 MHz, i.e. 47 dB below the intrinsic frequency noise level observed on the free running lasers.

Figure 7 presents the electrical spectrum of the beat signal produced by detecting simultaneously the master laser and the second slave laser with a common photodiode. The Dirac peak at 453.5 MHz results from the interference between the optical carriers of both lasers. The rest of the curve is noise that is mostly due to uncorrelated phase variations of the lasers. The noise depression surrounding the Dirac peak is due to the OPLL loop that aligns the phase of the slave laser with that of the master laser. As indicated, this phase control mechanism operates over a bandwidth of 121 MHz. Shorter optical and electrical delays afforded by the present compact configuration were instrumental in increasing the OPLL loop bandwidth.

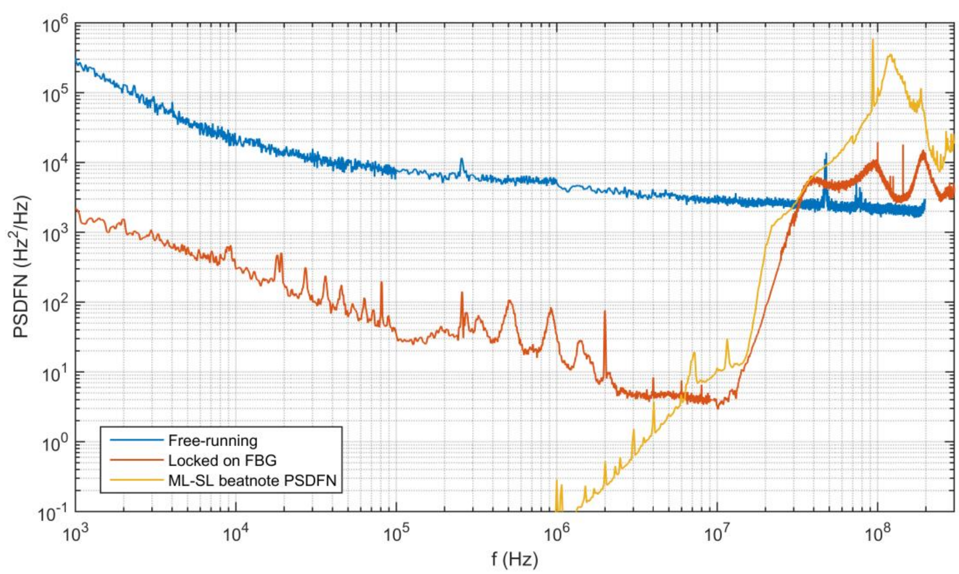

Figure 6. Measured power spectral densities of frequency noise

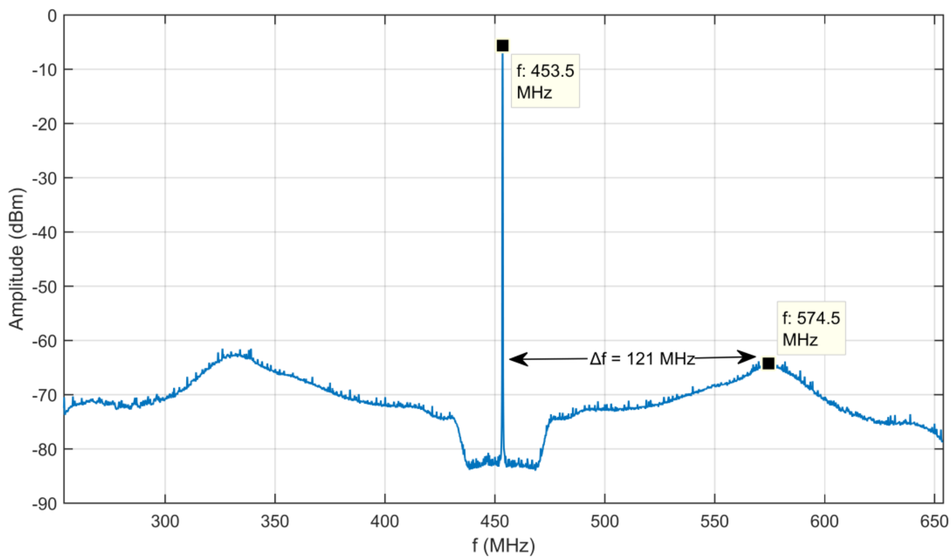

Figure 7. Electrical spectrum of the beat signal between the master laser and slave laser 2 phase-locked by an OPLL loop

4. RESULTS IN FM-CW LIDAR CONFIGURATION

The FM-CW source is a simplified version of the laser module described in the previous sections. It features a single Teraxion custom DFB laser biased with a stable current source. A triangular wave is also fed to the laser to modulate its output optical frequency as in a FM-CW lidar system devised to measure distance and speed. Ideally, the laser optical frequency should reproduce exactly the triangular wave function. This case is depicted by the blue curve in Figure 8 representing the optical frequency of the laser signal transmitted by a FM-CW lidar. The red curve represents the optical frequency of the light received at the lidar after reflection by a target. The return signal is delayed by the time taken by light to move from the lidar to the target and back. It is also shifted spectrally when the target is in motion, as shown here. In the present instance, the target is moving towards the lidar and the ensuing Doppler shift leads to an increase in the optical frequency of the reflected light. The green curve represents the much lower frequency of the RF beats resulting from the interference between the transmit and return signals. The RF frequency alternates between two constant values from which one can deduce the target distance and speed component towards the lidar[12].

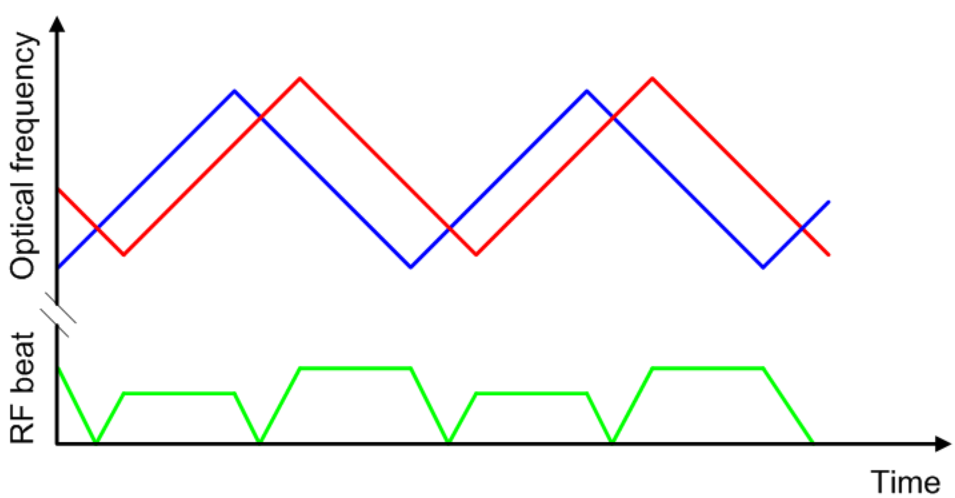

Figure 8. Optical frequency of the signal transmitted by an ideal laser in a FM-CW lidar (blue curve), optical frequency of the signal received at the lidar after reflection by a moving target (red curve), RF frequency of the beats resulting from the interference between these signals (green curve)

The optical frequency of a real laser signal coming out of a FM-CW lidar does not vary as a perfect triangular waveform. As a result, the plateaus in the RF beat frequency shown in the previous figure are distorted as well. This introduces uncertainty when measuring the distance and speed of a target. In order to assess the importance of this distortion, the output from the laser was coupled into an optical fiber and characterized with the system illustrated in Figure 9. It comprises an all fiber Mach-Zehnder interferometer that produces the beating of two copies of the laser output delayed relatively by a time determined by the length of the fiber coil. This delay corresponds to the roundtrip time experienced by the laser reflected by a target in a FM-CW lidar system, e.g. a 150 m fiber coil corresponds to a lidar-to-target distance of 108 m. Figure 10 shows the signal observed with an oscilloscope when detecting the intensity beats. On the left side, a chirp in the beats is clearly visible, indicating a sizable distortion in the optical frequency of the laser under a triangular modulation. The frequency of the beats on the right hand side of the figure presents a much better uniformity.

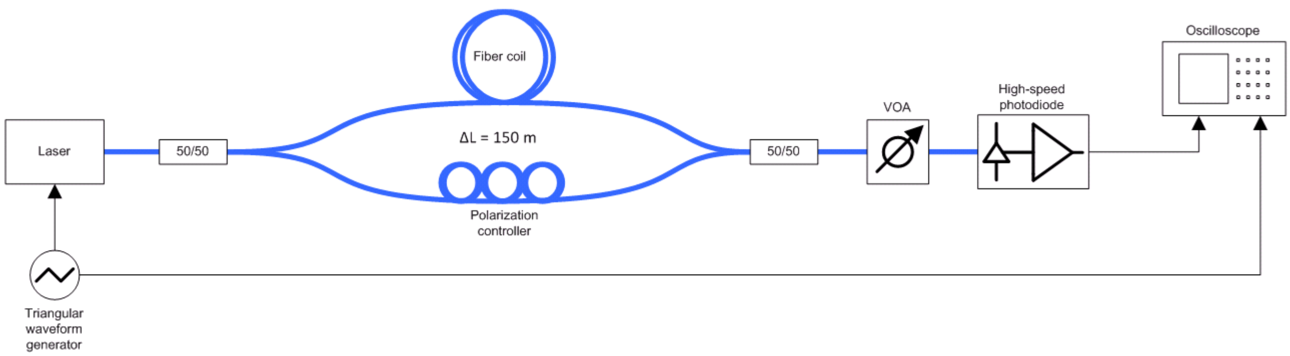

Figure 9. Characterization set-up for the measurement of the frequency distortion

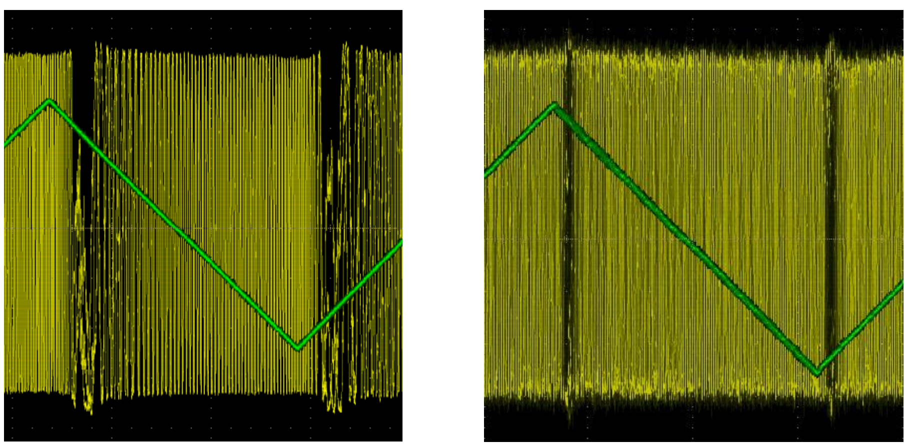

Figure 10. RF beats at the output of the characterization system as observed on an oscilloscope. A commercial DFB laser produced the beats on the left that display a visible chirp

Given the interferometric setup shown in Figure 9, it can be shown that the phase of the RF beat note is related to the optical frequency of the source f_o, through

$$\phi_{RF}(t) = 2\pi f_o(t) * rect\left(\frac{t}{T}\right),$$

where T is the delay introduced by the interferometer, and * denotes the convolution operator. When the laser frequency $f_o(t)$ has a sufficiently limited spectral content, this can be approximated as

$$\phi_{RF}(t) = 2\pi T f_o(t),$$

where the phase of the RF beat note is directly proportional to the optical frequency f_o. The optical frequency profile is obtained by extracting the phase of the interferogram corresponding to a single frequency sweep from the associated analytical signal. The computed phase is then converted into the optical frequency, taking into account the optical path difference of the interferometer. A linear fit is finally subtracted from the optical frequency to obtain its nonlinear distortion on either the up-ramp or down-ramp of the triangular waveform. Figure 11 presents a result obtained with a 150-meter fiber coil and a triangular modulation with a period of 100 kHz and a frequency excursion of 1 GHz. The graph on the left presents the time variation of the optical frequency measured over 70% (15% - 85%) of a ramp of the triangular modulation. The graph on the right presents the remaining nonlinear distortion after subtraction of a linear fit. It amounts to 1.5 MHz pk-pk, i.e. 0.2% of the 0.7 GHz excursion on the time slot considered. Measurements from multiple modulation periods are superimposed in the graphs. The thickness of the nonlinear curves results from the ultra-low frequency noise of the laser. Figure 12 presents results obtained under the same conditions but with a frequency excursion of 2 GHz. It compares the behaviour of TeraXion's custom DFB laser to that of a commercial DFB laser. The nonlinear distortion with the custom laser amounted to 3 MHz, i.e. 0.2% of the 1.4 GHz excursion on the time slot considered and was much weaker than obtained with the conventional DFB laser.

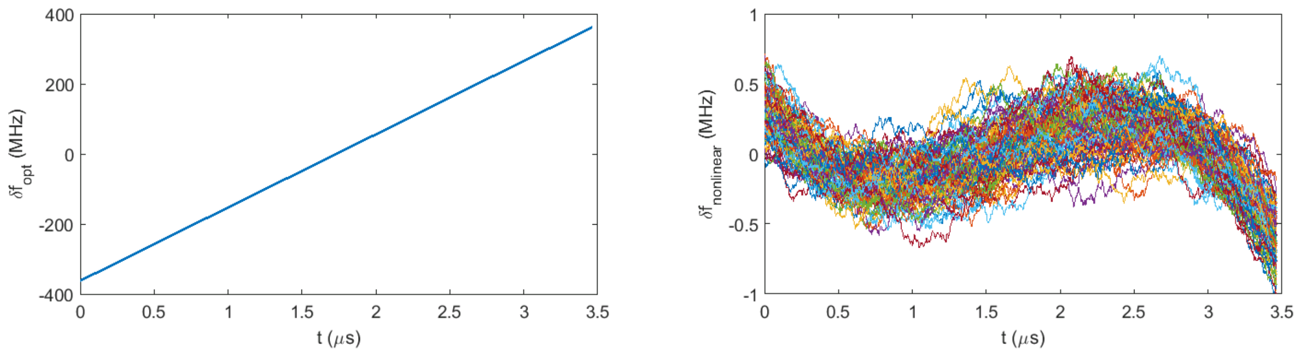

Figure 11. Optical frequency variation on 70% (15% - 85%) of a ramp (left graph) and nonlinear frequency distortion after subtraction of a linear fit (right graph)

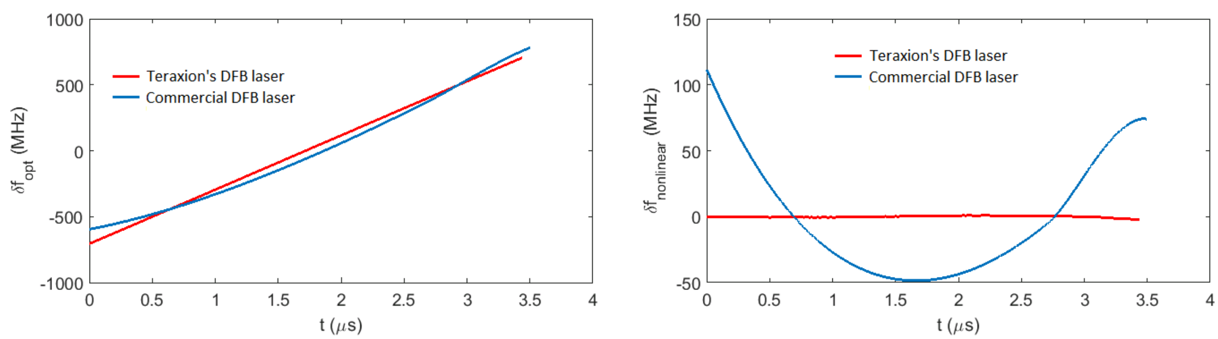

Figure 12. Comparison of the frequency distortion of a commercial DFB laser and of TeraXion's custom DFB laser over a frequency excursion of 1.4 GHz

5. CONCLUSION

A compact three-laser source for optical sensing has been designed and built. The source comprises three custom semiconductor DFB lasers, a complex silicon photonics chip comprising passive and active components and a FBG used as a frequency discriminator. The SiP chip and the accompanying electronics allow locking a master laser to an optical resonator through the Pound-Drever-Hall method and phase-locking two slave lasers to the master laser with OPLL loops. It also provides monitoring signals to control the laser outputs within the chip. The functionalities of this source have been demonstrated. Phase-locking with the OPLL loops has been achieved over a bandwidth of 121 MHz. High-density packaging allowed a 10x reduction in volume of the source including electronics, compared to a previous version[11]. This highly adaptable multi-laser source can address various sensing applications requiring the tracking of up to three narrow spectral features with a high bandwidth. A simpler version of this source comprising a single laser was shown to provide a linear frequency output when modulated by a triangular waveform, as required in FM-CW lidars.

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REFERENCES

[1] Abbott, B. P. et al., "Observation of Gravitational Waves from a Binary Black Hole Merger," Phys. Rev. Lett. **116**(061102), 1-16 (2016).

[2] Drever, R. W. P., Hall, J. L. et al., "Laser phase and frequency stabilization using an optical resonator," Appl. Phys. B: Lasers Opt. **31**, 97-105 (1983).

[3] Liu, Q. et al., "Ultra-high-resolution large-dynamic-range optical fiber static strain sensor using Pound–Drever–Hall technique," Opt. Lett. **36**, 4044-4046 (2011).

[4] Swaim, J. D. et al., "Detection of nanoparticles with a frequency locked whispering gallery mode microresonator," Appl. Phys. Lett. **102**, 183106 (2013).

[5] Gagliardi, G. et al., "Optical Fiber Sensing Based on Reflection Laser Spectroscopy," Sensors **10**, 1823-1845 (2010).

[6] Wu, J. et al., "Resonator fiber optic gyro with high backscatter-error suppression using two independent phase-locked lasers," Proc. SPIE **9634**, 96341O (2015).

[7] Sanders, G. A. et al., "Fiber optic gyro development at Honeywell," Proc. SPIE **9852**, 985207 (2016).

[8] Smiciklas, M. et al., "Development and Evaluation of a Navigation Grade Resonator Fiber Optic Gyroscope," Joint Navigation Conference (2017).

[9] Sanders, G. A. et al., "Development of compact resonator fiber optic gyroscopes," IEEE Int. Symposium on Inertial Sensors and Systems (2017).

[10] Ayotte, S. et al., "Silicon Photonics-Based Laser System for High Performance Fiber Sensing," Proc. SPIE **9634**, 963413 (2015).

[11] Ayotte, S. et al., "Compact silicon photonics-based multi laser module for sensing," Proc. SPIE **10537**, 1053717 (2018).

[12] Pierrottet, D. et al., "Development of an All-Fiber Coherent Laser Radar for Precision Range and Velocity Measurements," MRS online Proceedings **883**, PROC-883-FF2.3 (2005).