# Compact silicon photonics-based multi laser module for sensing

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## ABSTRACT

A compact three-laser source for optical sensing is presented. It is based on a low-noise implementation of the Pound-Drever-Hall method and comprises high-bandwidth optical phase-locked loops. The outputs from three semiconductor distributed feedback lasers, mounted on thermo-electric coolers (TEC), are coupled with micro-lenses into a silicon photonics (SiP) chip that performs beat note detection and several other functions. The chip comprises phase modulators, variable optical attenuators, multi-mode-interference couplers, variable ratio tap couplers, integrated photodiodes and optical fiber butt-couplers. Electrical connections between a metallized ceramic and the TECs, lasers and SiP chip are achieved by wirebonds. All these components stand within a 35 mm by 35 mm package which is interfaced with 90 electrical pins and two fiber pigtails. One pigtail carries the signals from a master and slave lasers, while another carries that from a second slave laser. The pins are soldered to a printed circuit board featuring a micro-processor that controls and monitors the system to ensure stable operation over fluctuating environmental conditions.

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. It is used to sense a fiber-based ring resonator emulating a resonant fiber optics gyroscope. The master laser is locked to the 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.

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

## 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 where it is converted into an intensity variation that can be detected with a photodetector. Rather than measuring the intensity fluctuations resulting from an applied measurand, one may instead 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) laser frequency locking loop can achieve both objectives, namely tracking a narrow spectral feature and doing so with a bandwidth in the MHz range[2]. Finally, some sensing applications require tracking the frequency difference between two narrow spectral features[3]. For example, a first feature can be used as a sensor and a second one as a reference. It can thus prove useful to precisely control the frequency difference between two lasers to perform such differential sensing. 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].

An earlier version of a compact optical source for sensing narrow spectral features was presented[10]. It 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. Each semiconductor laser was encapsulated individually in a butterfly package. Some compactness was achieved by integrating on a single silicon photonic (SiP) chip the passive optical components and photodiodes used to control the four lasers.

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Further integration of a similar source has been realized by encapsulating unpackaged semiconductor lasers on a common substrate with a SiP chip comprising active and passive components. 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 in this new source carries more functionality such as the PDH modulation of the master laser, power monitoring and variable optical attenuation for relative intensity noise (RIN) reduction and control of the optical output power. The construction of this new source is discussed in section 2 and experimental results are presented in section 3.

## 2. LASER SYSTEM DESCRIPTION

### 2.1 Pound-Drever-Hall locking loop

The basic configuration of a PDH locking loop as implemented in the laser source is illustrated in Figure 1. The master laser (ML) consists in a distributed feedback (DFB) semiconductor laser oscillating at 1.55 µm with an intrinsic linewidth smaller than 50 kHz. Light from the master laser is phase-modulated before being reflected by an optical resonator (OR) such as a Fabry-Perot or a Sagnac interferometer and detected by a photodiode (PD). The phase modulator (PM) is driven at a zero-peak amplitude of 0.6 rad by a pure RF tone between 10 and 100 MHz provided by a direct digital synthesizer (DDS)[10]. The photodetection signal is mixed with the RF wave from the DDS and filtered to produce a correction signal that adds to the current driving the laser to tune its optical frequency of emission. The correction signal stabilizes when the laser is in anti-resonance with the optical resonator, i.e. perfectly aligned with a maximum reflectivity peak.

In semiconductor lasers, the high level of spontaneous emission and the index of refraction dependence on the carrier density can result in a sizable frequency noise. Locking the laser to an optical resonator can reduce markedly this frequency noise over a bandwidth limited by the PDH loop bandwidth. The master laser thus controlled can be used to interrogate a sensing interferometer with a much improved sensitivity in comparison to that achievable with a stand-alone laser. The optical resonator to which the master laser is locked can be used for sensing as well. In this case, slave lasers that are tuned independently from the master laser interrogate the interferometer for sensing purposes. For example, in a resonant fiber optic gyroscope (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 each track 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 gets subtracted when the lasers beat together. This condition can be created by locking the slave lasers to the master laser with an OPLL loop. The slave lasers then share a common frequency noise equal to that of the master laser over a bandwidth limited by the OPLL bandwidth.

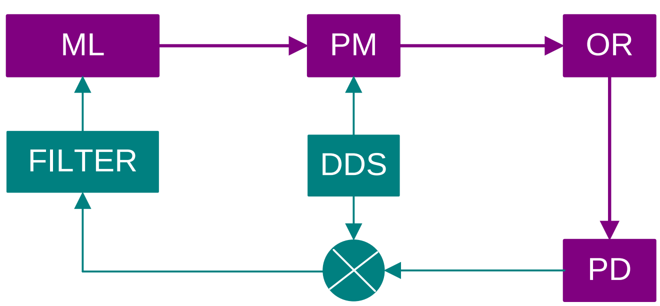


Figure 1. Pound-Drever-Hall locking of a master laser (ML) to an optical resonator (OR) (PM: phase modulator, DDS: direct digital synthesizer, PD: photodetector).

### 2.2 OPLL locking loop

The interference of two DFB semiconductor lasers that oscillate independently produces a noisy beat signal as illustrated in Figure 2 (a). The macroscopic beat frequency is determined by the difference in the optical frequencies of the lasers.

The noise results from the addition of the uncorrelated phase noises from both lasers. A slave laser (SL) can be phased-locked to a master laser with an OPLL as shown in Figure 2b. The beat signal produced by the balanced photodetection of the interfering lasers is mixed with a RF reference signal and then filtered appropriately to produce a correction signal that is added to the current driving the slave laser. This procedure aligns the temporal phase noise variations of the slave laser with those of the master laser over a bandwidth limited by the OPLL bandwidth. As a result, a clean beat signal is produced at a frequency equal to the RF tone frequency. Tuning of the optical frequency of the slave laser relatively to that of the master laser is determined by the RF signal frequency. 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.

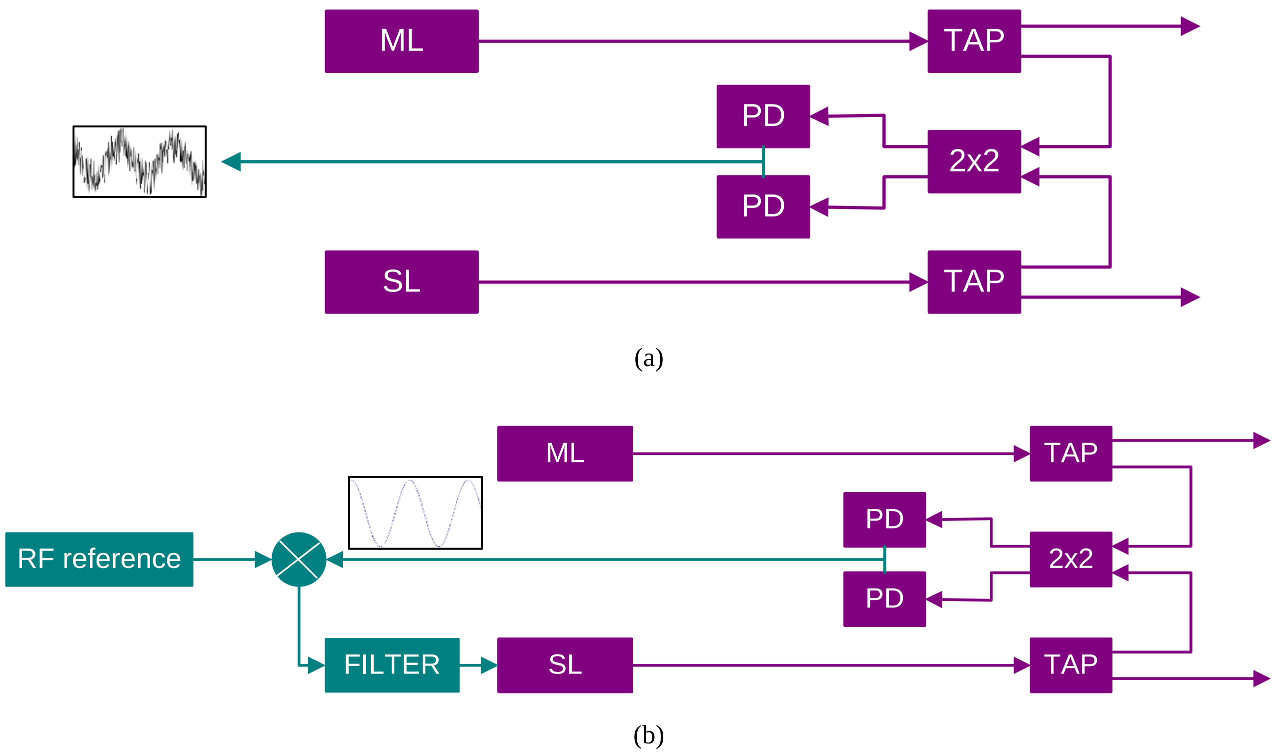


Figure 2. (a) Noisy beat signal produced with independent lasers. (b) Phase-locking of a slave laser (SL) to a master laser with an OPLL, leading to a clean beat signal.

## 2.3 System configuration

The main elements of the receiver are presented schematically in Figure 3. In order to improve compactness and performance, optical components are mounted on a common metallized ceramic substrate and encapsulated within a single enclosure. This core package includes three DFB semiconductor lasers, i.e. 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. Each laser provides 25-30 mW of optical power at a pump current of 300-340 mA. The output beam from each laser is first 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 regrouping the rest of the optical components. This chip comprises routing components (waveguides, multimode-interference couplers, tap couplers, optical fiber butt couplers) to mix the master laser with each slave laser for phase-locking and to output light towards a sensing resonator. The SiP chip includes a number of active components. A phase modulator (PM) with a 3 dB bandwidth of 70 MHz provides the modulation required to lock the master laser to an optical resonator. Variable optical attenuators (VOA) with a similar bandwidth as the phase modulator are used to reduce light intensity noise (RIN) that can be converted into phase noise by a sensing fiber through the optical Kerr effect[7]. They also allow adjusting the optical output power leaving the multi laser source. The chip includes a number of integrated photodiodes (PD) with a responsivity of 1 A/W and a 3 dB bandwidth of 20-25 GHz. Balanced photodiodes are used to generate the beat signals required for phase-locking the slave lasers to the master laser. Integrated photodiodes also provide monitoring signals (MONITOR1 and MONITOR2) that can be used to determine control signals IM1 and IM2 applied to the VOAs. The SiP chip was designed with flexibility in mind and includes other features. For example, two phase modulators, not shown in Figure 3, allow modulating the frequency of the slave lasers for resonance tracking purposes[7]. Electrical connections between the metallized ceramic and the TECs, lasers and SiP chip are achieved by wire bonds.

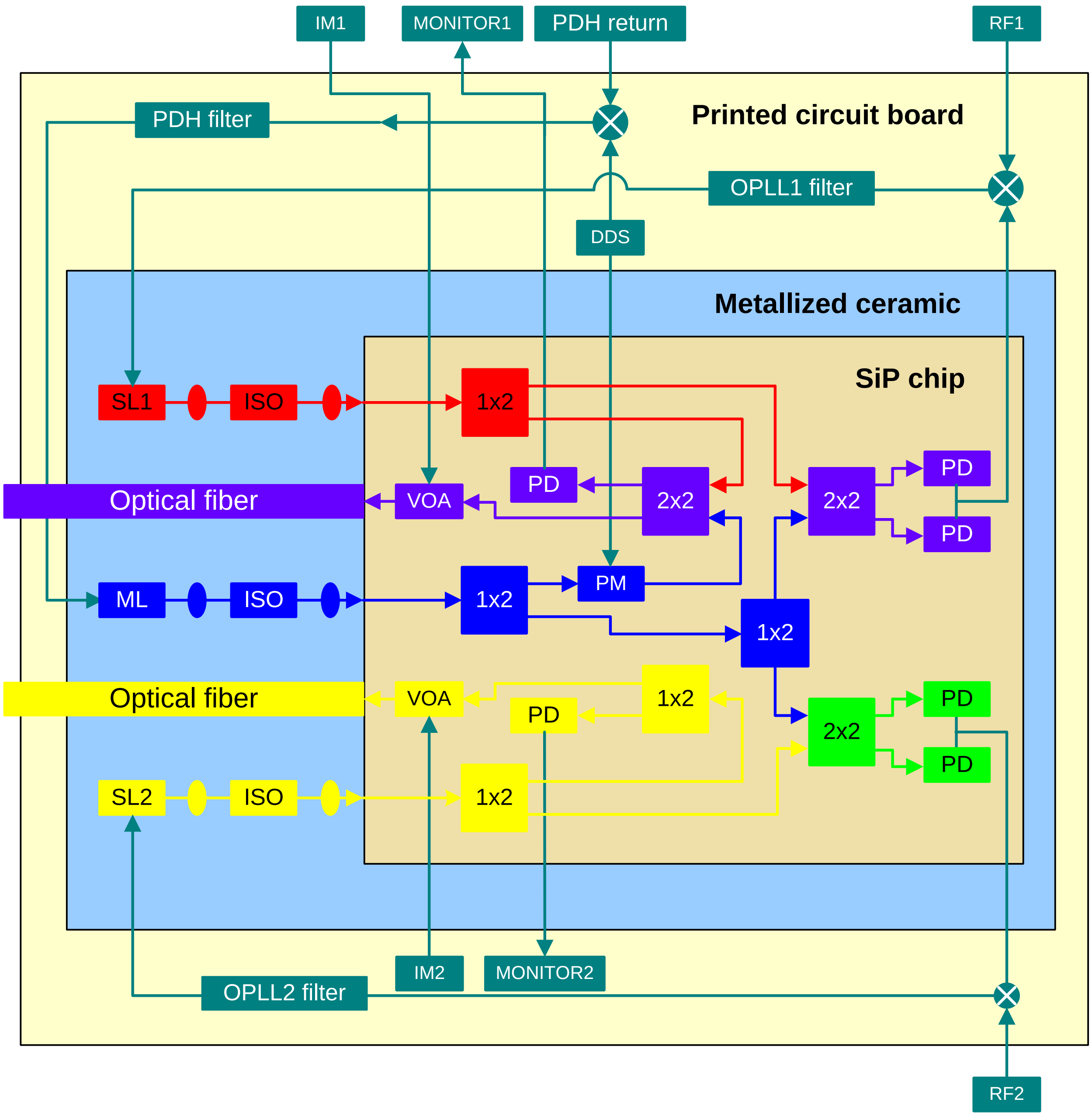


Figure 3. General configuration of the multi laser source.

The core package containing the lasers and SiP chip covers an area of 35 mm x 35 mm. It is interfaced with 90 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 multi laser source does not include an optical input. As illustrated in Figure 4, the photodiode required to close the PDH loop (see Figure 1) is located on a separate printed circuit board that communicates with the main one through a coaxial cable. Likewise, the RF reference signals (RF1, RF2) that determine the frequency offset between the master laser and the phase-locked slave lasers are not generated internally but provided as inputs.

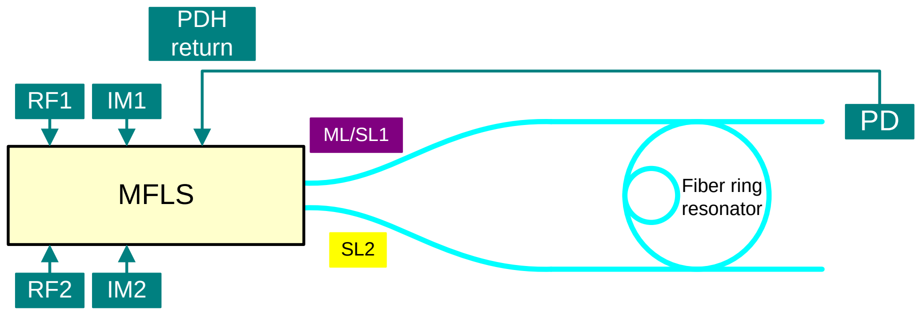


Figure 4. Interrogation of a fiber ring resonator.

Figure 5 shows a magnified photograph of the three lasers with their collimation and focusing optics. Also shown are the 3 mm x 16 mm SiP chip and the output fiber pigtails. As illustrated in Figure 3, light enters and leaves the chip from the same side. Figure 6 presents a complete view of the core package with its connecting pins and of the core package mounted on the PCB.

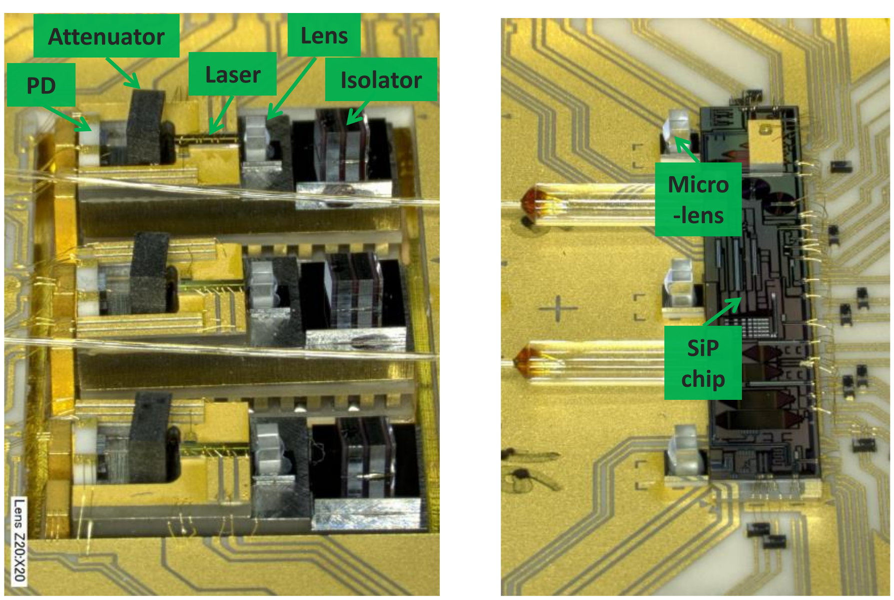


Figure 5. Lasers with their collimation optics (left). Focusing lenses, SiP chip and fiber pigtail ferrules (right). The actual size of the SiP chip is 3 mm x 16 mm.

(a) (b)

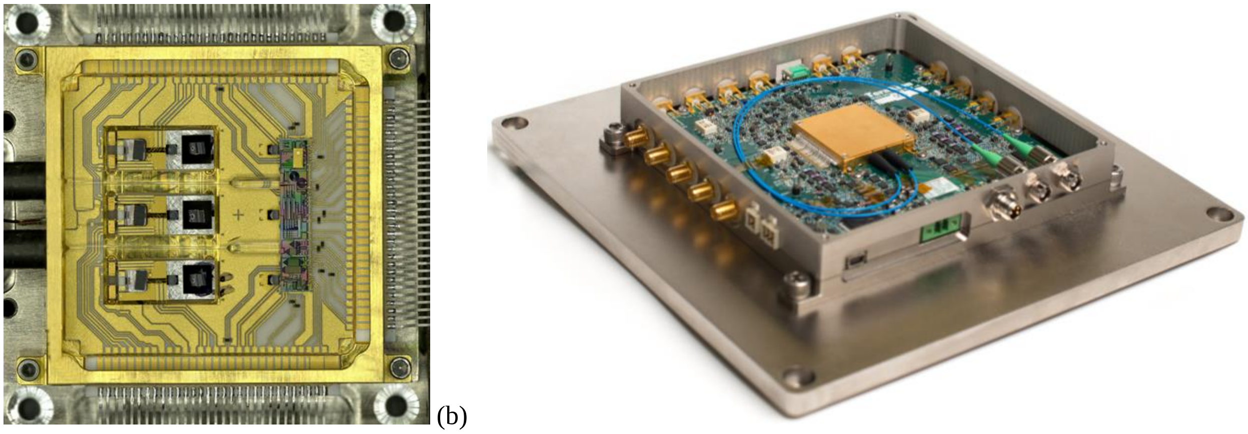

Figure 6. (a) Core package including three lasers and a SiP chip mounted on a metallized ceramic. (b) Core package mounted on the PCB (right).

## 3. EXPERIMENTAL RESULTS

A multi laser source as described has been built and characterized. The coupling loss into the optical fibers, defined by the ratio between the optical power launched into a fiber and the output power of a laser, has been measured between 8 and 12 dB, the master laser incurring the largest attenuation. Of these, about 2 dB come from the coupling between each laser and the SiP chip, while 1-1.5 dB results from the coupling between the chip and the optical fibers. The rest of the optical loss occurs on the chip itself. Figure 7 presents the power spectral densities of the frequency noise (PSDFN) of the master and slave lasers. The lasers display a white noise at high frequencies of $10^4$ $Hz^2/Hz$.

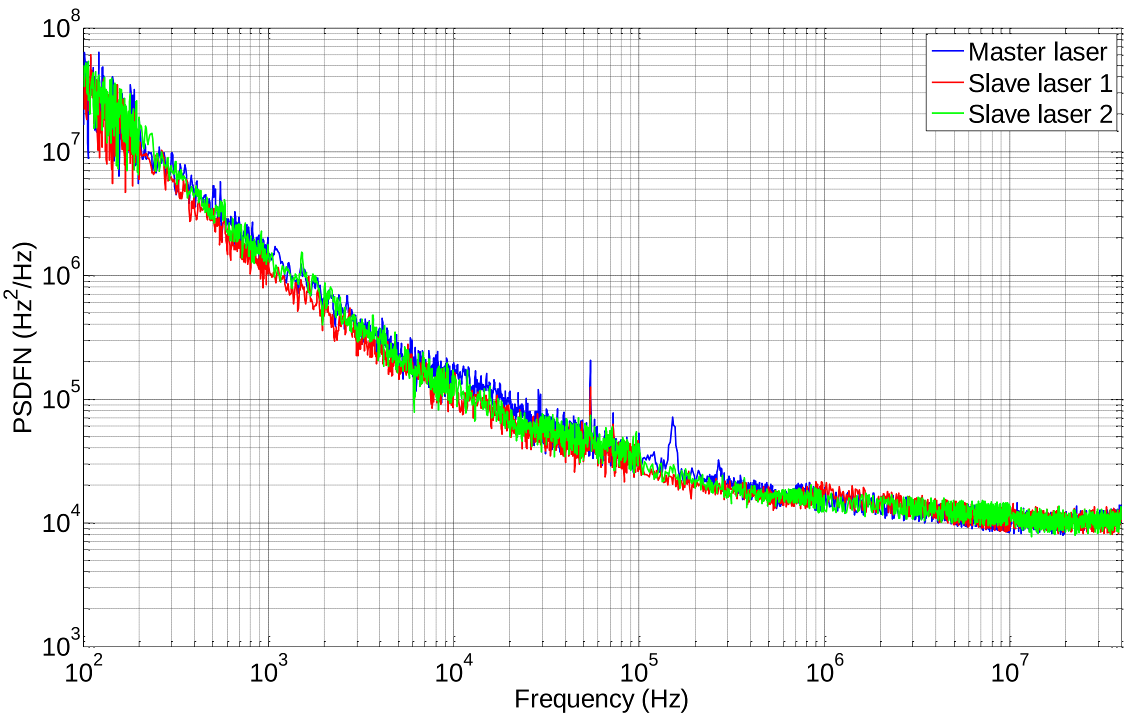


Figure 7. Power spectral densities of the frequency noise of the master and slave lasers.

The PDH locking capability of the receiver was tested using as OR an optical fiber ring interferometer made of two polarization maintaining (PM) fiber couplers and a PM fiber coil (see e.g. Figure 4). The fiber coil has a nominal length of 100 meters and a free spectral range of about 2 MHz[7]. Figure 8 compares the PSDFN of the master laser measured under free running operation or PDH-locked to the fiber resonator. The PDH loop reduces markedly the frequency noise up to 500 kHz and has a low frequency floor of 10 $Hz^2/Hz$, which represents a noise reduction by 66 dB at 100 Hz. The observed peak at 1 MHz results mostly from electronic noise.

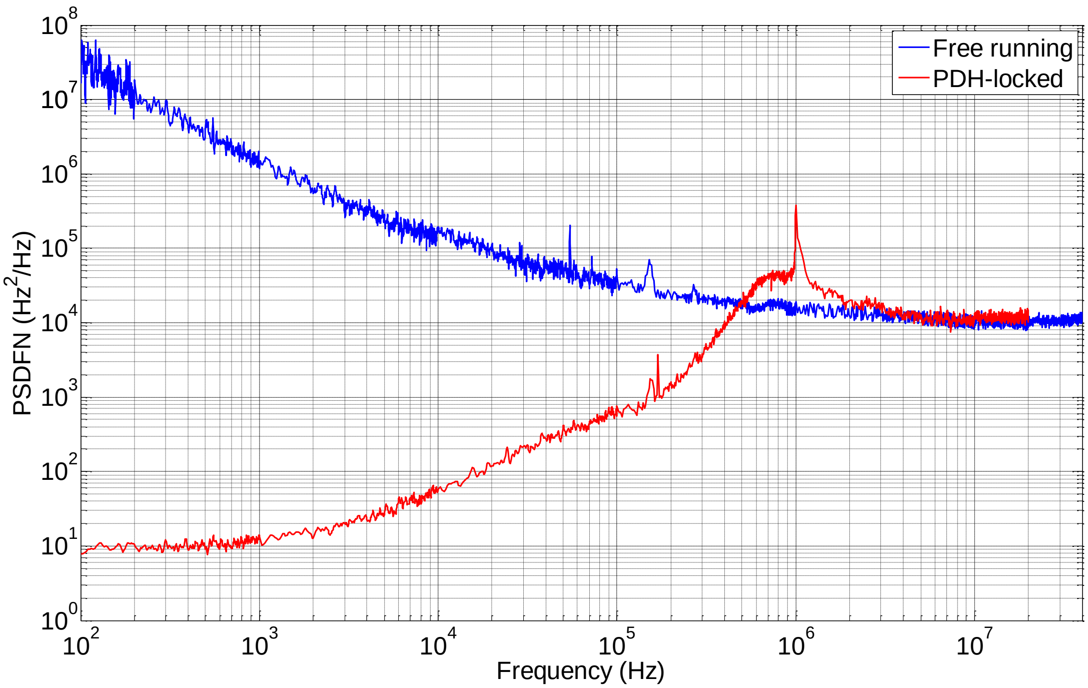


Figure 8. Power spectral densities of the frequency noise of the master laser in a free running mode and locked to a fiber ring resonator.

Phase-locking of the slave lasers to the master laser has been demonstrated. Figure 9 presents the electrical spectrum of the beat signal produced by detecting simultaneously the master laser and the second slave laser with a common photodiode. Marker 1 identifies the Dirac peak resulting 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 by marker 2, this phase control mechanism operates over a bandwidth of 110 MHz, much larger than that demonstrated previously[10]. Shorter optical and electrical delays afforded by the present compact configuration were instrumental in increasing the OPLL loop bandwidth. Figure 10 presents the PSDFN of the beat signal between the master laser and the second slave laser generated within the SiP chip and measured with a signal analyzer 5052B from Keysight Technologies. The PSDFN at 1 kHz stands at $10^{-6}$ $Hz^2/Hz$, i.e. 120 dB below the intrinsic frequency noise level observed on the free running lasers.

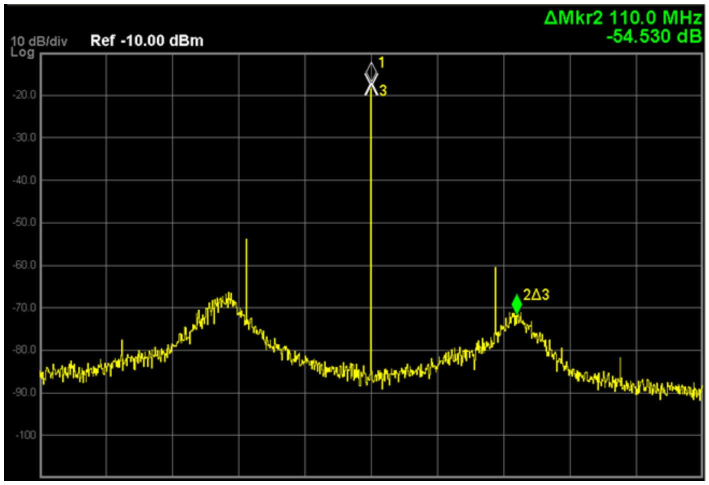


Figure 9. Electrical spectrum of the beat signal between the master laser and slave laser 2 phase-locked by an OPLL loop.

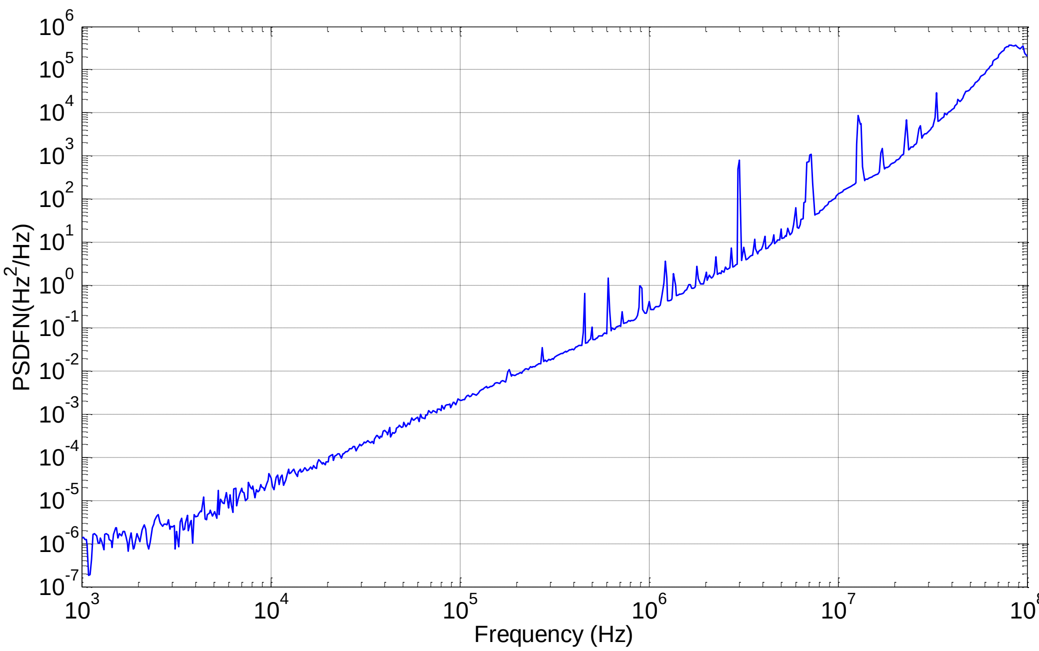


Figure 10. PSDFN of the beat signal between the master laser and the second slave laser generated within the SiP chip.

## 4. CONCLUSION

A compact three-laser source for optical sensing has been designed and built. The outputs from three semiconductor DFB lasers are coupled with micro-lenses into a complex silicon photonics chip comprising phase modulators, variable optical attenuators, multi-mode-interference couplers, variable ratio tap couplers, integrated photodiodes and optical fiber butt-couplers. This 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 that can be used to control the RIN of 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 110 MHz. 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.

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