# Frequency Locking on a DDO-OFDM System with Two Optical Carriers using a Silicon Nitride PIC

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***Abstract*** *The design and optical characterization of an integrated silicon nitride frequency stabilizer is demonstrated. The system provides simultaneous locking of 50 GHz-spaced C-band lasers with a maximum deviation of 60 MHz from their nominal value. The algorithm enables channel drift-resistant DDO-OFDM data transmission. ©2023 The Author(s)*

## Introduction

Silicon Photonics enables the implementation of a range of complex circuit designs for applications in short-distance optical communications[1]. One of the main challenges in the development of photonic integrated circuits (PICs) remains their integration with optical sources of high frequency stability, suited for advanced applications, such as those related to THz wave generation[2], Tb/s communications and basic-science experiment settings[3]. Meanwhile, semiconductor lasers represent a mature technology for source integration in PICs and might offer a credible route for the generation of Tb/s super-channels[4],[5] and 6G THz signals for future communications, via beating-based configurations[6]. However, such devices are typically prone to frequency drifts due to environmental conditions, thermal fluctuations and electrical disturbances. Therefore, frequency stabilization of these devices via integrated components, is a critical task to accomplish in order to make PICs a valuable technology in the development of future high-rate and wide-bandwidth transmission systems. One method that can be used to achieve stabilized optical sources involves the optical-to-electrical conversion of the signal to generate a negative feedback loop[7]. In this paper, we discuss the design and optical characterization of a packaged integrated silicon nitride photonic circuit that has been specifically designed to detect any frequency fluctuations of lasers that are sent into the chip and provide the necessary feedback to stabilize their operation. The circuit is designed to accommodate in principle up to 16 independent lasers, using an on-chip code-division multiple access (CDMA)-based optical modulation scheme to distinguish one laser from the next. Here we show two sets of characterizations, the first one devoted to the frequency stability capabilities of the system: this was based on the detection of a beating tone of two lasers fed into the PIC, and shows that their frequencies can be stabilised to within 60 MHz. The second set of experiments was designed to demonstrate the operation of the system when used in a two-channel direct-detection optical orthogonal frequency division multiple access (DDO-OFDM) transmission experiment with each channel carrying 50.244-Gb/s data. While the channels are spaced by a nominal 50-GHz spacing, we show that through the corrections applied by the PIC, the system is tolerant to frequency shifts of the lasers up to 500 MHz.

### Frequency stabilization architecture

The system is based on a SiN photonic integrated circuit (its schematic representation is given in Fig. 1(a)), which is designed to independently code the laser signals fed to it by on-chip thermo-optical modulators and then generate an error signal for their frequency stabilisation. The PIC has 16 inputs, for operation with up to an equivalent number of laser sources, however we have occupied only two of these inputs in this study ($I_1$ and $I_2$). The lasers are coupled to the PIC via a packaged optical fibre array. A thermo-optic ring modulator ($R_1$ to $R_{16}$) assigns a CDMA code (1 kHz bit rate) to each laser wave to allow to differentiate them from one another. The resulting waves are sent to a locking ring-resonator ($R_{LRR}$ in Fig. 1(a), Q-factor of 5.14x$10^4$) with 50 GHz free spectral

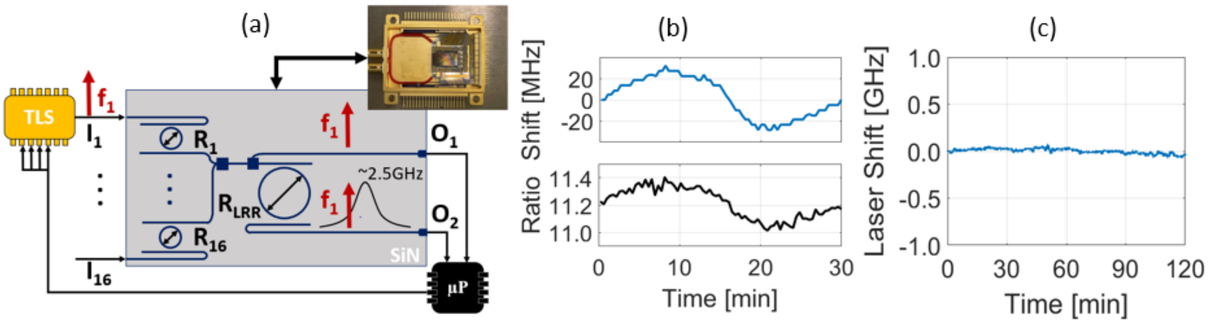


**Fig. 1:** (a) Laser frequency stabilization architecture based on a packaged integrated SiN PIC and a negative feedback algorithm. The inset shows a picture of the packaged integrated PIC. (b) The ratio parameter trend as function of time accurately follows the laser frequency that has been derived by the wavelength acquired on a wavelength meter. (c) Single laser frequency shift as function of time enabled by the frequency stabilisation algorithm. TLS= tunable laser source; $\mu$P = micro-processor

range, that is shared among all lasers (see Fig. 1, $I_1$ to $I_{16}$ respectively). The optical outputs are then converted into electrical signals through the insertion of on-chip photodetectors and amplified by an external transimpedance amplifier that sets a -2V reverse bias to the photodiode terminals to operate them in the linear region. An initial calibration is needed to place the laser wavelengths in the inflection point of one LRR resonance, so that the output power may become extremely sensitive to small frequency variations (the slope of the curve is $\sim$10 mV/pm). In order to eliminate the ambiguity that might originate from power fluctuations of the source itself, the laser signals are also coupled to another output ($O_1$ in Fig. 1(a)) that does not involve the LRR. By performing the ratio between the power recorded at the two outputs, only the frequency fluctuations can be detected, discarding any laser power fluctuation that might also take place during the operation. Feedback signals produced by this architecture are elaborated by a micro-processor ($\mu$P) coded in Python and sent back to the external-cavity semiconductor lasers, driving internal heaters devoted to the thermo-optical frequency tuning of integrated photonic filters and thus of the lasing mode. To ensure thermo-optical stability, the structure has been designed and fabricated on a low-loss (0.2 dB/cm) silicon nitride on insulator material with a low thermo-optic coefficient (k = 2.45x$10^{-5}$ $K^{-1}$ at 1550 nm).

To test the reliability of the system, the wavelength of a 1537-nm laser fed to $I_1$ was monitored in free-running mode using a wavelength meter. The ratio between $O_1$ and $O_2$ was computed over a period of 30 min, showing accurate mirroring of the frequency trend and a resolution in the order of 10 MHz (see Fig 1(b)), determined by the 2.5-GHz LRR bandwidth. Finally, the algorithm was tested over a period of 2 hours. Fig. 1(c) shows the laser shift from the nominal value over time exhibiting a frequency stability within $\pm$63 MHz.

### Mutual locking of lasers on a 50-GHz grid

Since the lasers fed to the SiN chip share the same LRR of an FSR of 50 GHz, their wavelengths can be tuned to lock on two consecutive LRR resonances, thus obtaining two different stabilized laser signals at the output, differing by 50 GHz in frequency.

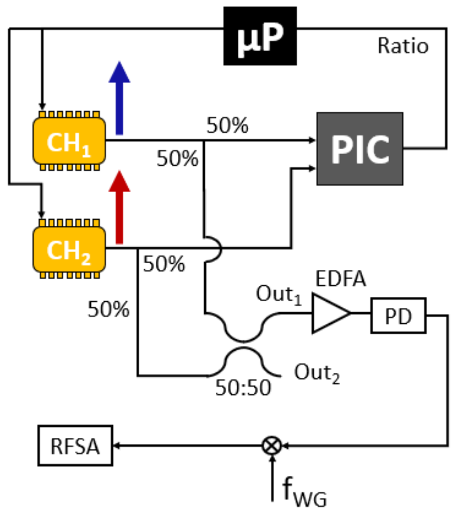


**Fig. 2:** Two 50 GHz-spaced lasers ($CH_1$ and $CH_2$) frequency stabilization set-up through the detection of a 50 GHz beating note. WG = waveform generator; RFSA = RF spectrum analyzer; PD = photodetector; EDFA = Erbium-doped fibre amplifier

In the following experiments (Fig. 2), two lasers ($CH_1$ and $CH_2$) were tuned at $\sim$1537 nm and at $\sim$1537.4 nm, respectively (50 GHz separation) and coupled via 3-dB couplers both to the SiN PIC and an optically amplified external photodiode generating a beating tone corresponding to their frequency separation, which was used to study the frequency stability of the two lasers with and without the stabilisation system in operation. The beating was recorded on an RF Spectrum Analyser (RFSA - Agilent E4446A) after being

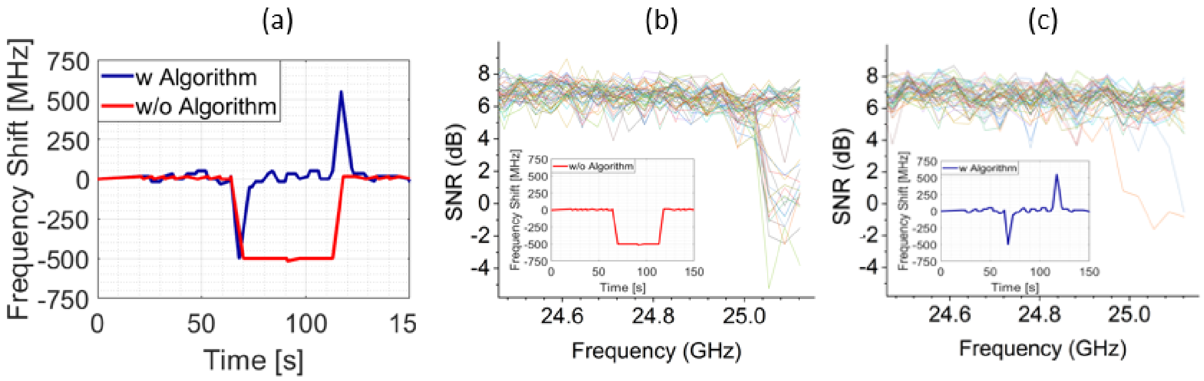


**Fig. 3:** (a) Two 50 GHz-spaced lasers-generated beating note shift as function of time. The cases with and without algorithm are shown as a consequence of 500 MHz external perturbation experienced by one laser. (b)-(c) Different electrical spectra of one channel sub-carriers as function of time acquired during DDO-OFDM transmission experiments. The relative performances are shown without (b) and with (c) algorithm correction.

mixed with a 45.9 GHz tone ($f_{WG}$) generated by a synthesizer (Anritsu MG3695B).

To test the linearity and the large-signal resistance of the circuit to external perturbations, a square wave variation of 100 s duration was applied to the temperature controller of one of the lasers via external voltage modulation. This gave rise to a 500 MHz frequency shift of the laser, which was detected on the beating note. As shown in Fig. 3(a), the use of the algorithm ensures a correction of the externally-induced frequency shift within $\sim$5 s allowing a final fluctuation of $\pm$60MHz around the nominal value. The algorithm response time is currently limited by the microprocessor acquisition time; future implementations will incorporate computation on kHz-scale microprocessors, matching the speed of the integrated thermo-optic modulators.

The two laser signals were also extracted from the $\mathrm{Out}_2$ port and used to generate two 50.244Gb/s DDO-OFDM data channels. The bandwidth of the DDO-OFDM channels was chosen so that it provided a narrow guard band of 160 MHz when the two wavelengths were separated by exactly 50GHz. As a consequence, the 500 MHz shift imposed by the square temperature change on one of the lasers, generated a 340 MHz overlap on the two channels when the stabilisation system was not in operation, which was readily captured at the receiver. This is shown in Fig 3(b), which presents the signal-to-noise ratio (SNR) of the different sub-carriers of $\mathrm{CH}_1$, as acquired after digital signal processing at the receiver (for clarity, the figure zooms on those sub-carriers close to the high-frequency edge of the DDO-OFDM signal). The figure presents measurements acquired every 2.5 s, and one can readily detect the instances when the laser has experienced the frequency shift, during which the performance of the extreme sub-carriers is downgraded, from an almost 7 dB SNR to an average of 0 dB SNR. With the stabilisation in operation (as shown in Fig 3(c)), one can only discern an SNR degradation on these sub-carriers only during the brief transition instances while the algorithm action takes effect (see the corresponding blue peaks in Fig. 3(a)).

## Conclusions

The optical design and characterization of a packaged integrated silicon nitride circuit enabling the frequency stabilization of two 50 GHz-spaced C-band lasers within $\pm$60 MHz of the nominal value has been presented. By design, the system can be extended to 16 laser sources coded in parallel and locked together leading to the possibility to generate an extended bandwidth super-channel. A DDO-OFDM modulated two-laser system with a 50-GHz carrier spacing and a narrow guard band of 160 MHz has been explored by applying an external temperature perturbation on one laser and inducing a relative 500 MHz shift with respect to the nominal channel frequency. The developed integrated platform together with the locking algorithm is demonstrated as a simple and compelling method enabling tightly spaced channels in high-rate transmission, leading to possible outcomes for stable THz-frequency sources and Tb/s super-channel generation based photonic circuits. Future implementations will include faster microprocessor components, allowing for kHz-rate feedback controls.

## Acknowledgements

The research was supported by Huawei Technologies Italia S.r.l and the UK's EPSRC through grant EP/T007303/1.

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