Stable Arbitrary Frequency Generator

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***Abstract*—We demonstrate a technique to precisely control and stabilize the beat frequency of a photonic microwave signal generator based on beating the optical signals of two lasers on a high-speed photodetector. The approach does not require high-speed electronic circuitry, but allows the control of the generated signal frequency up to hundreds of GHz. The demonstrated technique can readily be integrated on a chip-scale device using heterogeneous silicon platform, opening possibilities for widespread use in signal generation, sensing, instrumentation, and communications.**

***Index Terms*—Interferometry, microwave photonics, semiconductor lasers.**

I. Introduction

SPECTRUM congestion and demand for higher data rates are driving a push towards higher and higher carrier frequencies, necessitating sources of pure, widely tunable radiofrequency carrier signals. There is an increasing interest in the exploration of ultrawide-bandwidth systems with carrier frequencies ranging from 30 GHz up to more than 300 GHz and well into the terahertz region.

Signal generation at such high frequencies is challenging and has been addressed in both electronic and photonic domains, and interestingly, the highest data rates have been reached using photonic devices as transmitter, combined with cutting-edge III–V THz electronic devices as receivers [1].

Photonics is especially interesting at such high frequencies due to the ultra-wide bandwidth and low losses provided by single-mode optical fiber that allows for efficient signal distribution over longer link lengths. There is a number of photonic approaches for generating microwave and higher frequency signals, with arguably the simplest one being optical heterodyning, in which optical waves of different wavelengths beat on a fast photodetector [2].

There have been numerous demonstrations of optical heterodyning signal generation, some of which utilized the strengths of integrated photonics to demonstrate chip-scale photonic signal generators in both native III–V platform [3] and in the heterogeneous silicon platform [4]. While demonstrating impressive performance from a chip-sized signal generator and continuous signal generation from DC to above 100 GHz, neither addressed the problem of controlling the precise operating frequency without resorting to instrumentation such as optical spectrum analyzers and high-speed electrical spectrum analyzers for a laboratory demonstration, or high-speed electronics for potential out-of-lab use. Similar problems face bulk optics demonstrations. The problem is accentuated because semiconductor lasers tune on the order of 10 GHz/°C and on the order of 1 GHz/mA of drive current. Pre-generated lookup tables can help to a certain extent, but they do not address the issue of aging and it is unrealistic to expect that they can provide MHz level of control.

Here we present a straightforward technique that allows fine control of generated frequency, long term stability of the set frequency as well as controlled continuous tuning without a need for high-speed control circuitry. Furthermore, all the key components have been realized in the heterogeneous silicon platform [4], [5], [6], providing a path to realize a chip-scale stable arbitrary frequency generator based on optical heterodyning.

A similar approach, reusing the same reference to lock the lasers, has been first demonstrated in late 80s [7], and recently it has been used to generate microwave signals up to 92 GHz using the polarization diversity of the resonator [8]. The performance in [8] was exceptional, showing RF linewidths in the 30 Hz range across the tuning range. Compared to our approach, that demonstration is significantly more complex using a high-Q Fabry-Perot cavity with 1 MHz linewidth and Pound-Drever-Hall (PDH) locking technique. As the lasers are locked to the resonances of the cavity, the system allows for generation of only a fixed set of frequencies and does not allow for continuous tuning, as is the case in our approach. It should also be noted that the demonstrated long-term drift 170 kHz @ 7.5 h is comparable to the one we measured. Similar approaches may be realized with rings and other types of resonators that are more suitable for photonic integration, but with the limitation of offering only a fixed set of frequencies.

A different demonstration, using comb self-referencing, has shown spectacular 1 Hz resolution and traceability to the SI second in 4 THz span near 1550 nm using chip-scale components that have a potential to be fully integrated [9]. The authors have demonstrated record absolute laser stabilities using chip-scale components, but for the demonstration they have utilized two locked combs from different resonators (SiO_2 and SiN based), second harmonic generation and advanced offset locking electronics that greatly surpasses the complexity of our proposed

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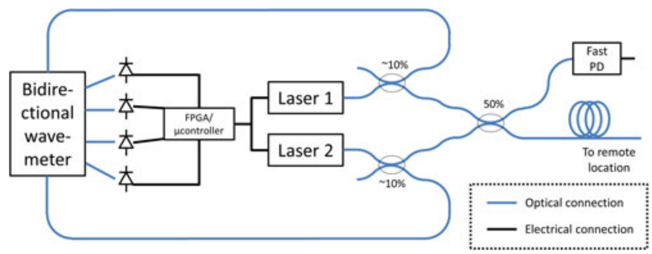

Fig. 1. A schematic of the stable arbitrary frequency generator. A single wavemeter is used to track the drift of both lasers and provide stable RF signal. The same wavemeter is also used for measuring and adjusting the RF frequency. (PD – photodetector)

approach that aims only to provide the relative frequency stability between the lasers.

The manuscript is organized as follows. In Section II we briefly outline the architecture of the stable arbitrary frequency generator and introduce the concept of a bidirectional wavemeter. In Section III we show a number of measurements. First, we show the typical stability of RF generators based on beating two independent lasers on fast photodetectors and then demonstrate that the bidirectional wavemeter can be used to track the frequency offset between the two lasers by comparing it to the frequency counter. We implement a PID lock and show that by locking the lasers, we can keep the offset frequency stable over extended periods of time and, also, controllably tune it. Finally, we measure the RF linewidth of the generated tone. In Section IV we discuss the potential for integration and give conclusions.

II. Stable Arbitrary Frequency Generator Architecture

A schematic of the proposed 3 × 3 wavemeter architecture is shown in Fig. 1. The main novelty, compared to standard optical heterodyne techniques, is the introduction of an interferometric wavemeter that is used bidirectionally. This allows both lasers to be stabilized to the same reference, suppressing the common drift inherent to the wavemeter. As the wavemeter is used bidirectionally, the two lasers might interfere. Lasers used for the experiment had integrated optical isolators preventing unintentional feedback.

The wavemeter can be realized in a number of ways, but the use of a 3 × 3 wavemeter, comprising of two 3 × 3 optical couplers providing ∼120° phase shift between the arms [10], has at least two advantages. First, it provides means for reconstruction of quadrature signals and phase unwrapping allowing for precise frequency measurements and determination of the direction of the frequency change, and, second, it provides this functionality with a minimum number of components. Reconstruction of quadrature signals is not possible in a 2 × 2 couplers based wavemeter. Hence issues with ambiguity in the direction of the frequency change. By using the 3 × 3 wavemeter signals to provide feedback to the lasers, we show that all the sources of laser drift with respect to the wavemeter can be suppressed and long term microwave frequency stability can be achieved.

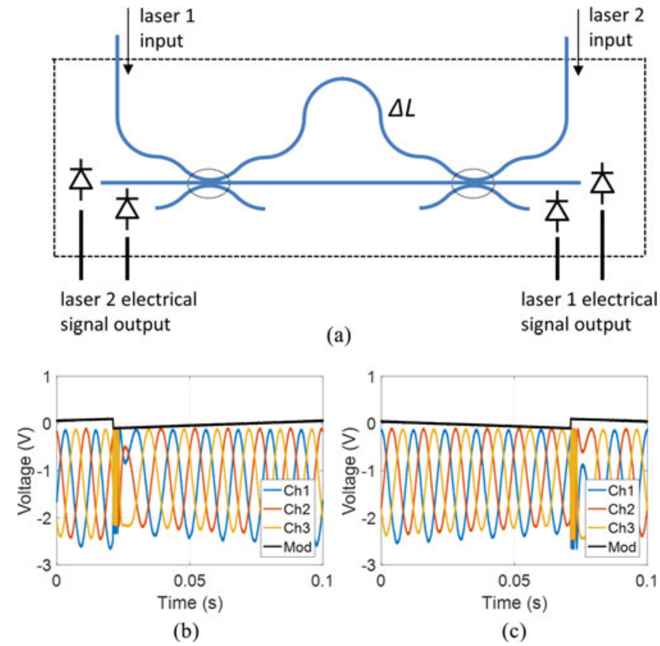

Fig. 2. (a) 3 × 3 bidirectional wavemeter schematic. (b) Response of all three outputs (Ch1, Ch2 and Ch3) of a 3 × 3 wavemeter to continuous laser tuning when bias current is (b) increased and (c) decreased. Note the change in channel order and ∼120° phase difference between wavemeter arms. The black trace is the modulation signal applied to the laser current driver.

A. Bidirectional Wavemeter

We first characterize the 3 × 3 wavemeter as shown in Fig. 2(a). The wavemeter is based on two 3 × 3 fiber optic couplers connected with a ∼ 1.2 m path imbalance, while the third arms are not connected. We have placed the wavemeter into a double cardboard box with no extra insulation to provide some protection from rapid thermal changes to bare fibers used to realize the wavemeter. Due to the ∼120° phase difference between the optical waves of the 3 × 3 coupler, spectral responses of the wavemeter are also shifted ∼120° between the outputs and allow reconstruction of the quadrature signals and for phase retrieval of the incident optical signals as well as determination of the direction of tuning as shown in Fig. 2(b) and (c). The receivers, based on 3 × 3 optical couplers, were used for coherent detection in [11]. The path-length imbalance is an optimization parameter that affects the interferometer frequency resolution and, consequently, precision of the frequency control. Both the precise path-length imbalance and the exact phase shift (that can slightly vary from ideal 120°) between the arms can be calibrated for a given wavemeter.

III. Measurements

A. Free-Running Beat-Note Stability

The RF tone generation by the heterodyne beating of two free running lasers requires control of the beat tone center frequency and control of its stability. Semiconductor lasers drift with both temperature and bias current. An exemplary drift measurement is shown in Fig. 3. The measurements demonstrate that even

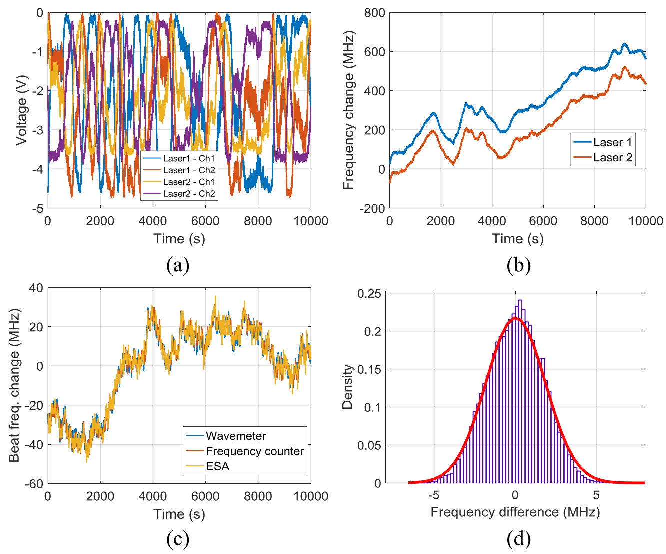

Fig. 3. (a) Response of a 3 × 3 wavemeter when used in bidirectional configuration for monitoring two TEC controlled DFB lasers. (b) Frequency change of both lasers as measured with the 3 × 3 wavemeter. (c) Extracted beat note drift from wavemeter measurements compared to beat note drift measurements from a frequency counter and an ESA. (d) Histogram of the difference in beat frequency drift between the wavemeter method and the frequency counter. A Gaussian fit is plotted in red.

in laboratory conditions, where ambient temperature drift is <1 °C, and by using TEC controllers to stabilize the lasers and keeping the bias current constant, the beat frequency differs by as much as 60 MHz over the course of 10,000 s. To calculate the beat frequency drift from the wavemeter signal (Fig. 3(a)), we extract the phase and convert the phase to frequency using the free-spectral range (FSR) of the wavemeter (Fig. 3(b)). It is worth emphasizing that the wavemeter drift in our experiment was larger than laser drift, being approximately 600 MHz over the same time span, as we do not control the temperature of the wavemeter. By calculating the difference in the frequency change as measured by the wavemeter for both lasers, we determine the beat frequency change and compare it to the beat frequency variation as measured with a frequency counter and electrical spectrum analyzer (ESA) as shown in Fig. 3(c). In frequency measurements used to calculate Allan deviation we have used Hamag HM8123 frequency counter, internal 10 MHz reference and 100 ms gate time.[1] The match is excellent as shown with a histogram plot in Fig. 3(d). The histogram shows the difference in beat frequency drift between the wavemeter method and the frequency counter. We also plot a Gaussian distribution fit. We believe that the main source of error in this measurement was the 8-bit vertical resolution of the oscilloscope used to capture the wavemeter data.

As a conclusion of this section, we have shown that the bidirectional wavemeter can be used for monitoring the beat note frequency despite having approximately an order of magnitude larger drift than the temperature-stabilized laser. This is possible as both lasers are referenced to the same wavemeter and only the relative offset between the lasers has an influence on the signal generated as a beat-note.

B. Locked Beat-Note Stability

To test the beat-note stability of the closed loop system, we modify the test setup so that the signals from a pair of the photodetectors corresponding to each laser are subtracted and applied as feedback to the laser drivers via a PID control circuit. In this way, we lock each laser to the point where outputs from its detectors are identical. Thus, the interferometer phase is constant for each laser resulting in long term stability of the microwave frequency. To lock the laser at a different point, an offset in PID loop is all that is required, while for continuous tuning – continuous adjustment of the offset will result with controllable tuning of one of the lasers along its mode-hop free range while keeping it locked to the same wavemeter as the other unperturbed laser. An even more advanced implementation could control both the laser temperature and the drive current by the error signal generated from the wavemeter which is the preferred option for realizing very high frequency signals or large frequency offsets.

We show a direct comparison between free-running and locked lasers in Fig. 4 where we plot the frequency beat change, external (laboratory) and internal (wavemeter box) temperature change, and PID voltage output as a function of time over 10,000 seconds, and the corresponding Allan deviation plots of the frequency. In all measurements, the laser temperature was stabilized with an independent PID loop. We show that we can control the laser frequency down to $\sim \pm 1$ MHz over extended timescales with current state of the servo PID lock. A number of improvements are possible which should result with <1 MHz frequency variation such as increasing the bandwidth of the PID loop, reducing the noise in the electronics by using ADCs and DACs with a larger number of bits, increasing the signal-to-noise ratio of the photoreceivers, and reducing the linewidth of the lasers.

Stability, even at the current level, is quite impressive with an Allan deviation around 65 kHz at 128 s integration times, 33 kHz at 1024 s integration times and still decreasing, showing white frequency noise limited performance at longer integration times limited by the duration of the measurement. It is interesting to compare it to the laser carrier frequencies that are in the range of 194 THz, which is almost 10 orders of magnitude difference.

The frequency stability is ultimately limited by the stability of the interferometer FSR, and we discuss it in more detail in the conclusions.

C. Frequency Control

For the demonstration of frequency control, we implement the PID offset approach to one of the lasers, while keeping the second laser locked with zero offset. We show the results in Fig. 5 where we finely step the frequency around 760 MHz keeping it for ∼120 s at each step by applying a discretized cosine signal to the PID offset. Fig. 5(c) and (d) show the wavemeter readouts for both lasers where laser 1 (Fig. 5(c)) is tuned while laser 2

[1] We estimate the worst case error in our Allan deviation plots to be up to 33% following analysis in [13] for white frequency noise limited oscillators measured with frequency counters assuming Λ-type weighting.

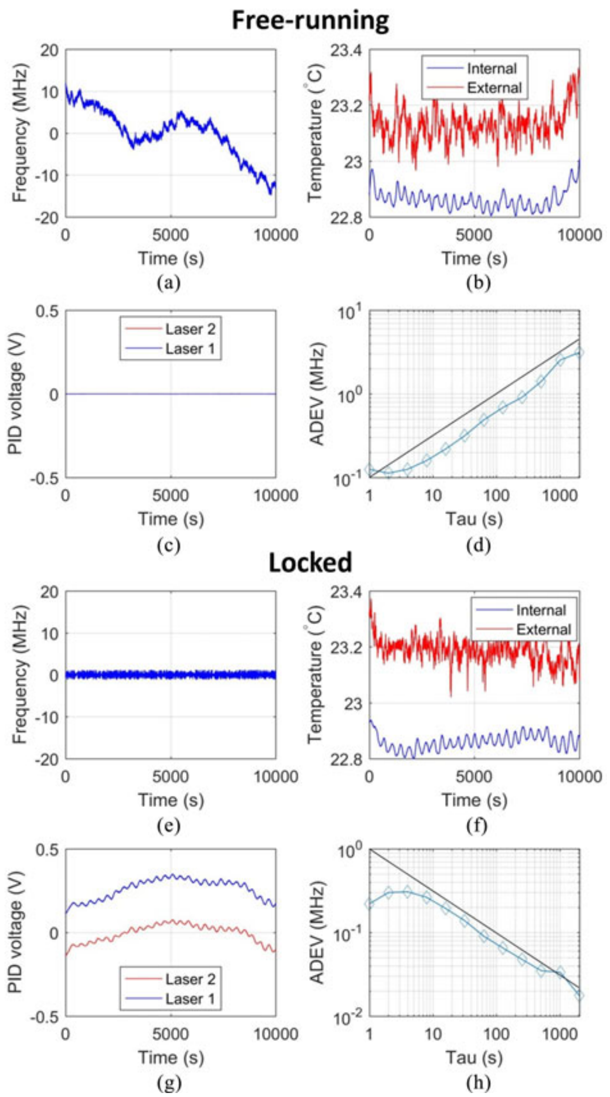

Fig. 4. Direct comparison of free-running (top: a–d) vs locked (bottom: e–h) stability. We plot the frequency change around its mean value (a and e), the temperature change (b and f) inside the laboratory (external) and the temperature change inside the wavemeter box (internal), the PID controller output signals for both lasers (c and g) and finally Allan deviation plots of the frequency in MHz (d and h). For the locked case we also plot the τ -1/2 line showing that we are white frequency noise limited even at long time scales, while for the free-running case we plot the $\tau^{1/2}$ line comparing the stability to the random walk.

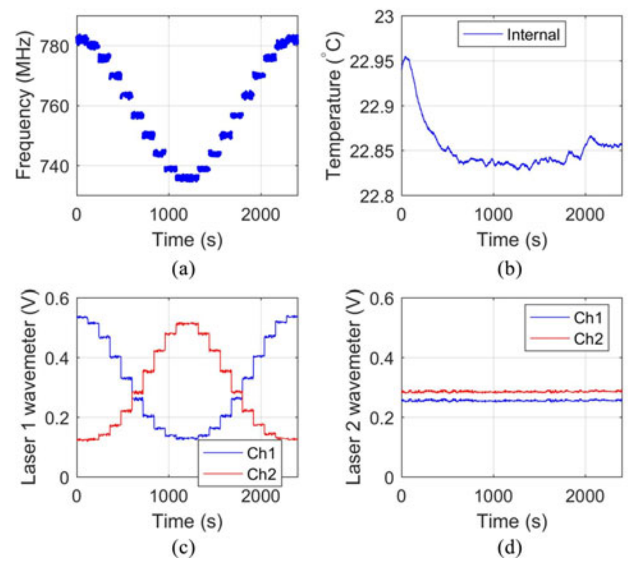

Fig. 5. (a) Fine frequency tuning around 760 MHz over 2400 s as measured with a frequency counter. (b) Temperature of the wavemeter during the measurement. (c) Wavemeter response for the laser that was tuned. (d) Wavemeter response for the laser that was kept stable in respect to the wavemeter.

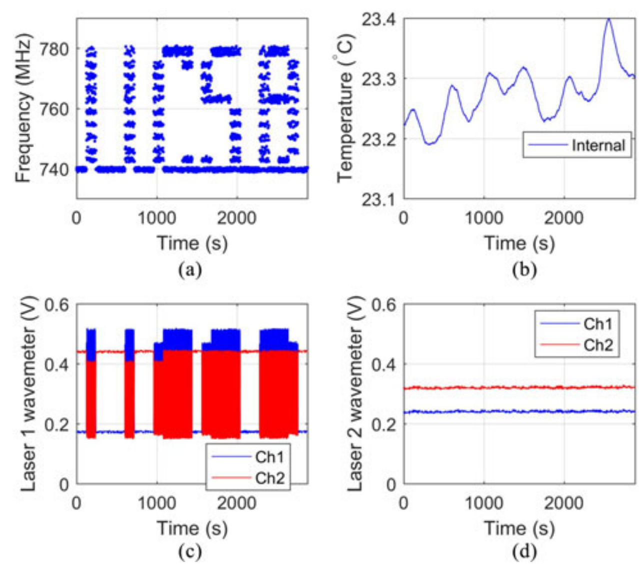

Fig. 6. (a) Arbitrary frequency control across 11 frequency setpoints to write "UCSB" showing rapid frequency hopping. (b) Temperature of the wavemeter during the measurement. (c) Wavemeter response for the laser that was tuned. (d) Wavemeter response for the laser that was kept stable in respect to the wavemeter.

(Fig. 5(d)) is locked to the wavemeter. We also plot the temperature change of the wavemeter in Fig. 5(b). Temperature does not affect the results of the experiment.

To demonstrate rapid frequency hopping, we write UCSB in time-frequency plot, rapidly switching between 11 different frequencies as shown in Fig. 6 using the PID offset approach. The tuning speed is limited by the settling speed of the PID loop and in our case, is in the range of 0.5 s.

D. RF Linewidth

For the RF linewidth measurements of our signal generator, we utilize two narrow-linewidth DFB lasers from Eblana Photonics. The linewidth of our lasers, under 150 mA bias current, was ∼150 kHz as measured using a delayed self-heterodyne method with 10 km of fiber delay. As the optical fields of the two lasers were not correlated, the expected short term RF tone linewidth was ∼300 kHz. For measuring the RF tone linewidth, we beat the two lasers on a photodetector and averaged the measurement 8192 times on an electrical spectrum analyzer at a 30 kHz resolution bandwidth setting. The total acquisition time was 925 s. We plot the corresponding traces in Fig. 7 and fit a Voight profile calculating the 3 dB linewidth from −3 dB, −10 dB and −20 dB points assuming

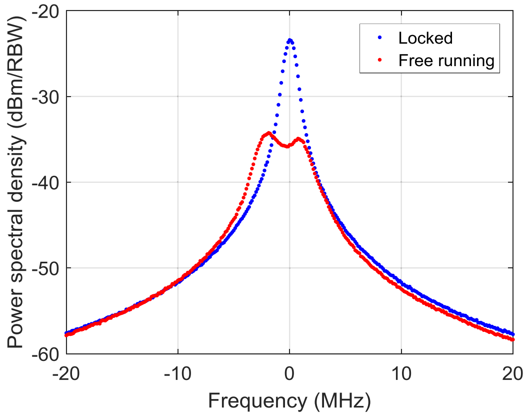

Fig. 7. Comparison of linewidth for the locked and free-running laser. Measured with ESA by averaging over 8192 traces (113 ms per trace, 30 kHz RBW)

a Lorentzian linewidth. For the locked case, the linewidths are 590 kHz, 440 kHz, and 380 kHz showing some degradation from the ideal case. The performance may be improved using the approaches for increasing the locked beat-note stability as outlined in Section III-B. For the free-running case, the corresponding linewidths are 2.6 MHz, 1.6 MHz and 840 kHz, respectively. Longer measurement times would further degrade the performance of free-running case as shown in Fig. 4(d).

IV. Conclusion and Integration Potential

We have shown a straightforward method to control and lock the frequency generated by optical heterodyning of two independent lasers by using a bidirectional wavemeter. An improved demonstration or a commercial device could utilize a microprocessor or an FPGA paired with low-noise ADCs and DACs to control both lasers via current servo and thermal control with potentially < 1 MHz level of control. There are two different mechanisms limiting the performance; what we call "absolute" and "relative" to the generated RF frequency. Absolute limitation does not change with set frequency and originates mostly from laser linewidth and other electrical noise sources (receiver noise, quantization noise, other sources of electrical noise), while relative limitation scales with set frequency and originates from the wavemeter free-spectral range (FSR) drift. For a fiber-based wavemeter, where $\mathrm{d}n/\mathrm{d}T \approx$ 1e-5 /°K and $n_{\mathrm{eff}} \approx 1.45$, the drift performance is limited to $\sim$ 700 kHz/°C @ 100 GHz. If in the end performance becomes limited by the relative contribution (with sufficiently low-noise electronics and narrow-linewidth lasers), either temperature control of the wavemeter or, as a simpler solution, a look-up table correcting for the wavemeter FSR change with temperature can be implemented. We would like to point out that this correction with a look-up table is possible as we can lock the lasers to any point in the wavemeter response, in contrast to locking to the resonance as demonstrated previously. Both techniques should make the wavemeter FSR drift limitation largely irrelevant in most applications.

Chip-scale microwave signal generators combining two lasers with high-speed photodetectors have already been demonstrated [3], [4] and they can be heterogeneously integrated with chip-scale wavemeters [5]. As mentioned, the bidirectional use of the wavemeter might lead to unintentional injection locking or instability between the lasers so isolators are generally preferred. Up to 32 dB of on-chip isolation was recently demonstrated using the heterogeneous silicon photonics platform [12].

An advantage of chip-scale wavemeters is the increased robustness to vibrations and temperature variations leading to much improved stability over fiber based solutions with up to 62 cm of on-chip path-length imbalance demonstrated [5]. Increased robustness would simplify the drive electronics requirements for the stable arbitrary frequency generator. Comparing the sizes of both chips [4], [5], the whole stable arbitrary frequency generator could be made in $\sim$3.5 mm $\times$ $\sim$6.5 mm area providing interesting opportunities for various applications that require high-frequency signal generation and continuous tuning across the whole tuning range from DC to hundreds of GHz; limited either by the bandwidth of the photodetector or by the mode-hop free tuning range of the lasers. Having both lasers on the same chip would also increase the stability of the device, and separate heaters for the two lasers can be envisioned for extension of the tuning range compared to just current injection, while sharing the same TEC below the chip.

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