

Tunable laser for compensation of Doppler shift for optical inter-satellite links

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ABSTRACT

We present a nano form-factor integrated Tunable Laser Assembly (nano-ITLA) capable of digital tuning across the C-band on a 50 GHz grid. The laser demonstrates low linewidth of < 300 kHz, making it suitable for coherent communication applications, as well as fast electro-optic switching speeds (< 10 ns). Using this nano-ITLA, we demonstrate continuous tuning of up to ± 6 GHz around 4 ITU frequencies with strong linearity and to an accuracy of within than ± 0.25 GHz. We propose that this technology could be suitable for inter-satellite links by taking advantage of this continuous tunability to compensate for Doppler shifts that cannot be corrected with Digital Signal Processing (DSP) alone.

Keywords: Tunable lasers, Optical sources, Doppler shift, Satellite communications

1. INTRODUCTION

A significant challenge in coherent optical inter-satellite communication is the Doppler shift experienced between transmitter (Tx) and receiver (Rx) as satellites move relative to each other. A limited amount of Doppler shift can be compensated for by Digital Signal Processing (DSP), however optical compensation, achieved by adjusting the wavelength of the optical carrier in real time as the satellites move with respect to each other, is a means to remove the burden of DSP required. This increases the tolerance and enables more extreme cases and orbits. For low Earth orbits, a typical Doppler shift of up to ± 3.5 GHz can be expected during a single orbit, which can be compensated for using DSP,¹ while the largest expected Doppler shift can be of the order of ± 10 GHz when two satellites are transiting each other.²

Tunable laser sources play a significant role in a wide array of applications, such as spectroscopy,³ gas-sensing,⁴ LiDAR,⁵ and coherent optical communications.⁶ Typically, these applications require a mix of wide tunability, narrow linewidth and/or high-speed tuning. Diode lasers in Photonic Integrated Circuits (PICs) have enabled the development of integrated Tunable Laser Assemblies (iTTLAs), which have allowed for significant minituration over conventional bench-top instruments.

The main features of a tunable laser are monochromatic output with variable power and wavelength. Several tuning mechanisms exist for varying the output frequency of a laser cavity using on chip or external modulation. For small form factor PICS, on-chip modulation is preferred. Typically a grating structure is manufactured in the waveguide of the laser, which provides frequency selectivity and tunability. For a Distributed Feedback (DFB) laser, a grating structure is manufactured inside the optical gain section. This provides frequency tuning as gain current is varied, providing power and frequency tuning in one parameter. A Distributed Bragg Reflector (DBR) laser also features a grating in the waveguide, but outside of the gain section. This allows the system to be decoupled between optical gain, peak operating wavelength (via grating reflectivity) and phase. DFB and DBR lasers are typically designed with a broad free spectral range (FSR), such that only a single operating wavelength is emphasised. By instead using two narrow FSR gratings, as is the case with the sampled-grating (SG)-DBR laser,⁷ digital mode selection is possible via Vernier alignment of grating reflectivity modes, enabling wide-tunability.

Here, we describe a laser in which the frequency tuning mechanism is provided by two ring/racetrack structures and a common phase section. As they are designed with a small offset in their perimeter, the rings have

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different values for their FSR, which is a requirement for Vernier tuning. The FSR of the rings is also different to the FSR produced by the net laser cavity, which can be tuned using the phase section of the laser. By tuning the ring sections and the phase section, we can locate a combination where the two ring modes and the cavity modes are aligned at a single point, providing monochromatic output of the laser at a desired frequency. Tuning is achieved via a reverse bias to each section of the laser, where an electro-optic (EO) Pockels effect changes the refractive index of the chosen section, which introduces a phase shift in that section and causes the transmission modes of that section to move and align with the other tuners at a different frequency. This reverse biased design draws a much lower current than a similar forward biased design, leading to a lower power consumption. The reduction of injected carriers reduces noise in the tuners, while the EO tuning allows for much faster tuning compared to thermal tuning mechanism. By designing the three sections to have a full 2π phase shift, the output of the laser can be tuned over a 36 nm range, with a mode spacing of 50 GHz, centered at either 1550 nm or 1310 nm depending on the material composition. The combination of low size, weight and power consumption, as well as low linewidth and fast EO tuning to facilitate Doppler compensation make it a promising candidate for coherent space communications.

2. LASER DESCRIPTION

The Pilot Photonics iTLA chip is fabricated in InP using the SMART Photonics PDK⁸ and is suitable for monolithic integration. As shown in figure 1, it consists of a loop cavity with four discrete tuning sections, in addition to a booster SOA to amplify the output power ahead of the output facet at the chip edge. The gain section provides optical gain to the cavity, with a threshold current of around 30 mA and saturation current of around 80 mA. Tuning above the saturation current allows for thermal phase tuning via Joule heating, though slower than EO tuning. The two race-track ring structures (Ring 1 & Ring 2) have slightly different FSRs to allow for mode selection via Vernier tuning, while the common phase section facilitates fine tuning of the longitudinal cavity modes. These three EO tuners are tuned via reverse-bias voltage tuning over a range of 0 to -12 V. The total chip footprint is roughly 3x1 mm. This design has previously been demonstrated in both the optical C-band⁹ and O-band.¹⁰ The laser has demonstrated 90 GBaud DP-16QAM with a fast switching speed of < 10 ns,¹¹ while also demonstrating the capability of further monolithic integration with a MZM capable of 128 GBaud OOK.¹²

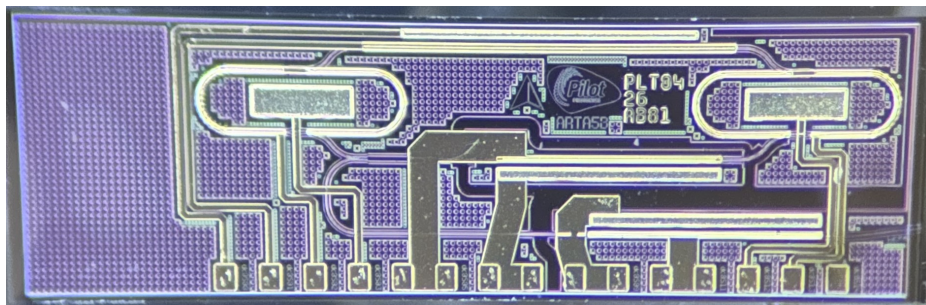


Figure 1: A picture of a Pilot iTLA chip, fabricated by SMART Photonics. Visible are two racetrack-shaped ring sections. Between the rings at the top of the chip is the phase section. Between the rings in the centre of the chip is the Gain section. Before the output in the lower right of the chip is the SOA section. The dark tracks between the Gain and SOA sections are an isolation layer to prevent leakage between the Gain and SOA sections. The chip features all contact pads on one edge of the chip, featuring both the P and N contacts on the top of the chip.

The PIC shown in figure 1 is packaged into a nano-form-factor optical assembly, featuring an internal free-space isolator and feedback photodetectors for wavelength monitoring and locking. The optical package is then integrated with a custom control PCB and heatsink to complete the Pilot Photonics nano-iTLA. The control electronics make use of 12-bit DACs to supply up to -12 V to each tuner, with a 3 mV resolution, to facilitate tuning. Shown in figure 2 is a nano-iTLA contained in a development kit (dev-kit), which provides power

and allows for interfacing with the unit via USB. In this configuration, commands can be sent to the control electronics via a standard OIF-MSA interface, though full debug-level control was available for the purposes of these measurements carried out here.

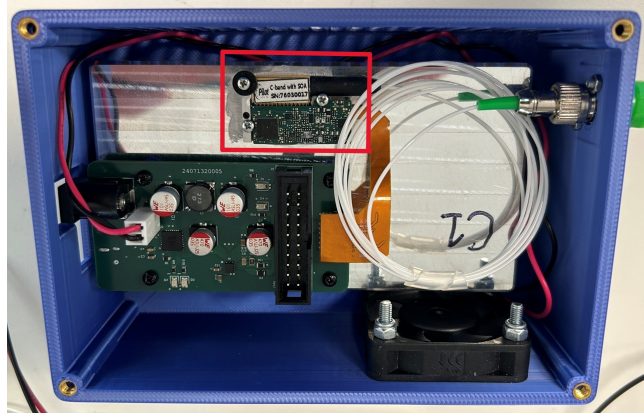


Figure 2: A picture of the Pilot Photonics nano-iTLA (highlighted in red box) under test in a dev-kit. The nano-iTLA consists of a 14-pin gold-box laser package integrated with a control PCB, with current/voltage supply DACs and microcontroller. The dev-kit includes a PCB supplying 3.3 V and UART serial communications to the unit via a flex-cable. The unit is powered by a 5 V barrel plug and interfaced with a micro-USB connector.

3. DIGITAL OPERATION

The nano-iTLA is primarily designed for digital operation - ie, the internal memory of the unit contains a look-up table for the combination of tuner voltages and currents required to achieve operation at the desired channel frequency. In practice, one can generate a tuning map (as seen in Ref. 10) to fill the characterisation space of the three EO tuners, allowing the optimum operating points to be selected. During the selection of operating points, all points outside the desired channel accuracy of ± 1.25 GHz and SMSR > 35 dB are filtered. Due to the periodic nature of the Vernier system, there can be multiple solutions in the 3-tuner parameter space that fulfills the desired output frequency - As such, we define "mode-size" as an additional figure of merit. Mode-size can be described as the area or volume in the 3-tuner parameter space, bound by discontinuities, that allows for continuous mode-hop-free tuning. A larger mode-size indicates a more stable and repeatable operating point.

Figure 3 shows a set of solutions for the three tuners (Ring 1, Ring 2, Phase) extracted from tuning map data, sampled at each 50 GHz-spaced grid frequency. The two rings voltages follow a clear sawtooth waveform, with Ring 2 having a shorter period than that of Ring 1. While the tuning data was measured from 0 to -12 V, the solutions to Ring 1 and Ring 2 land mostly on the interval of 0 to -10 V, indicating the voltage required to tune over 2π . The plot of Ring 1 shows an example of the overlapping solutions, where high and low voltages can give the valid solutions over some intervals. The sawtooth waveform is also notably non-linear - This can be attributed to current drawn at higher voltages introducing a quadratic thermal component. No clear pattern can be identified from the phase voltage, however this is due to the longitudinal mode spacing being of the order of 15 GHz. As a result, the 50 GHz channel sampling is insufficient to identify the periodicity. There are also some notable gaps in the solution space for certain frequencies - These can be filled by adjusting the gain current in order to add a stronger secondary phase shift.

The resulting digital spectra generated from the voltage sweep shown in figure 3 is demonstrated in figure 4. Each individual spectrum is shown, as extracted from a multi-wavelength meter normalised with peak power at a 0 dB reference level, on an interval from 1535 to 1570 nm. Each peak is spaced by 50 GHz to within a tolerance of ± 1.25 GHz with an SMSR above 35 dB.

Figure 5 shows some linewidth measurements sampled from five different channels of the unit under test. Linewidth was measured using the delayed self heterodyne (DSH) method, as described in Ref. 13, using a 10

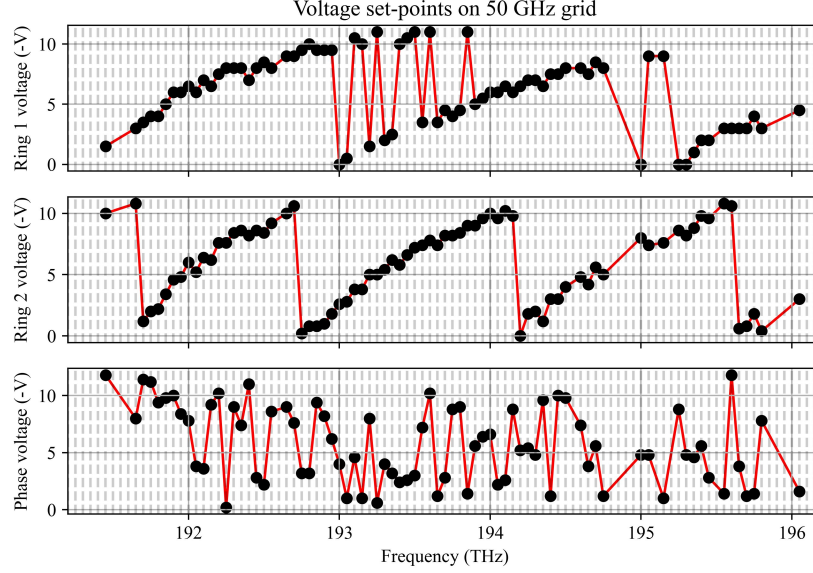


Figure 3: The voltage set-points required for the three tuners to achieve digital tuning on a 50 GHz grid. The two rings follow a sawtooth pattern with a large period to achieve Vernier tuning across the range, while the phase follows a much smaller period that cannot be sampled correctly at 50 GHz. Due to the periodic nature of the system, there may be multiple solutions that produce the same target frequency.

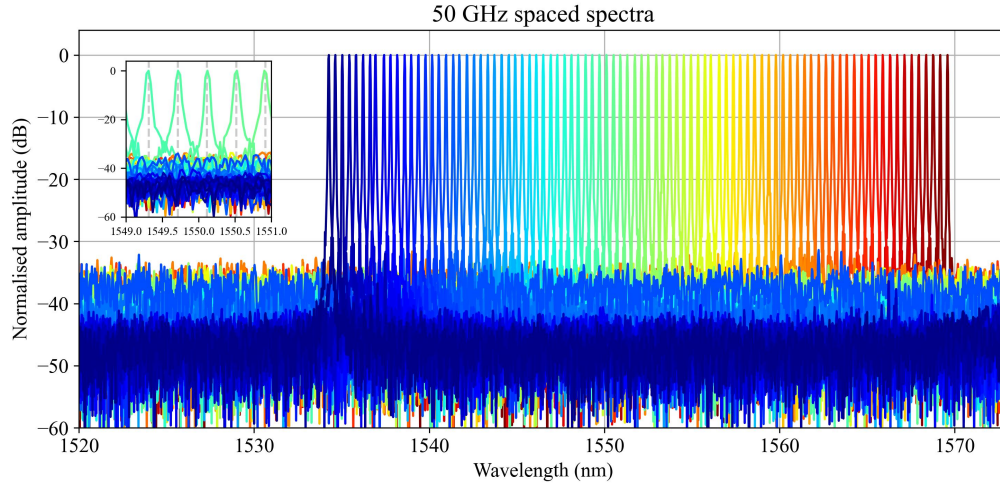


Figure 4: A plot showing the normalised optical spectra of the laser spanning from 1535 to 1570 nm. Each operating point is selected digitally from a 50 GHz / 0.4 nm grid, as shown in the inset plot.

km fiber delay and a 200 MHz acousto-optic modulator. The beat-signal measured from this technique was measured on a spectrum analyser and the resulting spectrum fitted to a Voigt profile. The values for linewidth shown for the five channel frequencies are the Lorentzian components of the Voigt fits. Notably, some spectra feature a prominent Gaussian component, which can be attributed to a known issue with the integrated TEC controller - In order to mitigate this, a suitable operating temperature was selected to minimise the TEC load and allow a proper Lorentzian signal to be measured. The mean linewidth measured for most points falls in the range of 250-300 kHz, with a worst-case of up to 500 kHz. Through careful optimisation of set-points and TEC

temperature, a best-case linewidth of as low as 150 kHz can be measured.

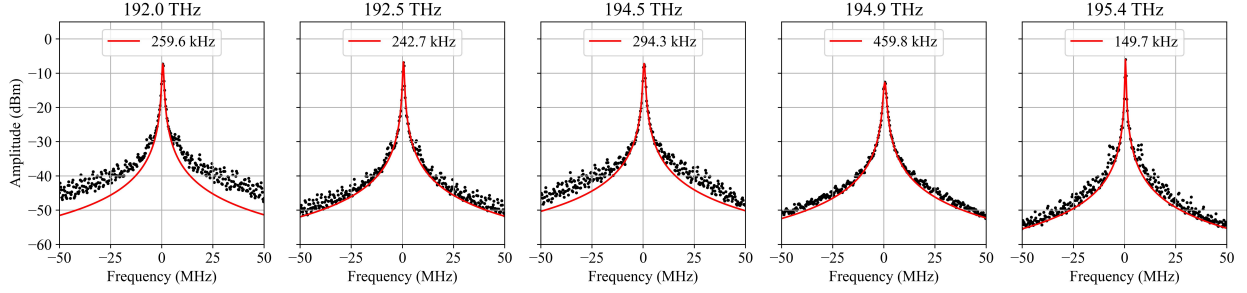


Figure 5: Linewidth measurements taken in five different grid-points. Lorentzian linewidth is extracted from a Voigt fit of the DSH spectrum data. A known issue with the integrated TEC controller generates additional Gaussian noise, leading to linewidth broadening, so a high operating temperature was selected to minimise TEC current. Linewidth could be maintained below 500 kHz and to as low as 150 kHz.

4. CONTINUOUS TUNING FOR DOPPLER CORRECTION

Typically, in DFB or DBR lasers, continuous tuning achieved via modulation of the effective cavity length using a single tuner - In which case the most significant limitation is the bandwidth of the tuner. However, for Vernier-tuned systems like the SG-DBR and ring laser, one needs to also consider the FSR of the filters. Too much tuning of the phase section can lead to unwanted mode-hops into other lasing modes. As demonstrated in figure 6, attempting to vary only the phase voltage results in a very limited continuous range of ± 1 GHz before mode-hopping into an adjacent channel.

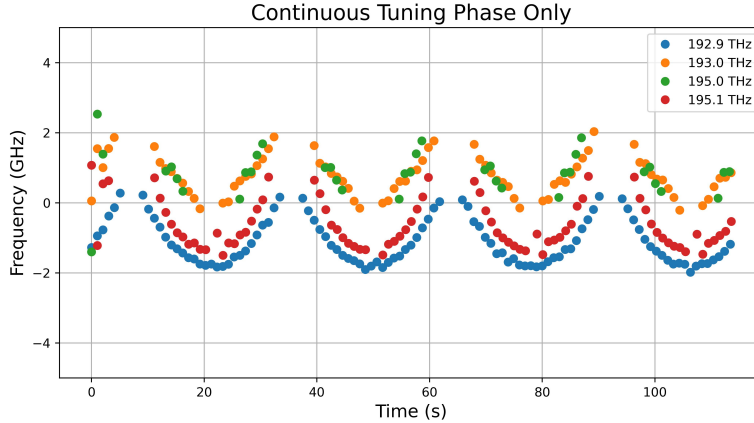


Figure 6: A plot showing the output of the Pilot iTLA while tuning the phase section only. Here we show a close view of the laser output which excludes any jumps into different operating modes. Each frequency channel shows up to ± 1 GHz of continuous tuning before jumping into a different mode. The single section tuning also gives a highly non-linear change in laser output.

In order to extend the range of mode-hop-free tuning, one needs to ensure that the ring modes are locked to the dominant cavity mode as it is being modulated. This is done by identifying the optimal ratio of the four primary tuners (V_{R1} , V_{R2} , V_P , I_G) - By doing so correctly, the dominant cavity mode will be tuned at the same rate as the ring modes, preventing any mode-hops over a larger range. Practically, this is done by defining an amplitude scaling factor (A) relating the four tuners:

$$A = \frac{dA}{dV_{R1}} \Delta V_{R1} = \frac{dA}{dV_{R2}} \Delta V_{R2} = \frac{dA}{dV_P} \Delta V_P = \frac{dA}{dI_G} \Delta I_G \quad (1)$$

where ΔV , ΔI are the offsets in voltage and current from the grid set-points. Each tuner is known to have a non-linear relationship to frequency, however this non-linearity is quite minor over the operating range of 0 to -12 V. This non-linearity can manifest itself as significant differences in the above ratio, depending on the absolute voltage or current of the channel setpoint. From this equation, we can assert a single relation that describes the value of A required for a channel offset frequency (Δf), which encompasses the four tuners:

$$A(\Delta f) = \frac{dA}{df} \Delta f + \frac{d^2 A}{df^2} \Delta f^2 \quad (2)$$

where the system non-linearity is addressed as a single quadratic correction factor. Finally, the tuner grid-point offsets can be reduced to a set of parametric equations in Δf :

$$\begin{aligned} \Delta V_{R1}(\Delta f) &= \frac{dV_{R1}}{dA} A(\Delta f) \\ \Delta V_{R2}(\Delta f) &= \frac{dV_{R2}}{dA} A(\Delta f) \\ \Delta V_P(\Delta f) &= \frac{dV_P}{dA} A(\Delta f) \\ \Delta I_G(\Delta f) &= \frac{dI_G}{dA} A(\Delta f) \end{aligned} \quad (3)$$

which describes the changes in voltage and current required for each tuner from each channel set-point, in order to maintain continuous operation. Naturally, these equations are only valid over a limited domain of valid voltages and currents, exceeding which is likely to cause a mode-hop.

5. RESULTS AND DISCUSSIONS

Frequency chirp measurements were performed using a Pilot niTLA unit, with the output measured using a Keysight 86122C Wavemeter. Four starting points were identified on the 100 GHz ITU grid: 192.9 THz, 193.0 THz, 195.0 THz & 195.1 THz. Initial tests were performed using only the phase section (V_P) of the laser, varying the voltage applied to achieve continuous tuning of the laser output until the output mode-hopped into a new operating mode of the laser. A mode-hop is classified by a large discontinuity of >50 GHz, or when the SMSR of the output drops below 35 dB. It can be seen that this approach is extremely limited for this design, with a maximum tuning range of ± 1 GHz for each mode.

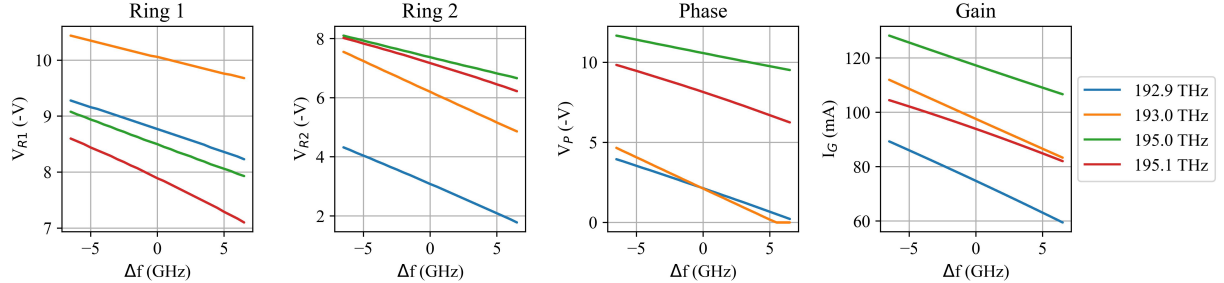


Figure 7: A plot showing the required tuner setpoints for the four target channel frequencies as functions of channel frequency offset (Δf). A very minor non-linearity can be seen, accounting for the quadratic correction. Note that the voltages are displayed as magnitudes.

For each channel setpoint, the six differential parameters defined in equations (1) and (2) are required to solve the system of equations in (3). Table 1 shows the results of calibrating the four target frequencies to maximise the continuous tuning range. This calibration was carried out by starting from the channel setpoint ($\Delta f = 0$) and manually adjusting all four tuners sequentially to determine the operating points that can achieve the largest positive and negative values of Δf . These values were then fitted to a linear function to determine the four ratio values and lock them together. Once the four tuners are locked, a quadratic fit with Δf can be carried out.

Table 1: Channel operating points and respective parametric tuning parameters

f_0 (THz)	V_{R1} (V)	V_{R2} (V)	V_P (V)	I_G (mA)	$\frac{dV_{R1}}{dA}$ (V ⁻¹)	$\frac{dV_{R2}}{dA}$ (V ⁻¹)	$\frac{dV_P}{dA}$ (V ⁻¹)	$\frac{dI_G}{dA}$ (mA ⁻¹)	$\frac{dA}{df}$ (GHz ⁻¹)	$\frac{d^2A}{df^2}$ (GHz ⁻²)
192.9	8.9	3.4	2.6	78.5	0.7	1.7	2.5	20	-0.12	$-4.6e^{-4}$
193.0	10.0	6.0	1.75	95.5	0.45	1.6	3.0	17	-0.13	$-1.1e^{-4}$
195.0	8.4	7.25	10.4	115.5	0.8	1.0	1.5	15	-0.11	$-2.8e^{-4}$
195.1	8.0	7.3	8.4	95.5	1.0	1.2	2.4	15	-0.12	$-1.0e^{-3}$

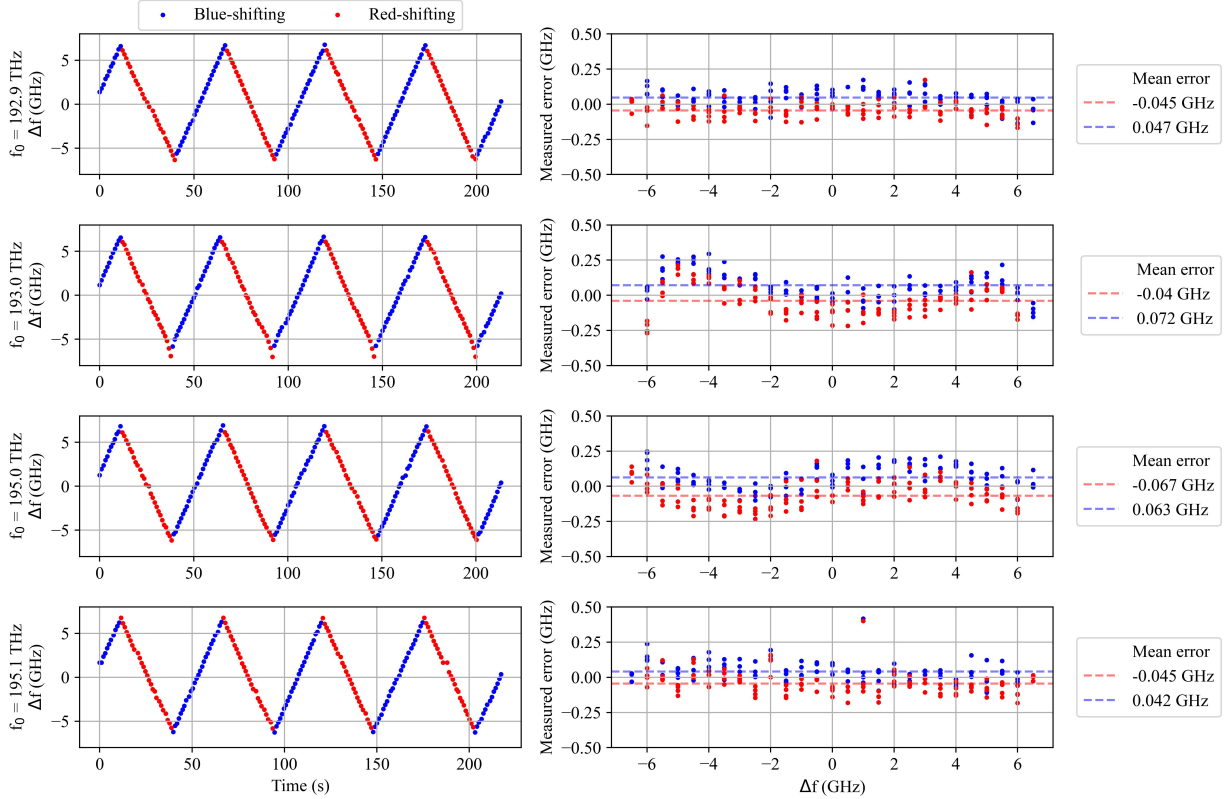


Figure 8: A plot demonstrating a the sawtooth chirp carried out at the four target channel frequencies. The left-hand plots show the trace of channel frequency offset (Δf) over time, while the right-hand plots show measured error with respect to each set value of Δf (subtracting the error at $\Delta f = 0$). The blue points the elements of the trace are where frequency is increasing, while the red points are where the frequency is decreasing. The mean error of these elements show the effect of hysteresis on the system.

In order to test the calibration of the channels under investigation, a sawtooth ramp in Δf was defined, with an amplitude of 6 GHz, a resolution of 0.5 GHz and a period of 8π . The respective tuner values extracted from equation (3) are shown in figure 7, demonstrating the absolute setpoints required for each channel over the 6 GHz amplitude. Each tuner setpoint was updated digitally through the serial interface, then the output frequency and SMSR measured on the Wavemeter - As a result, the measurement time was of the order of 1 s, so it took ~ 50 seconds to complete a full period. This was a limitation of the test setup and it is expected that similar results should be possible on a kHz time-scale, given the EO tuning mechanism.

Figure 8 shows the results of the frequency chirp carried out on the four target channels. Both the time trace of the sawtooth sweep (left) and the respective measured error (right) are shown for each channel. All four channels show very good linearity over the 6 GHz amplitude, indicating the efficacy of the quadratic correction. The measured error with respect to the desired offset frequency falls within the tolerance of ± 0.25 GHz for a majority of set points. The blue and red components of the trace indicate where frequency is increasing and decreasing respectively, which highlights a hysteresis effect. The average error of the blue-shifting chirp is positive, while that of the red-shifting chirp is negative. Therefore, it should be possible to reduce the error tolerance further by correcting for the systematic error produced by hysteresis. The fundamental channel accuracy is within ± 1.25 GHz, which can be improved slightly with small amounts of temperature tuning (<1 °C) - However this results in a frequency offset at $\Delta f = 0$, which affects all measured points. To account for this, the measured error subtracts this offset such that we can observe only the effects of the continuous correction.

6. SUMMARY

We describe a small form-factor integrated tunable laser, suitable for pluggable transceiver applications, and capable of digital tuning on the 50 GHz ITU grid over a range of 35 nm in the C-band. The laser is capable of fast electro-optic-based tuning, while achieving linewidth in the range of 150-300 kHz. We also demonstrate the capability of continuous tuning of up to ± 6 GHz around a grid-point to within a tolerance of ± 0.25 GHz, limited by hysteresis. This would allow for continuous Doppler compensation of Tx/Rx optical signals in coherent inter-satellite links prior to any DSP compensation. Combined with low weight, form-factor and power consumption, the nano-iTLA is a promising candidate for coherent space communications. Future efforts are to both extend the tuning capabilities to cover all frequencies between channels quasi-continuously, as well as to investigate space-hardening and environmental testing.

ACKNOWLEDGMENTS

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