Voltage-Based Wavelength Tuning of a DFB Laser using a Frequency-to-Voltage Converter for OPLL Applications

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Abstract. We demonstrate voltage-based control of a Distributed Feedback (DFB) laser, forming a foundational step toward the implementation of an Optical Phase Locked Loop (OPLL). The voltage control mechanism was realized using the LM331N Frequency-to-Voltage Converter (FVC), which converts an offset frequency into a corresponding DC voltage signal. The voltage was directly fed into the DFB laser, effectively tuning its emission wavelength. A key challenge addressed in this work is the inherent 100kHz upper limit of the LM331N-based FVC. By carefully modifying the circuit design, the conversion range is extended to accommodate frequencies of up to 3 MHz. The experimental results show a clear voltage response starting from 25 kHz, reaching approximately 4.6 V at 3 MHz. The results show a consistent frequency-voltage response, enabling effective wavelength tuning from 1551.725 nm to 1551.79 nm. This approach shows a cost-effective and practical way of enabling coarse frequency locking in OPLLs, essential for high-speed optical communication, coherent detection schemes, and Radio-over-Fibre (RoF) systems.

1 Introduction

The emergence of new technologies and broadband-intensive applications such as augmented and virtual reality (AR/VR), high-definition video streaming, autonomous vehicles, and Internet of Things (IoT) has led to an increase in the demand of high-speed broadband low-latency, reliable connectivity [1]. The all-electrical generation and processing of these high-frequency signals has proved challenging due to the bandwidth limitation of electrical components, electromagnetic interference, as well as the increasing cost and complexity of these components [2]. Although prevalent in millimeter waves (mmWave), the challenges also significantly affect the sub-6 GHz range, particularly when scalability and long-distance transmission are required. These challenges can be solved by Radio-over-Fiber (RoF) systems.

Radio-over-Fibre refers to the transmission of radio frequencies over optical fibres as opposed to free space. Optical fibres are advantageous as they have low attenuation, high bandwidth and are immune to electromagnetic interference. The radio frequencies are generated through microwave photonics (MWP). These frequencies experience phase shifts which lead to instantaneous changes in frequency. To enable coherent detection, it is important to correct for these phase changes.

Phase stabilization can be achieved through different locking mechanisms such as optical injection locking (OIL), optical phase locked loop (OPLL) and optical injection phase-lock loop (OIPLL) [3]. OIL has been used to suppress unwanted sidebands [1] and to generate high frequencies in the orders of hundreds of gigahertz by injection locking to spectral lines from an optical comb [4], [5]. Though easier to implement compared to OPLL, it has a narrow locking range (few hundred MHz) and is extremely sensitive to changes in current and temperature. OIPLL is a solution to the milli-Kelvin precision challenge required to control the laser temperature [6], [7]. OILPLL combines two phase stabilization techniques; optical injection locking and phase locked loops. OIL is responsible for the reduction of wideband phase noise while the phase-locked loop controls the laser frequency drift and close-to-carrier phase noise [8]. OIPLLs have a wider locking range compared to OILs. However, their implementation is quite complex and are quite sensitive to environmental disturbances. Applications include coherent receivers [9], satellite-to-ground communication [3], and high-frequency signal synthesis [8].

Optical phase locked loops offer simpler implementation [3] than OIPLL. A heterodyne OPLL uses a master laser and a slave laser. The wavelength difference between the two lasers determines the value of the generated frequency. The two lasers are coupled and beat at a photodiode, generating a beat frequency. This frequency is compared to a frequency of the same value from a stable source using a mixer, which generates the sum and difference of the two frequencies. The high frequency components are filtered using a low pass filter. The offset frequency (difference) is converted to a proportional voltage which is fed back to the slave laser for tuning purposes. This feedback loop ensures that the slave laser always tracks the master laser, generating a stable frequency [1]. An OPLL attempts to maintain a constant phase relationship between the two lasers, even if the master laser drifts over time [3]. Due to their low phase noise and stable frequency output, they are widely used in quantum precision measurements [1], optical clock recovery in digital communication systems [10], dense wavelength-division multiplexed (DWDM) systems [11], LIDAR systems [12], sensing, spectroscopy [3], coherent terahertz photonics [13], and coherent optical communication systems [14]. Despite their numerous applications, OPLLs are difficult to realize in practice due to limitations in loop bandwidth and the short phase-error propagation time within the loop, which is a function of laser linewidth [3]. To properly track and correct for phase fluctuations, the loop bandwidth of the OPLL should significantly exceed the linewidth of the laser to be controlled. Realizing such a bandwidth is difficult especially when working with broad linewidth lasers [15].

Most literature reports on using a mixer and loop filter to generate the phase error and control voltage respectively. However, in this research we focus on using a frequency-to-voltage converter (FVC) for coarse locking (frequency locking), before using a loop filter for phase locking. This approach is necessary when the frequency drift is too fast, too slow or too large as the loop filter has a limited capture range. Frequency locking is necessary in various research and commercial applications where a clear relationship between the slave laser and the reference signal is needed [15]. These applications include coherent optical communication systems[16], spectroscopic measurements [15], and frequency stabilization of high-power lasers [17]. An FVC operating at 5 GHz speeds in 0.18 m CMOS technology in the electrical domain was designed [18]. Frequency locking was achieved by using an FVC circuit that reduces frequency drifts to less than 400 Hz for time scales longer than 0.1 seconds. This system can remain locked for a couple of hours. The value of the beat frequency is not indicated [15].

This work demonstrates a voltage-based wavelength tuning of a laser using an FVC with an extended range. The FVC used is built around the LM331N, which is commercially available and cost-efficient. It has a frequency response of up to 100 kHz. In this work, we extend the frequency cut-off of the FVC by trading off the linearity. We demonstrate the ability of the voltage signal from the FVC to control laser wavelength and hence the frequency, and the tuning behavior of a standard distributed feedback (DFB) laser.

2 Experimental Methods

2.1 Characterization of the FVC

The set up for the characterization of the FVC included a low frequency signal generator (Beckman Industrial Function Generator), a power supply, a mixed signal oscilloscope (Tektronix MSO54), a digital multimeter, and of the FVC. The setup was as shown in Figure 1. The frequency generator was connected to the FVC via a BNC cable. The input frequency was monitored via the MSO while the output voltage was monitored via the digital multimeter. The frequency generator was tuned into the hundred kHz range and changes were observed in the output voltage. Figure 1 shows the FVC circuit.

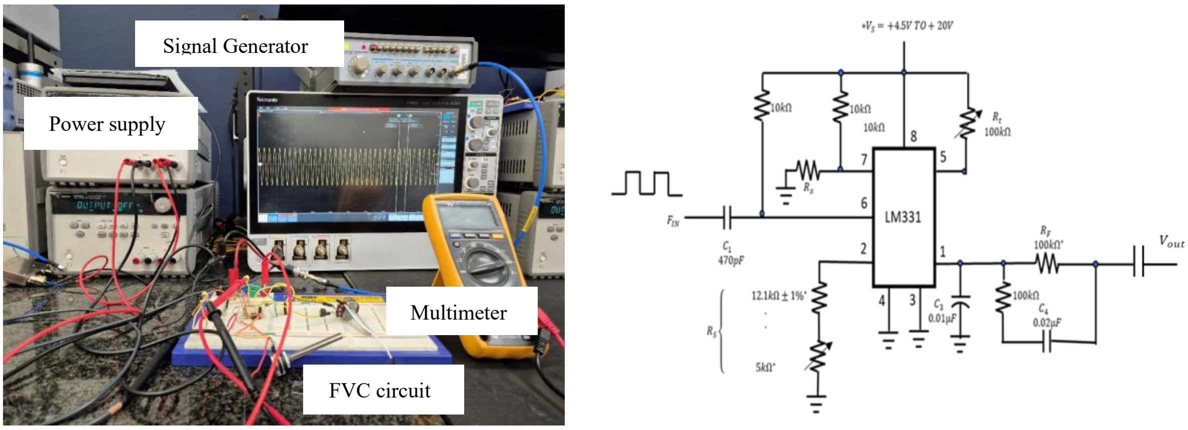

Figure 1: *(left)* Experimental set up for the characterization of the FVC, *(right)* the FVC circuit.

The experiment was repeated using an offset frequency as a result of mixing two electrical sources; a crystal oscillator as a reference signal and the Rohde & Schwarz SMB 100A signal generator producing Rf signals as shown in Figure 2. The FVC requires quite a high gain, so an amplifier was used to increase the input voltage to FVC

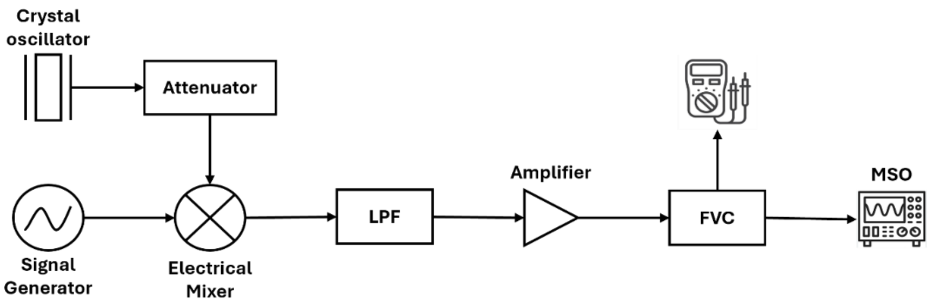

Figure 2: Experimental set up for the generation of the offset frequency and conversion to the control voltage.

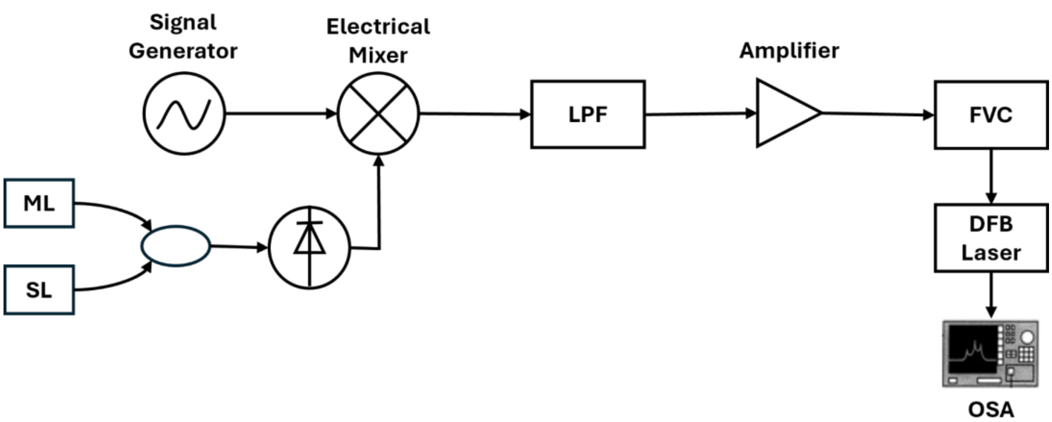

Figure 3: Experimental setup to demonstrate the tuning of the slave laser.

2.2 Wavelength tuning of the DFB

Figure 3 shows the experimental setup for tuning the wavelength of the DFB. The beat frequency was generated using two NKT Koheras BASIK highly coherent laser modules at different but close wavelengths. The reference signal was generated using the Rubidium clock stabilized Rohde & Schwarz SMB 100A signal generator with its frequency set to match the beat frequency.. The offset frequency was then passed through a low pass filter. The output voltage from the FVC was fed into the DFB laser and the wavelength shift as a result of changes in the offset frequency was viewed on the Anritsu MS9740B optical spectrum analyzer (OSA).

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3 Results & Discussion

Figure 4 shows the results from the characterization of the FVC. There are two linear regions that can be used for correction of the laser; 20-40 kHz, and 45-330 kHz.. At 0 MHz, the two signals are perfectly frequency matched, so the FVC output voltage is 0 V, and it remains in this state up to 25 kHz, as the FVC senses no frequency difference. At 25 kHz, the FVC outputs a voltage of 4.12 V, which would then be used for correction in an OPLL. Between 25 kHz and 45 kHz, the FVC exhibits the highest linearity thereafter, the voltage increases gradually. The original FVC circuit has an upper frequency limit of 100 kHz. With minor modifications, we were able to extend this upper limit to 330 kHz with a trade off in the linearity. This might slightly increase the latency of the feedback loop, which is negligible.

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We were able to further push this upper limit using the setup from Figure 2. The results are shown in Figure 4. The voltage response was different for different signal generators. FVCs rely on amplitude-based detection. Therefore, the higher the input power, the stronger the signal, the more detectable the frequency information. The lower the input signal, the weaker the signal, the more noisy or ambiguous the signal detection is. It can also be noted that FVC exhibits mirror symmetry about 0 MHz. This is because the FVC is only sensitive to the magnitude of the offset frequency, not its sign.

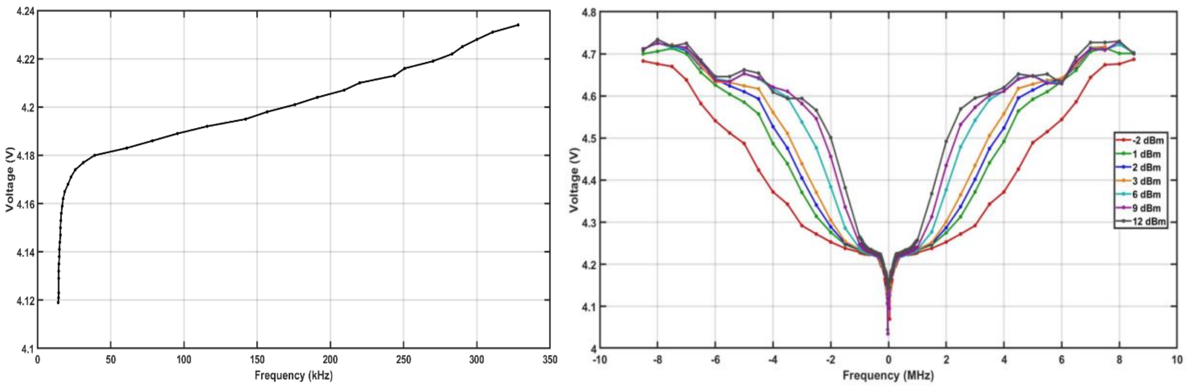

Figure 4: *(left)* Characterization of the FVC, *(right)* the frequency-voltage relationship for different signal generator powers.

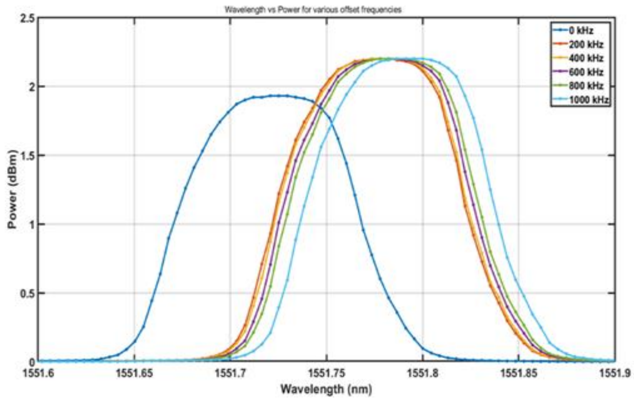

Figure 5: Wavelength tuning of the DFB laser.

The voltage from the FVC was used to drive the DFB laser. The results are shown in Figure 5. The DFB laser was initially at a wavelength of 1551.725 nm, which corresponded to a frequency offset of 0 kHz. The wavelength change was recorded after every 100 kHz. There is a significant power increase between the wavelength corresponding to a frequency offset of 0 kHz and the wavelength corresponding to an offset frequency of 100 kHz. This is because at 0 kHz, the output voltage is 0 V. However, at around 100 kHz, there was a significant increase in the output voltage, which is added to the DFB laser driver hence the increase in power. The output voltage increased gradually, leading to a gradual power increase.

4 Conclusion

In this experiment, we demonstrated the use of the LM331N FVC in frequency locking. We were able to extend the frequency limit from the standard 100 kHz to greater than 2 MHz, depending on the power of the input signal, with a trade-off in the linearity. We also demonstrated that the output voltage from the FVC can be used to tune the wavelength of the DFB laser. Such signals can be implemented in an OPLL when used to drive a slave laser to control its frequency relative to another coherent laser. An optical phase locked loop is used to lock the phase and frequency of a slave laser to master laser to ensure a stable frequency, which is necessary in coherent communication systems. When working with highly unstable frequencies, it is necessary to frequency lock before phase locking, hence the need for a frequency-to-voltage converter.

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