

Laser Frequency Modulation Characterization Using a Programmable Photonic Processor

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Abstract: We demonstrate the capability of programmable photonic circuits to function as a characterization platform for optical devices. As proof of concept, we characterize a laser's frequency modulation response and explore its bias current dependence.

1. Introduction

Programmable photonics is the field focused on developing integrated photonic circuits whose functionality can be reconfigured in software, enabling a single chip to implement a broad range of optical operations without any modification to the physical hardware [1]. This reconfigurability has already been demonstrated in diverse contexts, including optical communication [2], microwave photonics [3] and quantum [4] systems, while also serving as a powerful tool for rapid prototyping [5]. However, we can also use programmable photonic circuits as a platform for characterization of optical devices such as lasers. Lasers are fundamental building blocks for many applications whose performance critically determines the overall behavior of the systems they operate in, and their characterization is an important part of the qualification process. A particularly important parameter is the laser frequency modulation (FM) response, which is crucial for the design and stabilization of optical phase-locked loops (OPLLs) [6]. Motivated by this need, in this paper we show that our programmable photonic processor [2] can fulfill this role by implementing a measurement scheme that extracts the FM response of a directly modulated laser.

2. Principle of Operation

The modulated injection current in a laser modulates both the intensity (IM) and the frequency (FM) of the optical signal, as it is depicted in Fig. 1(a) [7]. In order to measure the FM, an asymmetrical MZI (AMZI) was used as a frequency discriminator [7]–[9], converting the frequency variations to amplitude ones. AMZI has two output ports, bar and cross, as shown in Fig. 1(b). Both exhibit a sinusoidal transfer function for different optical phase shifts introduced by the phase shifter that is located in the bottom arm, with the two output powers being 180° out of phase, due to the complementary nature of interference, as it is depicted in Fig. 1(c).

The AMZI filters both IM and FM components of the input optical signal. To extract the FM response of the device under test, two measurements are performed at two quadrature (3 dB) points on opposing slopes, i.e., positive (QUAD+) and negative slope (QUAD-), as shown in Fig. 1(c). The FM response is derived by subtracting the two measured photocurrents from the photodiode (PD) at the bar port [6], [9]. To isolate the FM response of the laser, a scalar calibration step is performed to remove the influence of all other components. This is achieved by performing an IM measurement with the shortest arm of the AMZI disconnected, i.e., the bottom branch in Fig. 1(b) [6]. After calibration, the FM response of the laser is obtained, as shown in eq. (1) in Fig. 1, with I^+ and I^- referring to the IM response measured at QUAD+ and QUAD- points, respectively, and I^{OPEN} the calibration measurement. Alternatively, the FM response can be extracted in a single measurement by biasing the AMZI at QUAD+ for the bar PD and using the cross PD as the negative slope measurement. Calibration is then performed using both PD outputs, a method referred to as Method 2, and is presented in eq. (2) in Fig. 1.

3. Experiment

The experimental set-up for the FM measurement of the laser under test is shown in Fig. 1(d). The laser is biased through a voltage source that supplies the injection current, to which the VNA adds the modulation signal. After passing through an isolator and a polarization controller, the optical signal enters our programmable photonic

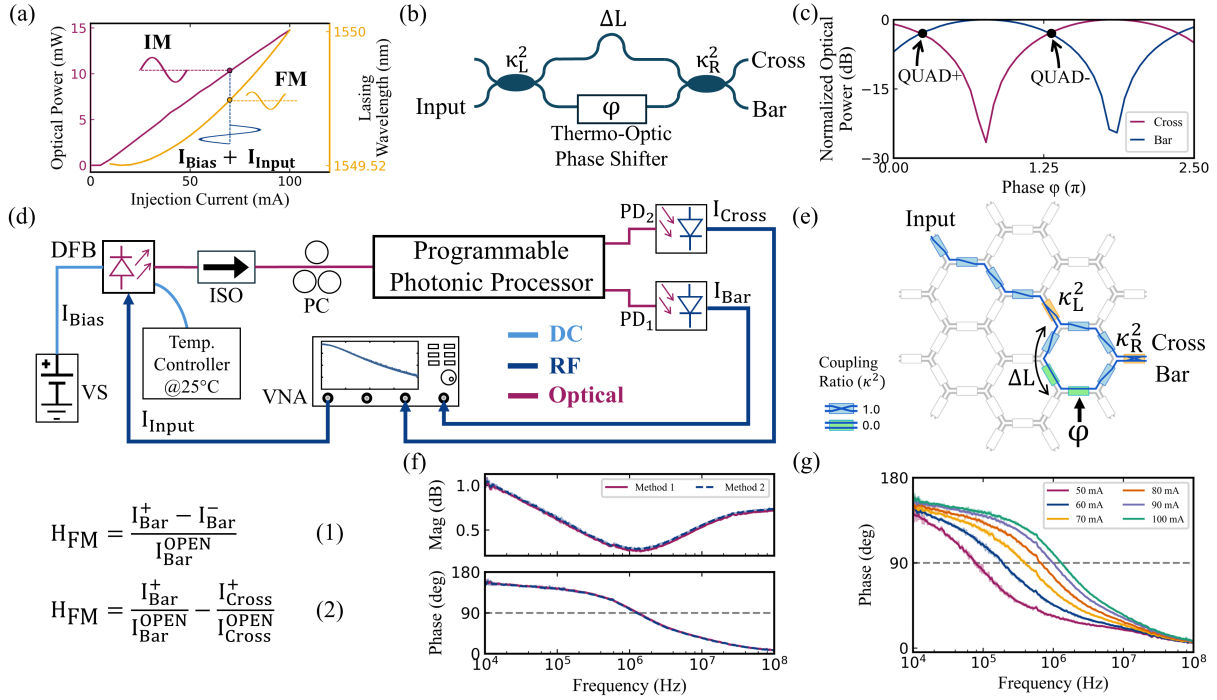


Fig. 1: (a) Laser characteristic. (b) AMZI schematic. (c) AMZI transfer function. (d) Experimental testbed. VS: Voltage source. ISO: Isolator. PC: Polarization controller. PD: Photodiode. VNA: Vector network analyzer. (e) AMZI configuration in our integrated programmable photonic processor. (f) Magnitude and phase of the FM response. (g) Phase response for different bias currents.

processor, where the AMZI is implemented and the two output ports of the AMZI, bar and cross, are then detected by photodiodes, and the resulting photocurrents are sent to the VNA.

The AMZI was implemented using our stand-alone integrated programmable photonic processor, whose fundamental building block is an optical gate realized with a balanced MZI equipped with two thermo-optic tuners. By connecting multiple gates in a hexagonal mesh the resulting architecture, which comprises seven cells, is obtained. Each gate can act as a tunable coupler and/or a phase shifter, enabling full programmability of the photonic circuit. Fig. 1(e) shows the programmed AMZI configuration, with an optical path-length difference of two logic gates ($\Delta L = 806 \mu\text{m}$) and both the splitter (κ_L^2) and combiner (κ_R^2) coupling ratio set to 50%.

4. Results

To verify the characterization method, a commercial DFB laser (EX-DY7005-C-P10) was measured. The resulting FM response using Method 1 and 2 are depicted in Fig. 1(f) with the purple and blue curves, respectively. It can be seen that both methods give the same result after normalization. The FM response for a DFB laser arises from two opposing mechanisms, with thermal FM dominating only at low frequencies while carrier-induced FM remains flat from DC up to near the relaxation frequency [6], [10]. The former mechanism is in phase with the modulating current, while the latter is out of phase. This results in a π phase reversal (f_π), which is of importance for e.g. the loop stability of OPLLs. Therefore, a sweep was performed over the bias current, shifting f_π to higher frequencies for increasing bias currents, as shown in Fig. 1(g). This shift occurs because a higher bias current generates more heat, and thereby increases the thermal efficiency [10].

5. Conclusion

In this paper, we verify the capability of programmable photonics to serve as a platform for the characterization of optical devices. As a proof of concept, we extract the FM of a DFB laser by implementing the required frequency discriminator in our programmable photonic processor. This work demonstrates the potential of integrated programmable photonic circuits for extracting laser characteristics, and it paves the way for more comprehensive on-chip laser characterization, including the frequency noise spectrum and linewidth [11].

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References

- [1] W. Bogaerts et al., “Programmable photonic circuits,” *Nature*, vol. 586, pp. 207–216, 7828 Oct. 2020. DOI: 10.1038/s41586-020-2764-0.
- [2] Y. Zhang et al., “General-Purpose Hexagonal Programmable Photonic Integrated Circuit with a >30 GHz Free Spectral Range,” *Laser & Photonics Rev.*, 2026. DOI: <https://doi.org/10.1002/lpor.202502270>.
- [3] D. Pérez-López et al., “General-purpose programmable photonic processor for advanced radiofrequency applications,” *Nat. Commun.*, vol. 15, 1 Dec. 2024. DOI: 10.1038/s41467-024-45888-7.
- [4] L. S. Madsen et al., “Quantum computational advantage with a programmable photonic processor,” *Nat.* 2022 606:7912, vol. 606, pp. 75–81, 7912 Jun. 2022. DOI: 10.1038/s41586-022-04725-x.
- [5] W. Bogaerts et al., “Programmable Photonic Circuits: a flexible way of manipulating light on chips,” in *Frontiers in Optics / Laser Science*, Optica Publishing Group, 2020, FTh1C.1. DOI: 10.1364/FIO.2020.FTh1C.1.
- [6] W. Liang, “Study of Optical Phase Lock Loops and the Applications in Coherent Beam Combining and Coherence Cloning,” 2008.
- [7] G. Charalambous et al., “Integrated Photonic Linear Frequency Discriminator Filter for 5G Phase-Modulated Microwave Photonic Links,” *J. Light. Technol.*, vol. 39, no. 24, pp. 7563–7572, 2021. DOI: 10.1109/JLT.2021.3105242.
- [8] V. J. Urick et al., “Phase Modulation With Interferometric Detection as an Alternative to Intensity Modulation With Direct Detection for Analog-Photonic Links,” *IEEE Trans. on Microw. Theory Tech.*, vol. 55, no. 9, pp. 1978–1985, 2007. DOI: 10.1109/TMTT.2007.904087.
- [9] W. Sorin et al., “Frequency Domain Analysis of an Optical FM Discriminator,” *J. Light. Technol.*, vol. 10, no. 6, pp. 787–793, 1992. DOI: 10.1109/50.143079.
- [10] P. Corrc et al., “On the thermal contribution to the FM response of DFB lasers: theory and experiment,” *IEEE J. Quantum Electron.*, vol. 30, no. 11, pp. 2485–2490, 1994. DOI: 10.1109/3.333699.
- [11] M. Bagheri et al., “Linewidth Measurement of Distributed-Feedback Semiconductor Lasers Operating Near 2.05 μm ,” *IEEE Photonics Technol. Lett.*, vol. 27, no. 18, pp. 1934–1937, 2015. DOI: 10.1109/LPT.2015.2447286.