# Single-mode Distributed Feedback Lasers for $^{87}$Rb Two-Photon Quantum Technology Systems

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***Abstract*— Distributed feedback (DFB) lasers have been demonstrated at 778.1 nm wavelength with 48 mW output power, 20.5º vertical divergence, –150 dBc/Hz relative intensity noise (RIN), and linewidth of 3.67 kHz. Such devices were employed to successfully resolve the $^{87}$Rb two-photon hyperfine levels in free-running conditions.**

***Keywords—semiconductor lasers, narrow-linewidth, quantum technology***

## I. INTRODUCTION

Optical atomic clocks have demonstrated accuracies around 1 part in $10^{18}$ but to date they have been large based research systems that are impractical to use outside of controlled laboratories [1]. Proposals have been made to produce far smaller and more practical microfabricated atomic clocks using two-photon transitions of thermal $^{87}$Rb atoms at a wavelength of 778.1 nm [1]. Key to being able to reduce the size and power of such atomic clocks are small and tunable lasers such as distributed feedback (DFB) semiconductor diode lasers. High accuracy optical clocks require lasers with sufficiently narrow linewidth, in this case significantly less than the $^{87}$Rb 2-photon transition of 300 kHz [1]. Such diode lasers can also be integrated with $Si_3N_4$ photonic platforms [2,3] whilst maintaining single mode and narrow linewidth operation [4-6] with the potential for future chip-scale quantum technology systems. In this paper we present 3 mm long cavity DFB lasers with over 48 mW power output, side-mode suppression ratios (SMSRs) approaching 40 dB, and linewidths of 3.67 kHz that demonstrated suitable for $^{87}$Rb two-photon transitions at 778.1 nm in free-running conditions.

## II. DFB LASER FABRICATION

The DFB lasers were fabricated on an aluminium-free active area [5,6] four-quantum-well GaAs/AlGaAs wafer material, with an epilayer structure that was designed for narrow-linewidth applications. The epilayer material was

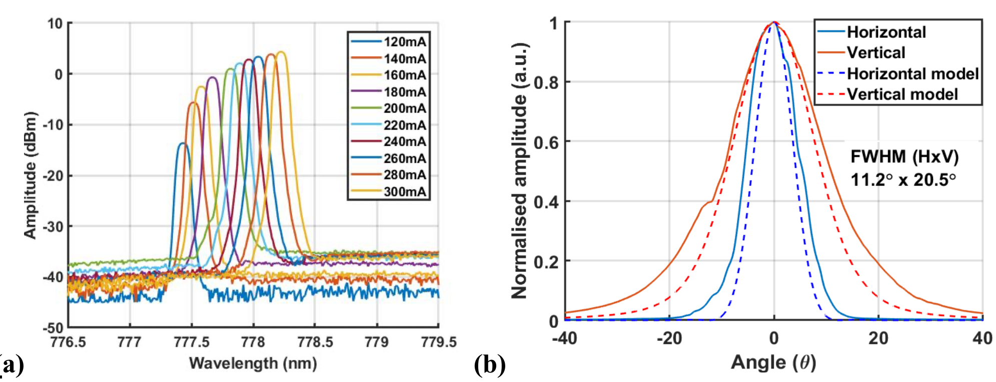
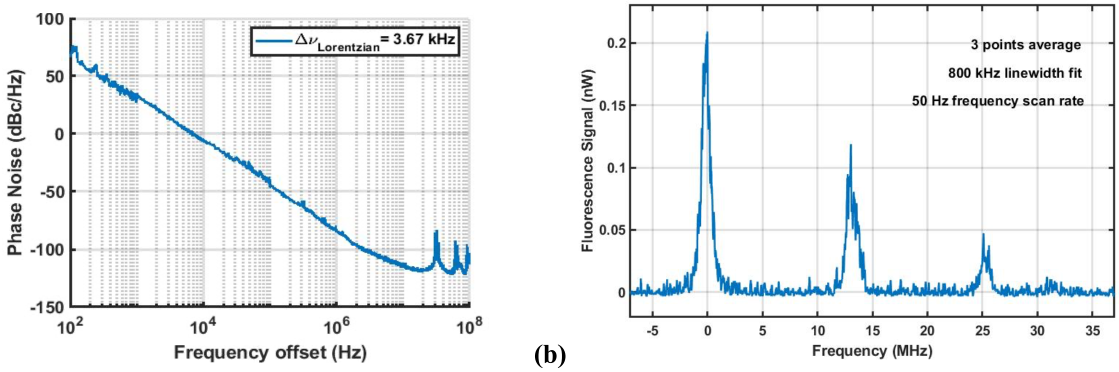



Fig. 1 (a) The DFB laser spectrum continuously tuned by current injection around the 778.1 nm wavelength of interest. (b) Beam divergence in the horizontal and vertical axis, the continuous lines are the measured data which are in good agreement with the modeled values in dashed lines




**(a)** **(b)**

Fig. 2 (a) The phase noise measured at current of 240 mA and temperature of 15˚C. The noise level at a high-frequency offset (> 10 kHz) indicated a Lorentzian linewidth of 3.67 kHz. (b) The fluorescence signal from the heated Rb cell after 778.1 nm laser illumination, reported with a 3-points average. The frequency scan, detuned from the position of the main transition peak, reveals the hyperfine levels, whose natural linewidth is 334 kHz of the $^{87}$Rb two-photon transition.

optimized over previous designs at 780.24 nm [5,6] to reduce modal propagation losses and far-field emission pattern to decrease the beam divergence in the epilayer direction to 20º, potentially improving the single-mode fibre coupling up to a simulated value of 80%. A third-order Bragg grating was patterned on a 500 nm thick hydrogen silsesquioxane (HSQ) resist mask by electron beam lithography (EBL). The sample was passivated by a SiO2 deposition and planarised by a spun-on polymer, followed by the etched of a contact window for the metal evaporation. Both top (Ti/Pt/Au) and bottom (Au/Ge/Au/Ni/Au) contacts were deposited by metal evaporation after the sample thickness was mechanically reduced to 250 µm. Finally, the sample was cleaved into single bars, with one facet coated with an anti-reflection (AR) coating and the other with a high reflection (HR) coating. Then the bars were mounted on brass supports to ensure both thermic and electric conductivity during the testing of the devices.

## III. DFB Laser Characterisation

The light-current-voltage (LIV) characteristics of the 3 mm long AR/HR-coated DFB laser shows a threshold current at 120 mA with a high slope efficiency of 0.26 W/A, achieving power emission over 48 mW at the current injection of 300 mA. Fig. 1 (a) demonstrates the spectral behaviour as a function of the injection current through thermal effects. The DFB laser device exhibits a continuous peak wavelength tunability of 0.8 nm in a wavelength range, including 778.1 nm, with no mode hopping. The emitted spectra also demonstrate SMSRs which exceed 35 dB, approaching 40 dB at high injection currents. Fig. 1 (b) reports the beam divergence in the vertical and horizontal axes. The measured vertical divergence exhibits a FWHM of 20.5° in agreement with the value modelled on the epilayer design, while the horizontal divergence is as low as 11.2º due to the up-tapering of the AR facet end. The device phase and intensity noise were measured by an OEWaves 4000 automated noise characterization analyzer, through a homodyne detection technique, which does not require a low-noise reference laser, as for the standard heterodyne detection technique [7]. From the phase noise in Fig. 2 (a), an instantaneous Lorentzian linewidth over an integration time of 25 µs of 3.67 kHz was obtained while the intensity noise normalised in power (RIN) proved to be as low as -150 dBc/Hz for frequency offset > 100 MHz. Fig. 2 (b) shows a fluorescence spectrum with three of the four hyperfine peaks for the $^{87}$Rb transition. The measurement was acquired using a heated Rb cell in retroreflection configuration. The frequency scan was performed by an acousto-optical modulator while the fluorescence signal at 420 nm wavelength was amplified by a photomultiplier tube before detection. Further work will investigate the linewidth and RIN after the laser locking to the $^{87}$Rb 2-photon transition or a high-Q $Si_3N_4$ microring [3] as is required for most quantum technology applications. In conclusion, we demonstrated DFB lasers emitting at 778.1 nm with a mode-hop free tunability range of 1 nm, power output exceeding 48 mW, SMSR approaching 40 dB, low RIN of -150 dBc/Hz, and linewidth of 3.67 kHz, respectively, and proved the resolution of the hyperfine levels for the $^{87}$Rb 2-photon transition.

## References


[1] Z.L. Newman et al., "Architecture for the photonic integration of an optical atomic clock", Optica, vol. **6**, pp. 680–685, 2019.

[2] K. Gallacher et al., "Integrated DFB lasers on Si3N4 photonic platform for chip-scale atomic systems", IEEE Conference on Lasers and Electro-Optics (CLEO), 2019 [OSA Technical Digest paper STu4O.7, 2019].

[3] M. Sinclair et al.,"1.4 million Q factor $Si_3N_4$ micro-ring resonator at 780 nm wavelength for chip-scale atomic systems" Opt. Exp. vol. **28**, pp.4010-4020, 2020.

[4] E. Di Gaetano, and M. Sorel, "Design of chirped-coupling sidewall Bragg gratings for narrow linewidth distributed feedback lasers," Opt. Lett., vol. **44**, pp. 1642-1645, 2019.

[5] E. Di Gaetano, S. Watson, E. McBrearty, M. Sorel, and D. J. Paul, "Sub-megahertz linewidth 780.24 nm distributed feedback laser for 87Rb applications" Opt. Lett., vol. **45**, pp. 3529-3532 (2020).

[6] S. Watson, E. Di Gaetano, E. McBrearty, M. Sorel, and D. J. Paul, "Narrow Linewidth Distributed Feedback Diode Lasers for Cooling in Cold Atom Systems", IEEE Conference on Lasers and Electro-Optics (CLEO), 2020 [OSA Technical Digest paper AF3I.5, 2020].

[7] H. Ludvigsen, M. Tossavainen, and M. Kaivola, "Laser linewidth measurements using self-homodyne detection with short delay," Opt. Comm., vol. **155**, pp. 180–186 (1998).



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