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Iodine-stabilized VECSEL at 689 nm with 3×10^{-13} stability

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Abstract: We report frequency stabilization of a 689 nm AlGaInP-based vertical-external-cavity surface-emitting laser (VECSEL) directly and exclusively to molecular iodine. Sub-Doppler saturation spectroscopy of iodine around the 689 nm wavelength region was performed to identify suitable absorption features for laser locking. Four spectral features were identified within ±2 GHz of the absolute frequency of the $^1S_0 \rightarrow {}^3P_1$ transition of neutral strontium-88 atoms (434.829 THz). The VECSEL was subsequently directly locked to a transition at +1.77 GHz relative to the $^1S_0 \rightarrow {}^3P_1$ target. The resulting iodine-locked system exhibited a linewidth of 6.2(1) kHz (4 s averaging time) as determined via beat note measurement to a reference VECSEL (integrated linewidth of ~400 Hz). Using the Allan deviation, minimum instability of 2.7×10^{-13} at 4 s averaging time was identified. Over a 20-minute period, the oscillation frequency of the iodine-locked system was observed to drift by only 18 kHz, compared with 88 kHz when using the conventional technique of locking to a reference cavity (finesse = 1k). By stabilizing exclusively to molecular iodine – a species compatible with compact glass-blown or micro-machined cell embodiments and usage at room temperatures – the VECSEL offers potentially significant reductions in complexity for quantum technology applications reliant on addressing narrow transitions of neutral Sr atoms. Enhancement of spectroscopy signals presents future opportunities to lock more closely to the $^1S_0 \rightarrow {}^3P_1$ target, within the range of a standard electronic modulator.

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1. Introduction

In recent decades, the strategic advancement of quantum technologies has fueled the development of advanced laser systems as a key underpinning technology [1], performing vital functions in the manipulation, interrogation, production and maintenance of cold atoms [2]. The various target transitions in atomic, molecular and ionic species impose distinct requirements on the wavelength, brightness, stability and spectral purity of such laser systems. The demands on laser performance are more challenging in quantum sensing [3] and timing applications [4], where narrow or ultra-narrow atomic transitions are used for timekeeping requiring ultra-low noise and linewidth lasers. For example, neutral strontium (Sr) optical clocks utilize different ultra-coherent light sources for laser cooling and clock interrogation. Laser cooling down to sub-μK temperatures is performed by targeting the broad singlet ($^1S_0 \rightarrow {}^1P_1$) transition at 461 nm, then the narrow triplet ($^1S_0 \rightarrow {}^3P_1$) transition at 689 nm with linewidths of 30.5 MHz and 7.6 kHz, respectively [5]. For the clock transition, the requirements are even more strict as the target is a mHz-level linewidth triplet transition ($^1S_0 \rightarrow {}^3P_0$) at 698 nm [5].

Current systems employed in optical clock setups are based on external cavity diode lasers (ECDLs) that are then stabilized to high-finesse Fabry-Pérot cavities to achieve linewidth requirements [6]. While suitably stabilized ECDL-based systems can produce single-frequency

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light at the required wavelength and linewidth, the ECDLs often require further optical processing, such as beam correction optics and stabilized amplifiers, to achieve high brightness [7]. These additional modules add bulk and complexity, making them challenging systems to install in a field-deployable device. Alternatively, vertical-external-cavity surface-emitting laser (VECSEL) technology offers ultra-coherence, extended wavelength coverage, high brightness and stability without additional optical processing steps. In combination with the characteristic class-A low noise performance of VECSELs, with mHz-level Schawlow-Townes-Henry [8,9], or intrinsic, linewidth [10,11], the benefits of these properties are being explored for quantum technology applications.

For any laser system, including ECDLs or VECSELs, a fundamental concern regarding cavity stabilization for the reduction of free-running frequency noise is the unavoidable frequency drift of the reference cavity. This drift is principally due to thermal fluctuations, vibrations and even Brownian motion of atoms within anti-reflection coatings of cavity mirrors that cannot be remedied, leading to drifts of up to 20 mHz/s [12]. Depending on the cavity geometry and associated free spectral range, the optical resonance of a reference cavity can become detuned from the target transition by some GHz, incurring significant power efficiency losses in the required frequency compensation for large detunings. To minimize these instabilities and inefficiencies, a spectral referencing element can be introduced, and this is most reliably done with spectroscopy.

By referencing stable transitions of atoms or molecules, a spectrally locked system can be robustly protected against unwanted drifts. However, spectral locking schemes also introduce additional elements to the laser system, and since the laser beam size and power must be adjusted to compensate for transient and collisional broadening effects [13], optical power requirements are also increased depending on the electronic transition of interest. The discrepancy in requirements when targeting different electronic transitions is especially significant in the case of neutral strontium. For the $^1S_0 \rightarrow {}^1P_1$ blue transition of neutral Sr at 461 nm, a variety of cell architectures are available, including hollow cathode lamps [14], light-induced atomic desorption devices [15], or microfabricated vapor cells [16], thus allowing for the development of relatively compact and low temperature setups for laser stabilization. However, these small cell architectures are still unexplored for the $^1S_0 \rightarrow {}^3P_1$ transition at 689 nm due to its narrow linewidth, which introduces additional challenges. Firstly, to facilitate adequate interactions with red light, increases of the spectroscopy cell length (to >40 cm) and temperature (to >400 °C) are required [13]. Secondly, it is well known that Sr atoms readily adsorb to glass [16] such that Sr reference cells have a limited lifetime despite compensatory measures (including the use of buffer gases, localized heating, and materials other than glass as optical windows).

Any alternative spectral reference species to neutral Sr must offer sufficiently strong signals at frequencies around the target 689 nm transition. To this end a number of candidate molecules can be considered, such as iodine [17] and acetylene [18]. Generally, the complex energy structures of molecular references can offer greater numbers of possible transitions, improving the chance of resolving suitable lines in wavelength ranges where the spectra of other species may be too weak or absent. For instance, the molecular iodine spectrum runs from green to mid-infrared wavelengths and has previously been well-studied and characterized by Gerstenkorn and Luc [19]. Molecular iodine is also widely commercially available in glass packaging, and has favorable vapor pressure and reactivity as a gas at lower temperatures (in comparison to Sr) that make it suitable for spectroscopy. Due to its popularity as a molecular reference, developments in manufacturing miniaturized iodine embodiments are underway [20,21], indicating scope for further bulk reduction in future laser systems using these cell types as references.

Despite its prevalence as a molecular reference, there is currently little characterization of iodine in the 680-700 nm range. This is because spectral lines in this region are relatively weak: molecular transitions between the corresponding energy states in the B-X system [19] (the set

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of rotation-vibrational transitions covering the red and infrared region) become less probable with increasing energy and decreasing state overlap [22], leading to spectral lines in the red wavelength region being much less intense when compared to their infrared counterparts. Direct laser locking in this region is therefore expected to be challenging, particularly for laser sources that also require significant linewidth narrowing; however, given the high brightness and narrow free-running linewidth of VECSELs, we propose iodine-locking as a compact means to correct frequency drift and achieve excellent stability over long measurement times (> minutes) for these lasers, even at wavelengths around 689 nm.

Here, we utilize a red-emitting AlGaInP-based VECSEL [23], with >100 mW direct emission in a diffraction-limited, circularly symmetric Gaussian beam ($M^2 < 1.01$), and with a free-running linewidth of approximately 50 kHz, to perform precision molecular iodine laser spectroscopy at around 689 nm. Suitable transitions for laser stabilization, with detuning from the red cooling transition of neutral Sr in the few (-5 to 2) GHz range, were identified for subsequent frequency stabilization. The resulting low frequency and intensity noise of the iodine-locked VECSEL, with a 6.6(5) kHz integrated linewidth (1000 s sampling time), long-term frequency stability reaching 2.7 $x10^{-13}$ at an averaging time of 4s, and a drift of only 18 kHz over a 20-minute period, is suitable for use in neutral strontium-based quantum technologies.

2. Experimental setup

2.1. AlGaInP-based VECSEL

Figure 1 displays a schematic representation of the AlGaInP VECSEL system used for the iodine spectroscopy and subsequent frequency locking experiments. The VECSEL gain chip is identical to that reported previously by our group [10]. It was grown on a 2-inch GaAs wafer, with a distributed Bragg reflector and the gain region. The former is composed of alternating layers of AlGaAs/AlAs for high-reflectivity around 689 nm. The latter is composed of 10 pairs of compressively-strained GaInP quantum wells (QWs) and corresponding tensile-strained AlGaInP barriers. The gain chip is designed for use with a green pump source (here we use a Coherent VERDI G5 emitting at 532 nm) and emission at around 689 nm.

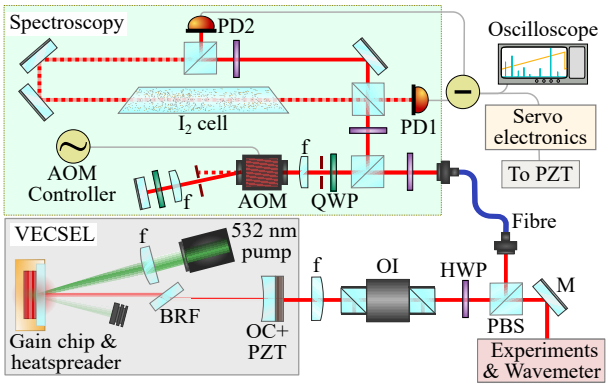

Fig. 1. Experimental setup schematic showing the AlGaInP-based VECSEL (lower left) and molecular iodine spectroscopy (top), including a double-pass acousto-optical modulator configuration. f: lens; BRF: birefringent filter; OC: output coupler mirror; PZT: piezo-electric transducer; OI: optical isolator; HWP: half-wave plate; PBS: polarizing beam splitter; M: broadband dielectric mirror; QWP: quarter-wave plate; fibre: polarization maintaining fibre; AOM: acousto-optical modulator; PD: photodiode; I_2 cell: molecular iodine spectroscopy cell.

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A diamond heatspreader is capillary bonded to the gain chip surface, and the bonded unit is placed in a thermo-electrically temperature-controlled brass mount, kept at room temperature (around 18°C) with sub-mK stability. A 2% transmission output coupling mirror, mounted on a piezo-electric transducer (PZT) for frequency stabilization actuation, with radius-of-curvature 100 mm, is positioned opposite the gain chip to create a two-mirror external cavity of length 99 mm. A temperature-controlled birefringent crystal of thickness 5 mm is inserted at Brewster's angle into the intracavity beam path as a birefringent filter for coarse wavelength tuning (FSR ~ 30 GHz, ~ 0.05 nm) to select the 689.4 nm wavelength region. Fine tuning of the VECSEL emission towards the red cooling transition of neutral ^{88}Sr at 434.829 THz, is achieved by adjusting the temperature of the VECSEL gain chip via the thermally-controlled heatsink mount. A 7 GHz continuous frequency tuning range is achieved via the cavity PZT around the target frequency. Finally, in order to reduce the effects of local vibrations and air-flow disturbances, the VECSEL components are mounted within a closed metal box.

The VECSEL system, pumped with up to 4 W at 532 nm over a 90 µm diameter spot, produces up to 160 mW of stable single-frequency light with a free-running linewidth of 50 kHz that can be tuned between 686 nm and 694 nm by scanning the VECSEL sample and adjusting sample and BRF temperature. The beam is directly emitted into the fundamental transverse Gaussian mode, with $M^2 < 1.01$. For the purposes of this work, the VECSEL emission wavelength was tuned to near the red Sr cooling transition [6].

2.2. Spectroscopy and frequency stabilization setups

In order to perform sub-Doppler spectroscopy a co-linear saturated absorption configuration [24] was used (see Fig. 1). In this method, the VECSEL output is divided into a saturating pump beam and a low-intensity probe beam that counter-propagate through a vapor cell (Thorlabs, GC19100-I). When the light frequency matches that of a hyperfine feature, the pump and probe beams address the same velocity class of molecules — the molecules are fully saturated by the pump beam and the probe beam is readily transmitted. By scanning the laser frequency using the VECSEL cavity PZT, thereby scanning the pump and probe beams simultaneously, the balanced photodetectors PD1 and PD2 are used to reveal the Doppler-free spectrum of the weak iodine lines.

Frequency modulating the AOM scan (at 100 MHz single-pass, producing 200 MHz in double-pass, see Fig. 1) produces a time-varying signal that is then demodulated and low-pass filtered with a servo-mechanism to produce a phase discriminator, or error signal, the crossing-point of which can be used as a frequency reference. Returning this signal to the laser PZT modulates the VECSEL cavity length, allowing the laser frequency to be directly stabilized, within the bandwidth of the PZT (up to 15 MHz), to the selected absorption feature. The VECSEL frequency is monitored using a wavemeter (WS7-30, HighFinesse) that is calibrated using a 633 nm HeNe laser with absolute accuracy of 30 MHz (resolution of 1 MHz).

The iodine cell was maintained at temperatures up to 65 °C by a temperature-controlled mount, allowing the cold finger to protrude and remain at room temperature throughout use. The spectroscopy and stabilization stages used, in combination, approximately 40 and 20 mW of the total VECSEL emission, respectively, leaving up to 100 mW available for experiments. After fiber coupling (efficiency = 68%) and a double pass of the AOM (45%), a total of 12 mW is available for iodine spectroscopy. The pump and probe beam have a diameter of 2 mm with powers up to 10 and 1 mW available for the respective beams.

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3. Results

3.1. Sub-Doppler molecular iodine spectrum around 689 nm

Figure 2 shows the measured hyperfine spectroscopy signals, and derived error signals, of iodine at frequencies close to the absolute frequency of the $^1S_0 \rightarrow {}^3P_1$ transition of neutral strontium-88 atoms ($\nu_{Sr}{}^{88}{}_{,689} = 434.8291213$ THz [25]). Within a range of 7 GHz (-5 to +2 GHz) around the target transition frequency there exists a total of seven individual lines of varying widths and intensities (see Table 1). The most intense line in this range occurs at -4.45 GHz and the next most intense at +1.77 GHz. The closest line to our target frequency has a detuning of +290 MHz but with a lower absorption. Since no peaks occur exactly half-way between any others, none are identifiable as cross-over resonances. Five additional features are present in the error signal with no corresponding absorption feature visible, indicating that extremely weak lines may be present but undetected by the probe beam. Improvement of the signal-to-noise ratio, by adopting a multi-pass spectroscopy method, is required to investigate the nature of these features.

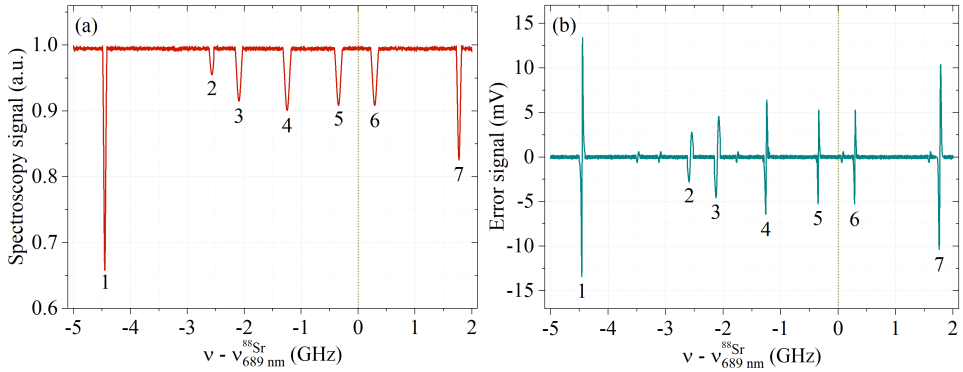

Fig. 2. (a) Sub-Doppler spectrum of molecular iodine for frequencies close to the target transition frequency of neutral strontium-88 atoms. Properties of the identified peaks, indexed 1-7, are given in Table 1. (b) Error signal derived from the spectroscopy signal in (a). Peaks are indexed 1-7 corresponding to those in (a).

Table 1. Properties of peaks identified in Fig. 2(a). Δ: detuning from the $^1S_0 \rightarrow {}^3P_1$ transition frequency of neutral strontium-88 atoms [25]. Wavemeter (WS7-30, HighFinesse) absolute accuracy = 30 MHz, resolution = 1 MHz.

Peak index	Frequency (MHz)	Δ (GHz)	FWHM (MHz)	Relative absorption (a.u.)
1	434 824 508(30)	-4.45	36.6	0.342
2	434 826 389(30)	-2.57	55.6	0.045
3	434 826 865(30)	-2.09	72.9	0.085
4	434 827 712(30)	-1.25	81.0	0.099
5	434 828 615(30)	-0.34	77.4	0.092
6	434 829 251(30)	+0.29	77.0	0.092
7	434 830 732(30)	+1.77	50.5	0.174

Due to the lack of high-resolution sub-Doppler spectroscopy available in the literature at this wavelength there are no appropriate datasets to which we can compare our spectrum, to our knowledge. Additionally, due to the range of our dataset, and the potential for observing overlapping sets of hyperfine structures, we are currently unable to confidently attribute the lines to any particular ro-vibrational transition of molecular iodine, however, based on calculations

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using constants from the work of Gerstenkorn and Luc [26], we estimate the possible attribution is to hyperfine components of transitions R(70)4-8, R(8)2-7 and R(7)2-7.

3.2. Frequency stabilization and noise measurements

In this configuration, the two transitions detuned by -4.45 and +1.77 GHz can be used for VECSEL frequency stabilization. Testing was performed using both peaks, with similar results, but to assess the iodine-locked VECSEL noise performance as close to the target transition as possible, the +1.77 GHz line was used as a reference. For comparison, the VECSEL noise performance when exclusively frequency stabilized to an air-spaced Fabry-Perot reference cavity (finesse = 1k, free spectral range = 300 MHz) via the Pound-Drever-Hall scheme was also assessed.

Free-running, iodine- and cavity-locked VECSEL noise performance and estimated linewidths are shown in Fig. 3. In Fig. 3(a), comparison with the free-running case shows a clear reduction in relative intensity noise (RIN) for the iodine- and cavity-locked VECSEL systems at frequencies above 60 Hz, with the RIN reaching a minimum value < -156 dBc/Hz for f > 10 kHz in all cases, set by the noise floor of the detector. The low RIN, when compared to our group's previous cavity-locking results with the same gain structure [10,27], can be attributed to an improvement in thermal and mechanical stability, thus allowing for noise performance approaching the VECSEL shot noise limit (-161 dBc/Hz) [28,29] well below the cavity cut-off frequency (~4.8 MHz – above this frequency the VECSEL is assumed to be shot noise limited [30]). Specifically, the temperature stabilization performed exclusively via thermo-electric cooling removes vibrations that were previously injected by water cooling. Also, better temperature control of intracavity elements (e.g. the BRF) allows for better control of the wavelength stability. Finally, the packaging of the VECSEL cavity aids in the removal of other environmental excess noise – i.e. mechanical and acoustic noise, and air-fluctuations – affecting not only the mechanical stability of the VECSEL cavity but also the overall temperature stabilization performance.

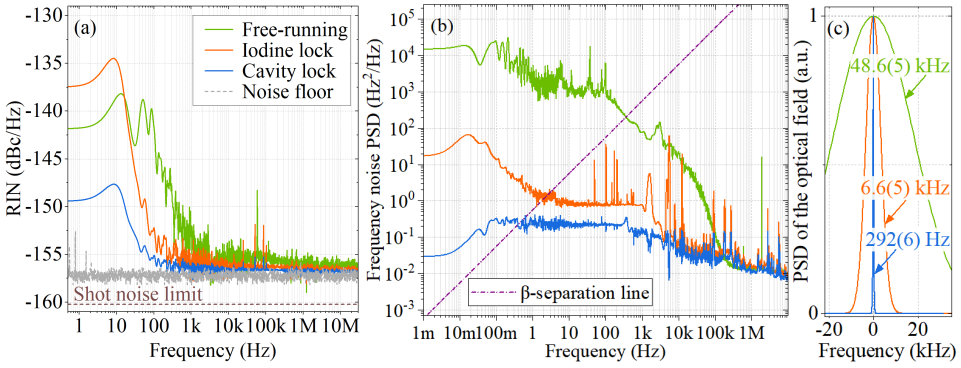

Fig. 3. Comparison of VECSEL noise performance while free-running (green), locked to iodine (orange) and, exclusively, a high-finesse Fabry-Perot reference cavity (blue). (a) Relative intensity noise (RIN). (b) Frequency noise power spectral density (PSD) and β-separation line. (c) Estimated integrated linewidths (1000 s sampling time) reconstructed via auto-correlation of optical field PSD and the Wiener-Khintchine theorem.

A commensurate scale of reduction is observed in frequency noise (see Fig. 3(b)). Locking the VECSEL to iodine significantly reduces the frequency noise contribution above the β-separation line [31], resulting in narrower Gaussian linewidths which can be confirmed by estimating the VECSEL linewidth via auto-correlation and the Wiener-Khintchine theorem [31] (as shown in Fig. 3(c)). Here, the free-running VECSEL linewidth of 48.6(5) kHz (1000 s sampling time) is reduced to 6.6(5) kHz (1000 s) when locked directly to iodine. As anticipated, the cavity-locked

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VECSEL sees the most significant reduction in frequency noise. Here, the estimated linewidth is reduced to 292(6) Hz (1000s).

3.3. Beat note measurement

Due to the kHz-level linewidth of the iodine-locked system (as estimated from the optical field autocorrelation), further investigation of the linewidth via a beat note measurement was performed using a monolithic VECSEL [11] with a cavity-locked linewidth of ~400 Hz. For this measurement, the two beams were combined at a non-polarizing beamsplitter and the resulting RF beat signal peak observed using a fast photodetector (PD-VIS, QUBIG).

Figure 4 shows the beat note, which returns a linewidth of 6.2(1) kHz for an averaging time of 4 s, as calculated from the full-width at half-maximum of the fitted Voigt line-shape (see Fig. 4(a)). This value is in good agreement with the autocorrelation linewidth, given in Fig. 3(c), and confirms the low-noise performance of the iodine-locked VECSEL in Fig. 3(b).

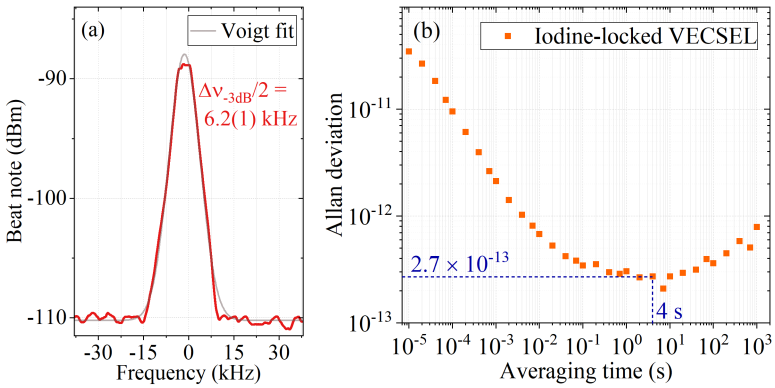

Fig. 4. (a) Heterodyne beat note measurement between the iodine-locked VECSEL and a cavity-stabilized monolithic VECSEL with integrated linewidth of ~400 Hz. (b) Allan deviation of the iodine-locked VECSEL. Minimum instability of 2.7×10^{-13} occurs at an averaging time of 4 s, as indicated.

3.4. Allan deviation

The Allan deviation (Fig. 4(b)) was determined by sampling the beat note measurement data, as a measure of fractional frequency, over a range of averaging times, giving a representation of the instability of the iodine-locked laser frequency relative to the monolithic VECSEL reference. The minimum instability occurs at 4s averaging time and has a magnitude of 2.7×10^{-13}. The increase in Allan deviation after this point reflects the frequency drift of both the iodine-locked VECSEL and the monolithic reference VECSEL, due to both intrinsic and environmental factors, although we expect the contribution from the latter to be far greater than the former at longer averaging times.

3.5. Long-term stability

Figure 5 presents the wavelength stability of the iodine- and cavity-locked VECSEL, measured in terms of variation of the beat note frequency over time. After a twenty minute period, the cavity lock drifted a total of 88 kHz from its initial value (excursion = 125 kHz), whereas the iodine lock drifted only 18 kHz (excursion = 22.5 kHz), showing a five-fold improvement in drift under the same laboratory conditions and comparable with other results in literature [32,33]. This result exemplifies the vulnerability of cavity references to thermal and mechanical drift, which is certainly a factor here owing to the breadboard mounting and high-quality but commercial

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standard optics [34]. It also demonstrates the superiority of the reference provided by the molecular iodine, which shows relatively limited drift in this case largely owing to the weakness of the absorption signals and the resulting low signal-to-noise ratio, compared to that achieved using PDH stabilization. The high-sensitivity of the iodine absorption signal to population and density distribution variation can be managed by implementing an improved temperature stabilization across the iodine cell, which is more conveniently achieved by moving to a compact cell embodiment [20,21]. The shorter path length of such a compact cell will further reduce the impact of population and density variation along the cell length. A multi-pass spectroscopy setup can be used to improve the signal-to-noise ratio, reducing sensitivity to drift sources, and further reducing system size and potentially reducing power demands.

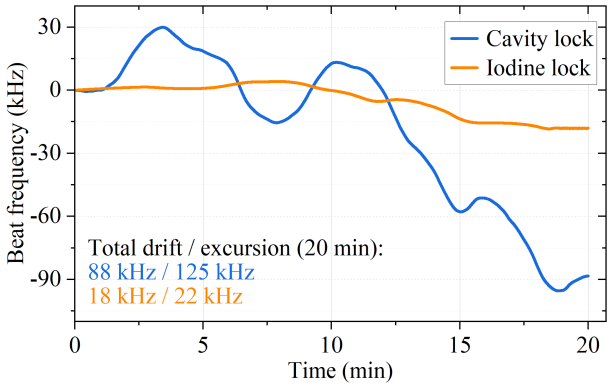

Fig. 5. Beat frequency variation of cavity- and iodine-locked VECSEL systems measured over 20 min.

4. Discussion

The narrow instantaneous and free-running linewidth of the VECSEL is beneficial here in that it allows locking *directly* to a transition of molecular iodine, achieving high-power, narrow-linewidth and low-instability performance suitable for cold Sr applications without pre-stabilization steps or a reference cavity. This distinguishes our system from other laser systems performing around 689 nm for Sr cooling and trapping, since cavity stabilization is a prerequisite for spectral referencing in these cases due to the narrow transition linewidth of the Sr reference.

While an additional cavity pre-stabilization step may not pose an issue in controlled settings, allowing narrowing of the laser linewidth as pertaining to the reference cavity engineering, such stages may be undesirable if the intent is to produce simplified and more compact cold-neutral-Sr devices for non-controlled environments. Advantages of VECSEL technology in this respect are found in their compatibility with diode-pumping, for pump optics miniaturization, and monolithic cavity integration [11], for robust low-noise performance.

Perhaps more significantly, this work represents an expansion of iodine spectroscopy to deep red wavelengths, especially around 689 nm, and subsequently laser locking to one of these transitions near the red cooling transition of Sr. Given the properties of the lines present in this region (having low relative absorption compared to well-known references around 633 [35] and 532 [17] nm, and with spectral widths of the order MHz), the capacity to directly lock to these features may be available to other laser systems providing enough power is available. However, to meet requirements for Sr cooling and trapping at 689 nm, it may be that cavity pre-stabilization still remains necessary for such lasers, to narrow the linewidth to the kHz level, making this demonstration using an AlGaInP-based VECSEL significant regarding the direct and exclusive referencing to these spectral lines in the absence of pre-stabilization.

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The properties of molecular iodine – including low temperature operation compared to Sr itself for 689 nm spectroscopy and scope for miniaturized cell availability – should allow the adaptation of our system for stabilization to transitions closer to the 689 nm target [6], within the range of a standard modulator (usually <500 MHz, but available at higher frequencies with lower efficiency). Such adaptations may include cavity enhancement to increase absorption path length, thereby increasing the relative absorption of the weaker transitions. By using iodine lines closer to the target frequency, the offset frequency may be suitably corrected using an AOM to achieve precise frequency control. The high-power performance of VECSEL technology, demonstrated here at up to 160 mW, may accommodate this setup without amplifiers, which are often required by other laser types.

Comparison throughout this work between iodine- and cavity-locked VECSEL systems demonstrates the effectiveness of cavity-based stabilization techniques, particularly with regards to associated lower technical noise and excellent linewidth narrowing capability; however, it also highlights a limitation of cavity stabilization, where the long-term wavelength of the cavity-locked VECSEL suffers pronounced drift over a 20-minute period. While, in this instance, this is potentially attributable to the cavity being breadboard-mounted and of a commercial, rather than specialist, standard, drift remains a key concern for many cavity stabilized laser systems. For instance, the stability of molecular iodine references was demonstrated by Roslund *et al* [36] to be superior to ultra-low expansion cavities in an uncontrolled environment. The iodine-locked breadboard system demonstrated here reflects this benefit compared to the reference cavity case, observing significant reduction in the wavelength drift while maintaining integrity in other performance criteria. Further work to reduce the bulkiness and complexity of the spectroscopy system by implementing a different pump-probe configuration [37] and more compact chip vapor cells [20,21] will be performed to reduce the overall VECSEL system size, weight, power and costs (SWaP-C). In this setup, calibration and tuning of the spectroscopy signal may offer lower minimal instability at longer averaging times, which are beneficial for quantum enhanced sensing and timing applications.

5. Conclusion

Using AlGaInP-based VECSEL technology we have demonstrated, for the first time, sub-Doppler spectroscopy of molecular iodine around the 689 nm region. By locking directly to these spectroscopy signals, the free-running VECSEL integrated linewidth was reduced to 6.2(1) kHz (1000s), suitable for μK cooling of neutral Sr at 689 nm. Comparison between this and the same system locked only to a commercial high-finesse reference cavity, revealed a significant reduction in long-term frequency drift, where the cavity- and iodine-locked systems experienced sub-100 kHz and sub-20 kHz drifts, respectively. By enhancing and precisely calibrating the absorption signals of molecular iodine lines closer to the 689 nm frequency target, further reductions of frequency offset and long-term drift may be possible to reduce minimum instability towards the quantum limit. Furthermore, the reduced size, weight, power and cost of a system locked to a miniaturized iodine vapor cell may present an appealing and simplified alternative to high-finesse reference cavity systems for cold-Sr applications.

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Optics EXPRESS

Disclosures. The authors declare no conflicts of interest.

Data availability. All data underpinning this publication are openly available from the University of Strathclyde Knowledge-Base [38].

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