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Tunable self-injection locked green laser diode

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We report, to the best of our knowledge, the first employment of a self-injection locking scheme for the demonstration of a tunable InGaN/GaN semiconductor laser diode. We have achieved a 7.11 nm (521.10–528.21 nm) tunability in a green color with different injection currents and temperatures. The system exhibited mode spectral linewidth as narrow as ~69 pm and a side mode suppression ratio as high as ~28 dB, with a maximum optical power of ~16.7 mW. In the entire tuning window, extending beyond 520 nm, a spectral linewidth of ≤ 100 pm, high power, and stable performance were consistently achieved, making this, to the best of our knowledge, the first-of-its-kind compact tunable laser system attractive for spectroscopy, imaging, sensing systems, and visible light communication.

OCIS codes: (140.3520) Lasers, injection-locked; (140.5960) Semiconductor lasers; (060.2605) Free-space optical communication; (140.3600) Lasers, tunable; (140.7300) Visible lasers.

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Green lasers are finding niche applications in bio-imaging [1], holographic displays [2], infrared spectroscopy [3], interferometric metrology, sensing, etc. However, multi-mode broad emission and inept wavelength tuning characteristics of InGaN/GaN diode-based lasers pose a challenge for their practical application. Hence, a narrow linewidth lasing from these light emitters and the ability to control its wavelength are essential, thus providing a larger degree of flexibility to the deployed systems. In this regard, distributed feedback and distributed Bragg reflector lasers are generally exercised to obtain a single longitudinal mode (SLM) operation, but is living in its infancy in the visible region. Therefore, external cavity diode lasers (ECDLs) are more commonly employed systems in achieving tunability and near SLM operation utilizing a laser diode. Consequently, Chi *et al.* and Chen *et al.* demonstrated a tunable high power (>1 W) [4] and low power (<100 mW) [5] laser system based on a green semiconductor laser diode.

Among ECDL systems, the Littrow configuration has been the most popular and widely used approach to achieve tunable SLM using a visible laser diode [4–11]. A diffraction grating structure is usually employed with a precise electronic controller in the system, for wavelength selection and mode splitting into different diffraction orders. While the first order is feedback into the laser active region, the zeroth-order mode serves as an output optical beam. Tuning ranges of ~9.2 [4] and ~10.5 nm [5] covering 508.8 to 518 nm and 512.53 to 523.03 nm, respectively, and corresponding linewidths of 8 pm and 10 MHz, have been reported. However, output beam misalignment [12], huge power loss (inefficient usable optical power) [13], the trade-off between output optical power and tuning range [4], etc., are the known limitations of this system. While the former shortcoming was later resolved in the Littman–Metcalf configuration with the expense of an additional mirror to fix the output beam direction, it resulted in additional complexity in the system. Hence, a cost-effective, compact, and efficient tunable laser system is preferred in real scenarios.

Furthermore, these systems generally operate semiconductor laser diodes at lower injection currents, above the threshold, to ensure tunable and near SLM generation, since the system suffers from stability and retaining SLM operation, if the laser exhibits several multi-longitudinal lasing modes, which is the case at higher current injections. This poses another limitation of the system wherein the optical power generating capability of the laser diode is not fully exploited.

In this Letter, we propose and experimentally demonstrate the employment of self-injection locking (SIL) scheme to realize a tunable laser system. The configuration is based on a partially reflective mirror and a green InGaN/GaN commercial laser diode, thus making the system simple and cost-effective. Because of the partial nature of the reflector, from which the usable output light beam exits, a small part of this light beam is optically fed back into the laser active region for locking purposes, thus ensuring fixed direction and robust operation. By controlling the distance between the laser diode and the mirror, which forms an external cavity, successful locking of various longitudinal modes is accomplished. The system is discretely tunable up to 7.11 nm in the green color region, and even at high injection currents. Through optimization of controlling parameters, spectral linewidths up to 69 pm and a side mode suppression ratio (SMSR) of 28 dB are measured with high optical powers. To the best of our knowledge, this is the first report of a self-injection locked-based tunable laser system, which uses no grating structure or any additional mirror unlike the existing configurations. Moreover, this robust system is also implementable under any bias current and temperature.

Figure 1 represents the block diagram and the laboratory photograph (inset) of the self-injection locked green color tunable laser system utilizing a commercial InGaN/GaN green laser diode, exhibiting 50 mW optical power at a maximum 160 mA continuous-wave injection current (Thorlabs L520P50), mounted on a Thorlabs TCLDM9 laser diode mount. The output light beam from the laser facet was collimated by an aspheric lens (Thorlabs, A110TM-A) of a focal length of 6.24 mm and numerical aperture 0.40. A 92:8 pellicle beam splitter (BS, Thorlabs, BP108) was used to split 8% of the light beam into an optical spectrum analyzer (OSA, Yokogawa AQ6373B with 0.02 nm resolution) via a bi-convex lens, L3 (Thorlabs, LB1471-A-ML) of focal length 50 mm for diagnostic purposes. The rest of the 92% collimated laser light beam falls on the polka-dot beam splitter (Edmund Optics) with 70% transmissivity working as a partially reflective mirror (splitting the beam at 0° angle), thus forming an external cavity from the laser facet to the mirror. The beam splitter is mounted on a kinematic mount (Thorlabs, KM100) with two knobs to adjust the feedback angle, and placed on a single-axis translational stage to control the external cavity length, thus providing three degrees of freedom for fine-tuning. 30% of the incoming light beam is fed back into the laser active region by polka-dot beam splitter, while the transmitted 70% (at "L2") is the usable optical power for various multidisciplinary applications. Two external cavity lengths are studied in this Letter: 28 and 12 cm.

The reduction in threshold current of the laser diode is a key signature of efficient SIL, determined by a significant improvement of the laser optical power at a fixed injection current above the threshold, and is evident from the L-I characteristics curve in Fig. 2(a). The threshold current is found to reduce from 40 to 34 mA at 20°C and 52 to 44 mA at 40°C heat sink temperature. This is attributed to the lower gain threshold in an ECDL system compared to the free-running laser counterpart [14]. Moreover, the slope efficiency increased from 0.09 (0.075) to 0.11 (0.083) W/A at 20 (40)°C, thus improving the optical power, in general, by >0.6 mW at higher injections, under SIL. The near SLM operation of the tunable laser system at 20 and 40°C at sub-threshold (defined as current values below the free-running and above the self-injection locked threshold currents) injection currents is presented in Fig. 2(b). The spectral linewidths of 83 and 73 pm are measured at 36 (20°C) and 47 mA (40°C) injection currents, respectively, at 28 cm external cavity length.

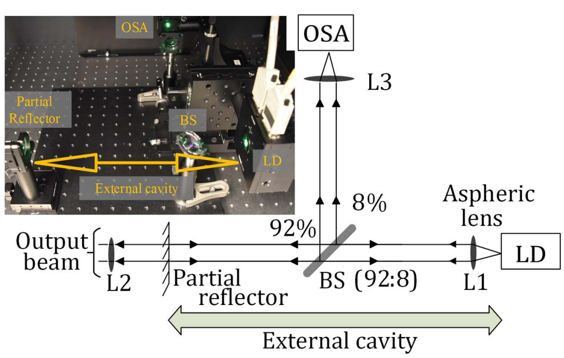

Fig. 1. Block diagram of a self-injection locked tunable laser system. A laboratory photograph is shown in the inset.

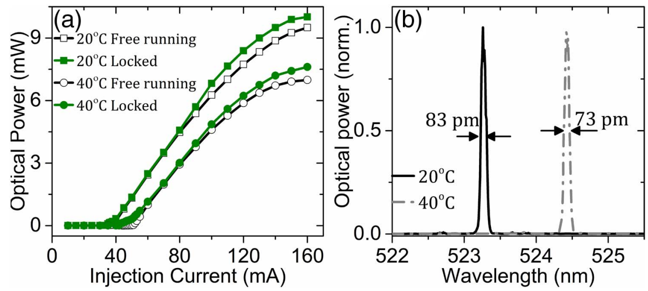

Fig. 2. (a) L-I characteristics of a self-injection locked tunable laser system at 20°C and 40°C. The free-running characteristics are also shown for comparison purposes. (b) Single longitudinal lasing mode operation at 36 (20) and 47 (40) mA (°C) injection currents.

Figures 3(a) and 3(b) show an extended tunability of 4.16 nm (521.10–525.26 nm) at 36 mA injection current compared to 2.84 nm (525.07–527.91 nm) at 160 mA, at 20°C room temperature, along with redshifting of the modes (emission spectra) in the latter case, an effect of bandgap shrinkage due to junction heating at high injection current. Thanks to less mode competition in the lasing spectrum at lower injection compared to higher injection current, a wider tuning window is exhibited [5]. The tunability is accomplished by the careful control of the external cavity length and feedback angle to achieve a round-trip phase match of any particular longitudinal mode, whose wavelength (frequency) resonates within the composite cavity (i.e., laser and external cavity). This ensures SIL of that particular mode, and all the power from the neighboring side modes consolidates in increasing this dominant mode power while being suppressed, thus significantly improving the SMSR. It is to be noted that, although tunability was possible at all injection currents discretely, for ease in discussion, we have selected low (36 mA) and high (160 mA) current values that collectively cover the entire demonstrated tuning window. Moreover, we also set an SMSR threshold of 10 dB for the system performance investigation throughout this

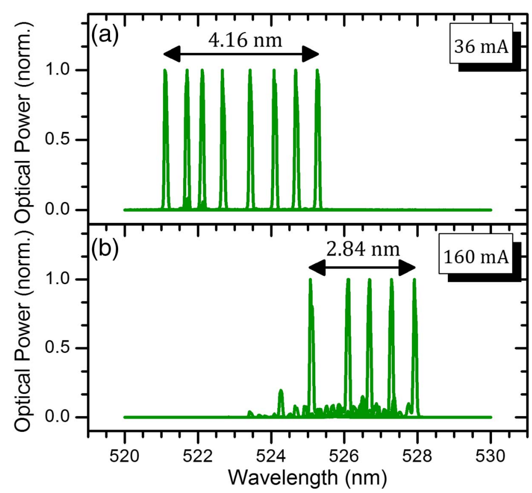

Fig. 3. Superimposed lasing spectra demonstrating the tunability of a green laser diode at 20°C and at (a) a low injection current of 36 mA and (b) a high injection current of 160 mA.

Letter. Hence, the actual wavelength tunability is found to be considerably larger than the reported ones when a threshold SMSR of 6 dB is considered.

The measured optical power (at "L2") of the system, from a tunable locked mode, is compared with the free-running case in Fig. 4(a) at different injection currents. At low current injection, a power extraction efficiency of 65%–70% is noted, with a maximum value of 74% at 160 mA, corresponding to an optical power of ~16.7 mW with a 524.85 nm locked mode. It is worth mentioning at this point that in our SIL-based tunable laser system there is no trade-off between the tunability and power efficiency, which is very common in Littrow configuration [6,7], thus enabling us to achieve such a high efficiency at high injection currents as well. The measured spectral linewidth and SMSR of various locked modes across the tuning window are plotted in Fig. 4(b) at both low and high injection currents. At 36 mA (i.e., across a 4.16 nm tuning window), all the locked modes showed a ≥20 dB SMSR, which is more than twice the value compared to 160 mA (i.e., >10 dB) while, across the collective tuning window of 6.81 nm, the spectral linewidth of the modes is found to be ≤100 pm. Lastly, we found that SMSR values corresponding to the extreme locked mode wavelengths at both currents are found to decrease. This indicates operation at the extreme of the active region gain profile, thus fully exploiting it.

The effect of temperature is studied in two different instances at 20°C room temperature and 40°C, and the results are plotted in Fig. 5. A tunability spanning from 521.10 to 527.91 nm, covering 6.81 nm is measured at 20°C whereas, at 40°C, the range of tunability is from 522.3 to 528.21 nm, which covers 5.91 nm, as depicted in Fig. 5(a). This redshift in the tuning window is attributed to the temperature-dependent bandgap shrinkage, thereby causing redshift of the active-region gain profile. Notice that increasing the temperature reduces the total tuning range; however, a closer look at individual injection currents contribution towards the tunability, as illustrated in the inset of Fig. 5(a), shows that lower and higher injection currents behave reciprocally. On increasing the temperature from 20°C to 40°C, a lower injection current (36 mA at 20°C and 47 mA at 40°C) secures a higher tuning range from 4.16 to 4.73 nm. In contrast, a high injection current of 160 mA experiences a reduction in the tuning range from 2.84 to 2.41 nm when increasing the temperature. This is ascribed to wider gain profile access at the higher temperature with mere lasing mode competition at a low injection current, thus extending the tuning range. On the other hand, at high injection currents, the mode competition probably intensifies and dominates at the high temperature that results in the narrowing of the tuning window.

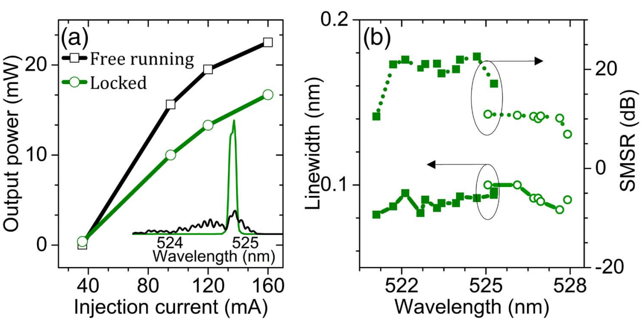

Fig. 4. (a) Comparison of the output optical power under the free-running and self-injection locked cases with an inset showing a free-running and locked mode at 160 mA. (b) Measured spectral linewidth and SMSR of the tunable locked modes along the tunable wavelengths at 36 mA (square symbols) and 160 mA (circle symbols) injection currents. The external cavity is fixed at 28 cm and temperature at 20°C.

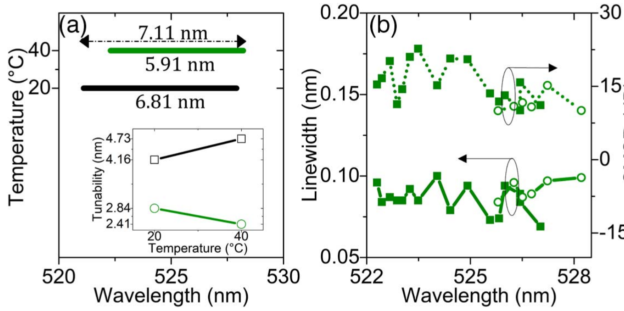

Fig. 5. (a) Collective tuning range of the system at low injection, 36 mA for 20°C and 47 mA for 40°C, and high injection, 160 mA at 20°C and 40°C. The inset shows the individual contribution of low (square symbols) and high (circle symbols) injection current towards the achieved tunability. (b) Measured spectral linewidth and SMSR across the collective tuning span of 5.91 nm for low (square symbols) and high (circle symbols) injection currents at 40°C. The external cavity is fixed at 28 cm.

Figure 5(b) summarizes the results of the spectral linewidth and SMSR across the tuning range of 5.91 nm at 40°C at both injection currents. A very consistent locked mode linewidth, staying below 100 pm, is measured throughout the tuning window, with the smallest value of 69 pm at a 47 mA injection current. We strongly believe that the inclusion of an additional partial mirror-based cavity, within an external cavity, would reduce the mode linewidths further. On the other hand, an SMSR at a low (high) injection current is observed in the range of 22.7–10.1 (15.2–10.0) dB. We postulate that this fluctuation across the various locked modes is due to active-region gain profile alteration as a result of optical feedback, which could be profound at high temperature. In a nutshell, an aggregate tunability of 7.11 nm is measured from the system as a function of injection current and temperature, with a >10 dB SMSR and <100 pm spectral linewidth.

To understand the effect of the cavity length on the tuning range of the SIL-based tunable laser system, we have investigated the effect of low (36 mA) and high (160 mA) injection currents on a reduced 12 cm external cavity and at 20°C room temperature. From Fig. 6(a), we observe that a collective tunable span of the SIL laser diode reduced from 6.81 to 5.55 nm after reducing the external cavity from 28 to 12 cm, respectively. Moreover, as depicted in the inset of Fig. 6(a), the tunability at a 36 mA injection current is found to increase from 4.16 to 4.96 nm, while it reduces from 3.14 to 1.28 nm at 160 mA on reducing the external cavity length from 28 to 12 cm. This is ascribed to the higher level of difficulty in precise tuning of the tilting knobs at the shorter external cavity, which we believe can be solved using a high-precision motorized translational stage. Moreover, a shorter cavity leads to a higher power injection ratio that increases the instability in the system, thus making it more difficult to lock a near SLM with a >10 dB SMSR. Deployment of an appropriate high-precision

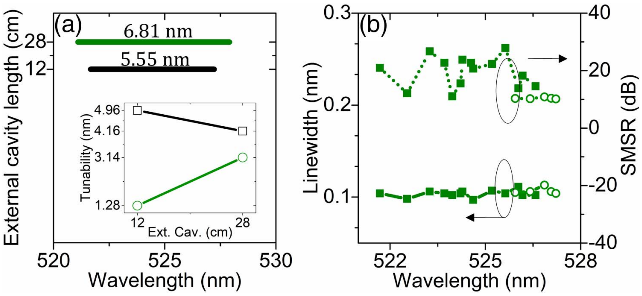

Fig. 6. (a) Collective tuning range of the system at low injection, 36 mA, and high injection, 160 mA, at two different external cavity lengths, and at 20°C. The inset shows the individual contributions of low (square symbols) and high (circle symbols) injection currents towards the achieved tunability. (b) Measured spectral linewidth and SMSR across the collective tuning span of 5.55 nm for low (square symbols) and high (circle symbols) injection currents at 12 cm external cavity.

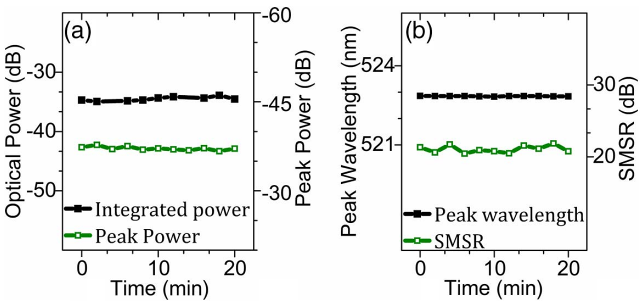

Fig. 7. Short-term stability of the self-injection locked tunable laser system showing the stability of (a) the total integrated and peak optical power (measured at "L3") and (b) the peak wavelength and SMSR, of a 522.86 nm locked mode, at a 36 mA injection current, 20°C temperature, and 28 cm external cavity.

tuning controlling device in the reduced external cavity system should enhance the tunability performance further.

Moreover, we have investigated the performance of the reduced external cavity tunable system by examining the measured spectral linewidth and SMSR across the tuning window of 5.55 nm. Referring to Fig. 6(b), again, at a low injection current, the SMSR is found to vary in the range of 27.8 to 10.2 dB, with the former value being the best result achieved. While at high injection current the SMSR displayed a steady average value of ~10.5 dB across the tuning range. This observation dictates SIL being sensitive at a low injection current compared to a high injection current, probably due to reduced optical feedback and operation in the sub-threshold current region. Nonetheless, the observed linewidth of the tunable SIL modes across the tuning wavelengths stays close to 100 pm at both injection currents.

Finally, we performed the short-term stability test on a tunable 522.86 nm locked mode at an injection current of 36 mA and 20°C for 20 min. The results are plotted in Fig. 7 at 2 min intervals. The total integrated and peak optical powers are very stable throughout the time span, as can be observed from Fig. 7(a), with a mere variation of ~1 dB across the entire 20 min of the experiment. In Fig. 7(b), which represents the fluctuation of the corresponding mode SMSR and peak wavelength over time, is found to be steady at ~20 dB (~1 dB variation) and within a range of 522.84–522.86 (~20 pm variation), respectively. Thus, superior performance is exhibited by the SIL-based tunable system strengthening the scope of deploying this configuration in practical applications.

In summary, a self-injection locked-based 7.11 nm tunable laser system is proposed and demonstrated on a green InGaN/GaN laser diode. A near SLM tunability was observed in the entire tuning range with SMSR and spectral linewidth reaching values of 28 dB and 69 pm, respectively. The tunable laser system exhibited 74% power efficiency with a measured tunable locked mode optical power of 16.7 mW. This compact and cost-effective configuration would enable a simplified tunable laser system for practical deployment in multi-disciplinary applications.

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