

Tunable Violet Laser Diode System for Optical Wireless Communication

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Abstract— we report a tunable self-injection locked violet laser diode external cavity system exhibiting a continuous wavelength tunability of 5.15 nm (400.28 - 405.43 nm) with mean side-mode-suppression-ratio (SMSR) and linewidth of ~ 23 dB and ~ 190 pm, respectively. The effects of injection current and temperature indicate a robust system besides being cost-effective and straightforward. Moreover, a successful indoor on-off keying transmission at two different locked modes on a 0.4 m free space channel showed ~ 10 times improvement in the bit-error-rate (BER) with value $\sim 8 \times 10^{-4}$ at 2 Gb/s, and better performance on 0.8 m channel length at 1.75 Gb/s compared to the free-running laser case. Our work is a potential step towards the realization of future high data capacity narrow-wavelength-spaced multiplexed optical wireless communication system wherein continuously tunable laser sources are expected to play a crucial role as transmitters.

Index Terms— Violet laser, tunable laser, external cavity systems, self-injection locking, optical wireless communication.

I. INTRODUCTION

OPTICAL wireless communication (OWC) remained mostly unexplored until recently, has taken center stage, thanks to the advent of visible laser diodes (LDs), emerging visible light communication (VLC), and underwater optical wireless communication (UOWC). Moreover, the inherent limitations in the radio frequency (RF) spectrum, added with higher secured end-user data requirements, low power consumption, etc. [2], [3] have prompted exploring VLC and its subset Li-Fi (light fidelity) for short-reach communication as well as last-mile access solution, seamlessly integrating with the existing optical fiber network infrastructure and

hence complementing the present Wi-Fi (wireless fidelity) technology [4]. Moreover, visible wavelength division multiplexing (WDM) is also gaining interest where wide wavelengths spaced red (~ 630 nm) - blue (~ 430 nm) - green (~ 530 nm) colors are employed as subcarrier channels to increase the OWC system data capacity [5].

Accordingly, InGaN/GaN blue-violet semiconductor LDs are widely employed not only in VLC but also in UWOC due to their least absorption in water. However, their inherent broad lasing emission exhibiting several longitudinal modes poses restriction to this Fabry-Perot resonator-based devices in terms of direct-modulation capability, signal-to-noise-ratio (SNR) and hence the transmitted data rate. A LD with narrow optical linewidth, high SMSR and SNR, and therefore large modulation bandwidth, is preferred in these applications. Additionally, the possibility of tuning the narrow emission wavelength of blue-violet LD would not only unlock its potential deployment in various multidisciplinary field applications such as high-resolution spectroscopy [6], sensing [7], etc. but also enable the realization of future narrow wavelength spaced blue-violet color WDM-OWC system. Moreover, integration of multiplexed blue-violet color with red and green color for future LD based large data capacity Li-Fi systems would be the next potential step, thus optimizing the available unregulated optical bandwidth of visible region.

To achieve narrow optical linewidth and wavelength tunability in the blue-violet region, the external cavity diode laser (ECDL) system has been the most conventional approach in literature besides other techniques, and their performances are summarized in Table I. As noted from the table, the largest tuning window of 6.3 nm centered at ~ 400 nm is reported in [8] with linewidth < 11 MHz utilizing a Littrow ECDL system with a wavelength grating filter. However, complexity, misalignment, and instability at higher injection current are some of the limitations of these systems besides being costly. Hence, a robust and simple tuning scheme is preferred for practical applications. Additionally, hydrostatic pressure has also been employed to tune the wavelength from ~ 406.5 -416 nm (9.5 nm) in [9], but the optical linewidth was very broad with multiple longitudinal modes.

Very recently, a tunable visible LD system with assistive self-injection locking (SIL) scheme stands out as a competing candidate to obtain spectral purity and wavelength tunability, while being compact and cost-effective [10]. Moreover, such a configuration would be a promising candidate for the realization of future narrow wavelength spaced WDM-VLC as well as WDM-UWOC systems and easily integrated with the

Manuscript received February 12, 2020; revised March 15, 2020; accepted March 23, 2020. Date of publication March 26, 2020; date of current version April 13, 2020. This work was supported in part by King Fahd University of Petroleum and Minerals (KFUPM) via King Abdulaziz City for Science and Technology (KACST) sub-awarded Grant EE2381, from the main Grant KACST TIC R2-FP-008, for KFUPM authors, and in part by the King Abdullah University of Science and Technology (KAUST) under Grant BAS/1/1614-01-01, Grant KCR/1/2081-01-01, and Grant GEN/1/6607-01-01, and in part by the KAUST-KFUPM Special Initiative (KKI) Program (REP/1/2878-01-01), for KAUST authors. (*Corresponding author: M. Z. M. Khan.*)

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Digital Object Identifier 10.1109/LPT.2020.2983548

TABLE I
ADVANCEMENT IN TUNABLE VIOLET LASER DIODES AND THEIR PERFORMANCE IN OWC

Wavelength (nm)	Δw (nm)	TM	SMSR (dB)	$\Delta\lambda$ (pm)	C_L (m)	D (Gb/s)	Scheme	BER	Ref.
395.60– 401.90	2.7	L	-	5 MHz	-	-	-	-	[14]
397.20– 403.50	6.3	LM	-	11MHz	-	-	-	-	[8]
396.45– 400.20	5.5	L	-	-	-	-	-	-	[15]
404.25– 405.00	0.8	HG	15	200	-	-	-	-	[16]
403.82– 408.29	4.4	L	20	100	-	-	-	-	[17]
404.11– 410.12	6.0	L	-	30	-	-	-	-	[18]
405	-	-	-	-	4.8 ^{UW}	1.45	16-QAM OFDM	$9.1e^{-4}$	[19]
404	-	-	-	-	7.0 ^{FS}	12	16-QAM OFDM	$3.8e^{-3}$	[1]
410 (RGB)	-	-	-	-	0.15 ^{FS}	1.5	OOK NRZ	$1.8e^{-3}$	[2]
405	-	-	-	-	0.5 ^{FS}	26.4	64-QAM DMT	$3.17e^{-3}$	[3]
400.28– 405.4	5.1	SIL	>16	-	0.4 ^{FS}	2	OOK NRZ	$8e^{-4}$	This
					0.8 ^{FS}	1.75	OOK NRZ	$3e^{-3}$	Work

Δw : Tuning span, TM: Tuning Method, L: Littrow, LM: Littman, HG: Holographic grating, $\Delta\lambda$: Linewidth, C_L : Channel length, FS: Free Space, UW: Underwater, D : Data rate, RGB: Red-blue-green multiplexed system

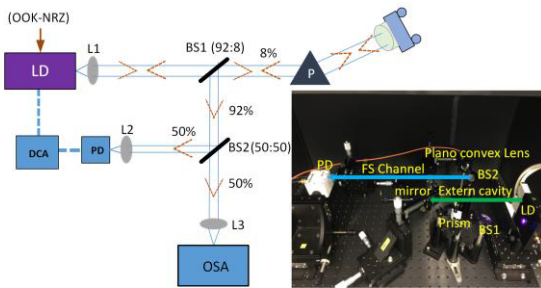


Fig. 1. The Schematic diagram of the SIL violet laser diode system with integrated transmission module. The inset show the photograph of the laboratory setup.

existing optical access infrastructure. To this end, Table I also summarizes the advances in single-channel OWC employing a free-running (FR) violet LD with the largest reported data rates of 1.5 and 26.4 Gb/s using on-off keying (OOK) and quadrature amplitude modulation (64-QAM) schemes, respectively. Employing a narrow optical linewidth LD in OWC, with added tunability feature, is expected to improve the transmission characteristics further while providing wavelength flexibility, which is crucial for eventual visible WDM systems.

In this letter, we report a self-injection locked ECDL (SIL-ECDL) system for a violet LD, where a continuous wavelength tunability of $\Delta w = 5.15$ nm with average SMSR and $\Delta\lambda$ of ~ 23 dB and ~ 190 pm, respectively, have been achieved. An error-free indoor OOK transmission on 0.4 m channel length is demonstrated on two widely tuned wavelengths of 401.14 and 403.18 nm with a realized data rate of 2.0 Gb/s showing superior performance compared to the FR case. Moreover, extending the channel length to 0.8 m depicted similar transmission characteristics with a maximum data rate of 1.75 Gb/s. This work further strengthens the prospects of compact tunable laser diode system for future multiplexed VOWC systems as well as for cross-disciplinary field applications.

II. EXPERIMENTAL SETUP

The schematic block diagram of the tunable laser system is illustrated in Fig. 1. A commercial low power 405 nm violet laser (Thorlabs, DL5146-101S) is fixed on a temperature-controlled laser diode mount (Thorlabs, TCLDM9) with designated 1 GHz bandwidth. A pellicle beam splitter (BS1) with

92:8% splitting ratio (Thorlabs, BP107) is employed within the external cavity, where the transmitted 92% of the optical power is passed through a prism P (Thorlabs, PS858) and then reflected back into the laser front facet using a silver-coated mirror with 97.5% reflection (Thorlabs, PF10-03-P01). The distance between the laser front facet and the mirror forms the external cavity whose length is fixed at 17 cm. The reflected 8% of the usable optical power from the tunable system is further split by BS2 (Thorlabs, BSW27) with 50% falling on the Photodiode PD (Thorlabs, APD210, 1 GHz bandwidth) and the other 50% going into an optical spectrum analyzer (Yokogawa, AQ6373B, 20 pm resolution) after each being collimated with plano-convex lens (Thorlabs, LA-1951-A) L2 and L3, respectively. An indoor free space channel length of 0.4 or 0.8 m is formed between the tunable source (*i.e.*, from BS2) and the photodiode. For the transmission experiments, a 0.9 V OOK non-return to zero (OOK-NRZ) signal is generated from a pattern generator (Keysight N4903B) with pseudorandom binary sequence (PRBS) length $2^{10}-1$, and used to modulate the LD (intensity modulation, IM), and then the received signal after the photodiode is analyzed via direct detection (DD) configuration on digital communication analyzer (DCA, Agilent DCA-J 86100C) and a bit error-rate-tester (BERT, Keysight N4903B). The dynamic range of laser biasing is selected above the threshold, with modulation index ~ 0.17 . A fully reflecting mirror mounted on flip Mount (Thorlabs, TRF90/M) is placed within the external cavity to misalign the optical feedback beam during the transmission experiments for performance comparison between the FR and the locked mode lasing spectrums, and at identical current and temperature operation.

III. THEORETICAL DISCUSSION

Let the phase of a particular LD longitudinal mode under FR and under optical feedback be ϕ_f and ϕ_o , respectively, and the phase provided by the external cavity be ϕ_{co} . Then, the conditional relation of the LD's phase under optical injection can be given as follows [11]:

$$\phi_o = \alpha \sqrt{1 + \beta^2} \sin(\phi_{co} + \tan^{-1} \beta) + \phi_f \quad (1)$$

where α is the optical injection coefficient, which is a function of feedback optical power coupling efficiency, β is the

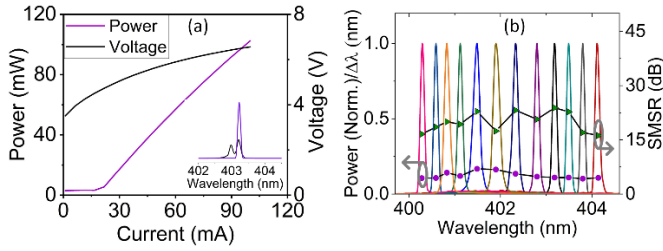


Fig. 2. (a) Room temperature L-I-V characteristics of the violet InGaN/GaN LD with the comparison between the FR and SIL spectrum at 25 mA in the inset. (b) Room temperature wavelength tunability of the violet tunable SIL-ECDL system at 21 mA alongside the corresponding extracted $\Delta\lambda$ and the SMSR.

linewidth enhancement factor of the LD that depends on the change in refractive index due to the change in gain threshold. Now, ϕ_{co} can be steered by tuning the external cavity length to obtain matching phase condition ($\phi_o = \phi_f$ or multiple of 2π) to assure this particular LD mode resonates in the two-cavity system, giving rise to a locked mode with a reduced gain threshold. Thus, allowing this locked mode to reach lasing condition earlier than the other modes, and hence dominates by suppressing all the adjacent modes. This phenomenon leads to the enhancement in $\Delta\lambda$, SMSR of the dominant mode, and, consequently, the spectral purity of the laser with reduced amplified spontaneous emission (ASE) noise and high SNR [12], [13]. Moreover, altering the external cavity with solutions to any LD mode could be attained, thus tuning the locked mode wavelength within the gain profile of the LD active region.

IV. WAVELENGTH TUNABILITY CHARACTERIZATION

First, the front single facet L-I-V performance of the FR violet LD is obtained, as shown in Fig. 2(a), exhibiting a threshold current $I_{th} = 20$ mA and a near-threshold slope efficiency of 1.2 W/A at room temperature. A comparison between the SIL mode and the FR spectrum is illustrated in the inset of Fig. 2(a) demonstrating a significant improvement by ~ 3.0 , ~ 16.5 , and ~ 3.1 times in $\Delta\lambda$, SMSR, and the peak power, respectively. Thanks to the SIL scheme that enabled this profound improvement besides improving the modulation bandwidth and the noise of the LD [12], [13]. The tunability of the system is accessed at three injection currents of 21 ($\sim 1.0I_{th}$), 42 ($\sim 2.0I_{th}$), and 63 mA ($\sim 3.0I_{th}$), and two distinct temperatures of 20 (room temperature) and 40°C. A continuous wavelength tuning of the locked modes satisfying Eqn. 1 is achieved by fine-tuning the external cavity length and the optical feedback angle manually. The room temperature results of the tuning span at $\sim 1.0I_{th}$ are summarized in Fig. 2(b) with the corresponding extracted $\Delta\lambda$ and SMSR. As shown, a wavelength tuning of 3.84 nm (400.28 to 404.12 nm) is achieved, exhibiting a minimum (maximum) $\Delta\lambda$ of 106 (168) pm while the SMSR is maintained at > 16 dB (highest 24 dB) in the entire tuning range. However, on increasing the injection current to $\sim 2.0I_{th}$ and $\sim 3.0I_{th}$, the tuning window drops to 2.37 nm (401.58 to 403.95 nm) and 1.56 nm (402.42 to 403.98 nm), respectively, as depicted in Fig. 3(a). A similar trend is also observed on increasing the temperature to 40°C, as shown in Fig 3(b).

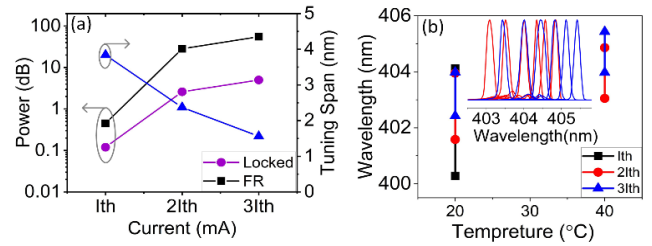


Fig. 3. (a) Comparison of the usable optical power of the violet tunable SIL-ECDL system with the FR LD power at three different injection currents along with the corresponding measured wavelength tuning window. (b) Temperature effect on the wavelength span of the violet tunable SIL-ECDL system at different injection currents. The inset of (b) depicts the normalized locked spectrums tunability at various current injections, and at 40°C.

In this case, the tuning span reduced to 1.77 nm (403.09 to 404.86 nm) and 1.45 nm (403.98 to 405.43 nm) at $\sim 2.0I_{th}$ and $\sim 3.0I_{th}$, respectively, with associated mean $\Delta\lambda$ and SMSR values of ~ 186 pm and ~ 15 dB, and ~ 230 pm and ~ 20 dB, respectively. In general, the overall tunability of the system degraded at a higher temperature at any injection current. This inferior performance at high injection currents and temperature is attributed to the dynamic behavior of the optical feedback system, which supplements mode competition in a bid to satisfy Eqn. 1 as well as the change in β that is injection current and temperature dependent. It is worth mentioning at this instant that the system exhibits an overall tunability of 5.15 nm (400.28 to 405.43 nm) should temperature and injection current are considered as a tuning parameter. Moreover, employing a prism within the external cavity enhances the system performance and stability, which is ascribed to improved locking efficiency (effectively satisfying Eqn. 1) by slightly dispersing the optical feedback modes wavelength, thereby reducing their encounter with a LD mode in satisfying Eqn. 1. The usable optical power of the tunable SIL-ECDL system is compared with the FR LD power in Fig. 3(a) at room temperature and different injection currents. As expected, the output power of the system is approximately 8.0 % of the FR power, reaching from 0.12 mW at $\sim 1.0I_{th}$ to 5.0 mW at $\sim 3.0I_{th}$, while the corresponding measured FR LD powers are 0.45 mW and 55 mW. Moreover, it is to be noted that if the rear as-cleaved facet of the LD is accessible, then ~ 70 -80% of the FR power would be available as the working power.

Lastly, a stability check of the system is performed by monitoring the peak wavelength, peak power, SMSR and $\Delta\lambda$ of 402.29 nm locked mode for 30 min with a step size of 3 min, and the results are plotted in Fig. 4. The integrated and peak powers displayed a variation of ± 0.25 dB while the SMSR remained at ± 0.5 dB, as depicted in Fig. 4(a). On the other hand, from Fig. 4(b), the peak wavelength fluctuation of ± 4.0 pm, and $\Delta\lambda$ variation of ± 1.5 pm are noted. These performance indicators exhibiting minimal deviation affirm the high stability of the system and its potential for practical deployment.

V. VISIBLE OPTICAL WIRELESS COMMUNICATION

To further substantiate the improved spectral purity of the violet tunable SIL-ECDL system as a potential transmitter for future narrow-wavelength spaced OWC-WDM system,

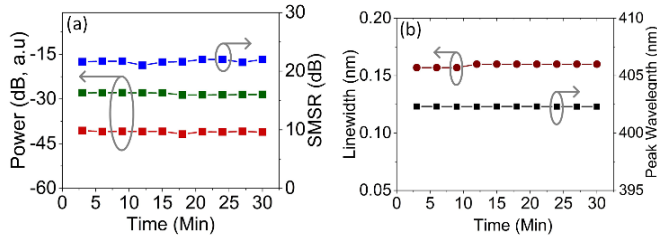


Fig. 4. Stability performance of the violet tunable SIL-ECDL system at a tuned wavelength of 402.29 nm in terms of (a) SMSR (blue), integrated power (green) and peak power (red), and (b) optical linewidth and peak wavelength.

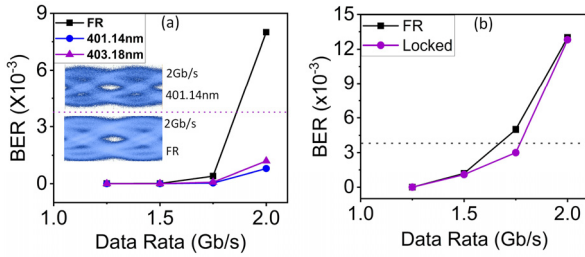


Fig. 5. BER versus the data rate of OOK-NRZ transmission experiments on (a) 0.4 m indoor free-space channel length at 35 mA and at two distinct tuned wavelengths of 401.14 and 403.18 nm (b) 0.8 m indoor free-space channel length at 50 mA and at a tuned wavelength of 401.14 nm. The unlocked FR LD results are also shown. Insets of (a) are the eye diagrams.

OOK-NRZ transmission experiments are conducted on different tuned locked modes and compared with the FR case at different data rates, injection currents, and channel lengths. The parameters for the modulation are common for both the SIL and the FR cases, while the optical spectra with/without modulation are similar to the inset of Fig. 2(a). Fig. 5(a) shows the performance of two widely apart locked modes at 401.14 and 403.18 nm alongside the FR case for 0.4 m OWC and at 35 mA (~ 5.2 V). At a lower data rate of ≤ 1.5 Gb/s, the performance of both the cases are similar to a measured BER of $\sim 3 \times 10^{-6}$. However, increasing the data rate to ≥ 1.75 Gb/s, a clear improvement in the BER of both SIL modes is noted compared to the FR counterpart. For instance, at 2.0 Gb/s, the shorter (longer) locked mode exhibited BER of $\sim 4 \times 10^{-4}$ ($\sim 8 \times 10^{-4}$) with the wide-open eye, while the FR LD demonstrated $\sim 8 \times 10^{-3}$ that is above the forward error correction limit with an inferior open eye. This corresponds to ~ 10 times improvement in the performance of the system, which is ascribed to the reduced ASE noise and hence high SNR of the locked modes, exhibited by the SIL-ECDL system.

Moreover, similar performance improvement is also noted at a high injection current of 50 mA (~ 5.6 V) with an extended channel length of 0.8 m, as depicted in Fig. 5(b). In this case, at 1.75 (2.0) Gb/s, the 401.141 nm SIL mode demonstrates a measured BER of $\sim 3 \times 10^{-3}$ ($\sim 12.8 \times 10^{-3}$) compared to the FR LD spectrum that exhibits $\sim 5 \times 10^{-3}$ ($\sim 13 \times 10^{-3}$). Nevertheless, with these demonstrations, the potential of tunable violet LD SIL-ECDL system prospects are bright in the future for both OWC as well as flexible wavelength light source in various cross-disciplinary field applications.

VI. CONCLUSION

A prism-based SIL-ECDL system with a violet InGaN/GaN LD is demonstrated with a continuous wavelength tunability from 400.28 to 405.43 nm (5.15 nm). A rigorous analysis of the system performance showed a mean SMSR and optical linewidth of ~ 23 dB and ~ 190 pm, respectively, while displaying high system stability. Furthermore, an error-free indoor free-space transmission based on OOK-NRZ modulation scheme on 0.4 and 0.8 m channel length, and under different injection currents, is achieved with a maximum data rate of 2.0 Gb/s and ~ 10 times improved BER when compared to the FR LD case.

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