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# Tunable Dual-Wavelength Self-injection Locked InGaN/GaN Green Laser Diode

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**ABSTRACT** We implemented a tunable dual-longitudinal-mode spacing InGaN/GaN green (521–528 nm) laser diode by employing a self-injection locking scheme that is based on an external cavity configuration and utilizing either a high or partial-reflecting mirror. A tunable longitudinal-mode spacing of 0.20 – 5.96 nm was accomplished, corresponding to a calculated frequency difference of 0.22–6.51 THz, as a result. The influence of operating current and temperature on the system performance was also investigated with a measured maximum side-mode-suppression ratio of 30.4 dB and minimum dual-mode peak optical power ratio of 0.03 dB. To shed light on the operation of the dual-wavelength device arising from the tunable longitudinal-mode spacing mechanism, the underlying physics is qualitatively described. To the best of our knowledge, this tunable longitudinal-mode-spacing dual-wavelength device is novel, and has potential applications as an alternative means in millimeter wave and THz generation, thus possibly addressing the terahertz technology gap. The dual-wavelength operation is also attractive for high-resolution imaging and broadband wireless communication.

**INDEX TERMS** Dual wavelength lasers, optical injection locking, semiconductor lasers, InGaN/GaN visible lasers.

## I. INTRODUCTION

Two-wavelength diode lasers has applications in different multidisciplinary fields like interferometry [1], optical communication [2], sensing and imaging [3], spectroscopy [4], terahertz (THz) signal generation [5], broadband wireless communication [6], etc. In particular, the use of dual longitudinal lasing modes from a laser cavity for photonic THz beat-frequency generation is garnering attention due to the advantages of ultra-high bandwidth, lower electromagnetic interference, larger tunability, long-distance coverage [7], and hence suitable as a potential THz source. In the near infrared regime, various techniques for dual wavelength generation have been explored, and the heterodyne mixing of two laser output is found to be the most common and simplest scheme. Moreover, these schemes have been realized in both, monolithic [8] as well as discrete system, such as external cavity diode laser (ECDL) [9], configurations, exhibiting fine performance characteristics [10]. However, the coherency of these lasers is a vital issue to obtain a reduced phase noise of the system. Subsequently, various existing approaches to further improve the performance of these configurations have been reported; for instance, external optical injection [11], side mode injection [12], self- injection [13], etc.

Incorporation of optical injection locking in tandem with the heterodyne approach for dual-wavelength generation in 1310 nm and 1550 nm range [14], on distributed feedback lasers (DFB), distributed Bragg's reflector (DBR) [15] and

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vertical cavity surface emitting lasers (VCSEL) [16] have been reported in the literature. Moreover, a new class of InAs/InP quantum dot [14] and quantum dash [17] diode laser has also been engaged in millimeter (MMW) and THz applications. A notable discrete frequency difference tunability of 1.0 up to 2.9 THz have been demonstrated from this novel active region based laser diodes compared to quantum-well laser counterparts [18]. Besides, among ECDL systems, Littrow configuration has been widely utilized to realize dual wavelength laser system to demonstrate wide-band tunable THz beat frequency [10]. All these demonstrations are concentrated in the near-infrared wavelength region of the optical spectrum spanning 780 nm to 1550 nm, which is quite matured in terms of material as well as device technologies.

Recently, an interesting development in realizing optical THz frequency in the visible region while exploiting semiconductor InGaN/GaN technology has uncovered, with the demonstration of up to 2.2 THz frequency based on light emitting diode heterostructures excited via photoluminescence [19]. However, these reports are limited to material demonstration, and electrically pumped devices has yet to be realized. Moreover, success in visible wavelengths are limited to single-wavelength mode-generation with InGaN/GaN lasers using various assisting schemes [20] owing to the inherent broad lasing bandwidth as well as injection current and temperature sensitive performance. For instance, Littrow ECDL configurations has been employed with reported narrow-wavelength lasing linewidth of ∼4.7 MHz and 50 pm in [21] and [22], respectively. To mitigate the misalignment issues and high power loss due to diffraction gratings [23] in Littrow systems, very recently, we proposed a grating-less self-injection locked ECDL system and demonstrated a high power single narrow lasing linewidth (∼100 pm) with discrete tunability in the range of ∼521–528 nm [24]. Moreover, multiple simultaneous steady longitudinal modes were also achieved [25]. Nevertheless, widely tunable wavelength spacing dual mode visible laser diode system has not been comprehensively studied, to the authors' knowledge.

In this work, we demonstrate a dual-wavelength InGaN/GaN diode laser system as a potential simple and low-cost solution for MMW and THz applications. A tunable frequency difference in THz region is achieved by simultaneous self-injection locking of two longitudinal-modes in a grating-less external cavity configuration. This inherently robust system solves the coherency issue between the two modes altogether making it simpler with possibly less system noise. Moreover, the system operates at any bias current and temperature as dictated by the laser diode, and a wide range of discrete tunable mode spacing from 0.2 – 5.96 nm, corresponding to calculated beat frequency from 0.22 to 6.51 THz is accomplished. Our comprehensive analysis of the proposed system suggests that this scheme could be a promising solution to address the terahertz gap of the electromagnetic spectrum [26] as well as for various other applications.

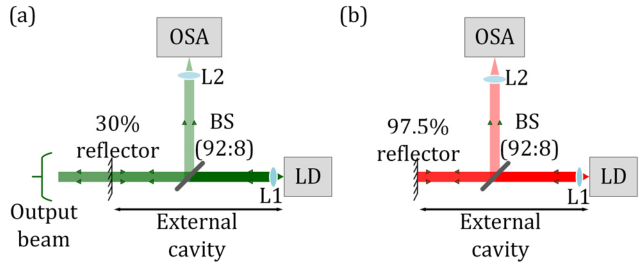


**FIGURE 1.** Block diagram of dual-wavelength laser diode system based on self-injection locked InGaN/GaN green laser diode in external cavity and free-space configuration, employing (a) polka dot beam splitter as a partial reflector (PDR) and (b) silver coated high reflecting mirror (SMR).

## II. EXPERIMENTAL DETAILS

Fig. 1 (a)-(b) shows the block diagrams of dual-wavelength laser diode system with a tunable frequency difference utilizing an off-the-shelf InGaN/GaN green laser diode (Thorlabs L520P50), under self-injection locking scheme, mounted on Thorlabs TCLDM9 laser diode mount. In both setups, the output light beam was collimated by an aspheric lens (L1, A110TM-A) with a numerical aperture 0.40. Using a 92:8% pellicle beam splitter (BS, Thorlabs, BP108), the laser light beam is split in two perpendicular directions. The 8% optical power output was used for detection and analysis by a high-resolution (0.02 nm) optical spectrum analyzer (OSA, Yokogawa AQ6373B) via a lens (L2, Thorlabs, LB1471-A-ML) of focal length 50 mm. On the other hand, the 92% of the optical power from the other end of the beam splitter was reflected back into the laser active region thus enabling optical feedback and creating an external cavity of length 25 cm. The first system employs a polka dot beam splitter (PDR, Edmund Optics) with 30% reflectivity as a partial reflector, as shown in Fig. 1 (a), with ∼ 65% of the laser diode power as the usable output power that is collected from the other end of the reflector. In contrast, the second system in Fig. 1(b) employs a silver-coated mirror (SMR, Thorlabs, PF10-03-P01) with high reflectivity of 97.5%, to ensure high optical feedback into the laser. Hence, the usable output power is collected after L2 (8% of the laser diode power) or from the rear facet of the laser diode if as-cleaved, which would be ∼ 17%. In both systems, the reflectors were fixed on a kinematic mount (Thorlabs, KM100) thus providing the flexibility to alter the feedback beam angle. Moreover, a z-axis translation stage was also used to hold the reflectors to facilitate tuning of the external cavity length. Hence, the feedback angle and cavity length are the only parameters to tune the system.

## III. RESULTS AND DISCUSSION

Fig. 2(a)-(b) depict the lasing spectrums of dual self-injection locked modes corresponding to the PDR system of Fig. 1(a) while Fig. 2(c)-(d) are the emission spectrums from the SMR system of Fig. 1(b). These figures correspond to respective smallest (Fig. 2(a) and (c)) and largest (Fig. 2(b) and (d)) mode spacing or calculated frequency difference (beat frequency) from our proposed systems. A minimum (maximum)

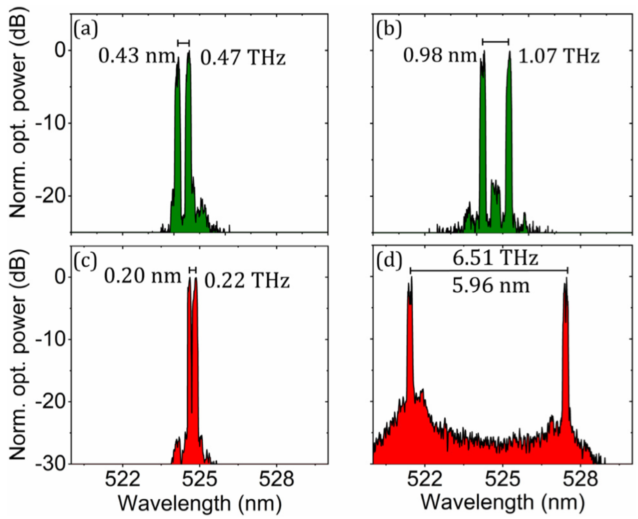


**FIGURE 2.** **Dual self-injection locked longitudinal modes at 20°C room temperature. The figure shows smallest, (a) and (c), and largest, (b) and (d), $\Delta\lambda$ values, and the corresponding calculated beat frequency $\Delta f$, achieved from the PDR (green) and SMR (orange) systems. The measured SMSR and the biasing currents are, respectively, (a) 35 mA & 22.8 dB, (b) 37 mA & 17.7 dB, (c) 36 mA & 21.3 dB, and (d) 36 mA & 17.8 dB.**

mode spacing, $\Delta\lambda$, of 0.43 (0.98) nm, corresponding to 0.47 (1.07) THz beat frequency, $\Delta f$, at an injection current 36 (37) mA is demonstrated by the PDR system at room temperature, 20 °C. On the other hand, the SMR system demonstrated the smallest 0.20 nm and the largest 5.96 nm free spectral ranges (FSR) or $\Delta\lambda$, enabling a very large calculated beat frequency tunability of 0.22–6.51 THz. It is noteworthy to mention that the SMR system, in fact, has spanned a record tunable value using a semiconductor laser, to the authors' knowledge. Thanks to the short visible wavelength operation that enabled this achievement since, $\Delta f = c^2\lambda^{-2}\Delta\lambda$, where $\lambda$ and c are the wavelength and the speed of the light, respectively. Moreover, we set thresholds on the side-mode-suppression ratio (SMSR), defined as the ratio of the lowest peak power among the two locked modes, to the highest peak of any suppressed side mode in the lasing spectrum, to be $\geq$ 10 dB, and the peak ratio (PR), defined as the peak power ratio between the two locked modes, to be $\leq$ 3 dB for our analysis. Both of these values would be sufficient to electrically generate the photonic THz signal with corresponding beat frequencies in the frequency domain as has been demonstrated in. Due to limitation of resources, we did not demonstrate the electrical frequencies rather constrained our work entirely in the optical domain. We performed a rigorous analysis of the system by setting these thresholds and found that our system showed excellent stability of the dual modes (discussed in the next section) and good repeatability of the discrete mode spacing. It is to be noted that we utilized manual means for our analysis; however, with piezo stages the system should show much better and smooth tunability as well as repeatability.

This accomplishment is essentially a result of self-injection locking of simultaneous two FP laser modes as they appear around multiples of $\Delta\lambda$. This is possible in an external cavity system with an optical feedback and we qualitatively discussed this phenomenon below:

Consider the change in the laser gain threshold $g_c$ under optical feedback, required to initiate lasing operation, which depends on the free-running threshold gain $g_{th}$, the feedback coefficient $\kappa = 2|C|\sqrt{R}$ ( where R is optical power injection ratio and C is the coupling efficiency between the laser and the external cavity), and the phase of the optical feedback $\phi_{ext} = \omega\tau_{ext} = 2\omega L_{ext}/C$ (with optical frequency, $\omega$, roundtrip delay $\tau_{ext}$ in the external cavity of length $L_{ext}$). This change $\Delta g$ for a laser cavity $L$ is given by [28]:

$$\Delta g = g_c - g_{th} = -\frac{\kappa}{L}cos\phi_{ext} = -\frac{\kappa}{L}cos\omega\tau_{ext} \quad (1)$$

Hence, from (1), a slight change of $\phi_{ext}$ or $\omega$ may result in considerable change in $g_c$, which varies asymmetrically periodic with $\tau_{ext}$ as determined by $\kappa$ value, well reported in literature [29]. In this case, a specific FP mode with smallest $g_c$ (maximum $\Delta g$) could be attained at $\omega\tau_{ext} = 0$ (or multiples of $2\pi$) and, thus, would be the dominant mode existing in the system while suppressing the adjacent modes. The steady state output power of this mode, under optical feedback is approximated as [29]

$$P \approx \tilde{E}_0^2 \approx \left(E_0^2 - \tau_p\tau_s^{-1}\Delta n\right)\left(1 + \tau_p g_c \Delta n\right)^{-1} \quad (2)$$

where $\tilde{E}_0^2(E_0^2)$ is the square of the electric field amplitude of the dominant mode, in the laser cavity with (without) optical feedback, $\tau_s$ is the spontaneous emission lifetime in the laser cavity, and $\Delta n$ corresponds to the change in the carrier density, given by:

$$\Delta n = n_c - n_{th} = -\frac{2\kappa}{\tau_L g_c}cos\omega\tau_{ext} \quad (3)$$

Here, $n_c(n_{th})$ is the carrier density with (without) optical feedback and $\tau_L$ is the round trip delay of the laser cavity. Hence, under optical feedback, a dominant FP mode could potentially exhibit considerably high optical power, according to (2), thus, accumulating all the energy and raising its peak power while suppressing the other side modes, and with a reduced threshold carrier density (3) of the system.

Another crucial requirement for the modes in an optical feedback system to exist, besides the threshold gain condition, is the phase condition, which is the round-trip phase of an external cavity mode under optical feedback $\omega\tau_{ext}$ be synchronized with that without the feedback, $\omega_{th}\tau_{ext}$ (with optical frequency $\omega_{th}$ corresponding to the $m^{th}$ mode), to resonate in the system. In other words, it is required that the effective round trip phase shift $\Delta\phi_L = 0$ (or multiples of $2\pi$), which is given by [30]:

$$\Delta\phi_L = \Delta\omega\tau_L + \kappa\sqrt{(1+\alpha^2)}\sin\left(\omega\tau_{ext} + \tan^{-1}\alpha\right) \quad (4)$$

where, $\Delta\omega = \omega - \omega_{th}$ and $\alpha$ is the linewidth enhancement factor that relates the change in the refractive index of the laser medium due to change in the threshold gain. Since $\omega\tau_{ext} \rightarrow \omega\tau_{ext} + 2\pi q$ and $\omega_{th}\tau_{ext} \rightarrow \omega_{th}\tau_{ext} + 2\pi q$ (q being an integer), each $\omega_{th}\tau_{ext}$ provides a number of solutions of

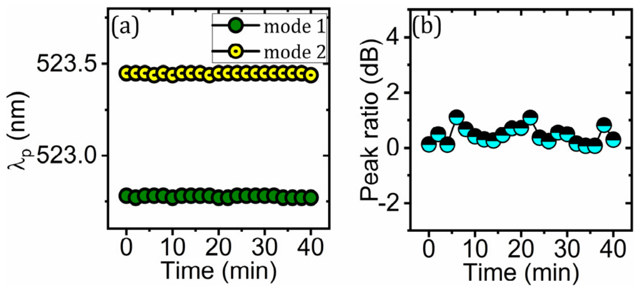


**FIGURE 3.** Summary of the stability performance for (a) peak wavelengths and (b) peak ratio of the dual self-injection locked mode 1 and mode 2. The measured data was recorded from the PDR system at 2-minute intervals for 40 minutes, at an injection current of 43 mA, and at 20 °C. A similar performance was also observed from the SMR system [31].

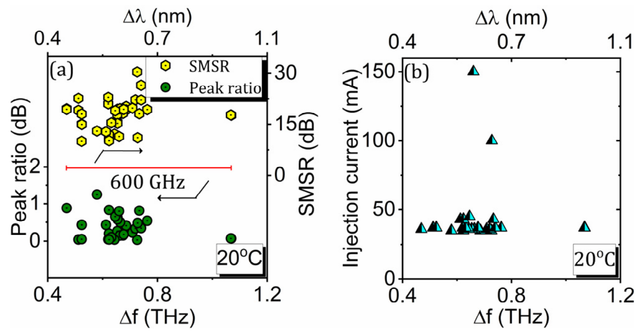


**FIGURE 4.** (a) The peak ratio (circle) and SMSR (hexagon) versus the calculated beat frequency (bottom x-axis) or experimentally observed mode spacing (top x-axis), obtained from the PDR system at 20 °C. (b) The corresponding mode spacing or beat frequency distribution at different bias currents (triangle).

$\omega\tau_{ext}$ that are basically the number of external cavity modes satisfying the above phase condition.

Hence, a careful tuning of $\tau_{ext}$ while controlling $g_c$ according to (1), and satisfying the phase condition (4), a multi-wavelength FP lasing spectra without optical feedback, could translate into a single ($m_{th}$ mode) or dual ($m_{th}$ and $m + n_{th}$ modes, $n$ being an integer) dominant locked modes under optical feedback while suppressing the respective adjacent laser FP modes. In this case, each of these laser modes would be resonant (or locked) with a single or multiple very closely spaced external cavity modes (since $\omega \ll \omega_{th}$ and each possibly exhibiting analogous $\Delta g$) that satisfy their corresponding $\Delta\phi_L = 0$, while both of them exhibiting comparable threshold gain $g_c$.

Now, referring back to Fig. 2, it is noteworthy to mention that, in the present setup, the mode spacing Δλ of the external cavity (∼0.5 pm) is much smaller than that of the laser cavity (∼65 pm), in other words, $\Delta f_{ext} \ll 0.5\ GHz \ll \Delta f_L \approx 550GHz$ ($\Delta f_{ext}$ and $\Delta f_L$ being the corresponding FSR of the external and laser cavity), hence several external cavity modes are the solutions to a particular locked laser FP mode. This possibly is the reason behind the noisy peak spikes of the locked laser longitudinal mode, as can be seen from Fig. 2. However, these spikes are small in height < 5 dB, which is below the minimum SMSR requirement to observe the beat frequency in the frequency domain [27], thereby, should not affect the system performance. In our case, locking is achieved by carefully tuning $L_{ext}$ (via z-axis change and slight tilt in reflected laser beam angle) to obtain the optimum conditions wherein self-locking of two different laser longitudinal modes is accomplished.

### A. STABILITY

To further reinforce the potential of our systems for MMW and THz applications, we performed a short-term stability test of the dual self-injection locked modes that are separated by $\Delta\lambda = 0.67\ nm$ ($\Delta f = 730\ GHz$), at 43 mA and 20 °C. The corresponding results, employing the PDR system of Fig. 1(a), for 40 minutes of observation time with a 2-minutes time interval between the recordings of the data, are summarized in Fig. 3. The fluctuations in the peak wavelengths of both modes are shown in Fig. 3(a), while the variation in PR, which inherently dictates individual mode's peak power stability, is plotted in Fig. 3(b). The system exhibits an extremely stable operation with 0.01 nm shift in the peak wavelengths of both the locked modes 1 and 2, at values of 522.78 nm and 523.45 nm, respectively, for the entire period; and implies an almost constant 730 GHz frequency difference. Moreover, the PR variation was also found to be limited within 0.58 ± 0.5 dB, thus demonstrating good stability in terms of power fluctuations. Hence, this analysis suggests a possibly low noise from the system when deployed for electrical THz signal generation, which is crucial for practical application. It is to be noted that a similar stability performance is also observed from the SMR system asserting both the system's competencies in potential realization of quality beat frequencies in terahertz regime. Moreover, the stability of both the system is expected to improve further should piezo stages be employed to precisely tune the external cavity length.

### B. TUNABLE WAVELENGTH SPACED DUAL MODE SYSTEM EMPLOYING A PARTIAL REFLECTOR

The PR and SMSR at different beat frequencies generated by dual self-injection locked modes from a PDR system is summarized in Fig. 4(a) at room temperature. As seen, a total calculated tunability of 600 GHz ranging from $\Delta f = 0.47$ to 1.07 THz (0.43 to 0.98 nm) is noted with PR confined within 0.03–1.25 dB, thus ensuring a comparable optical power of each longitudinal mode. Moreover, the measured SMSR of the various dual locked modes varies between 10 and 30.4 dB, which is representative of a high signal-to-noise ratio with potentially less system noise should the optical THz signals is generated. The effect of biasing current on Δλ and hence calculated beat frequencies $\Delta f$ is plotted in Fig. 4(b). For simplicity in discussion, we selected three current values, viz. small (36 mA), medium (100 mA), and high (150 mA), in accordance with the laser diode optical power – current injection characteristics. Nevertheless, it should be noted that tunable dual self-injection locking is possible at all injection currents. The beat frequency distribution over various injection currents (Fig. 4 (b)) of the

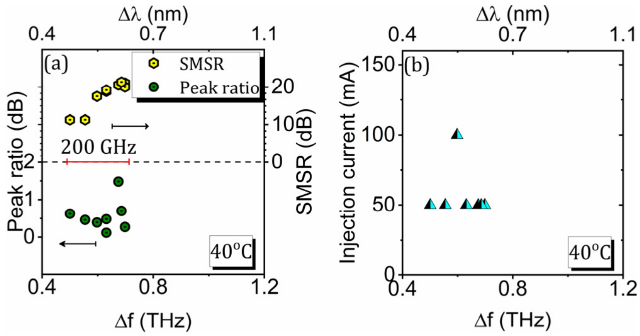


**FIGURE 5.** **(a) The peak ratio (circle) and SMSR (hexagon) versus the calculated beat frequency (bottom x-axis) or experimentally observed mode spacing (top x-axis), from the PDR system at 40 °C. (b) The corresponding beat frequency distribution at different bias currents (triangle).**

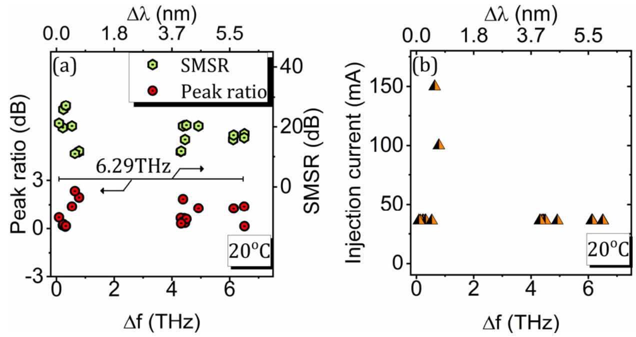


**FIGURE 6.** **(a) The peak ratio (circle) and SMSR (hexagon) versus the calculated beat frequency (bottom x-axis) or experimentally observed mode spacing (top x-axis), from the SMR system at 20 °C. (b) The corresponding beat frequency distribution at different bias currents (triangle).**

InGaN/GaN laser diode indicates that the smallest injection current dominates; encompassing almost all the obtained $\Delta f$ values. On the other hand, medium and large current injection operation displays comparatively few numbers of dual mode locking with relatively small $\Delta\lambda$ tunability. We postulate that the increased $\alpha$-factor at higher bias currents [32], which causes more solutions of the external cavity modes to be available in the system (see (4)) [28], [29] would result into higher mode competition. Besides, not only does high injection current operation promote intense mode competition among the FP modes making injection locking difficult via manual tuning, but also suffers in achieving the required SMSR and PR thresholds set in this work due to various non-linear phenomena occurring in the active region of the laser diode. Nonetheless, the system is efficient compared to the other external cavity configuration wherein ~75 $\mu$W (~65% of the laser diode power) of the optical power exits from the other side of the reflector as the working power, at 36 mA bias current.

To understand the effect of temperature on the performance of the PDR system, we repeated the analysis presented in Fig. 4 at 40 °C. The results, which are shown in Fig. 5, reveal a reduction of the beat frequency tenability from 600 GHz at 20 °C to 200 GHz ($\Delta\lambda = 0.20$ nm) at 40 °C. The calculated $\Delta f$ ranged from 500 to 700 GHz was obtained again at a smaller injection current of 50 mA (just above the threshold at this temperature) with a maximum SMSR of 21.3 dB and PR within 0.11–1.48 dB range. These values were obtained at 20 °C. This is an expected behavior found to be 9.04 dB lower and 0.15 dB higher than the values from 20 °C since increasing the operating temperature increases the mode hopping in the system, thus making it harder to stabilize. We again ascribe this complex dynamics under optical feedback being prompted by increase in $\alpha$-factor of the laser at elevated temperatures, thereby increasing the number of external cavity mode satisfying the phase condition. This possibly intensifies the mode hopping as well as various non-linear phenomena of the active region, which degrades the injection locking efficiency, besides enhancing the non-radiative recombination. Hence, higher temperature poses additional difficulty in stabilizing the dual locked modes in the system thus shrinking the tunability of the system. It is to be noted that at this temperature, high injection current of 150 mA was not possible and hence the results at medium (100 mA) along with smaller injection current are shown in Fig. 5(b). In general, the number of dual self-injection locked modes at both injection currents decreased substantially compared to the room temperature operation.

### C. TUNABLE WAVELENGTH SPACED DUAL MODE SYSTEM EMPLOYING A HIGHLY REFLECTIVE MIRROR

Next, we show the performance of SMR (Fig. 1(b)) system in Fig. 6. In contrast to PDR, a substantial enhancement in the calculated beat frequency tunability from 0.6 to 6.29 THz (5.77 nm) is demonstrated by this system at room temperature. A smallest (largest) $\Delta f$ was measured to be 0.22 (6.51) THz that remarkably covers most of the THz spectrum. Moreover, the measured PR and SMSR variation at different $\Delta f$ values, depicted in Fig. 6 (a), remains within the set boundary limits, reaching a minimum 0.12 dB and a maximum 27.1 dB, respectively, at 20 °C. In this case also, most of obtained tunable dual mode spacing are obtained at a small bias of 36 mA compared to the medium and high injection currents, as illustrated in Fig. 6(b), and are consistent with the acquired results from the PDR system (Fig. 1(a)) and similar attribution holds here as well. This significant improved performance at lower bias is ascribed to the increased mirror reflectivity that ensures more optical feedback power into the laser cavity (high R), and hence attaining large $\kappa$ value. Consequently, the threshold gain under optical feedback ($g_c$) reduces noticeably along with large number of external cavity modes satisfying the phase condition (Eqn. (4)) for a particular laser mode. Thanks to this increase in $\kappa$ that potentially enabled exploiting both of these aspects to span a wider lasing spectrum or gain bandwidth of the laser at lower injection current with relatively constant $\alpha$-factor value. This enabled the possibility of dual locking the likely two extreme modes within the gain profile, thereby, large tunability compared to the PDR system. It is to be noted that the usable optical power is collected from L2 of both the systems for demonstration purpose. In practical systems, the usable power could be collected from the as-cleaved rear facet of the laser diode, thus rendering the system highly efficient. Our comprehensive analysis of the proposed system suggests operating at lower injection current and employ PDR system for high power–moderate tunable frequency difference operation, and SMR system for low power–large tunable beat frequency operation. Besides, it is to be noted that our system employed a commercial green laser diode with small optical power, and hence limited the usable power of both the systems. Incorporating a high power InGaN/GaN green laser diode should enable high optical output power and larger tunability of beat frequency.

## IV. CONCLUSION

In conclusions, we proposed and demonstrated a simple and compact technique for generating two longitudinal-mode device with variable mode spacing, corresponding to calculated tunable beat frequency that covers 0.22-6.51 THz (6.3 THz or 5.77 nm window). This cost-effective and robust system employed a visible green semiconductor laser diode at 521 to 528 nm wavelength range, and exhibited a maximum SMSR of 30.4 dB and peak power ratio of 0.03 dB with excellent wavelength and peak power stability of the dual-wavelength output. Although lower biasing current is more suitable for wider range of beat frequencies, higher SMSRs, and better dual-wavelength peak-power ratios, it is also possible to use higher biasing points to attain beat frequencies with considerable output power. This compact and easily implementable technique could contribute to the exploration of THz frequencies and other cross-disciplinary area largely.

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