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Agile laser wavelength tuning using dynamic targeting

Robbe de Mey, Spencer W. Jolly, Alexandre Locquet, and Martin Virte

Abstract—Tunable lasers are essential and versatile tools in photonics, with applications including telecommunications, spectroscopy, and sensing. Advancements have aimed to precisely control the lasing wavelength, expand tuning ranges, suppress mode hopping, and enable photonic integration. In this work, we explore the adaptation of dynamic targeting, a technique originally developed to stabilize lasers under optical feedback, as a method for achieving agile, fast, and continuous wavelength tuning. This technique works by adjusting the feedback rate and phase, enabling a stable and controlled frequency shift. We experimentally demonstrate reliable and reproducible tuning over 2.1 GHz using a free-space optical setup. Simulations further suggest that this approach could extend the tuning range to tens of GHz, with a potential scan speed exceeding 10^{17} Hz/s. These results highlight dynamic targeting as a promising route toward agile frequency control in semiconductor lasers for photonic integrated circuits.

Index Terms—Semiconductor lasers, Laser tuning, Optical feedback

I. INTRODUCTION

TUNABLE semiconductor lasers are a cornerstone of future photonic systems, underpinning applications ranging from flexible optical communications to high-resolution spectroscopy and LiDAR [1], [2], [3]. To meet the demands of next-generation technologies, these lasers must offer precise and continuous wavelength tuning while remaining compatible with photonic integration, ensuring compactness and low cost. Despite their widespread use, achieving precise, fast, and stable tuning simultaneously remains a challenge with conventional technologies. The ability to integrate such capabilities on-chip is now considered essential for scalable deployment in advanced photonic systems.

Several approaches have been studied to address this challenge [4]. One way to tune the lasing wavelength is by coupling the laser to an external cavity. The lasing tuning then occurs by tuning this cavity typically by mechanical, thermal, or electro-optic adjustments. Mechanical adjustments are not compatible with integrated systems and thermal adjustments are slow. Although electro-optical tuning is faster, it is often combined with the Vernier principle to increase the tuning range at the cost of larger systems and less fine control, including mode-hops [3], [5], [6]. As a recent example, based on optical feedback, ultra-fast tuning rates have been achieved up to 12×10^{15} Hz/s, but only across a tuning range of 1.2 GHz and in a hybrid configuration [7], [8]. Other examples achieve

high tunability but are not monolithically integrated [6], [9]. These results show a critical gap: No existing technique simultaneously delivers mode-hop-free, fast, and precise wavelength tuning and is suitable for monolithically large-scale photonic integration. In this work, we propose and experimentally demonstrate a solution using dynamic targeting, an optical-feedback control technique originally developed for laser stabilization under strong feedback [10], [11], [12], [13]. The approach relies on actively controlling the feedback rate and phase to lock the laser to the maximum gain mode (MGM) of the external cavity [14]. By directly modulating these parameters, we achieve stable mode-hop-free wavelength tuning in real time. In a proof-of-principle experiment, we demonstrate continuous tuning on the order of several gigahertz, supported by numerical simulations that predict scalability to tens of gigahertz with tuning rates approaching 1×10^{17} Hz/s. This non-thermal, feedback-based tuning mechanism thus represents a new pathway toward ultrafast, precise, and integrable wavelength-agile semiconductor lasers. Beyond advancing the fundamental control of laser dynamics, our results pave the way for high-speed, low-cost, and compact sources for optical networks or sensing systems.

II. METHODS

Experimentally, we use the setup shown in Fig. 1. The laser is a single-mode, edge emitting DFB laser (3SP Technologies, 1953 LCV1), maintained at a constant temperature of 25°C . For an injection current of 60 mA, just below three times the threshold current, the free-running lasing wavelength is 1551.5 nm. Mirror M, at a distance of 110 mm, is mounted on a high-precision linear stage (Newport XMS50) that can move over a 50 mm range with nanometer-scale precision. The feedback phase is adjusted by moving the position of

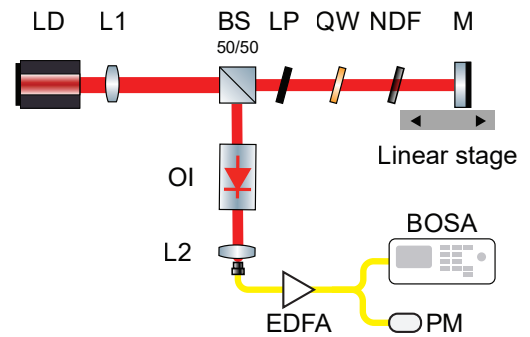


Fig. 1. Experimental setup. LD: Laser Diode, L: Lens, BS: 50/50 Beam-Splitter, LP: Linear Polarizer, QW: Quarter Waveplate, NDF: Neutral Density Filter, M: Mirror, OI: Optical Isolator, EDFA: Erbium-Doped Fiber Amplifier, PM: Power Meter, BOSA: Brillouin Optical Spectrum Analyzer. Red indicates free space, and yellow indicates single-mode fibers.

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the mirror on a sub-wavelength scale. The feedback rate is controlled in two steps: a neutral density filter (NDF) wheel is used to set the initial feedback strength, and dynamic adjustment is achieved using a linear polarizer (LP) and a quarter-wave plate (QWP) mounted on a motorized rotation stage (Thorlabs PRM1/MZ8E). The rotation angle is adjusted so that the feedback rate varies approximately linearly. Alignment of the feedback arm is verified via monitoring a drop in the laser voltage. For measurement, the light is coupled into a single-mode optical fiber after an isolator (OI). After amplification by an EDFA the optical spectra are recorded using a BOSA (Aragon Photonics, 0.08 pm).

Numerically, to model our semiconductor laser with optical feedback, we use the normalized Lang and Kobayashi equations which read as follows [15], [16]:

$$\dot{E}(t) = \frac{1}{2}(1 - i\alpha)N(t)E(t) + \kappa E(t - \tau) \exp(i\phi), \quad (1)$$

$$\dot{N}(t) = (P - N(t) - (1 + 2N(t))E^2(t))/T, \quad (2)$$

where E is the complex electric field and N represents the carrier density. The laser parameters are the linewidth enhancement factor $\alpha = 3$, the carrier lifetime $T = 1000$, and the pump current $P = 1$ (corresponding to twice the lasing threshold). The equations are normalized with respect to the photon lifetime. For these values, the relaxation oscillation period is 141 [17]. The feedback parameters are the feedback rate κ , the external cavity delay τ , and the feedback phase ϕ . From a physical point of view, the phase is equal to $\omega_0\tau$, where ω_0 is the angular frequency of the solitary laser. Here, we consider that sub-wavelength variations of the feedback length do not impact the delay itself but only lead to a change in the feedback phase, and thus control ϕ independently from τ . Equations are integrated numerically using a standard fourth-order Runge-Kutta (RK4) algorithm with a time step of 1.

Without feedback, the laser operates at a single fixed point, corresponding to the natural mode of a solitary laser. When optical feedback is introduced, external cavity modes (ECMs) emerge. As the laser can emit on these as well the lasing wavelength can be shifted away from that of the solitary laser. A particular ECM is called the maximum gain mode (MGM). This one shows the largest shifting in terms of frequency and cannot be destabilized by increasing feedback [14]. In Ref. [14], the authors provide an analytical description of the MGM for $\phi = \tau\alpha\kappa$. This equation shows that keeping the laser on the MGM requires an interplay between the feedback phase ϕ and feedback rate κ . The ratio between the two values being imposed by the delay τ and the linewidth enhancement factor α . The lasing wavelength shift follows the equation $\Delta\omega = -\kappa\alpha$, linking the tuning range to the α factor and the feedback rate. The idea behind the tuning mechanism we propose is therefore based on an increase of the feedback rate—inducing a wavelength shift—combined with a controlled variation of the feedback phase to keep the laser on the MGM. It is interesting to note that the tuning range does not depend on the time-delay, but only on the maximal feedback rate that can be achieved and the α -factor.

III. RESULTS AND DISCUSSION

To validate the tuning method, we conduct a series of simulations, exploring variations of different parameters to assess their impact on wavelength control. We first examine the effect of sweeping only the feedback phase while keeping the feedback rate fixed at an intermediate value of $\kappa = 0.001$, shown in Fig. 2 (a). The wavelength undergoes tuning, but jumps back periodically, indicating that the laser does not remain continuously locked to the MGM. In Fig. 2 (b), (c), and (d), both feedback rate and phase are tuned synchronously with a different ratio between them. Deviations from the ideal proportionality coefficient lead to instabilities, with the laser either undergoing mode hopping, as seen in Fig. 2 (b), or exhibiting chaotic fluctuations, see Fig. 2 (d). In Fig. 2 (c), we tune the feedback parameters with the ratio given by $\phi = \tau\alpha\kappa$. Unlike the previous cases, the laser output remains stable, and the tuning proceeds smoothly without mode hops. The lasing wavelength matches that of the MGM predicted when simulating the fixed points, confirming that the system remains in the MGM throughout the tuning process [18]. Finally, as a last comparison point, we sweep the feedback rate κ from 0 to 0.005 without adjusting the feedback phase in Fig. 2 (e). We observe that the system transitions from a stable state to oscillatory behavior and eventually enters a chaotic regime, confirming the destabilizing effect of increasing feedback rate without phase compensation.

While simultaneous tuning is used numerically, an iterative step-by-step adjustment of both the feedback rate and phase sequentially is used in the experiments. To avoid inducing instabilities, we use small steps of maximum 50 nm when changing the mirror position. The experimental results are shown in the second row of Fig. 2. For each case, the full range of feedback rates is covered, but the total displacement of the mirror is adjusted to explore different tuning ratios. In Fig. 2, the mirror is moved in 100 steps over a range of: (f) 2.38 μm , (g) 4.76 μm , (h) 2.38 μm , and (i) 1.59 μm . In Fig. 2 (f), only the feedback phase is varied. Like in the simulation, the lasing wavelength is swept but exhibits periodic jumps. The results of sweeping both the feedback rate and phase are shown in Figs. 2 (g), (h), and (i). The optimal ratio, where the lasing wavelength is tuned over a range of 2.1 GHz and for which the laser remains on the same mode along the whole range, is shown in Fig. 2 (h). The tuning range is limited by the accessible range of feedback strength, as the QWP is rotated from minimal to maximal transmission of the light in the external cavity. In Fig. 2 (g), the feedback phase is tuned faster than the feedback rate, leading to hops to different ECMs. On the other hand, in Fig. 2 (i), the feedback phase is swept slower which leads to instabilities for strong feedback. Finally, as a comparison point, we show in Fig. 2 (j) the case where only the feedback rate is swept. As expected, the laser initially operates on a stable state but soon becomes unstable, resulting in a broader spectrum. We observe excellent qualitative agreement for all these cases between the experimental and numerical results. While hysteresis has been reported when varying the feedback phase alone [13], we observed no hysteresis when the laser remains on the same mode. As a result, tuning by dynamic

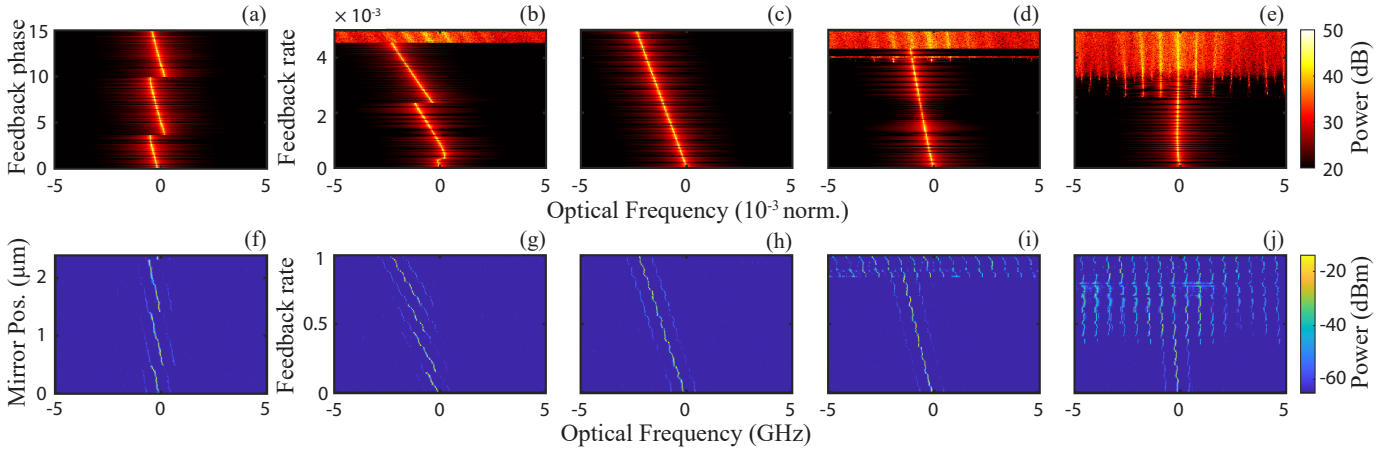


Fig. 2. Optical spectrum variations as a function of feedback parameters. **(a)-(e) Simulation results:** (a) Sweeping only the feedback phase. (b) Feedback phase changing as twice the ideal ratio. (c) Tuning of feedback rate and phase using the ideal ratio. (d) Feedback phase changing at half the ideal ratio. (e) Sweeping only the feedback rate (κ). The parameters used are $\alpha = 3$, $P = 1$, and $\tau = 1000$. **(f)-(j) Experimental results:** (f) Sweeping only the feedback phase. (g)-(i) Tuning with different tuning ratios: (g) feedback phase tuned more than in the ideal case, (h) ideal tuning ratio, and (i) feedback phase tuned less than in the ideal case. (j) Sweeping only the feedback rate.

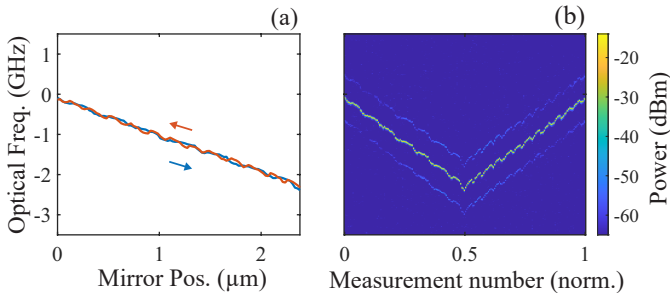


Fig. 3. Experimental bidirectional tuning of the lasing wavelength. (a) Lasing wavelength as a function of mirror position (and feedback rate). Blue: forward tuning, orange: backward tuning. (b) Optical spectrum map illustrating the wavelength shift.

targeting can be used back and forth without significant issues (Fig. 3). At the end, the laser emission return to its initial wavelength, demonstrating bidirectional tunability. On the other hand, we also observe oscillations or ‘wiggling’ of the lasing wavelength during tuning, reducing the linearity of the tuning. The origin of this remains unclear.

We now use simulations to investigate the limits of this tuning method, and especially the sweeping speed. A triangular signal of frequency f_m is applied to the feedback rate and phase. The feedback rate κ is modulated between 0 and 0.2 while the feedback phase ϕ is set as $\phi = \tau\alpha\kappa$. We then increase the modulation frequency and examine how fast the system can respond. In Fig. 4 (a-d), we show evolution of the laser optical spectrum versus time for $\tau = 1000$ and $f_m = 0.2, 0.4, 0.6$ and 0.8×10^{-5} respectively. Like the rate equations used, the frequency is normalized by the photon lifetime. For slow modulations, the system follows well the triangular signal and the laser remains on the MGM. For $f_m = 0.6 \times 10^{-5}$, however, an initial discrepancy appears: the wavelength follows the same pattern but with a much broader spectrum. Then, at the second period, the laser seems to have successfully reached the MGM. At $f_m = 0.8 \times 10^{-5}$, the laser exhibits the same

behavior but the same broader spectrum appears on the 5th period indicating that the laser can escape from the MGM. We extend these simulations to different delays to estimate the maximum tuning speed. In each case, we retain the largest modulation frequency f_m for which the laser remains on the MGM for several periods. The results are presented in Fig. 4 (e). For a delay of 1000, a value corresponding to the long-cavity regime, the system successfully tracks the modulation up to a frequency of 8.37×10^{-6} . Interestingly, the relationship between the delay and the maximum modulation frequency is non-monotonic. The case with a delay of 1000 exhibits better tracking of higher modulation frequencies than the case with a delay of 500, highlighting the intricate interplay between feedback dynamics and modulation response. These results indicate that while the delay does not directly affect the achievable tuning range, it plays an important role in determining the dynamical response and the system’s ability to track rapid modulations. Nevertheless, the short cavity is likely the most promising configuration to achieve fast tuning. To compare with experiments, we estimate the sweeping speed in SI units by de-normalizing the parameters. All equations are normalized in time by the photon lifetime τ_p which is typically around 5 ps for a common semiconductor laser. We successfully tune the laser wavelength up to $\Delta f = -\kappa\alpha = -0.6$ with $\alpha = 3$ and a maximal value of $\kappa = 0.2$, which corresponds to $\Delta f/\tau_p = -120$ GHz. In terms of modulation speed, $f_m > 0.2 \times 10^{-5}$ can be reached for most configurations while 10^{-5} appears to be within reach with shorter delays. In this case, the laser can be tuned over the full tuning range of 120 GHz in half a period $\tau_P/(2f_m) = 1.25 \mu s$ and $0.25 \mu s$ respectively. This yields a scan speed of 96×10^{15} Hz/s and 480×10^{15} Hz/s, more than one order of magnitude above the 12×10^{15} Hz/s speed reported in [7].

IV. CONCLUSION

The results of this study demonstrate the viability of dynamic targeting as a method for precise, fast, and continuous wave-

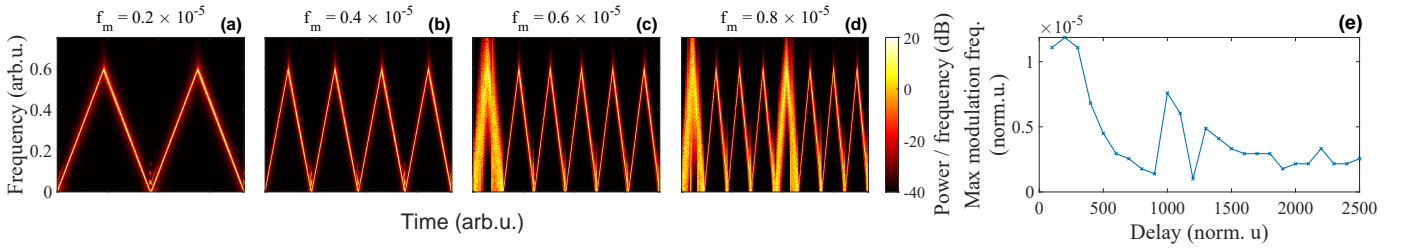


Fig. 4. (a)-(d) Simulation of the tuning the lasing wavelength at high speed with $\tau = 1000$. The optical spectrum is plotted versus the time. From (a) to (d) the frequency of the modulation frequency (f_m) is increased. (c) One roundtrip is needed before the transient settles down. (d) At a certain modulation frequency, the system tuning mechanism breaks down. (e) Simulation of the maximum modulation frequency when changing the delay.

length tuning. Originally developed to stabilize lasers under strong feedback, this technique enables tuning by adjusting both the feedback rate and phase, ensuring stable operation while shifting the lasing wavelength. Because it exploits generic delayed-feedback dynamics, the approach should, in principle, be applicable to a wide range of semiconductor lasers.

Experimentally, we validated this tuning approach and demonstrated that the method enables precise and reproducible tuning over a range of 2.1 GHz. Through rate equation simulations, we have shown that this method can achieve high-speed tuning, with simulated scan speeds potentially exceeding 10^{17} Hz/s. The ability to control the lasing wavelength with minimal perturbation makes this approach a strong candidate for integration into photonic integrated circuits (PICs), especially considering the potential performance improvement linked with the use of shorter external cavities. Nevertheless, some limitations remain to be considered. The laser must either start close to the desired mode as improper initialization can hinder stable tuning. The initial feedback phase must also be carefully set to ensure operation on the correct mode. The tuning process further requires tight synchronization of the feedback parameters, especially at high scan speeds, as deviations can trigger instabilities. Finally, the reliance on optical feedback makes the system vulnerable to parasitic reflections. Future work will focus on on-chip implementation. The free-space setup served as a proof-of-principle demonstration, but its reliance on mechanical actuators limits the speed, precision, and tuning range compared to what could be achieved with an integrated system. With continued development, this method has potential to become a key enabling technology for next-generation high-speed tunable laser systems.

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