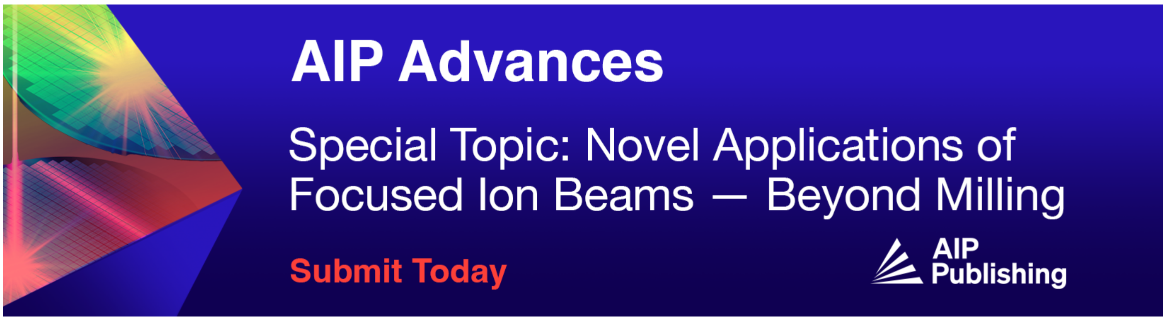
RESEARCH ARTICLE | MARCH 21 2024

Optical injection locking and optical-fiber data transmission by directly modulated wavelength tunable laser transmitters

N. Zakhleniuk ; O. Duzgol

AIP Advances 14, 035346 (2024)
https://doi.org/10.1063/5.0193550



Optical injection locking and optical-fiber data transmission by directly modulated wavelength tunable laser transmitters

Cite as: AIP Advances 14, 035346 (2024); doi: 10.1063/5.0193550
Submitted: 4 January 2024 • Accepted: 24 February 2024 •
Published Online: 21 March 2024

N. Zakhleniuk[a)] and O. Duzgol[b)]

AFFILIATIONS

School of Computer Science and Electronic Engineering, University of Essex, Colchester, CO4 3SQ Essex, United Kingdom

[a)]**Author to whom correspondence should be addressed:** naz@essex.ac.uk
[b)]**Current address:** VPI Photonics GmbH, Hallestrasse 6, 10587 Berlin, Germany.

ABSTRACT

Enhancement of the small- and large-signal modulation performance of wavelength tunable laser diode (TLD) transmitters under strong optical injection locking (OIL) is investigated numerically in back-to-back and optical-fiber transmission schemes. Our model is based on the spatiotemporal description of laser dynamics as due to the composite cavity design of TLDs, the usual rate equation formalism is not directly applicable. We demonstrate that TLD transmission strongly depends on wavelength tuning, which was investigated over a 21-nm range between 1529 and 1550 nm emission wavelengths. The best performance for both free-running (FR) and OIL TLDs is achieved at shorter wavelengths, 1529 nm for our device. Although in both cases this is due to larger differential material gain at shorter wavelengths, the underlying physics of the effect is completely different. For an FR TLD, it is the resonance oscillation frequency (ROF) that defines the best modulation speed, while for an OIL TLD, the achievable modulation speed depends on the cavity mode shift due to optical injection. Both the ROF and the cavity mode shift increase when the differential gain increases. However, the ROF is the device's fixed parameter, while the cavity mode shift is defined by the OIL conditions, and thus, it can be optimized. The superior performance of the optical fiber digital data transmission with the OIL TLD is demonstrated at around 20-Gb/s modulation speed for standard fibers. This result is attributed to an enhanced modulation response and suppressed frequency chirping of the OIL TLD, and it is important for practical utilization of TLD transmitters.

I. INTRODUCTION

Modern optical communication systems need compact high-speed laser transmitters as the number of users and bandwidth utilization are dramatically increasing. Wavelength Division Multiplexed (WDM) systems are widely used in fiber-optic networks to achieve multi-channel transmission to satisfy these needs. In order to cover the required multi-channel wavelength ranges, instead of using many fixed-frequency lasers, tunable laser diodes (TLDs) are considered a good alternative as TLDs can be tuned to transmit over a wide spectral range of all allocated channels. Initially, due to the relatively high cost, the TLD transmitters were aimed at long-haul and/or metro networks.[1] However, in recent years, significant progress has been achieved in widening the utilization of TLDs in access networks[2,3] and data center interconnects.[4] This has further increased the demand for TLDs with enhanced digital data transmission performance.

Due to fundamental physical constraints on carrier-photon dynamics in laser cavities under electrical current injection because of the turn-on delay and gain compression effects, all lasers, including TLDs, have limited direct modulation (DM) bandwidth, and they are also prone to the frequency chirping penalty. At the same time, the growing demand for low-cost efficient transmitters makes DM TLDs an attractive option for various applications and stimulates further search for novel laser designs,[5] or advanced operation conditions,[6] or a combination of both,[7] which allow to overcome the above-mentioned limitations. There have been efforts to increase the DM TLDs' modulation bandwidth with reduced frequency chirping, and it has been recently reported that a 10-Gb/s data transmission was achieved using two-section TLDs based on InGaAlAs multi-quantum well gain material.[8]

Optical injection-locking (OIL) is an effective technique that improves the stability of lasers by injecting light from a master laser (ML) into the cavity of a slave laser (SL). The effect of OIL on lasers has been widely studied, and it was shown that it enhances the modulation bandwidth[9–11] and reduces the frequency chirp (or linewidth) and relative intensity noise (RIN).[12] The stability of the emission frequency under DM is an important factor as fiber dispersion can cause spatial spreading of the spectrally broadened signal, which results in an inter-symbol interference. For the above-mentioned reasons, OIL DM lasers are currently the focus of intensive research as a promising option for application in advanced systems.[13–16] One of the very recent developments is utilization of the OIL technique in THz emitters,[17] with experimental demonstration of a dramatic decrease in the linewidth and noise component of the emission power spectrum under OIL conditions.

Most of the existing works on OIL deal with the fixed-frequency lasers,[18] with very little work on multi-section TLDs. This is in part because the dynamics of multi-section lasers are considerably more difficult to study.[19] As far as TLDs are concerned, previous publications were mainly focused on chaotic dynamics and stability studies,[20] rather than on OIL regimes, and, to best of our knowledge, no results were reported on OIL TLD data transmission performance.

In this paper, we numerically investigate the modulation dynamics of three-section InGaAsP/InP OIL TLD transmitters. We demonstrate substantial enhancement in the modulation response of OIL TLDs and its dependence on wavelength tuning. The latter is important from an application point of view since TLD transmitters by their nature operate at different wavelengths. Hence, it is important to know how their modulation characteristics vary with wavelength tuning. Our simulation model allows one to directly observe the correlation between the CW emission spectral features and modulation characteristics of OIL TLDs. Particularly notable results are obtained for optical-fiber transmission of digital data over a standard optical fiber where approximately 20-Gb/s modulation speed of the OIL TLD is demonstrated. To the best of our knowledge, this is the first study of the fiber transmission performance of DM TLDs under OIL. In addition, we show that differential gain has a strong effect on OIL TLDs. The modulation dynamics of OIL TLDs change considerably with wavelength tuning due to variation in differential gain at different lasing wavelengths. This is very different from the case of the fixed-frequency lasers where differential gain is a fixed value parameter.

II. MODEL AND MODULATION DYNAMICS OF OIL TLDs

Composite multi-section cavity design of TLDs makes it difficult to directly apply the rate equation formalism, which is typically used in studies of laser dynamics in single cavity devices.[21,22] Here, we use the VPI commercial simulator, which incorporates spatiotemporal cavity effects via the travelling-wave approach based on the transmission-line laser model,[23] shown in Fig. 1. The signal generated by DM OIL TLDs is analyzed by various optoelectronic and post-processing tools provided by the VPI, which are also shown in Fig. 1. However, VPI has serious limitations because it uses simplistic (parabolic) built-in gain spectra models, which are particularly restrictive in the case of widely tunable TLDs. Contrary to the lasers with fixed emission spectra, the TLD lasing wavelength can be tuned by injecting carriers into the tuning sections.[24,25] As a result, the entire bandwidth of the gain spectra and its shape are important in defining both the lasing wavelength of the TLD and the dynamics of its response to OIL conditions. (In addition, the optical losses in the DBR section also vary with wavelength tuning.) In order to overcome this problem, we had previously developed[26] an integrated dynamic simulation model, which incorporates separate calculation of the material gain spectra using physics-based software tool PICS3D,[27] which is then self-consistently incorporated via the interface into the VPI simulation model. This allows exact self-consistent calculation of such an important parameter for OIL as the active section differential gain and the group refractive index at every lasing wavelength of the TLD. A detailed description of the design of a three-section InGaAsP/InP TLD with the $In_{0.61}Ga_{0.39}As_{0.84}P_{0.16}$ active region operating at 1550 nm and all material and design parameters are given elsewhere.[28]

Although our main goal is to demonstrate the enhanced modulation performance of OIL TLD transmitters in optical fiber links, the small-signal back-to-back (BTB) analysis also provides good insight into the effect of OIL on laser dynamics. We first investigate the effect of wavelength tuning on the small-signal response of free-running (FR) TLD lasing at different frequencies (wavelengths) f_0 (λ_0).

As is seen from Fig. 2, the resonance frequency f_R in the FR TLD varies substantially from 2 to 5 GHz under wavelength tuning from λ_0 = 1550 nm to λ_0 = 1529 nm. This practically important result for TLDs can be explained by the wavelength dependence of the differential material gains,[26] which defines the resonance oscillation frequency (ROF).[12] In order to observe this effect in TLDs, one needs to take particular care in calculating the correct gain spectral shapes and their variation with carrier injection. Since f_R also depends on the output power, which varies with wavelength tuning,[29] in the simulation, we have adjusted the output power to 3 mW for all tuned emission wavelengths.

Under OIL conditions, the small-signal performance of the TLD is substantially improved. Here, we utilize the front-mirror injection scheme (see Fig. 1). The frequency detuning between the SL and ML lasing frequencies was $\Delta f = 0$, and the injection powers were determined by the border point in the stability map corresponding to the locked state.[30] Note that stability maps and thus the locking conditions change with wavelength tuning.[16] As is seen from Fig. 2, for shorter wavelengths, the frequency f_R and 3-dB bandwidth are increased to 18.7 and 25 GHz, respectively. The underlying physics of this effect is the emergence of two new optical states in the laser cavity under OIL—the shifted cavity mode f_{shift} (which is a result of change in the group refractive index due to the change in the carrier density caused in turn by the injected photons) and the injection-locked (lasing) mode defined by the ML frequency f_{inj}. Our model actually allows us to explicitly observe these modes in the emission spectra of the OIL TLD modulated by a weak AC sinusoidal signal.

Figure 3 shows the superposition of three emission spectra of the SL for three different modulation frequencies f_m defined in

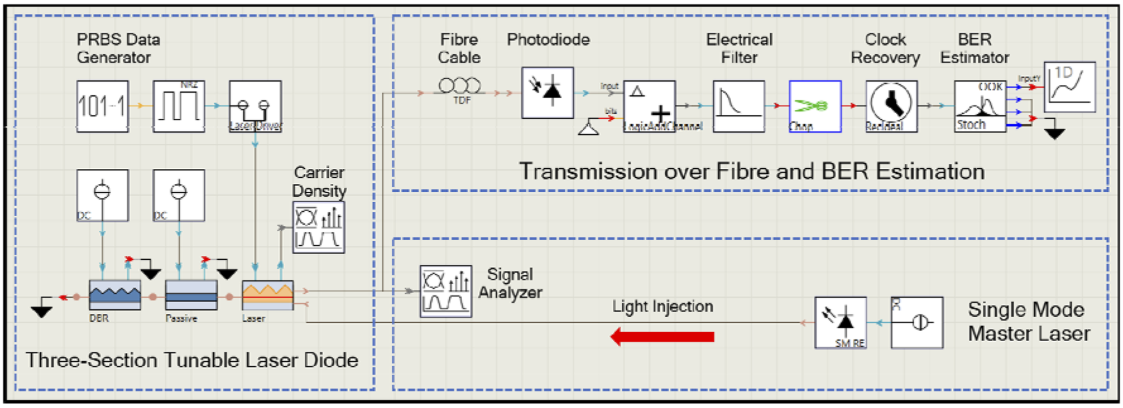


FIG. 1. VPI simulation setup of the three-section DM OIL TLD transmitter and data transmission over optical fiber.

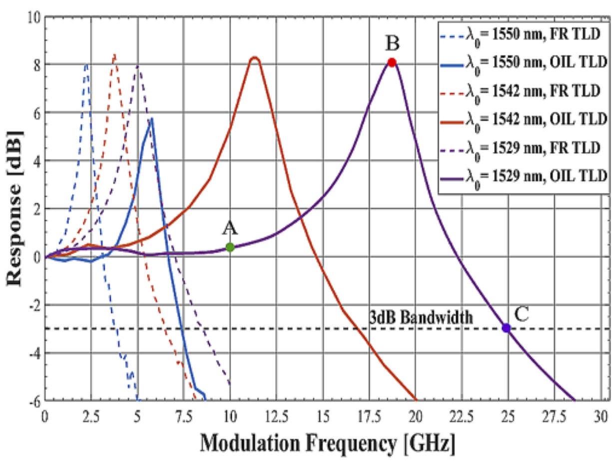


FIG. 2. Small-signal response of FR (dashed lines) and OIL (solid lines) TLDs under wavelength tuning to three wavelengths λ_0 indicated in the inset.

the inset. The corresponding modes are marked as A, B, and C in Fig. 2 (for modulation frequencies) and in Fig. 3 (for spectra). The symmetric blue-shifted modes A′, B′, and C′ are considerably weaker as they have smaller gain.[26] The TLD was tuned to 1529 nm wavelength, and the injected power was 4.7 mW. The frequency detuning was kept at $\Delta f = 0$, i.e., the ML injects light with 1529 nm wavelength (the locked mode marked as L_0 in Fig. 3). Here, of particular significance is mode B, which exactly coincides with the cavity shifted mode. The resonance condition is satisfied when the frequency difference between f_{inj} and f_{shift} modes is exactly equal to the modulation frequency f_m (18.7 GHz in this case). As is seen from Fig. 2, this is also the resonance frequency f_R of the response function corresponding to its peak value. The magnitude of the response function at frequencies f_m corresponding to modes A and C is considerably smaller than that for mode B. As a result, the spectral lines of modes A and C shown in Fig. 3 also have considerably smaller power. Mode B is amplified due to resonance between the injected (locked) mode and the cavity shifted mode when $f_m = f_R = f_{\text{inj}} - f_{\text{shift}}$. The right-hand-side of this condition is a nontrivial result, which allows one to directly evaluate the dynamic parameter f_R from the CW spectra of the OIL TLD laser (the frequencies f_{inj} and f_{shift}). For OIL Fabry–Perot (FP) laser, this was demonstrated in Refs. 9 and 10 from the rate-equation-based analysis of the optical spectra of damping oscillations, which were a result of the interference between f_{inj} and f_{shift} modes. Here, we show that the travelling-wave model allows us to directly observe these modes in the CW spectra of the OIL multi-section TLD, confirming the same physical origin of enhanced modulation response due to resonance interference between the two above-mentioned modes. This is completely different from the resonance response of FR DM laser, which is caused by the relaxation oscillations of the electron–photon interaction in the cavity. The latter is a fixed device characteristic, while the former depends also on the OIL parameters (injection-power ratio and frequency detuning), which can be optimized in order to achieve the best modulation enhancement performance of the laser. Another important observation from the simulation is that the cavity mode shift is directly proportional to differential gain.[10] This is a particularly significant result for TLDs because differential gain strongly depends on the tuning wavelength,[29] i.e., the shift will be different for different lasing wavelengths, and this must be taken into account in practical utilization of the OIL TLD transmitters working at different wavelengths under the DM regime.

III. LARGE-SIGNAL MODULATION AND OPTICAL FIBER DIGITAL DATA TRANSMISSION BY THE OIL TLD

In order to test the large-signal response of the DM OIL TLD, the laser was modulated by an NRZ pseudorandom bit sequence (PRBS) in BTB and the fiber transmission schemes. It is vital to take into account that for large-signal modulation, the OIL conditions are subject to dynamic variation during the pump current modulation as the SL output power changes from min (for a 0-bit) to max (for a 1-bit). This in turn results in a change in the power injection ratio,

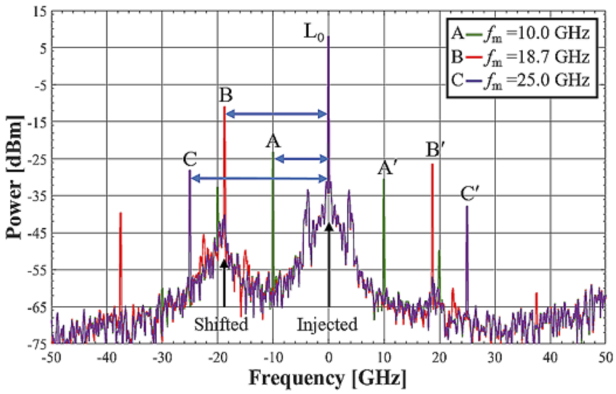


FIG. 3. Spectra of the OIL TLD tuned to λ_0 = 1529 nm under small-signal sinusoidal modulation with three different modulation frequencies f_m shown in the inset.

which is a critical parameter that defines the position of the laser state on a stability map. For the OIL TLD lasing at 1529 nm in the CW regime with an output power of 3 mW (bias current 16.35 mA), a stable locked point at the detuning $\Delta f = 0$ has an injection ratio of 1.57. Under the DM regime, a 1-bit current was kept at I_1 = 16.35 mA, and a 0-bit current was kept at I_0 = 8 mA. This swing of the modulation current ensures that the OIL TLD is in the lasing state at all times (the laser threshold current was just below of 7 mA). The importance of the correct choice of the lower-bound bias current I_0 is revealed in Fig. 4, which shows the CW power distribution along the active cavity region for the backward- and forward-propagating waves in the FR TLD [Fig. 4(a)] and OIL TLD [Fig. 4(b)]. In an FR TLD, a small decrease in I_0 from 8 to 7 mA (just above the threshold) does not change its lasing state (both forward and backward waves are amplified along their directions of the propagation), while the OIL TLD at I_0 = 7 mA acts as an absorber (the optical power of both waves decreases as they propagate) since the carrier density drops below its threshold value under the OIL regime. This severely weakens the dynamic response of the OIL TLD. No such problem occurs at I_0 = 8 mA. Thus, the optimal modulation of the OIL TLD requires careful adjustment of the I_0 current magnitude for 0-bits. The latter observation is important for practical use of OIL TLD transmitters.

In Fig. 5, we demonstrate the response to a 10-Gb/s large-signal DM of the BTB FR TLD [Fig. 5(a)] and OIL TLD [Fig. 5(b)] in the time domain for 1529 nm emission wavelength. The corresponding eye diagrams, shown in Figs. 5(c) and 5(d), respectively, clearly demonstrate dramatic improvement in the TLD performance under the OIL regime.

For an FR TLD, the output optical pulses are completely asynchronized from the PRBS digital data NRZ pulses [Fig. 5(a)], whereas under the OIL regime, the TLD pulses ideally follow the PRBS data pulses [Fig. 5(b)]. The frequency chirping (not shown here) was also improved (decreased) for the OIL TLD transmitter.

The bit-error rate (BER) performance of the BTB OIL TLD for PRBS transmission is shown in Fig. 6 for three emission wavelengths: 1529, 1542, and 1550 nm.

The OIL conditions for each wavelength were specified from the corresponding stability maps. The VPI post-processing tool allows us to directly estimate the BER of the TLD transmitter. The results in Fig. 6 demonstrate how sensitive the transmitter's BER performance is to a lower-bound current I_0, as was mentioned earlier. Interestingly, BER is a non-monotonous function of I_0. Initially, an increase in I_0 improves the TLD's BER response because it remains in a lasing state during the swing of the modulation current from I_0 to I_1. A further increase in I_0 results in a decrease in the aspect ratio, the eye diagram opening decreases, and thus, BER increases. The best BER performance was achieved for the BTB TLD transmitter tuned to 1529 nm lasing wavelength due to larger differential gain at shorter wavelength.[29] The optimal lower bound for the bias current was I_0 = 8.5 mA.

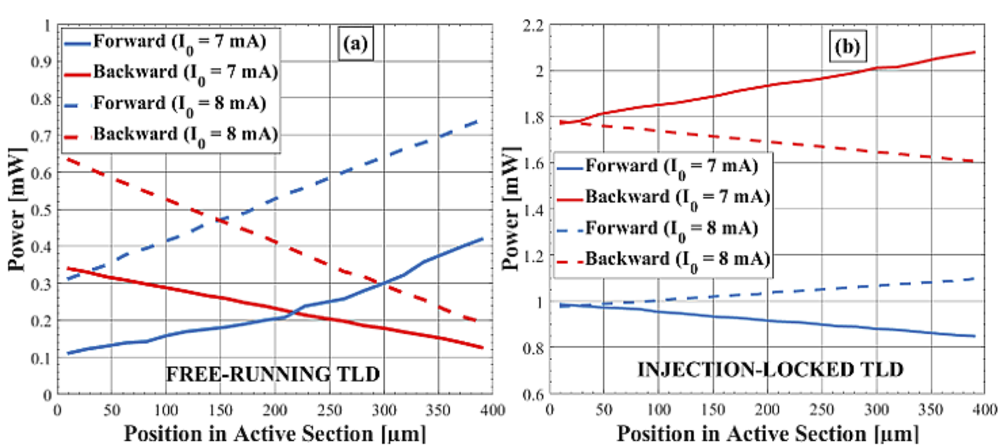


FIG. 4. CW power distribution for backward- and forward-propagating waves inside the active section cavity for (a) FR and (b) OIL TLDs for two lower-bound currents I_0 = 7 mA and I_0 = 8 mA.

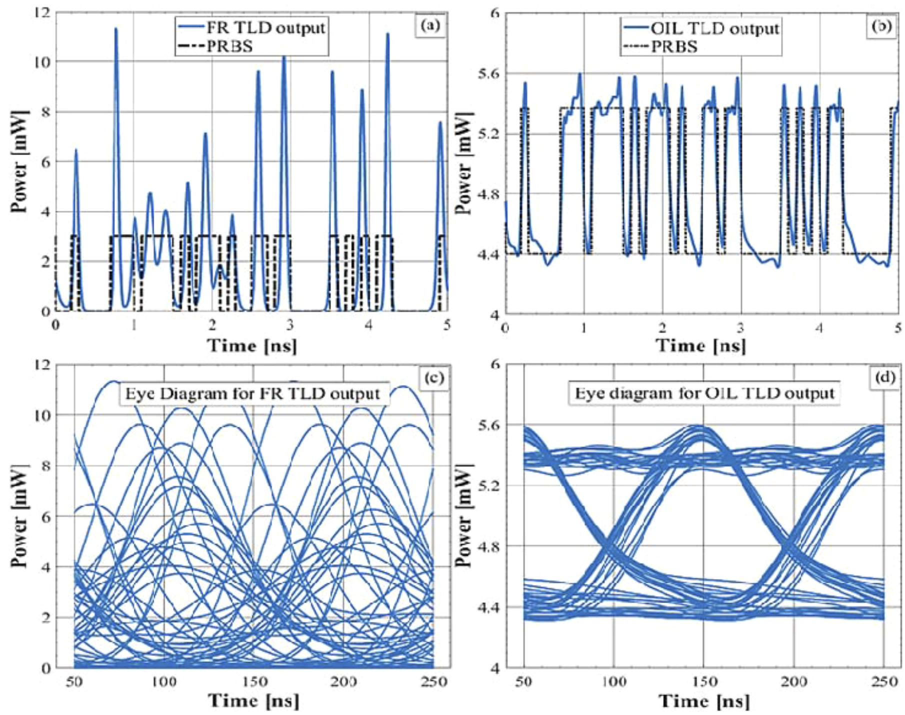


FIG. 5. 10-Gb/s large-signal response of BTB DM (a) FR and (b) OIL TLDs in the time domain; (c) and (d) their corresponding eye-diagrams.

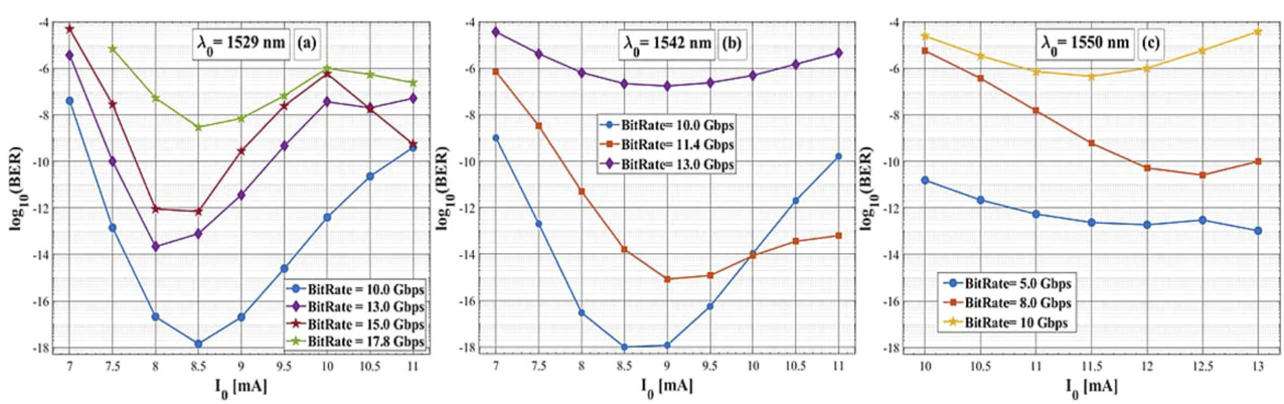


FIG. 6. BER performance of the BTB OIL TLD for three different lasing wavelengths: (a) λ_0 = 1529 nm, (b) λ_0 = 1542 nm, and (c) λ_0 = 1550 nm.

The dependences shown on Fig. 6 represent our main results. They demonstrate that the OIL of TLD transmitters is capable of considerably boosting their high-speed performance, and, importantly, this can be achieved over the entire range of the tuning wavelengths. Optimization of the operation of TLDs in the real-world systems will require careful calibration of the related modulation parameters, particularly the lower bound for the TLD bias current I_0 for each lasing wavelength.

Finally, we investigate the fiber transmission of PRBS digital data by the DM OIL TLD. The corresponding results are presented in Fig. 7. We aim here to just demonstrate that the results obtained for a BTB scheme (Fig. 6) are also confirmed in the fiber transmission scheme. It is necessary to note that the performance of the fiber transmission links is generally influenced by the optical properties of the fibers employed. In our simulation experiments, we use an ordinary single-mode fiber with typical values for

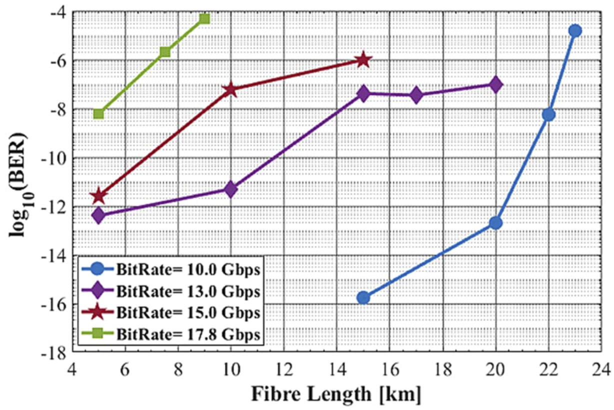


FIG. 7. BER performance of the OIL TLD transmitting at 1529 nm over fibers of different lengths for various modulation speeds.

the dispersion coefficient and fiber attenuation of 16 ps/(km-nm) and 0.25 dB/km, respectively. We consider lasing at the shortest wavelength of 1529 nm as this wavelength shows the best modulation performance in our BTB simulation. For the same reason, the optimal lower bound of the bias current was I_0 = 8.5 mA (see Fig. 6).

As is seen from Fig. 7, for acceptable values of BER, the fiber transmission length strongly depends on the modulation speed, which varies from 9 km for 17.8 Gb/s to 23 km for 10 Gb/s. This behavior is in agreement with the results shown in Fig. 6 for the BTB scheme. The results for the other tuning wavelengths are qualitatively similar; only numerical values will differ for the fiber length spans for each modulation speed. The FR TLD lasing at 1529 nm was not capable at all for fiber transmission at these modulation speeds. The maximum achievable modulation speed over a 10-km fiber was less than 3 Gb/s.

The analysis carried out shows that the main contribution to BER in the investigated transmissions links comes from the fiber dispersion. In practice, the achievable transmission length can be further increased by using dispersion-shifted and dispersion-compensating fibers (DCFs).[31] Such optimized fiber links will allow us to realize the modulation enhancement over the entire wavelength tuning range. In this work, we intended to demonstrate that even by using fibers with typical attenuation and dispersion parameters, it is still possible to attain substantial enhancement of the data transmission in terms of modulation speed and fiber span length.

A superior performance of the OIL TLD for all tuning wavelengths was due to two reasons—an enhanced dynamic response and suppressed frequency chirping of the optical signals. The BER and the fiber transmission length can be further enhanced using suitable fiber dispersion compensation schemes.

IV. CONCLUSION

We have demonstrated enhancement of small- and large-signal modulation performance of TLD transmitters under strong OIL in BTB and the optical-fiber transmission schemes. TLD transmission operation strongly depends on the emission wavelength. The 21-nm wavelength tuning range between 1529 and 1550 nm was studied in this work. The best performance for both FR and OIL TLDs is achieved at 1529 nm. Although in both cases this is due to larger differential material gain at shorter wavelengths, the underlying physics of the effect is completely different. For an FR TLD, it is the ROF that defines the achievable modulation speed, while for an OIL TLD, the achievable modulation speed depends on the main cavity mode shift due to optical injection. Both the ROF and the cavity mode shift are proportional to differential gain. However, ROF is a fixed device parameter, while the cavity mode shift is defined by the OIL conditions, and thus, it can be optimized for practical applications in real-world optical transmission systems. The stability maps need to be analyzed for each tuning wavelength since OIL conditions are different for each wavelength. In addition, we show that the achievable modulation frequencies can be directly observed and extracted from the CW spectra of the OIL lasers. Superior performance of the optical fiber digital data transmission with the OIL TLD is demonstrated at around 20-Gb/s modulation speed for standard fibers of various lengths. This result is attributed to an enhanced modulation response and suppressed frequency chirping of the TLD under the OIL regime.

AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

N. Zakhleniuk and O. Duzgol contributed equally to this work.

N. Zakhleniuk: Conceptualization (equal); Data curation (equal); Investigation (equal); Methodology (equal); Writing – original draft (equal). **O. Duzgol**: Conceptualization (equal); Data curation (equal); Investigation (equal); Methodology (equal); Writing – original draft (equal).

DATA AVAILABILITY

The data that support the findings of this study are available within the article.

REFERENCES

[1] L. A. Coldren, G. Fish, Y. Akulova, J. Barton, L. Johansson, and C. Coldren, J. Lightwave Technol. **22**, 193 (2004).
[2] K. Grobe, M. H. Eiselt, S. Pachnicke, and J. P. Elbers, J. Lightwave Technol. **32**, 2815 (2014).
[3] L. Li, S. Tang, L. Huang, T. Zhang, S. Li, Y. Shi, and X. Chen, Semicond. Sci. Technol. **29**, 095002 (2014).
[4] C. Kachris and I. Tomkos, IEEE Commun. Surv. Tutorials **14**, 1021 (2012).
[5] M. Matsuda, A. Uetake, T. Simoyama, S. Okumura, K. Takabayashi, and T. Yamamoto, in *Proceedings of the IEEE 24th International Semiconductor Laser Conference* (IEEExplore, 2014), pp. 64–65.
[6] P. Bardella and I. Montrosset, IEEE J. Sel. Top. Quantum Electron. **19**, 1502408 (2013).
[7] J.-M. Sarraute, K. Schires, S. LaRochelle, and F. Grillot, IEEE J. Sel. Top. Quantum Electron. **21**, 1801408 (2015).

[8]D. Zhou, S. Liang, G. Chen, Y. Mao, D. Lu, L. Zhao, H. Zhu, and W. Wang, IEEE Photonics Technol. Lett. **30**, 1937 (2018).
[9]T. B. Simpson and J. Liu, IEEE Photonics Technol. Lett. **9**, 1322 (1997).
[10]A. Murakami, K. Kawashima, and K. Atsuki, IEEE J. Quantum Electron. **39**, 1196 (2003).
[11]C. J. Chang-Hasnain and X. Zhao, in *Optical Fiber Telecommunications: Components and Subsystems*, edited by I. P. Kaminow, T. Li, and A. E. Willner (Elsevier Inc., Amsterdam, 2008), Vol. 5A, pp. 145–182.
[12]E. K. Lau, L. J. Wong, and M. C. Wu, IEEE J. Sel. Top. Quantum Electron. **15**, 618 (2009).
[13]Z. Liu, G. Hesketh, B. Kelly, J. O'Carroll, R. Phelan, D. J. Richardson, and R. Slavik, J. Lightwave Technol. **36**, 4967 (2018).
[14]Z. Liu, J. Kakande, B. Kelly, J. O'Carroll, R. Phelan *et al.*, Nat. Commun. **5**, 5911 (2014).
[15]M. Kye and C. H. Lee, IEEE Photonics Technol. Lett. **30**, 213 (2018).
[16]O. Duzgol, G. Kyritsis, and N. Zakhleniuk, in *Proceedings of the IEEE 25th International Semiconductor Laser Conference* (IEEEXplore, 2016), pp. 1–2.
[17]T. Hiraoka, T. Arikawa, H. Yasuda, Y. Inose, N. Sekine, I. Hosako, H. Ito, and K. Tanaka, APL Photonics **6**, 021301 (2021).
[18]C. H. Yeh, C. W. Chow, H. Y. Chen, J. Y. Sung, and Y. L. Liu, Electron. Lett. **48**, 940 (2012).
[19]U. Bendelow, M. Radziunas, J. Sieber, and M. Wolfrum, IEEE J. Quantum Electron. **37**, 183 (2001).
[20]C. A. Stolz, D. Labukhin, N. A. Zakhleniuk, and M. J. Adams, IEEE J. Quantum Electron. **46**, 220 (2010).
[21]R. Lang, IEEE J. Quantum Electron. **18**, 976 (1982).
[22]J. Ohtsubo, *Semiconductor Lasers: Stability, Instability, and Chaos* (Springer, 2006).
[23]VPIphotonics GmbH, VPIcomponentMaker Photonic Circuits, User Manual, 2023.
[24]J. Buus, M. C. Amann, and D. J. Blumentthal, *Tunable Laser Diodes and Related Optical Sources* (Wiley Interscience, Hoboken, NJ, 2005).
[25]L. A. Coldren, S. W. Corzine, and M. L. Mašanovi'c, *Diode Lasers and Photonic Integrated Circuits*, 2nd ed. (Wiley, Hoboken, NJ, 2012).
[26]O. Duzgol, G. Kyritsis, and N. Zakhleniuk, IET Optoelectron. **11**, 66 (2017).
[27]PICS3D User Guide, Crosslight Software Inc., 2010.
[28]G. Kyritsis and N. Zakhleniuk, IEEE J. Sel. Top. Quantum Electron. **19**, 1503311 (2013).
[29]G. Kyritsis and N. Zakhleniuk, IEEE J. Quantum Electron. **53**, 2500216 (2017).
[30]O. Duzgol, G. Kyritsis, and N. Zakhleniuk, IET Optoelectron. **11**, 58 (2017).
[31]G. P. Agrawal, *Fiber-Optic Communication Systems*, 5th ed. (Wiley, Hoboken, NJ, 2021).