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Dongmei Huang

`meihk.huang@polyu.edu.hk`

Photonics Research Institute, Department of Electrical and Electronic Engineering, The Hong Kong Polytechnic University

Wenhao Zhu

Photonics Research Institute, Department of Electrical and Electronic Engineering, The Hong Kong Polytechnic University

Laiyang Dang

Photonics Research Institute, Department of Electrical and Electronic Engineering, The Hong Kong Polytechnic University

Yihuan Shi

Photonics Research Institute, Department of Electrical and Electronic Engineering, The Hong Kong Polytechnic University

Feng Li

The Hong Kong Polytechnic University Shenzhen Research Institute

Qiwen Zhan

University of Shanghai for Science and Technology <https://orcid.org/0000-0001-8745-4213>

Ping Kong A Wai

Hong Kong Baptist University <https://orcid.org/0000-0002-4975-4175>

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Controllable transient coherent state reproduction in lasers

Wenhao Zhu^{1,2,†}, Laiyang Dang^{1,2,†}, Yihuan Shi^{1,2}, Feng Li², Qiwen Zhan^{3,4}, Dongmei Huang^{1,2,*}, and P. K. A. Wai⁵

¹ Photonics Research Institute, Department of Electrical and Electronic Engineering, The Hong Kong Polytechnic University, Hong Kong SAR, China

² The Hong Kong Polytechnic University Shenzhen Research Institute, Shenzhen 518057, China

³ Zhejiang Key Laboratory of 3d Micro/Nano Fabrication and Characterization, Department of Electronic and Information Engineering, School of Engineering, Westlake University, Hangzhou, Zhejiang 310030, China

⁴ School of Optical-Electrical and Computer Engineering, University of Shanghai for Science and Technology, Shanghai 200093, China

⁵ Department of Physics, Hong Kong Baptist University, Hong Kong SAR, China

†These authors contributed equally to this work.

*Corresponding to: meihk.huang@polyu.edu.hk

Abstract

Current research on coherent lasers typically focuses on configurations that maintain a long-term stable state, often ignoring transients during the laser buildup stage. In this paper, we propose and experimentally demonstrate that the transient coherent state (TCS) - occurring during the buildup of laser signals from amplified spontaneous emission (ASE) in a non-equilibrium long-fiber laser - can be harnessed by periodically resetting the pump power. Using a Fourier-domain mode-locked (FDML) laser as a model, we show that an FDML laser operating in the TCS achieves an intrinsic linewidth at the hertz level. This represents a nine-order-of-magnitude improvement over conventional FDML lasers. Furthermore, the residual phase jitter within the TCS can serve as an internal reference for self-regulation. By leveraging the unique combination of transient coherence and long-term chaos, we demonstrated a novel hybrid LiDAR scheme featuring micron-scale resolution and kilometer-scale measurable range. Finally, we apply the TCS concept to mitigate mode hopping in a self-injection-locked distributed feedback (DFB) laser, demonstrating that the TCS is equally valuable for lasers with long-term stable states.

Introduction

The pursuit of coherence is a longstanding goal in optics¹⁻³. Landmark achievements⁴⁻⁶ in coherent light generation are achieved in long-term stable states, which are achieved by balancing gain and loss, as well as nonlinearity and dispersion in laser cavities⁷⁻⁹. However, as the excitation strength^{10, 11} or spatial size^{12, 13} of the lasers increases, this equilibrium is eventually broken, leading to long-term unstable states with low coherence.

Over the past decade, a breakthrough in the photonic time-stretch technique¹⁴ has made it possible to observe non-repetitive and statistically rare events, opening up a new area of research in laser dynamics¹⁵⁻¹⁷. Studies of the turn-on dynamics of non-equilibrium lasers during the buildup from amplified spontaneous emission (ASE) noise have found that some lasers undergo a transient coherent state (TCS)^{13, 18, 19}, before evolving into long-term unstable states. While studies of TCS contribute to our understanding of laser dynamics¹⁴, they have not yet been utilized in practice. In this paper, we demonstrate that periodically resetting the laser pump power allows for deterministic access to the TCS. These non-equilibrium lasers can then emit coherent laser pulses, demonstrating a novel operational paradigm for lasers.

Fourier domain mode-locked (FDML) lasers have been found to operate in a long-term unstable state, primarily due to dispersion in the kilometer-long fiber of the cavity, as well as by other physical effects²⁰⁻²². The kilometer-long cavity plays a critical role in buffering the wavelength-swept laser (WSL) signal, thereby improving the repetition rate²³. It also enables video-rate swept-source optical coherence tomography (SS-OCT)²⁴. In the long-term unstable state, the FDML laser output has low coherence due to high-frequency fluctuations in the temporal waveforms. This results in GHz-level instantaneous linewidths²⁵, thus limiting the wider application of FDML lasers. To prevent FMDL lasers from evolving into unstable states, the dispersion mismatch in the cavity must be less than 200 fs²⁶ over a 100-nm bandwidth in a kilometer-long cavity.

Furthermore, the cavity length of the laser and the fiber Fabry-Pérot tunable filter (FFP-TF) are sensitive to environmental disturbances such as temperature and vibration. This makes achieving long-term stability of the FDML laser output difficult.

In this paper, we demonstrate an FDML laser operating in the TCS. This FDML laser can achieve a hertz-level intrinsic linewidth and robust stability without dispersion compensation or environmental control. This is achieved by periodically resetting the pump power to reproduce the TCS operating mode. The dispersion-induced accumulated frequency shift determines the number of roundtrips after which the FDML laser transitions from the TCS to an unstable state during the laser buildup process. We use residual phase jitter (RPJ)²⁵ per TCS period as an internal reference for a feedback control algorithm^{27, 28}, which enables self-regulated FDML laser operation in the TCS. This algorithm can initialize the FDML laser to operate in the TCS in under 60 seconds and stabilize it for at least 24 hours. To demonstrate the application of FDML operation in the TCS, we show how to use the FDML laser output from the TCS and the long-term unstable state together to enable frequency-modulated continuous wave (FMCW)^{29, 30} and random-modulated continuous wave (RMCW)^{31, 32} LiDAR. This novel hybrid LiDAR simultaneously achieves micron-scale resolution and kilometer-scale measurement range. We observe that even lasers with long-term stable states can have their equilibrium broken by environmental fluctuations, resulting in unstable laser output. One example is mode hopping in self-injection-locked distributed feedback (DFB) lasers. We demonstrate that mode hopping in a self-injection-locked DFB laser can be prevented through periodical resetting of the laser pump power, eliminating the need for an external reference. This shows the usefulness of the TCS for lasers with and without long-term stable states.

Principle

Figure 1 shows the schematic of the FDML laser and its turn-on dynamics.

Insets Figs. 1(a)-1(d) illustrate the principle of the FDML laser operating in the TCS. The experimental setup of the FDML laser and the measurement system are described in detail in the Methods. Chromatic dispersion is the main factor that deteriorates the coherence of FDML lasers²². In this study, we systematically examine the dynamics of the backward sweep signal (from long to short wavelength), which is influenced solely by chromatic dispersion. Details of both sweep directions are presented in Section 1.1 of the Supplementary.

Experimentally, when the SOA is turned on by the square signal generated by an arbitrary waveform generator (AWG), we observed that the FDML laser signal builds up after approximately 150 roundtrips, as shown by the intrinsic linewidth in Visualization 1. Then, the FDML laser operates in the TCS. The time-wavelength relationship of the FDML laser is determined by the sinusoidal voltage applied to the FFP-TF. Chromatic dispersion in the cavity causes the roundtrip time $RTT(\lambda)$ of the FDML laser to depend on wavelength λ . The time shift $\Delta T_s(\lambda)$ between $RTT(\lambda)$ and the tuning period of the FFP-TF T_F per roundtrip is given by $\Delta T_s(\lambda) = RTT(\lambda) - T_F$, as shown by the yellow solid curve of inset Fig. 1(a). The two zero-crossing points, indicated by the purple circles in inset Fig. 1(a), are the mode-locked “sweet spots”³³ at which the cavity roundtrip time, at these two wavelengths, perfectly matches the tuning period of the FFP-TF. The location of the sweet spots can be shifted by changing the T_F ³⁴. The frequency shift $\Delta f_s(\lambda)$ at wavelength λ per roundtrip relative to the central passband frequency of the FFP-TF is determined by $\Delta f_s(\lambda) = \Delta T_s(\lambda) \times f_{sr}(\lambda)$, as shown in the yellow solid curve in inset Fig. 1(b), where $f_{sr}(\lambda)$ is the optical frequency sweep rate. The derivations of $\Delta T_s(\lambda)$, $f_{sr}(\lambda)$, and $\Delta f_s(\lambda)$ in both backward and forward sweeps are presented in Section 1.1 of the Supplementary.

As the number of roundtrips increases, the accumulated frequency shift increases. When the accumulated frequency shift is close to the bandwidth of the FFP-TF B_F , which is 16 GHz in the experiment, the FFP-TF induces significant loss, forcing the laser signal to rebuild. The maximum number of

roundtrips $Q(\lambda)$ at wavelength λ at which the wavelength experiences net gain can be roughly estimated by

$$Q(\lambda) = \frac{B_F}{|\Delta f_s(\lambda)|}. \quad (1)$$

From inset Fig. 1(b), the maximum frequency shift due to dispersion per roundtrip is 555 MHz, occurring at $\lambda = 1507$ nm. The corresponding $Q(\lambda)$ is 29. However, since it takes approximately 150 roundtrips for a wavelength to build up from ASE at $\lambda = 1507$ nm, the wavelength is shifted out of the FFP-TF passband approximately every 29 roundtrips. Consequently, the cavity does not lase at this wavelength. Therefore, the coherence of the signal at this wavelength is expected to be poor.

On the other hand, the maximum frequency shift due to dispersion between the two sweet spots per roundtrip is 35 MHz, corresponding to a $Q(\lambda)$ greater than 450. Inset Fig. 1(c) shows the spectra of the laser output between the two sweet spots at the 150th, 250th, and 450th roundtrips. The FDML begins lasing at around the 150th roundtrip and continues lasing until approximately the 450th roundtrip. At this point, the laser signal is significantly attenuated by the FFP-TF, and it becomes further distorted after passing through the SOA because loss begins to overwhelm gain. The optical signal is then dominated by ASE noise, resulting in the loss of optical coherence.

Inset Fig. 1(d) shows the evolution of the accumulated frequency shift, $\Delta f_{as}(N, t)$, during the backward sweep of the FDML laser as a function of the number of roundtrips N and fast time t . Fast time is obtained from the wavelength using the time-wavelength relationship of the sinusoidal voltage applied to the FFP-TF. The color map shows the values of the $\Delta f_{as}(N, t)$. The magenta dotted-dashed lines represent the two sweet spots at which $\Delta f_{as}(N, t)$ are zero for all values of N . The turn-on dynamics of the FDML laser can be divided into three stages by the white dotted-dashed lines in inset Fig. 1(d). Stage I extends from when the laser is turned on to the 150th roundtrip. Stage II is between the 150th and the 450th roundtrip. Stage III begins after the 450th

roundtrip. In Stage I, the FDML laser signal builds up from ASE. The laser output is expected to have low coherence. In Stage II, the FDML laser operates in the TCS between the two sweet spots. The laser output is expected to be highly coherent. In Stage III, even the wavelengths between the sweet spots must rebuild as $\Delta f_{as}(N, t)$ approaches B_F . The white solid curves depict the condition $\Delta f_{as}(N, t) = B_F$. The laser output is expected to have low coherence. To capture the transient coherent operation of the FDML laser, we propose periodically resetting the SOA before the FDML laser evolve into the unstable states. This forces the laser to restart from ASE and evolve into the TCS. The FDML laser will then operate in pulse mode, producing highly coherent output pulses.

Section 1.2 of the Supplementary discusses the effective numbers of roundtrip, $Q_{eff}(\lambda)$, and bandwidths of the TCS region under different FFP-TF settings (center wavelength and T_F). Due to the trade-off between $Q_{eff}(\lambda)$ and the bandwidth of the TCS region, the center wavelength is set to 1542 nm. The T_F of the FFP-TF is set 20 ps higher than the roundtrip time at the zero-dispersion wavelength. The bandwidth (Eq. S10) and $Q_{eff}(\lambda)$ (Eq. S11) of the TCS region of the FDML laser are ~ 20 nm and ~ 450 , respectively.

Results

Figure 2(a) shows the evolution of the FDML laser output intensity during the backward sweep of the FDML laser as a function of the number of roundtrips and fast time. The color map shows the FDML laser intensity in arbitrary units. The detection bandwidth of the measurement system is set to 33 GHz, which is twice that of the FFP-TF (16 GHz). Fig. 2(a) shows the period between the two sweet spots marked by two magenta, dotted-dashed horizontal lines at 2.48 and 4.04 μ s, respectively. Consistent with the analysis in Fig. 1(d), the turn-on dynamics of the FDML laser can be divided into three stages by the two white, dotted-dashed vertical lines located at the 150th and 450th roundtrips, respectively. Fig. 2(b) shows the temporal waveform at the 350th roundtrip,

where the coherent laser output is between the two sweet spots and high-frequency fluctuations elsewhere. Beyond the 450th roundtrip (Stage III), the FDML laser output enters an unstable state. High-frequency fluctuations are observed even during the period between the two sweet spots. Figs. 2(c) and 2(d) show the temporal waveforms at the 500th and 970th roundtrips, respectively. As shown in the two figures, high-frequency fluctuations develop in different regions between the two sweet spots. These fluctuations indicate that the laser is rebuilding from ASE at these wavelengths.

Figures 2(e)-2(g) show the temporal waveforms (gray) and the interference signals (blue) of the laser output. The figures are zoomed in on the time period between 2.7 μs and 3.9 μs at the 350th, 500th, and 970th roundtrips, respectively. Fig. 2(e) shows that the intensity fluctuation of the temporal waveform is low within the TCS. Figs. 2(f) and 2(g) show that the intensity fluctuation is high in some intervals between the two sweet spots. The discontinuities in the interference signal in Figs. 2(f) and 2(g) indicate that the phases of the wavelengths are no longer locked. The π -phases shift indicates that the laser is rebuilding from ASE in these regions²¹. The intensity evolution of the forward sweep and that under different TF settings is shown and discussed in Supplementary Section 2.

Figure 2(h) shows the autocorrelation function (ACF) background levels measured with a delay of 40 ns at the 400th roundtrip. The ACF levels are nearly unity between 2.48 and 4.04 μs , indicating that the laser is coherent during this period. Outside this range, the ACF levels are nearly 0.5 before 2.48 μs and 0.6 after 4.04 μs , indicating incoherent laser output in these periods. The ACF levels are slightly higher after 6 μs due to the SOA's lower gain for shorter wavelengths, which results in reduced noise intensity.

The intra-roundtrip phase coherence of the transient coherent state of the FDML laser is characterized by the instantaneous frequency noise power spectral density (FNPSD), which is based on the residual phase jitter (RPJ) extracted using the average deduction method²⁵ (see Supplementary Section

3.1) on the interference signal between the two sweet spots. To record the interference signal throughout 1,000 roundtrips, an optical path difference (OPD) of 1 m is chosen, and the sample rate is reduced to 25 GSa/s. The intrinsic linewidth of the laser can be calculated as 2π times the FNPSP floor^{25, 35}. Figure 2(i) shows the evolution of the intrinsic linewidth as a function of the number of roundtrips. The intrinsic linewidth decreases in Stage I, converges to a minimum of around 500 Hz in Stage II (the TCS), then increases and fluctuates in Stage III. The fluctuation in Stage III is due to the Hilbert algorithm's inability to process the interference signal at discontinuity points (see Supplementary Section 3.1). Visualization 1 shows the detailed 1000-roundtrip evolution of the RPJ and FNPSP, as well as the temporal waveform and interference signal.

Figure 2(j) shows the FNPSP of the TCS-FDML laser measured with an OPD of 7.2 m and a sample rate of 200 GSa/s. The intrinsic linewidth is approximately 18.9 Hz. The negative correlation between the intrinsic linewidth and the OPD in the FDML laser-based coherent detection system was illustrated in our prior work²⁵. For comparison, the intrinsic linewidth of a conventional FDML laser in a long-term unstable state is 13.2 GHz (see Supplementary Section 3.2). This represents a nine orders of magnitude improvement in the intrinsic linewidth of the TCS-FDML laser compared to a conventional FDML laser. We also measured the inter-roundtrip phase coherence of the transient coherent state of the FDML laser output and obtained a coherence length of over 4 km with the TCS-FDML laser (see Supplementary Section 3.3).

Feedback control

Thermal contraction and expansion cause a drift in the cavity length of the FDML laser and the FFP-TF. To combat the thermal drift, feedback control is implemented on the tuning period (T_F) and voltage offset (V_o) of the FFP-TF. When the cavity length of the FDML laser thermally expands or contracts, $RTT(\lambda)$ for all wavelengths buffered in the FDML laser cavity increases or

decreases, respectively. Therefore, T_F should be increased or decreased, respectively, to track for the drifted cavity length of the FDML laser. Similarly, if the cavity length of the FFP-TF thermally expands or contracts, V_o should be decreased or increased to cancel out the drifted cavity length of the FFP-TF by piezoelectricity. Thus, for a given FMDL laser configuration, the optimal operating values of T_F and V_o must first be determined so that the FDML laser can operate in the TCS. Then, a feedback control algorithm should be implemented in the FDML laser to converge to and maintain the optimal operating values from initial startup. In the experiment, it is determined that the optimal operating values of the TCS-FDML are as follows: set V_o so that the center wavelength of the output signal spectrum is 1542 nm and set T_F 20 ps higher than the roundtrip time of the zero-dispersion wavelength.

For the feedback control, we use the RPJ waveform, which is demodulated from ten successive interference signals within the TCS-FDML region as an internal reference. The leftmost and rightmost low-phase-noise (LPN) regions on the RPJ waveform correspond to the temporal positions of the sweet spots²⁶. The temporal distance between the two sweet spots is related to T_F , while the central temporal position of the two sweet spots is related to V_o . The details of the feedback control algorithm are illustrated in Section 4.1 of the Supplementary. Compared to the temporal waveform³⁶, using the RPJ waveform as the internal reference offers higher sensitivity (see Supplementary Section 4.2).

The white dotted box in Fig. 1 shows the feedback control loop, including a Mach-Zehnder interferometer (MZI) with an OPD of 126 mm, a balanced photodetector (BPD), and an oscilloscope (OSC), which are used to generate, detect, and record the interference signal, respectively. A personal computer (PC) processes the interference signal in real time and derives the RPJ. The feedback control algorithm then calculates the deviation in T_F and V_o . Finally, this deviation is sent to the AWG, which adjusts the T_F and V_o of the FFP-TF accordingly.

Figure 3(a) shows the initialization of the FDML laser from a deliberately mismatched T_F . The detuning on the y-axis is defined as the temporal difference between the T_F and the $\text{RTT}(\lambda)$ at the zero-dispersion wavelength (Eq. S12). The targeted detuning value from the parametric simulation (Supplementary Section S1.2) is 20 ps. Each time the FDML laser is initialized, a significant detuning of approximately ± 350 ps is deliberately introduced. As shown in Fig. 3(a), the feedback control successfully restores the detuning to the optimized value within 60 seconds with good repeatability. The detailed temporal and RPJ waveforms during the adjustment of TF are shown in Section 4.3 of the Supplementary. Additionally, the proposed algorithm ensures long-term operating stability for the FDML laser. Figure 3(b) shows that a free-running FDML laser loses the TCS-FDML region within about two hours. By comparison, Figure 3(c) shows that the TCS-FDML region is maintained for 24 hours using feedback control. The optical spectrum of the output signal begins to drift two hours afterward, as shown in Fig. 3(d). By comparison, the optical spectrum of the output signal does not drift with feedback control, as shown in Fig. 3(e) for 24 hours. Thus, adopting the feedback control increases the duration of the TCS by a factor of ten. The optical frequency sweep range with and without the feedback control, together with the record of T_F and V_o , is discussed in Section 4.4 of the Supplementary.

Discussion

Significance. The main performance indicators for wavelength-sweep lasers (WSLs) are coherence, sweep range, and repetition rate. The solid circles in Fig. 4 show the parameters of highly coherent WSLs with a sweep range spanning the terahertz (THz) range. These parameters are achieved using an external cavity tunable laser (blue dot)³⁷, a microelectromechanical systems vertical cavity surface-emitting laser (MEMS-VCSEL, purple dot)³⁸, time-stretched ultrafast lasers (black dots)³⁹⁻⁴¹, and an extremely well dispersion-compensated FDML laser (red dots)²³. The measurable range is estimated with

a detection bandwidth of 70 GHz. Figure 4 shows the low-repetition-gap gap at the kilohertz level, where the laser cavity is over a kilometer long. Although MEMS-VCSELs can operate close to the low-repetition-gap regime, their coherence is typically constrained by the relatively short photon lifetime^{42, 43}. Alternatively, using a long-fiber cavity to fill the gap is constrained by the long-term unstable state and environmental sensitivity. This results in poor coherence and unstable laser output. The proposed TCS-FDML laser overcomes these limitations and achieves a record-low intrinsic linewidth of 18.9 Hz and a repetition rate of 50 kHz in the long cavity. Additionally, it offers high stability and a record-high^{41, 44} measurable range of 11.2 m (Supplementary Section 5.1).

The meter-level measurable range expands the application scope of FDML lasers beyond ophthalmology to include imaging objects with increased spatial dimensions^{38, 44}, especially for industrial inspections such as laser welding. The intrinsic linewidth is improved by nine orders of magnitude compared to conventional FDML lasers. This improvement is further supported by the interference signal with an OPD of 4 km (see Supplementary Section 3.4). These results suggest potential applications for the TCS-FDML laser in long-range LiDAR and laser metrology^{45, 46}.

By exploiting the TCS of FDML lasers, highly coherent FDML laser output is not limited to laser cavities with sweet spots close together^{26, 33}, but rather to cavities with a broad region between the two sweet spots. In other words, coherent FDML laser output can be achieved without tight control over cavity dispersion. Recently, new FDML laser setups featuring high sweep ranges^{47, 48}, shorter center wavelengths^{49, 50}, and higher repetition rates⁵¹ have been reported. These setups can benefit from operating in TCS to improve coherence. TCS can be used to significantly improve the coherence of the FDML laser at a lower repetition rate⁵² to achieve measurable ranges of hundreds of meters.

Application. Frequency-modulated continuous wave (FMCW) LiDARs^{29, 30} that

use coherent laser signals offer fine spectral ranging, high spatial resolution, and sensitivity. In contrast, random-modulated continuous wave (RMCW)^{31, 32} LiDARs that use incoherent laser signals offer coarse temporal ranging and a long measurable range. Using a single LiDAR system that combines coherent and incoherent lasers provides high spatial resolution and a long measurement range, but it requires a more complex experimental setup. In addition, synchronization issues may arise from the self-pulsating characteristics of certain lasers⁵³.

Since an FDML laser can output both coherent and chaotic WSL signals, a single FDML laser can be used for both FMCW-LiDAR (using the TCS region) and RMCW-LiDAR (using the post-TCS region). The hybrid LiDAR system can be synchronized through time-division multiplexing. Additionally, the RMCW-LiDAR measurement results can be used to adjust the length of the FMCW-LiDAR reference arm, thus facilitating fine ranging within the measurement range limited by the detection bandwidth.

We proposed a novel hybrid LiDAR system that leverages a unique combination of the transient coherence and long-term chaos in the FDML output. The hybrid LiDAR experimental setup is illustrated in Extended Data Fig. 1(a) and described in the Methods section. Section 5.1 of the Supplementary discusses the measured point spread functions (PSFs) of the RMCW-LiDAR and FMCW-LiDAR. This hybrid LiDAR scheme can achieve micron-scale resolution and kilometer-scale measurable range. As a proof of concept, we took morphological measurements of five laser-engraved English letters (POLYU), as shown in Extended Data Fig. 1(b). The inter-letter height difference is 0.5 mm. First, we used the chaotic laser signal from the TCS-FDML region at the 400th roundtrip to perform a preliminary morphological measurement with the RMCW-LiDAR, as shown in Extended Data Fig. 1(c). However, the low resolution and sensitivity of the RMCW-LiDAR resulted in an incomplete measurement, which failed to show the height differences between the letters and their round edges, which have lower reflectivity. Nevertheless,

the RMCW-LiDAR successfully localized the letters at approximately 2×25 m relative to the local reference beam. Then, we refined the measurement by adjusting the delay of the reference beam to bring the OPD of the interferometer within the measurement range of the FMCW-LiDAR. Extended Data Figure 1(d) shows the fine morphological measurements obtained through FMCW-LiDAR using the coherent laser signal within the TCS-FDML region at the 400th roundtrip. The enhanced sensitivity and resolution result in an accurate measurement of the height differences among the letters, and an image of all five letters. The dark circles on the morphological map are the M6 threaded holes on the optical platform that have no reflection signal.

Universality. FDML lasers accumulate frequency shifts deterministically due to dispersion (inset Fig. 1(c)) and operate in long-term unstable states. Other lasers operating in long-term unstable states with TCSs^{13, 18, 19} may also benefit from using the TCS. Furthermore, we demonstrate that adopting TCS operation mitigates the deleterious effects of mode hopping in self-injection-locked (SIL) distributed-feedback (DFB) lasers, which have long-term stable states. This shows the universality of TCS use.

Figure 2(a) in the Extended Data shows the experimental setup of a SIL-DFB laser and a heterodyne detection system that was used to capture the mode-hopping dynamics. Section 6.1 of the Supplementary provides a detailed schematic illustrating the mode-hopping dynamics in the SIL-DFB laser. Fig. 2(b) in the Extended Data shows the evolution of the modes of a conventional SIL-DFB laser over the course of an hour, during which the frequency (blue curve) of the SIL-DFB laser drifts by around 300 MHz. The gray curve shows the mode count. Each time the beat frequency jumps, and a mode-hopping event occurs, the mode count is either 2 or 3, indicating a mode-competition event. Visualization 2 shows the detailed evolution of one hour of mode hopping in a conventional SIL-DFB laser.

Currently, reported countermeasures against mode hopping, such as stringent constant-temperature vibration isolation² and the Pound-Drever-Hall

technique-based locking technique⁵⁴, are aimed at avoiding or compensating for thermal effects. While these countermeasures are effective, like the extremely well-dispersion-compensated FDML laser, their widespread application is limited by engineering difficulties. Inspired by the TCS concept, we propose resetting the pump power of the SIL-DFB laser before thermal effects accumulate in the optical feedback loop and cause mode hopping. The constant mode count (grey curve) of one in Fig. 2(c) of the Extended Data shows that mode hopping occurs significantly less frequently. Each time the SIL-DFB laser is reset, the new operating lasing mode may differ from the previous one, as indicated by the stepped frequency (blue curve) in Fig. 2(c) of the Extended Data. Here, we adopt a fixed resetting period. In the future, an adaptive algorithm could be developed to adjust the resetting period to further reduce the likelihood of mode hopping. The buildup dynamics of the SIL-DFB laser are discussed in Section 6.2 of the Supplementary. Visualization 3 and Section 6.3 of the Supplementary show the detailed one-hour evolution of a periodically reset SIL-DFB laser.

Conclusion

In summary, we introduce and experimentally demonstrate a transient coherent state (TCS) operating paradigm for lasers. Although stronger pumping and longer cavities are natural routes to higher output power and narrower linewidth, in practice, they often perturb the intracavity equilibrium required for coherent emission, thereby degrading laser coherence. We show that, before this equilibrium collapses, the laser build-up dynamics pass through the TCS, which can be deterministically reproduced by resetting the pump. Implemented in an FDML laser, the TCS transforms a conventionally poorly coherent long-cavity source with an intrinsic linewidth of 13.2 GHz into a highly coherent swept source with an intrinsic linewidth of 18.9 Hz, corresponding to a reduction of nearly nine orders of magnitude. With a repetition rate of approximately 50 kHz and high coherence, the TCS-FDML laser achieves a record-high measurable

range of 11.2 m. To eliminate drift in the cavity length of the FDML laser and the FFP-TF, we used the residual phase jitter (RPJ) waveform within the TCS-FDML region as an internal reference. We demonstrated turnkey initialization in 60 seconds and long-term operational stability of up to 24 hours. We developed a novel hybrid LiDAR using the stabilized TCS-FDML laser that simultaneously achieves micron-scale resolution and kilometer-scale range by using coherent and chaotic laser signals within and outside the TCS-FDML region.

The suppression of mode-hopping in a self-injection-locked DFB laser shows that the TCS concept can be applied to other complex photonic systems. These systems include integrated frequency combs⁹ and broad-area semiconductor lasers¹⁰. The former has long-term stable states, though environmental disturbances affect the stability of the laser output, and the latter operates in a long-term unstable state. Our work demonstrates the practical applications of transient laser dynamics.

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Author Contributions Statement

W.Z., L.D., and D.H. conceived the idea of the experiment. W.Z. and Y.S.

constructed the laser system. W.Z. and L.D. performed theoretical simulations. Q.Z., D.H., F.L., and P.W. provide guidance and support. Measurements were performed by W.Z., with assistance from L.D., D.H., F.L., and P.W. Analysis of the results was conducted by W.Z., L.D., D.H., F.L., and P.W. The manuscript was written by W.Z., L.D., Q.Z., D.H., and P.W., with input from all other authors. D.H. supervised the project.

Competing Interests Statement

The authors declare no competing interests.

The diagram illustrates a TCS-FDML system. The main setup includes a Fiber Ring Modulator (FRM), Dispersion Shifted Fiber (DSF), Coupler Isolator (CIR), Fiber Power Coupler (FPC), Optical Coupler (OC), Mach-Zehnder Interferometer (MZI), Feedback Control Loop, Bragg Resonator (BRD), Frequency-to-Pulse Transformer (FPP-TF), LUNA, Isolator (ISO), Semiconductor Optical Amplifier (SOA), and an AWG. A 2D color map (d) shows the evolution of the signal over roundtrips (0 to 1000) and fast time (0 to 10 μ s), divided into three regions (I, II, III). Insets (a) and (b) show time and frequency shifts versus wavelength, highlighting 'Sweet spots'.

Figure 1 Schematic of the FDML laser in the TCS. The laser signal is built up shortly after the semiconductor optical amplifier (SOA) is turned on by the periodic square wave signal from an arbitrary waveform generator (AWG). However, each time the laser signal completes a roundtrip in the cavity, its frequency shifts due to the chromatic dispersion of the long cavity. The TCS-FDML laser's feedback control system consists of a Mach-Zehnder interferometer (MZI) with an optical path difference (OPD) of 126 mm; a balanced photodetector (BPD) to detect the interference signal; an oscilloscope (OSC); a feedback control algorithm operated in a personal computer (PC); and an AWG to control the SOA and the FFP-TF. FRM: Faraday Rotator Mirror; DSF: dispersion-shifted fiber; CIR: circulator; FPC: fiber polarization controller; OC: optical coupler; ISO: isolator. Inset: (a) Time shift and (b) frequency shift, where the zero crossing points are the sweet spots (marked by light blue dashed lines and purple circles). (c) The spectrum evolution of the laser signal between the two sweet spots at the 150th, 250th, and 450th roundtrips. (d) The accumulated frequency shift, where the white contour line corresponds to the time at which the frequency shift reaches the bandwidth of the FFP-TF. Stage I: The build-up stage, II: The transient coherent state. III: The unstable state.

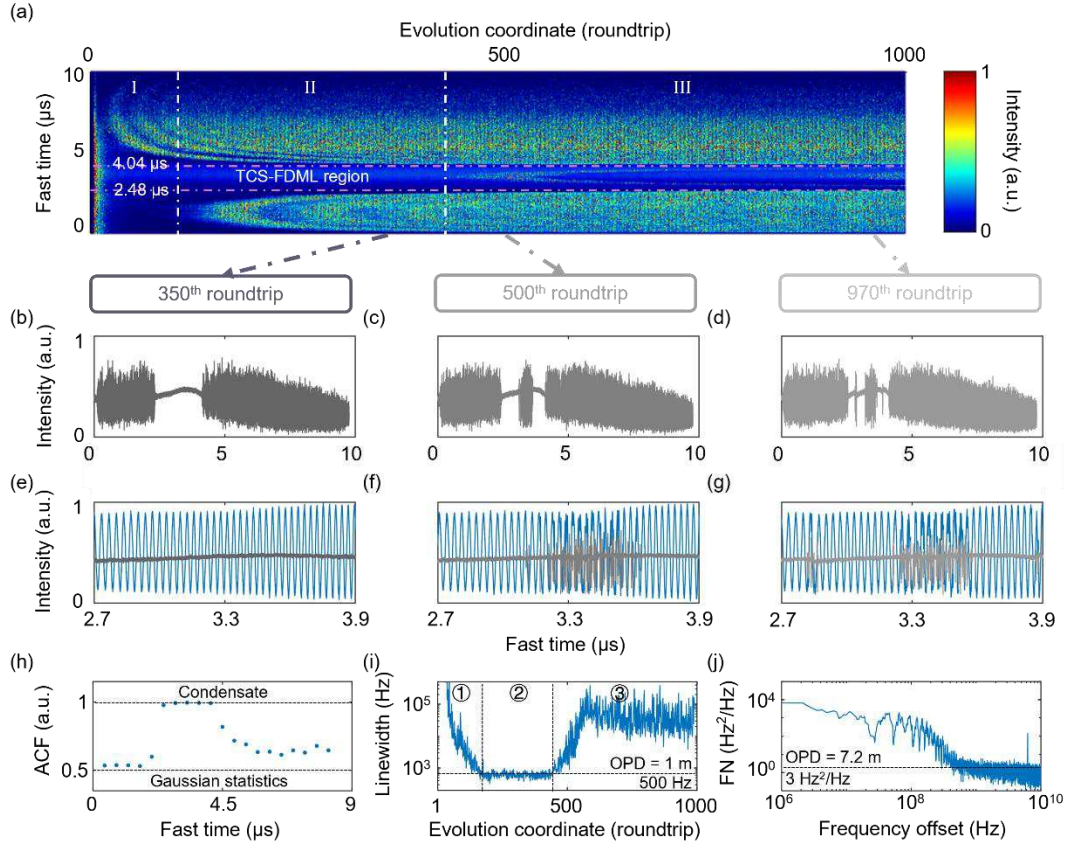


Figure 2 Experimental evolution dynamics and statistical analysis of the FDML laser. (a) Turn-on dynamics during the backward sweep. The white dot-dashed vertical lines divide the turn-on dynamics into three stages: I, Build-up stage. II, Transient coherent stage. III, Unstable stage. The purple dot-dashed lines mark the location of the sweet spots. The temporal waveform of the laser signal at the (b) 350th, (c) 500th, and (d) 970th roundtrip, respectively. The zoomed-in temporal waveform (gray) and interference signal (blue) of the laser signal between 2.7 μs and 3.9 μs at the (e) 350th, (f) 500th, and (g) 970th roundtrip. (h) The autocorrelation function (ACF) background level was measured with a 40 ns delay at the 400th roundtrip. For a completely coherent state, the ACF level approaches 1. The ACF level approaches 0.5 for stochastic radiation. (i) The evolution of the intrinsic linewidth as a function of the number of roundtrips. The optical path difference (OPD) is about 1 m in the optical fiber. (j) The instantaneous frequency noise power spectral density (FNPSD) of the laser signal within the TCS-FDML region between 2.48 μs and 4.04 μs at the 400th roundtrip. The OPD for the interference signal is around 7.2 m in the optical fiber.

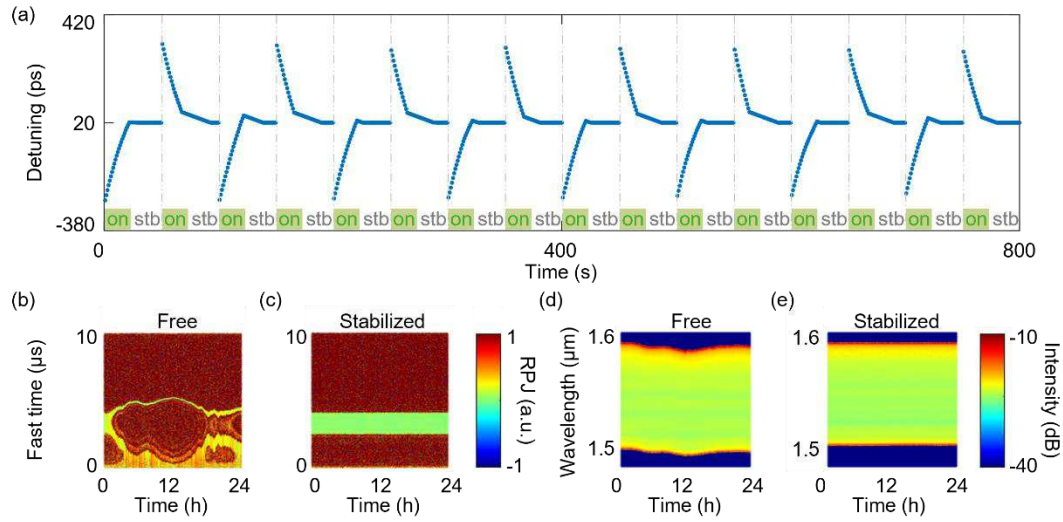


Figure 3 Initialization and stabilization of the FDML laser by feedback control. (a) Initialization of the FDML laser. Each time the FDML laser is initialized, it undergoes a significant detuning of around ± 350 ps (stb: stabilized). The RPJ at 400th roundtrip in the FDML laser over 24 hours (b) without and (c) with feedback control. The optical spectrum of the output signal from the FDML laser over 24 hours (d) without and (e) with feedback control.

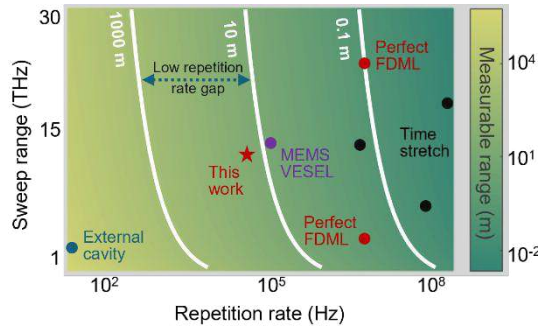
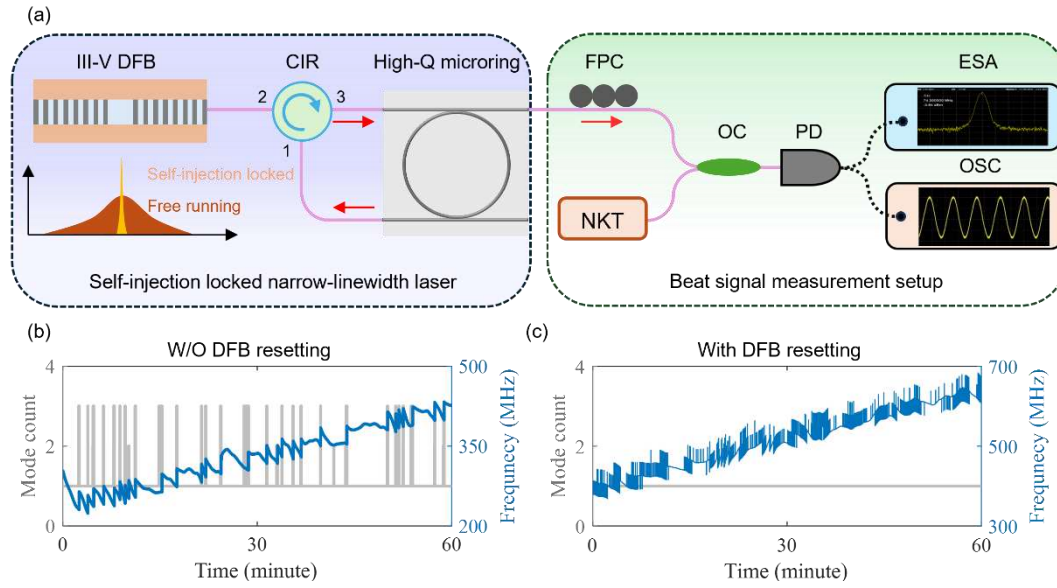


Figure 4 Comparison of the measurable range of WSLs with the THz-level sweep range. This work is indicated by a red star. The coherent sweep range of this study is 2.5 THz. With partial dispersion compensation and a tolerance of 20 ps, a full sweep range of 11.4 THz can be achieved in future studies.



Extended Data Figure 2 Experimental setup and results for the self-injection-locked (SIL) distributed-feedback (DFB) laser. (a) Experimental setup of the SIL-DFB laser and the heterodyne detection system. CIR: circulator; FPC: fiber polarization controller; OC: optical coupler; PD: photodetector; ESA: electrical spectrum analyzer; OSC: oscilloscope. Mode count (gray) and frequency (blue) of the beat signal (b) without (W/O) and (c) with DFB resetting within one hour.

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Methods

FDML laser configuration. The FDML laser consists of a Fabry-Pérot tunable filter (FFP-TF, LUNA Innovations) with a finesse of 1469 and a bandwidth of 16 GHz, a semiconductor optical amplifier (SOA, Thorlabs BOA1004S), and ~2.031 km of dispersion-shifted fiber (DSF, AT&T) with a zero-dispersion wavelength of 1562 nm and a slope of 0.08 ps/(nm²·km). An optical circulator (CIR) and a Faraday mirror (FRM) form a double-pass optical path. Two optical isolators (ISO) ensure unidirectional laser operation. A polarization controller (PC) optimizes the polarization state. 20% of the intra-cavity energy is output by an optical coupler (OC). The Newport Model 325 and 525B provide temperature control and driving current for the SOA, respectively. The FFP-TF and the pump current are modulated by a sinusoidal signal and a square signal generated by an arbitrary waveform generator (AWG, Keysight 33600A). The frequencies of these signals are coupled at a ratio of 1000, and their phases are synchronized. The duty ratio of the square signal is 99.5%. The center wavelength of the FDML laser is 1542 nm, and the wavelength sweep range is 90 nm. For the TCS-FDML region, the center wavelength and wavelength sweep range are 1562 nm and 20 nm, respectively.

Measurement system configuration. The optical spectrum is recorded by an optical spectrum analyzer (OSA, Yokogawa AQ6374). The optical signals are converted into electric signals by three balanced photodetectors (BPDs): PDB480C (Thorlabs), BPDV2120R (Coherent), and BPDV3120R (Coherent). Their respective bandwidths are 1.6 GHz, 43 GHz, and 70 GHz. PDB480C detects the interference signals for Figs. 2(e)-2(g) and Fig. 3a-c. BPDV2120R is used to detect the temporal waveforms for Figs. 2(b)-(2g), the interference signals for Figs. 2(h)-2(j), and the temporal waveforms for RMCW-LiDAR. The interference signals for Fig. 2(i) and the PSF for the FMCW-LiDAR are detected by BPDV3120R. The electric signals from the BPDs are recorded by an oscilloscope (OSC, Tektronix DPO77002SX). To record the temporal waveform

and most of the interference signal, channels 1 and 3 of the OSC with a bandwidth of 33 GHz are used. To record the interference signal of Fig. 2(i) and the PSF of the FMCW-LiDAR, channel 2 of the OSC with a bandwidth of 70 GHz is used.

Hybrid LiDAR configuration. In the RMCW-LiDAR, balanced detection is disabled. The relative temporal delay τ between the reference and probe beams is demodulated through autocorrelation analysis of the chaotic laser signal outside the TCS-FDML region. The coarse-ranging result of the distance D is derived by $D = c\tau/2$, where c is the speed of light. Next, the distance D from the RMCW-LiDAR is used to adjust the length of the reference arm by controlling the optical switch (OS). In the FMCW-LiDAR, the fast Fourier transform (FFT) is performed on the interference signal within the TCS-FDML region to demodulate the frequency f . The fine-ranging result is calculated using the relation $D = (fc)/(2\gamma)$, where γ is the chirp rate. The laser beam is focused on the letters via a lens assembly (LSM03 and F260APC-1550, Thorlabs). A motorized stage performs two-dimensional scanning with a step size of 0.25 mm, resulting in 408×100 pixels for the morphological measurement.

Data availability

The data related to this study are available under restricted access for data privacy law. The size of the data has exceeded the limit of public data repository. Access can be obtained by reasonable request to the corresponding author.

Code availability

The code related to this study is available upon reasonable request to the corresponding author.

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