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Spatiotemporal chaos synchronisation in broad-area lasers

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Abstract

Experiments on the unidirectional injection of broad-area vertical-cavity surface-emitting lasers demonstrate the synchronisation of fast spatiotemporal chaos and slow polarization-hopping dynamics under conditions of spectral alignment of the dominant transverse modes. These findings pave the way for high-capacity secure communications and massively parallel information processing enabled by spatial division multiplexing.

Keywords: Spatiotemporal dynamics, Chaos synchronisation, Semiconductor lasers

Chaos is a complex dynamic state in nonlinear systems characterised by noise-like temporal waveforms that exist widely in various fields. Chaos synchronisation[1] is a fascinating phenomenon in which nonlinear oscillators generate correlated complex waveforms through coupling, forming the cornerstone of chaos theory and its applications. Synchronisation in temporal chaotic systems has been investigated extensively, especially in optical systems[2,3] with fast time scales, which have shaped many important applications such as high-speed secure communication[4–9], fast physical key distribution[10,11], and photon information processing[12].

The synchronisation of spatiotemporal chaos in spatially extended nonlinear systems has emerged as a pivotal research direction owing to its promise of unleashing richer dynamical behaviours and enabling transformative applications such as parallel secure communication and high-performance computing. Spatiotemporal chaos synchronisation has been experimentally observed in natural systems such as ecological networks[13] and chemical reactions[14]. However, this remains underexplored in artificial systems, which have immense practical potential for advancing chaos-based technologies. Specifically, theoretical studies have predicted that systems such as map lattices[15] and optical ring cavities[16] can achieve spatiotemporal chaos synchronisation; however, experimental validation is still lacking. Although experimental spatiotemporal chaos synchronisation has only been realised in nonlinear optical systems based on liquid crystal devices[17–19], their timescales are too slow to meet the demands of high-speed information transmission and processing applications.

Recently, Mercadier et al. made a major contribution to the experimental realisation of fast spatiotemporal chaos synchronisation in laser systems[20]. Their experiments used broad-area vertical-cavity surface-emitting lasers (BA-VCSELs) with a circular output aperture of 15-μm diameter, which have multiple transverse modes, longitudinal modes, and two orthogonal polarisation modes, and can generate complex dynamics owing to mode competition[21]. The two lasers were coupled by unidirectional and polarisation-parallel injections in the master-slave configuration, as shown in Fig. 1. The master

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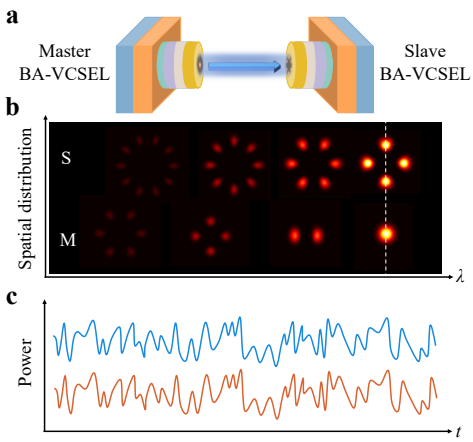

Fig. 1 Spatiotemporal chaos synchronisation of BA-VCSELs in master-slave configuration, achieved as spectral alignment between the dominant transverse modes.

laser was operated separately in two different dynamic states: the coexistence of fast irregular oscillation and low-speed polarisation hopping (approximately 100 MHz), and fast chaotic oscillation (spectrum coverage up to 20 GHz). Chaotic, polarisation-hopping, and inverse synchronisations were observed by carefully adjusting the operating current or temperature of the slave laser. The synchronisation coefficients of fast chaos were generally below 0.2, which is far lower than that of polarisation-hopping dynamics. This highlights the challenge of broadband chaos synchronisation being sensitive to laser parameter mismatches.

By exploiting the spectral separation characteristics of laser transverse modes, the authors experimentally investigated the effects of the transverse mode wavelength and spatial pattern on the synchronisation quality. A key finding is that the synchronisation of spatiotemporal laser dynamics can be achieved when a strong transverse mode of the master laser spectrally aligns with a transverse mode of the slave laser, even in the absence of identical spatial patterns. Particularly, as the dominant transverse mode of the master laser splits into two distinct spatial orientations that are (anti)symmetric about the symmetry axis, the spectrally aligned transverse modes of the slave laser can be excited in either or both orientations. The strongest synchronisation occurs when both orientations of the slave laser mode are excited. This demonstrates that the spatial patterns of the laser transverse mode also play an important role in chaos synchronisation.

This study provides the first experimental evidence and opens new perspectives for the spatiotemporal chaos synchronisation of lasers. This also suggests that broad-area VCSELs can be an ideal research platform for complex spatiotemporal dynamics owing to their small size and intrinsic dynamics. Further in-depth theoretical investigations and more precise explorations of synchronisation scenarios for coupled spatiotemporal lasers are required. It is also necessary to explore parallel temporal chaos synchronisation involving multiple transverse modes and further study synchronisation in spatial dimensions. The results of this work also highlight the importance of laser design in optimising the chaos synchronisation quality.

This study is also likely to inspire new studies on the application of spatiotemporal laser dynamics, especially in the field of secure communication. Spatiotemporal chaos synchronisation is expected to advance high-capacity secure communication to meet the needs of 5G/6G communication. It is also expected to provide a solution for multi-user secure communication, which is challenging for temporal chaotic systems. Furthermore, secondary research interests, such as long-distance synchronisation[22] and flexible mode control of spatiotemporal laser chaos have been stimulated.

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Data availability

All data are available from the corresponding authors upon reasonable request.

Conflict of interest

The author declares no competing interests.

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References

1. Pecora, L. M. & Carroll, T. L. Synchronization in chaotic systems. *Physical Review Letters* **64**, 821-824 (1990).
2. Sciamanna, M. & Shore, K. A. Physics and applications of laser diode chaos. *Nature Photonics* **9**, 151-162 (2015).
3. Soriano, M. C. et al. Complex photonics: dynamics and applications of delay-coupled semiconductors lasers. *Reviews of Modern Physics* **85**, 421-470 (2013).
4. Vanwiggeren, G. D. & Roy, R. Communication with chaotic lasers. *Science* **279**, 1198-1200 (1998).
5. Argyris, A. et al. Chaos-based communications at high bit rates using commercial fibre-optic links. *Nature* **438**, 343-346 (2005).
6. Spitz, O. et al. Private communication with quantum cascade laser photonic chaos. *Nature Communications* **12**, 3327 (2021).
7. Didier, P. et al. Data encryption with chaotic light in the long

wavelength infrared atmospheric window. *Optica* **11**, 626-633 (2024).
8. Mao, X. X. et al. 100-Gbit/s 100-km physical-layer secure fiber-optic communication using wideband chaotic semiconductor lasers. *Journal of Lightwave Technology* **43**, 2176-2183 (2025).
9. Xie, Y. H. et al. 100 Gb/s coherent chaotic optical communication over 800 km fiber transmission via advanced digital signal processing. *Advanced Photonics Nexus* **3**, 016003 (2024).
10. Yoshimura, K. et al. Secure key distribution using correlated randomness in lasers driven by common random light. *Physical Review Letters* **108**, 070602 (2012).
11. Gao, H. et al. 0.75 Gbit/s high-speed classical key distribution with mode-shift keying chaos synchronization of Fabry-Perot lasers. *Light: Science & Applications* **10**, 172 (2021).
12. Mihana, T. et al. Laser network decision making by lag synchronization of chaos in a ring configuration. *Optics Express* **28**, 40112-40130 (2020).
13. Blasius, B., Huppert, A. & Stone, L. Complex dynamics and phase synchronization in spatially extended ecological systems. *Nature* **399**, 354-359 (1999).
14. Hildebrand, M. et al. Synchronization of spatiotemporal patterns in locally coupled excitable media. *Physical Review E* **68**, 026205 (2003).
15. Xiao, J. H., Hu, G. & Qu, Z. L. Synchronization of spatiotemporal chaos and its application to multichannel spread-spectrum communication. *Physical Review Letters* **77**, 4162-4165 (1996).
16. García-Ojalvo, J. & Roy, R. Spatiotemporal communication with synchronized optical chaos. *Physical Review Letters* **86**, 5204-5207 (2001).
17. Rogers, E. A. et al. Generalized synchronization of spatiotemporal chaos in a liquid crystal spatial light modulator. *Physical Review Letters* **93**, 084101 (2004).
18. Ramazza, P. L., Bortolozzo, U. & Boccaletti, S. Experimental synchronization of spatiotemporal chaos in nonlinear optics. *Physical Review E* **73**, 036213 (2006).
19. Havermann, K., Gütlich, B. & Denz, C. Synchronisation of spatiotemporal complex states by incoherent coupling. *Journal of the European Optical Society-Rapid Publications* **3**, 08001 (2008).
20. Mercadier, J. , Bittner, S. & Sciamanna, M. Synchronization of complex spatio-temporal dynamics with lasers. *Light: Science & Applications* **15**, 131 (2026).
21. Bittner, S. & Sciamanna, M. Complex nonlinear dynamics of polarization and transverse modes in a broad-area VCSEL. *APL Photonics* **7**, 126108 (2022).
22. Wang, A. B. et al. Experimental demonstration of 8190-km long-haul semiconductor-laser chaos synchronization induced by digital optical communication signal. *Light: Science & Applications* **14**, 40 (2025).