Topological Mode-Locked Laser with Intracavity Couplings

Christian Leefmans[1], Midya Parto[2], James Williams[2], Avik Dutt[3], Franco Nori[4,5], Alireza Marandi[1,2]

[1]*Department of Applied Physics, Caltech, Pasadena, CA 91125, USA.*
[2]*Department of Electrical Engineering, Caltech, Pasadena, CA 91125, USA.*
[3]*Department of Electrical Engineering, Stanford University, Stanford, CA 94305, USA.*
[4]*Theoretical Quantum Physics Laboratory, RIKEN, Wako-shi, Saitama 351-0198, Japan.*
[5]*Department of Physics, University of Michigan, Ann Arbor, Michigan 48109-1040, USA.*
marandi@caltech.edu

Abstract: We experimentally realize a topological actively mode-locked laser by coupling the pulses with intracavity delay lines. Our work reveals a new regime of nonlinear topological photonics and has potential applications to short-pulse lasers.

Mode-locked lasers play an important role in modern science and technology and have myriad applications in both fundamental research and in industry. While the exceptional behaviors of topological lasers [1], including lasing in arbitrary cavity geometries, enhanced slope efficiencies, and improved spatial coherence, have been realized in the CW regime, mode-locked topological lasers have only been studied theoretically [2]. Here we synthesize the notions of point-gap topology, dissipative couplings, and active mode-locking to experimentally realize robust topological supermodes in a mode-locked laser. Our work reveals new opportunities to study fundamental non-Hermitian and nonlinear topological physics and provides a potential mechanism to enhance the peak powers of short-pulse actively mode-locked lasers.

A schematic of our topological mode-locked laser is shown in Fig. 1(a). Note that this system is similar to that used in our previous work to study topological dissipation in the linear regime [3]. The system consists of a laser cavity (labeled the "Main Cavity") and two delay lines, which introduce programmable time-delayed and time-advanced dissipative couplings between the pulses of the laser. We sinusoidally modulate the intensity modulator (IM) in the main cavity to produce $N = 64$ actively mode-locked laser pulses with pulse widths of ~ 100 ps [see Fig. 1(b,c)] and a repetition period of $T_{\text{rep}} \approx 4$ ns; and we set the lengths of the delay lines to produce nearest-neighbor couplings between the pulses. Because the lifetime τ of the erbium ions in our EDFA gain is much longer than the roundtrip time T_{RT} of our laser cavity ($\tau/T_{\text{RT}} \approx 10^5$), the EDFA gain saturates due to the average power in the cavity. In this collective gain saturation regime, we find that the steady-state temporal supermode of the mode-locked laser is the lowest-loss linear eigenstate defined by the dissipative couplings between the pulses. By engineering these couplings to implement point-gap topological lattice models [4], we drive our system into the quasi-edge modes and domain-wall modes that are characteristic of these non-Hermitian lattices. Moreover, the nonlinear process that drives this localization may be decomposed into nonlocal nonlinear interactions between the mode-locked laser pulses through the EDFA gain. Such nonlinear interactions have been challenging to achieve in photonics, and therefore our topological mode-locked laser presents opportunities to study a new regime of nonlinear topological photonics.

To highlight the ability of our topological mode-locked laser to expand the scope of what has be studied in topological photonic systems, we study a topological phase transition in the Hatano-Nelson (HN) model, which consists of a 1D chain with asymmetric nearest-neighbor couplings w and v [see inset of Fig. 1(g)]. This has not previously been realized in a photonic system. We program our dissipative couplings to realize the HN model with $w/v = \sqrt{2}$ and periodic boundary conditions (PBCs), for which the system has a nontrivial topological winding number. In the presence of PBCs, the power in the laser is evenly distributed among the pulses [see Fig. 1(f)]. We then abruptly switch the boundary conditions from PBCs to open boundary conditions (OBCs), for which the HN lattice exhibits the non-Hermitian skin effect (NHSE). Upon switching the boundary conditions, the laser undergoes a series of oscillations before finally settling into the lowest-loss quasi-edge mode of the HN lattice [Fig. 1(d)]. As shown in Fig. 1(e), the theoretical and experimental quasi-edge modes are in excellent agreement. In addition, the flexibility of our laser's dissipative couplings enables us to study the localization of the HN quasi-edge mode for boundary conditions intermediate to OBCs and PBCs. In Fig. 1(g), we plot the measured inverse participation ratio (IPR) of the steady-state quasi-edge mode as a function of the boundary conditions for an HN lattice with $w/v = \sqrt{2}$.

Next, we study domain wall localization in the HN model. First, we program the laser's dissipative couplings

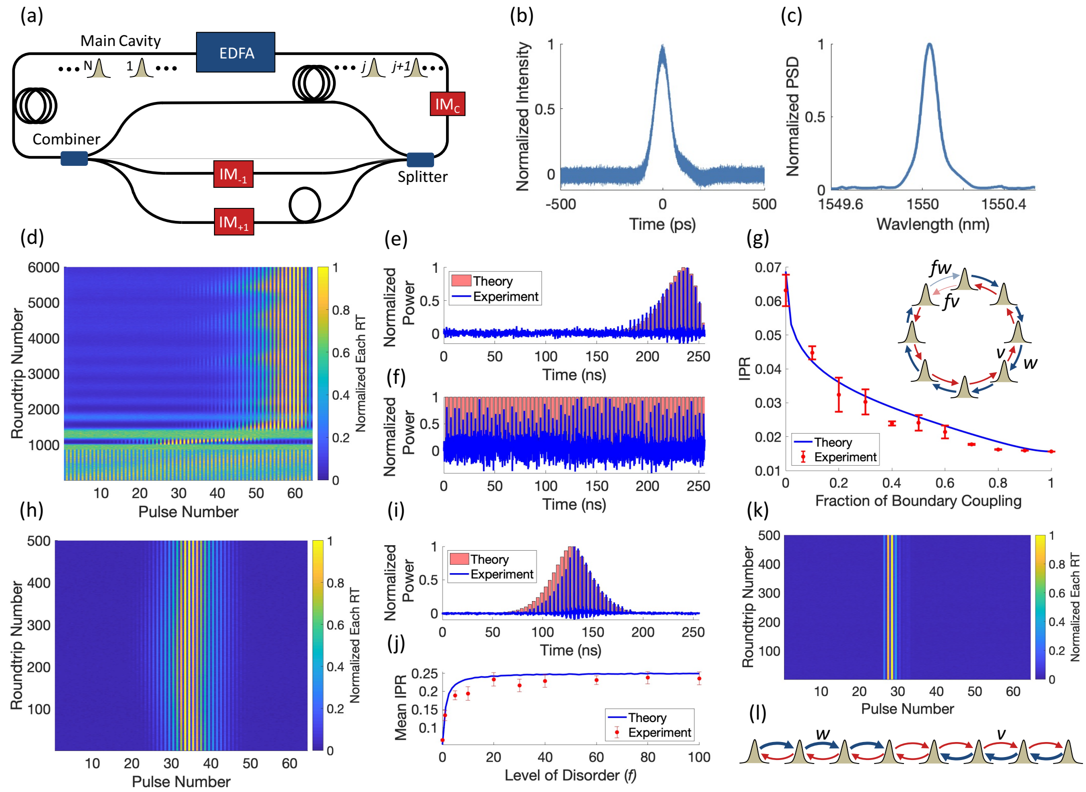

Fig. 1: **(a)** Schematic of mode-locked laser. **(b)** Mode-locked pulse in the time-domain. **(c)** Power spectral density of mode-locked pulse. **(d-f)** Non-Hermitian topological phase transition. **(g)** Quasi-edge mode localization vs. boundary conditions. **(h,i)** HN domain wall lasing with no additional disorder. **(j)** Mean IPR as a function of disorder. **(k)** Example of localization with disorder level $f = 100$. **(l)** Depiction of an HN domain wall.

to realize a domain wall between two inverted HN lattices [see Fig. 1(l). In this case, we find that the power in the mode-locked laser localizes in the pulses centered at the domain wall [see Fig. 1(h,i)]. We then introduce disorder into each of our dissipative couplings by adding disorder drawn from Unif$(0, fw)$, where f is the level of the disorder. Note that this disorder, which is drawn independently for the two delay lines, is fundamentally non-Hermitian. Moreover, this type of disorder stands in stark contrast to previous studies of non-Hermitian disorder [5], which considered disorder in the on-site gain and loss. As we increase the level of coupling disorder, we find that the domain wall localization gives way to disorder-induced localization. Evidence of this transition is shown in Fig. 1, where we show how the average localization of the laser steady-state changes as a function of disorder [see Fig. 1(j)] as well as an experimental observation of lasing in a lattice with strong disorder [see Fig. 1(k)]. Note that the localized state in Fig. 1(k) is no longer located at the domain wall, which indicates that the localization is a result of the coupling disorder and not the NHSE.

In summary, we have introduced topological mode-locked laser with intracavity couplings and experimentally demonstrated novel nonlinear topological phenomena. Our results expose new possibilities for the study of nonlinear topological physics and may have practical applications to the design of short-pulse lasers.

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