Towards the Experimental Realization of the Topological Insulator Laser

S. Wittek[1*], G. Harari[2], M. A. Bandres[2], H. Hodaei[1], M. Parto[1], P. Aleahmad[1], M.C. Rechtsman[3], Y. D. Chong[4], Demetri N. Christodoulides[1], Mercedeh Khajavikhan[1], and Mordechai Segev[2]

1 *CREOL – College of Optics and Photonics, University of Central Florida, Orlando, Florida, USA*
2 Physics Department and Solid State Institute, Technion, 32000 Haifa, Israel
3 Department of Physics, The Pennsylvania State University, University Park, Pennsylvania 16801, USA
4 School of Physical and Mathematical Sciences, Nanyang Technological University, 21 Nanyang Link, Singapore 637371, Singapore
* *switttek@knights.ucf.edu*

Abstract: We propose a practical design to implement of a topological insulator laser. Due to the topological protection, the topological laser maintains a high slope efficiency and single mode lasing even in the presence of defects and disorder.

OCIS codes: (140.0140) Lasers and laser optics; (140.3460) Lasers; (140.3410) Laser resonators; (240.0240) Optics at surfaces

The discovery of topological phases of matter had far reaching implications in condensed matter physics ranging from quantized electronic conductance [1,2] to photonics [3–6]. The topological phase is characterized, and affected by ability to transform one system into another via adiabatic transformations. The interface between media of different topology has edge states that bridge the topology gap, giving rise to topologically protected transport along the edges, immune to local disorder and defects. A topological insulator is a material which is an insulator in the bulk, but has a topologically protected edge conductance. In two dimensions this edge conductance manifests itself in unidirectional scatter-free edge currents. In electromagnetism, the first topological systems were the analogues of the quantum Hall effect, utilizing strong magnetic fields in microwave frequencies in gyro-optics media [3]. More recently, photonic topological insulators were demonstrated at optical frequencies in a modulated photonic lattice [4] and in silicon ring resonators arrays [5]. In these systems light was shown to propagate unidirectionally on the edge even under large disorder and strong defects.

Recently, we introduced the concept of a topological insulator laser [7], a laser whose lasing mode is a topologically protected edge mode. The laser system is an array of microring resonators, with coupling between rings designed to follow a topological model (e.g., the Haldane model [2]). By setting the gain on the edge of a topological array, we make the topological edge mode to lase first. This has very profound implications in the features of the laser system. First, since the topological edge modes are always extended over the perimeter of the cavity - they maintain a high overlap with the gain profile. This translates into a very high slope efficiency. Second, since the topological edge state is robust to disorder - it remains extended and does not localize even in the presence of disorder. Third, the topological edge state always couples well to the output port. In this way, the topological insulator laser is robust to disorder and defects and retains its high slope efficiency even in the presence of large disorder and defects. This is in contrast to non-topological lasers whose modes tend to localize under disorder and this prevents them from using all the pump power, resulting in a strong decrease of slope efficiency in the presence of disorder. Finally, since the topological modes are extended - the lasing mode spatially depletes the gain in the system and thus suppresses any other modes in the system even at very high gain values, achieving exceptionally robust single mode lasing. *Given the promising predictions, it is natural to ask, can we realize such a topological laser? Can we avoid the need to break time-reversal symmetry (TRS)?* This question is especially important since the Haldane model inherently relies on breaking time-reversal symmetry.

Here we present a new design for a topological insulator laser, geared towards experimental realization. The design is based on coupled laser-resonators array (similar to that in [5]). It is experimentally feasible with current semiconductor lasers technology [8] and does not require breaking time reversal symmetry. Each ring can accommodate two modes, clockwise (CW) and counterclockwise (CCW), a manifestation of the unbroken TRS. However, in the topological phase this symmetry is spontaneously broken due to the inherent nonlinearity (gain saturation, as in any laser system) and the exactly overlapping spatial extent of the modes, resulting in depletion of the gain by the winning mode, suppressing all modes by the first mode to lase. Figure 1 shows the geometry of the design from preliminary samples we have fabricated. (a) Shows the array of resonators (circular waveguides) and links (oval waveguides adjacent to the resonators). The resonators and links are coupled through evanescent waves. By slightly shifting the links between two rows, a CW (CCW) mode picks up an overall phase upon hopping in a closed circuit (CCW mode picks up exactly the negative phase), similar to the effect of a magnetic field (of different sign between the CW and CCW modes) [7]. Figure 1 (b) and (c) shows a SEM image of the structure. The waveguides are made of InGaAsP (indium-gallium-arsenide-phosphide) quantum wells with non-linear (saturable) optical gain. The trivial and topological phases in this design differ by the shifting of the link, in the trivial phase the links are always positioned in the same place with respect to the resonators.

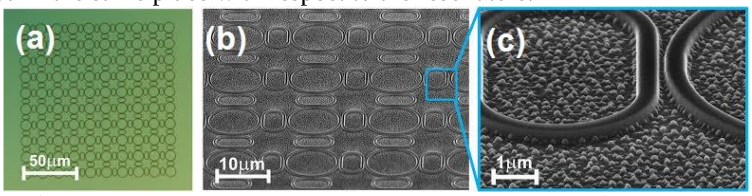

Figure 1: : (a) Microscope image of the topological insulator laser structure. The array is the cavity of the laser, consisting of resonators (circular waveguides) evanescently coupled to each other via links (oval waveguides). (b) SEM image of the structures, one can notice the links from each row are a bit shifted, yielding an overall phase when hopping in a close contour (c) Higher resolution SEM image.

Figure 2 shows preliminary experimental indications of topological insulator lasing. (a) Shows the entire array, the pumped region is in blue (the edge). The interior sites are not pumped and therefore are lossy. The pumping profile is achieved by illumination through a mask. (b) The output power of the laser was measured for both topological and trivial micro-resonator arrays at different pump intensities. As indicated in 2 (b), we found that the topological arrangement has always a larger slope efficiency and lower lasing threshold than any of the non-topological arrays we tested. Their corresponding intensity profiles at similar output powers (indicated in Fig. 2 (b)) are depicted in Figures 2 (c) and (d). In this regard, while the occupation in the topological array is mostly in the gain region, the occupation in the trivial configuration considerably extends into the bulk as indicated in Fig. 2 (d). This explains the higher slope efficiency and lower threshold for the topological laser.

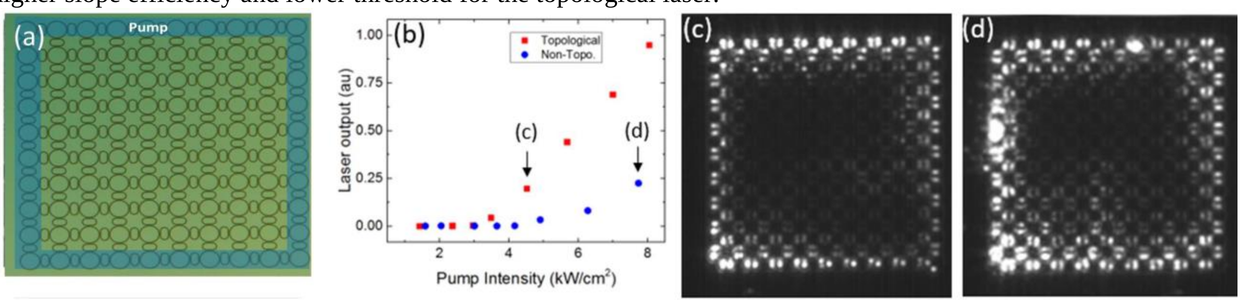

Figure 2: (a) Topological insulator laser pumping scheme. The blue region is the pumped area, the bulk (interior rings) is not being pumped and hence has some loss. (b) Light-light curves for non-topological (blue) and topological (red) micro-resonator arrays. Emission pattern for a topological (c) and non-topological pattern (d) at the pump intensities marked in (b). The mode resides mostly in the gain region in the case of the topological array.

In summary, we proposed a concrete design to realize the first topological insulator laser - a laser that lases in a topologically protected edge mode. The lasing mode is extended even in the presence of disorder and defects, yielding robust, high slope efficiency. Furthermore, the interplay between topology and non-linearity spontaneously breaks the CW/CCW symmetry, resulting in single mode lasing even at high levels of gain. Experimental demonstration is soon to follow, based on this realistic design, paving the way towards a new class of lasers.

[1] K. V. Klitzing, G. Dorda, and M. Pepper, Phys. Rev. Lett. 45, 494 (1980).
[2] F. D. M. Haldane, Phys. Rev. Lett. 61, 2015 (1988).
[3] Z. Wang, Y. D. Chong, J. D. Joannopoulos, and M. Soljacić, Nature 461, 772 (2009).
[4] M. C. Rechtsman, J. M. Zeuner, Y. Plotnik, Y. Lumer, D. Podolsky, F. Dreisow, S. Nolte, M. Segev, and A. Szameit, Nature 496, 196 (2013).
[5] M. Hafezi, S. Mittal, J. Fan, A. Migdall, and J. M. Taylor, Nat. Photonics 7, 1001 (2013).
[6] F. Gao, Z. Gao, X. Shi, Z. Yang, X. Lin, H. Xu, J. D. Joannopoulos, M. Soljačić, H. Chen, L. Lu, Y. D. Chong, and B. Zhang, Nat. Commun. 7, 11619 (2016).
[7] G. Harari, M. A. Bandres, Y. Lumer, Y. Plotnik, D. N. Christodoulides, and M. Segev, in CLEO. 2016, FM3A3.
[8] H. Hodaei, M. Miri, M. Heinrich, D. N. Christodoulides, and M. Khajavikhan, Science, 346, 975 (2014).