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Considerations for Electrically-Pumped Quantum Hall Effect Topological Laser Arrays

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***Abstract*—Recent demonstrations of topological lasers in the C-band based on emulation of the quantum Hall effect show possibility for low-threshold, highly-unidirectional lasers suitable for integrated photonics. Techniques for design and fabrication of electrically-pumped topological lasers arrays are presented.**

***Index Terms*—topological laser, semiconductor, III-V, photonics**

I. Introduction

Topological photonics is a rapidly growing area of research [1]. A significant breakthrough came with the demonstration of an optically-pumped topological laser (TL) [2]. This demonstration emulated the quantum Hall Effect (QHE) based on a synthetic gauge field resulting from the judicious shifting of the 'link' elements between the site resonators of the array [3]. The experimental demonstration matched theory [4] leading to a low-threshold robust edge mode when selective edge pumping was utilized. By including 'S-bends' within the site resonators, reciprocity was broken in the edge mode resulting in a highly unidirectional laser with 12 dB suppression between the left- and right-hand spins in the array. Prior non-reciprocal edge mode lasers required magnetic fields to break reciprocity [5].

While other TLs have been demonstrated in photonic crystals [6] and VCSELs [7], the TL based on the QHE is the most promising for integration. Here we look at the considerations relevant for current demonstrations of electrically-pumped TLs [8] as well as future implementations.

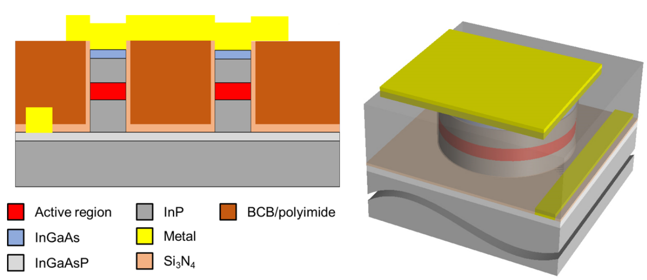

Fig. 1. (Left) Cross-section view of the edge resonators. (Right) Schematic of an individual ring resonator with a waveguide width of 1.4 μm radius of curvature of 15 μm at the edge of an array with electrical contacts.

II. Fabrication and Device Considerations

Initial QHE TL arrays were fabricated out of an InGaAsP MQW region that is clad in SiO_2 [2]. This requires substrate removal and bonding to a carrier substrate but leads to a convenient platform that results in a waveguide with a similar effective index as a 220 nm silicon photonics waveguide. Extending the QHE emulation to electrically-pumped arrays leads to significantly more processing that has been detailed elsewhere [8] but leads to three lithography steps, one dry etching step using $CH_4/H_2/Ar$ plasma, passivation of the etched sidewall, and surface planarization using polyimide, along with the two metallization steps for dual top side contacts. Additionally, the etch depth is now increased from ≈ 270 nm to nearly 1.8 μm for a similar active region design, see Fig. 1. This deeply etched profile leads to a larger minimum bend radius for an individual ring, $\approx 3\times$ larger than what can be achieved in the optically-pumped devices. Both top and bottom InP claddings keeps the modal overlap with the metal to a minimal level. Figure 2 shows the full chip for a fabricated chip containing TL arrays and test structures, and a single TL array at higher magnification, with dual top side contacts. Individual ring lasers fabricated as depicted can have quality factors of ≈ 10,000 or higher with sidewall angles near ninety degrees. However, various steps can lead to various defects and variations, or disorders, throughout the ring resonators within the array. With a quality factor this high, this leads to sparse spectral overlap of the resonators within the array. The sidewall angle and surface roughness can be tuned by the fabrication process to decrease the Q-factor (increase the linewidth) to improve the spectral overlap. Additionally, the resonator bend radius can be reduced but for a 1.4 μm waveguide width, the bend radius is $\approx 15\mu$m.

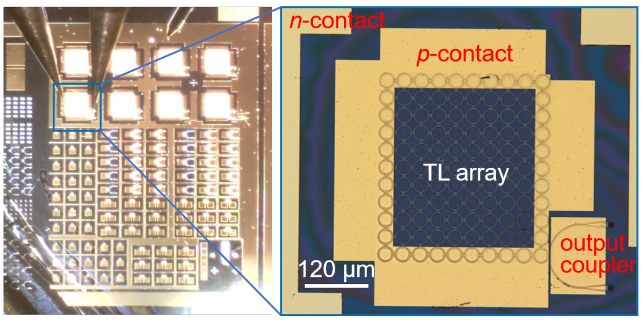

Fig. 2. (Left) Microscope image of fabricated chip imaging the top side contact and electrical probes. (Right) Individual TL array with 11x10 site resonators coupled via link rings at higher magnification.

III. Prospects for CW Operation

In current demonstrations of the QHE TL arrays and this work, the devices were operated at low duty cycles with pump pulse <0.5 μs. This keeps the regions that are selectively pumped from heating during the pump pulse. To achieve CW operation, not only does the disorder within the array need to be within limits, typically on the order of the coupling strength, but now the edge rings are heated significantly relative to the inner bulk rings. Just a ΔT of 10K within a ring leads to ≈ 1 nm shift, or ≈ 2× linewidth, in the resonance of the electrically-pumped ring resonator described above. The free spectral range (FSR) is ≈ 7.5 nm, thus tuning to a secondary resonance one FSR away purely from pumping is an unlikely option as it would still only offer operation over a limited range. Two coupled ring resonator lasers operating in CW with an individual output power of 300 μW prior to rollover, with lower thermal impedance in the active region has recently been reported [9]. It was shown that this device could operate with a gain contrast of up to 2×. Extending the gain contrast to higher levels within an array that has elements selectively pumped is still a challenge.

Heaters could be used to tune the detuned rings based on the steady-state resonance achieved at a desired pumping level. However, the thermal gradient both from selectively pumped rings and any heaters would require careful device design considerations.

An alternative path forward to CW operation is to emulate the anomalous QHE [10] rather than the integer QHE as has been demonstrated. The anomalous QHE array can utilize two sublattices consisting of different site resonators. This structure results in a single topological band gap centered on the average resonance of the two site resonators. The presence of topological states in the gap depends on the ratio between the detuning of the two sublattices and the hopping parameter between them. Therefore, the resonance disorder has a more subtle effect than in the QHE lattice. In a recent passive demonstration, the two resonators are made to be identical, however, detuning of up to 2× the coupling coefficient is found to be sustainable. Currently, this is on-par with the disorder found in fabricated devices but could aid in CW operation in the future. The presence of two sublattices could alternatively open possibilities for mode control and tunability via distributed gain and exceptional points, potentially aiding enabling a wider operation range under CW pumping.

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