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Topological Lasers with Epitaxially Grown InGaAs Nanowires on a SOI Substrate

Yongkang Gong, Cristian Messina, Stephan Wong, Oumaima Abouzaid, Bogdan-Petrin Ratiu, Qiang Li, and Sang Soon Oh*

School of Physics and Astronomy, Cardiff University, Cardiff, CF24 3AA, United Kingdom
Author e-mail address: OhS2@cardiff.ac.uk

Abstract: We report a semiconductor laser based on optical cavities formed by topologically distinct honeycomb lattice photonic crystals. Topological lasers, fabricated on SOI wafers by using a selective area epitaxy method, can have edge modes and bulk modes under optical pumping.

1. Introduction

Topological photonics have recently been proved a robust framework for manipulating light at wavelength scale [1]. Among many examples, time-reversal symmetric photonic topological insulators (PTIs) based on optical quantum spin Hall effect (QSHE) [2] or optical quantum valley Hall effect (QVHE) [3,4] have been widely studied because they can be made with dielectric materials only and can be easily integrated with other photonic devices. Whereas both QSHE and QVHE are based on passive systems, active topological photonics enable richer fundamental physics of nonlinear light-matter interaction and open a new landscape for various applications such as topological lasing [5,6].

In recent demonstrations of topological lasers, multiple-quantum-well structures have been used. Patterns such as rods, holes and ring resonators are formed using top-down approaches like electron beam (e-beam) lithography and dry etching. Although the top-down approaches are well-established, the quality of fabricated sample is very sensitive to the conditions of the e-beam writing and dry etching process and the aspect-ratio are limited. More importantly, it is challenging to form the active regions (which are mostly III-V semiconductors) on top of silicon substrates due to the large lattice mismatch between the III-V semiconductors and silicon.

In this work, we propose a new type of PTI lasers with honeycomb lattice photonic crystals (QSHE topological insulators) made of a 2D array of InGaAs nanowires. For experimental demonstration of lasing, we design InGaAs PTI lasers with band structure calculations and fabricate them using selective area epitaxy by metal organic chemical vapor deposition (MOCVD). We characterize the fabricated lasers with optical pumping and analyze the observed lasing mode with numerical simulations.

2. Topological Edge Mode Laser with Honeycomb Lattice

2.1 *Design of Topological Edge Mode Cavity*

The proposed all-dielectric topological laser is based on deformed (shrunken/extended) honeycomb lattice photonic crystals with high refractive index InGaAs nanowires ($n = 3.62$), which are arranged on a hexagonal lattice with primitive cell composed of six nanowires with the identical rod diameters ($D = 180$ nm) as shown in Fig. 1a. In this

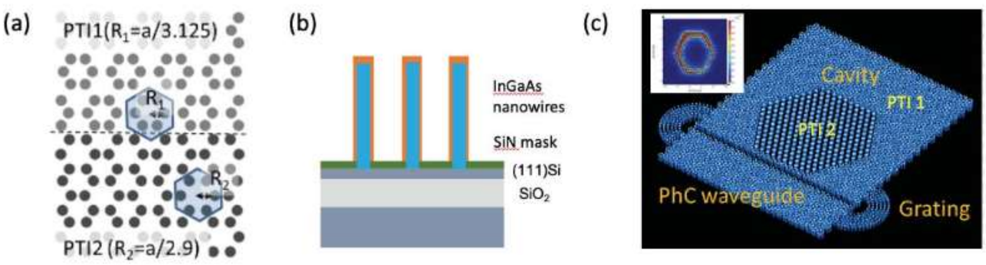

Fig. 1. (a) Honeycomb lattice with shrunken (extended) hexagons with the distance R_1 (R_2) in PTI1 (PTI2) and the lattice constant length of a. (b) Side view of InGaAs nanowire arrays on SOI substrates (c) Design of topological insulator cavity (inset) Electric field intensity profile of a cavity edge mode.

type of QSH PTIs, topological nontrivial modes exist and are controlled by changing the perturbation strength, i.e., by shifting six nanoholes closer (negative perturbation) or further away (positive perturbation) to each other. When the hole-to-center spacing (R) equals to the unperturbed hole-to-center spacing $R = a/3$, the photonic crystal is a typical honeycomb lattice featuring a Dirac cone at K and K′ points in the momentum space. A rod type structures can be designed using two-dimensional nanowire arrays as shown in Fig. 1b. The theory [2] and band structure numerical simulations ensures that edge modes exist between PTI1 and PTI2. Then, we can use the edge modes to design a hexagon-shaped cavity as shown in Fig. 1c. The cavity edge modes are obtained as shown in the inset of Fig. 1c. In addition to the edge modes, there can be topological bulk modes as reported in [7].

2.2 *Fabrication and Characterization of Topological Laser*

We fabricated the designed structure using selective area heteroepitaxy. A SiN mask is formed on top of SOI wafer on which nanoholes are patterned on the SiN mask using an e-beam lithography. InGaAs/InGaP core-shell nanowires are then grown by MOCVD. To improve the yield and uniformity of the nanowire arrays, we employed the flow-rate modulation epitaxy [8] at the beginning of InGaAs nanowire growth. The SEM images of fabricated samples are shown in Fig. 2a and 2b. The photoluminescence spectrum of the grown nanowires shows emission between 1000nm and 1350nm.

We further characterized lasing performance of the topological cavity. Room temperature optical pumping measurements were carried out with a pulse laser at wavelength of 633 nm. As shown in Fig. 2c, we observe the lasing peaks at the wavelength of 1248nm.

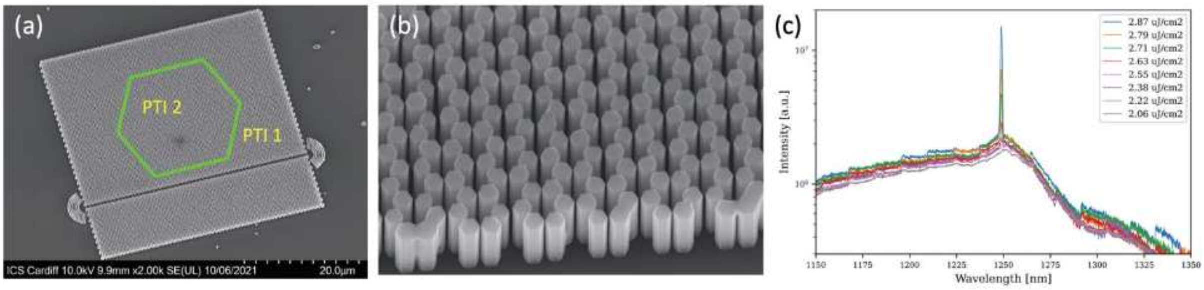

Fig. 2. (a) SEM image of the fabricated nanowire topological laser. (b) Zoomed SEM image of nanowires. (c) Room temperature photoluminescence spectra of a nanowire array laser with increasing pump power, showing the transition from spontaneous emission to lasing.

3. Conclusions

We have designed a topological laser with epitaxially grown InGaAs nanowire arrays on a SOI substrate and experimentally demonstrated the lasing modes in the fabricated topological lasers. Numerical 3-D FDTD simulations show that the cavity modes based on the edge modes exist. Optical pumping experiment clearly shows that the fabricated topological lasers are lasing at the wavelength around 1250nm.

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