Single-mode emission from a topological lattice with distributed gain and dielectric medium

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Abstract: We demonstrate a monolithically integrated active topological photonic structure. Using a unique design with distributed gain/dielectric medium, we selectively address the topological mode to achieve robust and tunable continuous-wave single-mode emission at room temperature.

1. Introduction

Systems with topological protection have received a lot of attention recently due to their inherently robust interface and surface states which are of interest for both electronics and photonics. Particularly in photonics, topology can be achieved via appropriate geometrical design using conventional semiconductors as opposed to the exotic materials or combinations thereof required in electronics. Topological photonic structures show great potential for improvements in engineering photonic applications such as directional waveguiding [1], ultrasmall lasers [2–4], and topological quantum networks [5,6] as well as possibilities to probe various exotic properties such as fractional charge state [7] and topological solitons [8].

The main interest in topology lies in the fact that it will potentially provide for more resilient systems. In photonics particularly, topological designs might be more robust to imperfections in design and fabrication [2]. Particularly, one-dimensional topological structures are well suited for integrated systems simply because they can be scaled further and the coupling to conventional scaled waveguides may be relatively easily achieved.

While silicon photonics sets the standards, benefitting from a low-cost and highly advanced fabrication platform, there is a need to integrate III-V-based active gain material for active elements. Monolithic integration of the III-V material is ultimately desirable for scalable integrated circuits but inherently challenging due to large lattice and thermal mismatch with Si. To overcome these challenges, we have developed a unique integration technique called template-assisted selective epitaxy (TASE) [9]. Using this technique, we achieve local self-aligned in-plane monolithic integration of III-Vs on silicon and with feature design precision at the nm-scale.

In this work, we take advantage of this unique method and realize a novel topological photonic architecture based on a combination of elements of gain and transparent dielectric within a topological photonic cavity to achieve an inherently single-mode light emitter.

2. Design and Fabrication

2.1. Design of the topological 1D beam

We design our one-dimensional structure based on the Su-Schrieffer-Heeger (SSH) model, describing a tight-binding chain where the coupling strength between neighboring sites alternates. Fig. 1(a) shows the concept and structure for our photonic implementation, which consists of an array of semiconductor nanorods spaced at an alternating distance from each other. This alternating configuration allows for two different definitions of symmetric unit cells, either with the shorter or the longer distance between the two rods inside this cell (called α or β, respectively), possessing different topology, i.e. a Zak phase of 0 for the (trivial) α lattice and π for the (topological) β lattice. Interfacing these two lattices creates a defect in the center of the structure, which is spectrally located in the center of the photonic bandgap.

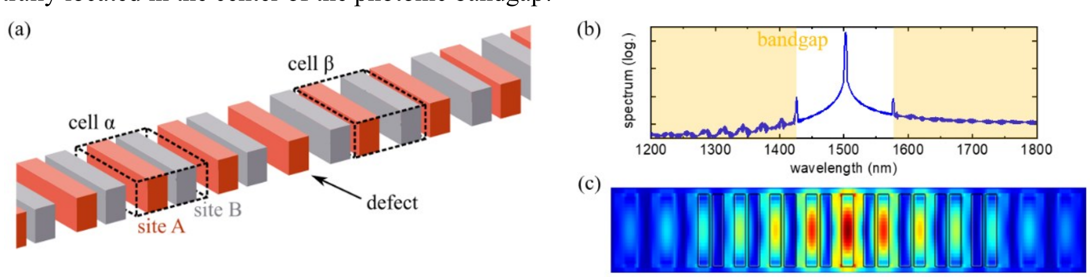

Fig. 1. (a) Concept for the creation of a topological interface between two photonic SSH lattices. (b) Simulated spectra of this structure. A topological interface mode lies in the center of the bandgap. (c) $|E_y|^2$-field intensity of the topological mode, overlayed with the device outline (black).

The corresponding spectrum of the entire topological structure is shown in fig. 1(b), as calculated from 3D simulations in Ansys Lumerical FDTD Solutions. This simulation clearly shows the existence of a mode that lies in the center of the bandgap, as expected for the topological interface state. Its mode profile is shown in fig. 1(c), displaying a particular property of this dimer design. Note that the E-field intensity is localized in the center of the structure, but only in every second nanorod, i.e. on the "A" sites.

A special case of this model has recently received much attention, which constists of the addition of gain and loss which are distributed between the alternating sites "A" and "B", specifically adding gain to the "A" and loss to the "B" sites. While a uniform SSH model of this configuration inherently supports a parity-time (PT) symmetry [10], the PT-symmetry is broken by introducing a defect in the above manner [11–13]. This may reduce the emission in a conventional mode, whereas the topological mode is not affected because it only lives in one (the "A") sublattice.

While these studies so far dealt with distributed gain and loss by adding an absorptive metal, here we present an alternative solution to enhancing the topological mode that manages without the lossy part, but instead by distributed gain and dielectric material. We are able to realize this because of the unique fabrication method called template-assisted selective epitaxy (TASE) developed in our group, with which we can replace an arbitrary Si structure with III-V material in a self-aligned manner.

2.2. Fabrication by Template-Assisted Selective Epitaxy

The fabrication process for TASE is shown in fig. 3(a). It starts with patterning the nanorod-like elements in silicon by standard electron beam lithography and dry etching using HBr chemistry (I). SiO_2 is then deposited embedding the Si structure (II) and a window is etched into this layer (III) to locally expose the Si again at one end of such a nanorod. From this point onwards, the silicon is partially etched back (IV) until only a small seed remains. The resulting hollow SiO_2 template is filled with the III-V semiconductor material (V) grown epitaxially on the Si seed by metalorganic chemical vapor deposition (MOCVD). Finally, the Si seed can also be removed by repeating the previous steps (VI). The hybrid III-V/Si structure then consists of an array of Si nanorods, whereby each rod can be individually addressed and replaced with III-V material, which in this work is an InP-InGaAs-InP heterojunction well suited for emission in the telecom band.

We use this method to insert the active material alternatingly with untouched Si nanorods as proposed above. The resulting structure where the "A" nanorods are replaced with III-V material is shown in the false-colored SEM image in figure 2(b). Additionally, since the topological mode is confined to the center of the device, it is sufficient to place gain material there, thus optimizing the overlap of the optical mode (and also the pump laser) with the active gain material.

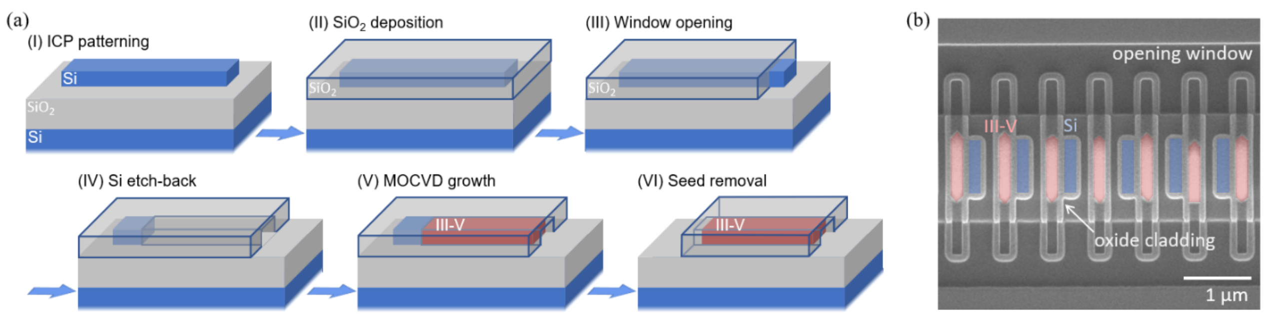

Fig. 2. (a) Schematic of the TASE process flow. (I) Patterning of a SOI wafer. (II) Deposition of SiO_2. (III) Etching of a window into the SiO_2 layer to expose part of the underlying Si. (IV) Partial etch-back of Si using TMAH, leaving behind a hollow template and a Si nucleation seed. (V) MOCVD growth of the III-V material into this template. (VI) 2^{nd} oxide opening and following Si seed removal. (b) False-colored SEM top view of the resulting topological structure.

3. Characterization and Experimental Results

The fabricated devices are characterized by optical micro-photoluminescence (PL) spectroscopy using a 1064 nm continuous-wave pump laser focused onto the sample through a 100x objective. Emission from the sample is collected by the same objective in reflection mode and characterized using a spectrometer with a line-array InGaAs detector. Measurements were performed after step V in the fabrication process explained above, meaning that the Si seed has not yet been removed. While this leads to a slight asymmetry in the design, we know from previous work that no significant degradation is to be expected.

First, we optically characterize the topological structure proposed above, and compare the two cases where either the "A" sites or the "B" sites are replaced with the III-V material. Fig. 3(a) shows the measured emission intensity under continuous-wave (cw) excitation at room temperature. A strong single emission peak is visible in the case when the active material is inserted at the "A" sites (see fig. 3(b)), whereas this peak is non-existent if the III-V material replaces the "B" sites, instead, small peaks appear at longer wavelengths. The drop-off close to 1600 nm is due to our detector cut-off.

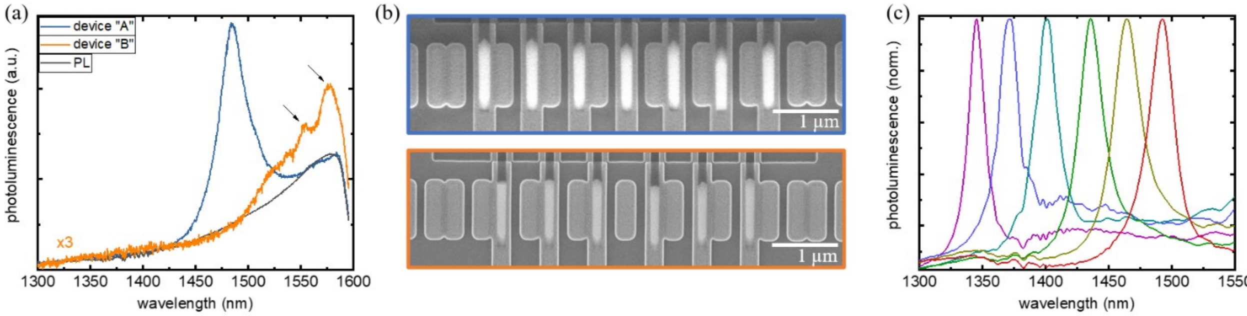

Fig. 3. (a) Measured micro-photoluminescence spectra of the topological photonic structure with the III-Vs at "A" sites (blue), showing continuous-wave emission at room temperature in the topological mid-gap state. For comparison, multiple trivial emission peaks are visible in the same design with III-Vs at "B" sites (orange). (b) Corresponding SEM images of the two devices. The III-Vs appear bright white and the Si nanorods remain almost invisible underneath the SiO_2 cladding. (c) Spectra of different "A"-type structures with increasing lattice parameter leading to longer emission wavelength.

It is generally desirable to be able to tune the wavelength of emission. This is demonstrated in fig. 3(c), where the emission wavelength is controlled by changing the underlying lattice constant of the entire chain while maintaining the distance ratio between the nanorod dimers. Note that the distortions at wavelengths around 1400 nm are artifacts due to water absorption in our set-up. Adhering to the designed incrementally increasing wavelength, equally spaced single emission peaks are visible. This enables the exact definition of emission wavelengths over the entire range where the III-V material offers optical gain. For control, on the same chip we also implemented conventional photonic crystal structures which show resonant multi-mode emission similar to our previously published work [14].

4. Conclusion

We demonstrate a novel approach to fabricating a topologically protected and inherently single-mode emitter based on a dimerized array with distributed gain and dielectric medium. By selectively placing the III-V material with high overlap to the topological mode, we achieve single-mode cw emission at room temperature over the entire telecom wavelength range. We consider this first demonstration very promising for the further development of fully integrated topological photonic devices and believe that the TASE technique holds unique possibilities to further explore this type of topological distributed gain systems.

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