Research article

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One-dimensional planar topological laser

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Abstract: Topological interface states are formed when two photonic crystals with overlapping band gaps are brought into contact. In this work, we show a planar binary structure with such an interface state in the visible spectral region. Furthermore, we incorporate a thin layer of an active organic material into the structure, providing gain under optical excitation. We observe a transition from fluorescence to lasing under sufficiently strong pump energy density. These results are the first realization of a planar topological laser, based on a topological interface state instead of a cavity like most of other laser devices. We show that the topological nature of the resonance leads to a so-called “topological protection”, i.e. stability against layer thickness variations as long as inversion symmetry is preserved: even for large changes in thickness of layers next to the interface, the resonant state remains relatively stable, enabling design flexibility superior to conventional planar microcavity devices.

Keywords: laser; microcavity; photonic crystal; topological photonics.

1 Introduction

Topological physics has been intensively investigated in the field of solid state physics. In 2008, Haldane et al. [1] proposed to use similar ideas for the propagation of electromagnetic waves in periodic structures. Topological effects in photonics were first shown in the microwave range [2] and shortly thereafter in a large number of different systems [3–7] in the visible spectral range. Experimentally, one of the simplest systems which can be analysed

using topological tools are planar periodic structures in one dimension (1D). Of special interest, from a practical and fundamental point of view, are resonant states which can be formed at an interface between two such photonic crystals (PCs). The existence of an interface state on a boundary between two periodic planar PCs composed from dielectric materials was first predicted by Kavokin et al. [8] and called optical Tamm state (OTS) in analogy with electronic Tamm states on surfaces of solids. These ideas were further developed using the standard description of electromagnetic wave propagation in dielectric media [9–11]. Recently, a connection between the surface states and a photonic band topology was shown by Xiao et al. [12]. This approach inspired a number of theoretical works on photonics topology in different planar structures. For example, PT symmetrical structures [13], quasi-periodical structures [14], and structures with multiple interface states [15] were reported. Furthermore, the influence of a finite size of the PC [16], topological structures with very high quality factors [17], and other topics [18, 19] have been studied. Additionally, experimental studies addressed the verification of topological predictions [20–22]. The combination of topological effects and lasing as a nonlinear effect is of obvious interest. The lasing in 1D topological structures which are commonly described by the Su-Schrieffer–Heeger (SSH) model and its modifications was previously observed in different experimental configurations, using coupled resonators [23–25] and photonic crystals [26]. However, all such devices require a sophisticated microstructuring and do not have the simplicity of a vertical cavity laser. So far, no experimental realization of a planar topological laser has been presented [27].

In this work, we demonstrate a laser based on a resonant interface state between two binary planar periodic structures. We discuss unique properties of this topological laser and compare it to conventional microcavity lasers. In particular, we show that the topological mode confinement has superior properties in terms of layer thickness control when compared to conventional structures.

The binary PC used here consists of alternating layers of high and low refractive indices. Transmission and reflection properties are governed by complex interference of electromagnetic waves propagating in the structure. Momentum space (k -space) of electromagnetic waves can

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be divided into regions in which propagation is allowed – photonics bands, and in which propagation is forbidden – photonics band gaps (also called stopbands). In general, different bands and band gaps are not equal and can possess different topological and symmetry properties. A key topological property is the geometric Zak phase [28]. The Zak phase is a one-dimensional analog of the topological Berry phase and can be ascribed to each band of a periodic structure. It can take any value depending on the specific distribution of materials in a unit cell. In this work, we are interested in a special case of a unit cell having an inversion symmetry. Then, the Zak phase is quantized and can only take two values: 0 and π , which correspond to two distinguished topological phases. For the n th band ($n > 0$), the Zak phase can be calculated according to [12]:

$$\theta_n = \int_{-\pi/\Lambda}^{\pi/\Lambda} \left[i \int_{\text{unit cell}} dz \varepsilon(z) u_{n,q}^*(z) \partial_q u_{n,q}(z) \right] dq, \quad (1)$$

where Λ is a unit cell length, $\varepsilon(z)$ is the position dependent relative permittivity and $u_{n,q}(z)$ is a periodic part of the solution of the Bloch problem for the electric field for band n and wavevector q : $E_{n,q}^x = u_{n,q}(z) \exp(iqz)$.

We assume that materials we use for the binary PC are not magnetic and have relative permittivity ε_A and ε_B for materials A and B, respectively. Also, we consider a special case of a material with ε_B is in the center of the unit cell. The Zak phase of the 0th band θ_0 can then be calculated from [12]

$$\exp(i\theta_0) = \text{sgn}[1 - \varepsilon_A/\varepsilon_B]. \quad (2)$$

For each band gap, we can define an impedance as a ratio between electric and magnetic fields on the structure surface: $Z = E_x/H_y$. Inside of a band gap where the impedance is purely imaginary, we define a relative impedance as: $i\zeta = Z/Z_0$, where Z_0 is a vacuum impedance. The importance of the impedance can be seen when we combine two different periodic PCs (left – L and right – R). The condition for the existence of an interface state for specific wavevector k is $Z_L(k) + Z_R(k) = 0$ on an interface or $\zeta_L + \zeta_R = 0$, since the Z is pure imaginary in the gap. It was shown [12] that having different signs for ζ_R and ζ_L is enough to fulfill this condition for some k in the band gap and therefore to have a resonant interface state. Furthermore, a simple connection between the sign of ζ in n th band gap and the Zak phase exists:

$$\text{sgn}[\zeta^n] = (-1)^n (-1)^l \exp\left(i \sum_{m=0}^{n-1} \theta_m\right) \quad (3)$$

where θ_m is the Zak phase in m th band and l is the number of band crossing points below n th gap. Therefore, the existence or non-existence of a resonant interface state on the interface between the two periodic PCs with central symmetric unit cells is directly linked to the topological phases of bands, resulting from the correspondence between the Zak phase and wave function symmetries.

2 Results

For a periodic structure consisting of two alternating dielectric materials with high and low refractive indices, we define a unit cell which is symmetric around the center of inversion and has the high refractive index material in the center of the cell (Figure 1(a)). As dielectric materials we choose SiO_2 ($n \approx 1.46$) and TiO_2 ($n \approx 2.1$) as low and high refractive index materials, respectively. The ratio of the materials in a unit cell is defined by $\delta = d_B n_B / (d_A n_A + d_B n_B)$, where d_A and d_B are physical thicknesses of materials A and B. Using the transfer matrix method, we map a transmission of the first three photonic band gaps as function of wavevector k for δ , taking values from 0 (unit cell composed from material A only) to 1 (unit cell composed from material B only) as shown in Figure 1(b). Here, blue regions are photonic band gaps with low optical transmission. Employing the method described by Xiao et al. [12], we calculate the Zak phase for each band as well as the sign of ζ using Eq. (3) for each gap. The topological phase transition can be seen when a gap closes and reopens with a different sign of ζ_R as a function of δ (see Figure 1(b)).

As mentioned previously, combining PCs having overlapping gaps with different signs of ζ_R results in a resonant interface state. We combine two PCs: the period of the right PC (RPC) has twice the optical path in comparison to the left PC (LPC), leading to an overlap between the 1st gap the LPC and 2nd gap of the RPC (Figure 2(a)). The resulting transmission is shown in Figure 2(b) and (c). It can be seen that the resonant state appears only for δ between 0 and 0.5 as expected for band gaps with different signs of ζ .

From now on, we will call a layer which consists of two half-width layers at the interface between LPC and RPC, the interface layer. To achieve an optically active system, we incorporate gain into the topological structure by replacing the interface layer by the fluorescent organic host–guest system tris-(8-hydroxyquinoline)aluminum (Alq_3) doped with 4-(dicyanomethylene)-2-methyl-6-(4-dimethylamino)styryl)-4H-pyran (DCM). We keep the optical path of the active layer the same compared to passive

Figure 1: (a) Schematics of a topological structure which consists of SiO_2 and TiO_2 (A and B respectively). (b) Optical transmission map as function of wavevectors k and thickness ratio parameter δ .

Figure 2: (a) Schematic of the two combined PCs with variable δ_R for RPC and fixed δ_L for LPC. (b) Calculated map of an optical transmission for overlapping of the 1st gap of LPC with the 2nd gap of RPC for fixed $\delta_L = 0.5$ and variable δ_R . (c) Calculated transmission for $\delta_L \approx 0.5$ $\delta_R \approx 0.24$.

PCs. The whole structure is designed to have an interface state in the spectral region around $\lambda = 630 \text{ nm}$, where Alq₃:DCM possesses high gain. For the LPC we use $\lambda/4$

layers for both materials corresponding to a thickness of 108 nm for SiO_2 and 75 nm for TiO_2 leading to $\delta_L = 0.5$. To obtain the desired symmetry of the unit cell, we deposit

a half-width layer of SiO_2 as the first layer for LPC. On top we deposit 21 alternating layers of SiO_2 and TiO_2 while for the last layer, we use TiO_2 . Further, we deposit a layer of $\text{Alq}_3\text{:DCM}$. The optical thickness of the active layer is an equivalent to the sum of optical paths of a half-width layer of SiO_2 in the LPC and a half-layer of SiO_2 in RPC (Figure 2(a)). With the refractive index for $\text{Alq}_3\text{:DCM}$ of 1.7, this leads to a total thickness of 188 nm. For the RPC, we deposit 19 alternating layers starting with TiO_2 and terminating by a half-width layer of SiO_2 on top. For each layer, we use 330 nm of SiO_2 and 71 nm of TiO_2 which corresponds to $\delta \approx 0.24$. We verify the properties of the LPC and RPC by separate measurements of the transmission spectra (Figure 3(a)). The first three band gaps can be resolved in RPC (blue curve) while the 2nd gap wavelength overlaps with 1st gap of the LPC (red curve). The LPC has a 0.05% transmission in the center of the gap and RPC has about 0.2% transmission at the same wavelength.

The device was excited by femtosecond pulses at 400 nm with a repetition rate of 20 Hz. Fluorescence was observed for pump energy density below 60 $\mu\text{J cm}^{-2}$ (Figure 3(d)). For higher pump energy density, the output intensity deviates from a linear behaviour, showing the onset of a lasing regime. The threshold in output intensity was accompanied by reduction of the emission linewidth from ~ 0.3 nm to ~ 0.12 nm (Figure 3(b) and (c)). Saturation of the output emission is reached at about 750 $\mu\text{J cm}^{-2}$. Together, these observations provide a typical signature of lasing emission.

In order to compare the lasing threshold of the topological planar laser to conventional microcavity organic

lasers, we first estimate some resonator properties: we find that the time needed for one round trip in the structure is about 25 fs. From the emission linewidth below the threshold, we estimate the quality factor of ≈ 2300 which corresponds to 3.25% losses per round trip. Accounting for the active layer thickness and field distribution, the gain needed to achieve the lasing threshold is about 870 cm^{-1} .

For further comparison, we fabricate a $\lambda/2$ microcavity laser having two dielectric mirrors composed of 21 layers each and $\text{Alq}_3\text{:DCM}$ as an active layer between them. This microcavity laser shows similar threshold value and in general, the gain value and the pump energy density needed to achieve the threshold in the topological laser are consistent with values in other $\text{Alq}_3\text{:DCM}$ microcavity lasers [29, 30].

Although the emission properties of a topological laser are similar to that of conventional microcavity lasers, several aspects are distinctly different:

Firstly, the straightforward topological treatment cannot be applied to $\lambda/2$ microcavities since due to irregularity in the layers' periodicity it is not possible to define a symmetric unit cell simultaneously for the left and for the right parts of the structure (although an attempt to generalize quantized Zak phase to non-centrosymmetric cases has been made [31]). Secondly, by changing δ we can observe a topological phase transition in RPC while an interface state exists only in one of these phases. Such a behaviour cannot be explained within the microcavity paradigm. Finally, a change in the parameter δ also leads to change of the active layer thickness, but as visible in Figure 2(b), it has a very small influence on the wavelength of the resonance. This is

Figure 3: (a) Measured transmission spectra of LPC and RPC. (b) Measured normalized emission spectrum at the resonance below and above the threshold. (c) Measured spectral linewidth of output emission for the topological laser. (d) Measured output intensity as a function of a pump energy density for the topological laser. The lines in the figure are guide for the eye.

a clear manifestation of the topological protection, i.e. stability against changes of δ within one topological phase. This is in a striking contrast to what is observed in metal or dielectric planar microcavities which are known for their tunability by changing the thickness of an interface layer.

It is important to emphasize that the device is not immune to disorder in the same sense as two-dimensional topological lasing systems [32, 33]. This is because the inversion symmetry is expected to be violated when a random noise is introduced. To further illustrate the topological protection, we map interface state resonances for different values of δ_L and δ_R for the left and the right structures, respectively (Figure 4(a)–(d)). Although for any combination of δ_L and δ_R (as long as they are in a different topological phase) an interface state exists, the resonances differ in their linewidth, transmission and spectral positions. Perfectly transmitting resonances are found along two diagonals in Figure 4(c), while a resonance linewidth increases when parameters are shifted away from the optimal point at $\delta_L = 0.5$ and $\delta_R = 0.25$. Nevertheless, the change in the wavelength of a resonance is relatively small (Figure 4(b)) for variation of thickness of the interface layer from 100 to 300 nm (Figure 4(d)). An even more fascinating feature of the topologically protected states is the ability to maintain a resonance almost unchanged for drastic changes of only unit cells which are next to the interface (Figure 5(a)–(d)), while keeping the rest of the structures constant. The wavelength of the resonance remains in the range of ± 2 nm of the central wavelength (Figure 5(b)), while resonances remain narrow (Figure 5(a)). The transparency of the resonances is higher for $\delta_R < 0.5$ but nevertheless, it is as high as at least 59% (Figure 5(c)) for the whole parametric space. This is due to the fact that topological protection can be applied even when individual unit cells deviate from the proper topological phase.

In conclusion, we show the first experimental realization of a topological planar laser. The laser is based on an interface state between two periodic, planar PCs having two different topological phases in overlapping photonic band gaps. We observe a threshold of the output emission and spectral narrowing as a function of the input energy density, typical for lasing. We showed simulations which demonstrate a symmetry-protected topological interface state, existing as long as a topological phase of both PCs remains unchanged for the relevant photonic band gap and inversion symmetry is not broken. We find that these states are highly stable against large changes of adjacent to an interface unit cell. This allows a new approach for

Figure 4: Calculated map of interface state resonances as function of δ_L and δ_R . (a) Linewidths of the resonances. (b) Wavelength of the resonances. (c) Transmission of the resonances (full transmission corresponds to 1). (d) Physical width of an interface layer.

Figure 5: Calculated map of the interface state resonances by varying next to interface unit cells only, in the left (δ_L) and in the right (δ_R) structures. (a) The resonance linewidth. (b) The resonance wavelength. (c) Transmission of the resonance (full transmission corresponds to 1). (d) Physical thickness of the interface layer.

a design of a microlasers in which the properties of a resonance are not defined by thickness of a specific layer. In particular, such flexibility may allow an efficient integration of layers of arbitrary thickness such as electrical contacts or transport layers for light emitting devices in planar configuration.

3 Methods

The SiO_2 and TiO_2 are deposited by electron-beam evaporation. The active layer is deposited by thermal co-evaporation of Alq_3 doped with

DCM. The concentration of DCM was adjusted to 2% by weight, since higher concentrations lead to non-radiative energy transfer and concentration quenching, and therefore higher lasing threshold [34]. The transmission spectra of the sample are measured by a spectrophotometer. To investigate emission and lasing properties, the sample was excited by femtosecond laser pulses with a duration of 100 fs and a repetition rate of 20 Hz. The pulses are produced with a Mira femtosecond oscillator and amplified with a regenerative amplifier (RA) Legend Elite Duo, both by Coherent. The second harmonic is generated at 400 nm from the output of the RA. The sample emission was collected and guided into a spectrometer equipped with a cooled CCD camera.

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