Bose-Einstein Condensation of Light in Photonic Crystals

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Abstract. Bose-Einstein condensate (BEC) of light is a non-classical (quantal) phase state of electromagnetic field when the light acts as a superfluid liquid. Theory predicts light can "liquefy" into BEC in a resonant optical microcavity. The paper reports an obtaining Bose-condensed light in the resonant microcavities of photonic crystals when crystals are irradiated by external optical sources matched to the photonic crystals' bandgaps edges. This way there formed the near-surface high-energetic optical Tamm states corresponding to Bose-condensed light into the near-surface photonic crystal's microcavities.

INTRODUCTION

Photonic crystal is an artificial metamaterial which periodical superlattice results to photonic bandgaps in the visible spectrum [1-10]. Nowadays, the most advanced one is an anodic aluminum oxide (AAO) mesoporous photonic crystal made by the aluminum oxide (Al_2O_3) periodically etched by the hydrofluoric acid (HF) during anodization (see [11] for synthesis details). SEM image (fig. 1) reveals a lot of optical cavities (pores) in the etched crystal to be used as resonant optical microcavities for getting the Bose-Einstein condensation (BEC) for a light [12]. This makes photonic crystals ideal to obtain BEC by an optical way.

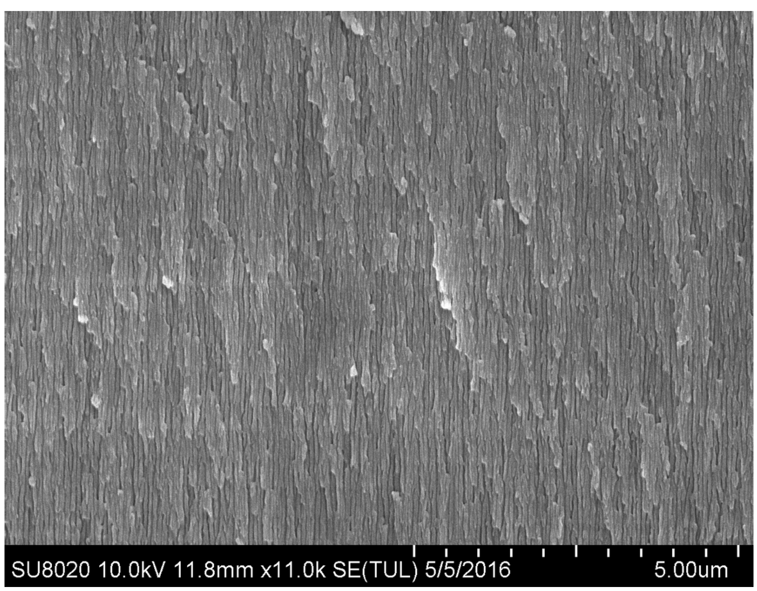

FIGURE 1. SEM image of the slice of AAO photonic crystal. Note many vertical cylindrical microcavities going through the crystal because of continuously etching during anodization

ANALYSIS

Bloch-Floquet Formalism. Because of synthesis technology, photonic crystals have the most ideal structure alongside the direction of its grow. Since this, the crystals are used alongside this direction. This makes the real three-dimensional (3D) photonic crystal acts as the effective one-dimensional (1D) one. This way its superlattice is 1D effective Bragg stack of regularly alternating layers, wherein all the odd layers are the same, as well as all the even ones.

For this 1D periodical structure the Bloch-Floquet formalism gives the following dispersion equation for a light propagating within :

$$\cos ka = \cos k_1a_1 \times \cos k_2a_2 - ½ \times (n_1/n_2 + n_2/n_1) \times \sin k_1a_1 \times \sin k_2a_2. \tag{1}$$

Here index $i = 1$ designates the odd layers of a crystal, $i = 2$ for the even ones, a_i are thicknesses, n_i are refractive indices, $k_i = \omega\times n_i/c$ are wavenumbers, $a = a_1 + a_2$ is the period of the structure, ω is wavefrequency and $c = 3\times10^8$ *m/s* is a speed of light in void.

Bandgaps. The solution for (1)

$$k(\omega) = (1/a)\times\mathrm{acos}\{\cos(\omega n_1a_1/c)\times\cos(\omega n_2a_2/c) - ½ \times (n_1/n_2 + n_2/n_1) \times \sin(\omega n_1a_1/c)\times\sin(\omega n_2a_2/c)\} \tag{2}$$

gives photonic bandgaps (ranges of no solution) at the critical point of Brillouin zone ($k = \pi/a$) as well as its center ($k = 0$), fig. 2.

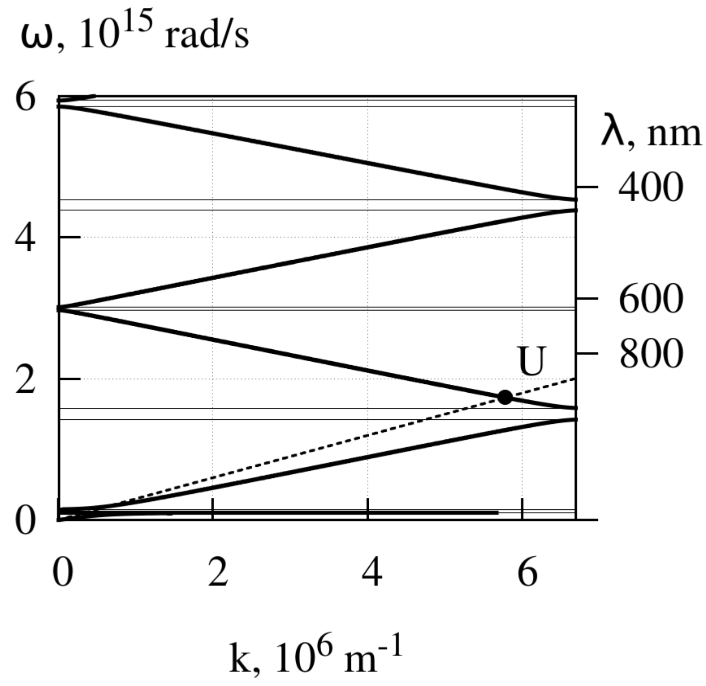

FIGURE 2. Brillouin zone bandstructure for the fig. 1 AAO photonic crystal. Crystal period $a = 465$ *nm*. Odd and even layers thicknesses $a_1 = a_2 = 0.5\times a$ and effective porosities $\eta_1 = 45\%$ and $\eta_2 = 75\%$ found by fitting of the experimental transmittance spectrum. The refractive indices of layers are $n_i^2 = (1 - \eta_i)^2 + \eta_i\times1.0$ because of additivity of dielectric constant. Lowest-frequency resonance is due to Al_2O_3 dielectric function one. Dash line marks dispersion of free photons in vacuum $\omega = c\times k$. The intersection *U* gives unitary polaritons correspond to the maximal transparency of the crystal. Horizontal lines mark bandgaps

Inside the bandgap light cannot propagate in the crystal, and at bandgap edges the group speed of light

$$v = d\omega/dk = \{dk(\omega)/d\omega\}^{-1} \tag{3}$$

is equal to zero. It means the light penetrates into the medium only at a depth of its wavelength, then stops. The resulting localized standing wave is BEC. Actually, the local density of states

$$\rho \propto v^{-1} = (v \rightarrow 0) = \infty \tag{4}$$

and reveals itself in the experiment as a bright peak (R = 100%) in the secondary emission spectrum of the crystal

$$R = \{(|n(\omega)| - 1)/(|n(\omega)| + 1)\}^2 \tag{5}$$

because of zero effective index of refraction

$$n(\omega) = \{c \times k(\omega)/\omega\} \times \text{sign } v(\omega) \tag{6}$$

when v = 0. This case the effective local field in the crystal

$$E = E_0/\varepsilon = E_0/n^2 = (n \rightarrow 0) = \infty \tag{7}$$

what can be interpreted as a superlensing of an external source light E_0 into the effective resonant E.

SIMULATION

Finite-difference time domain (FDTD) numerical simulation [13] shows the light of frequency matched to the photonic bandgap edge condenses inside the photonic crystal into drops of BEC (fig. 3).

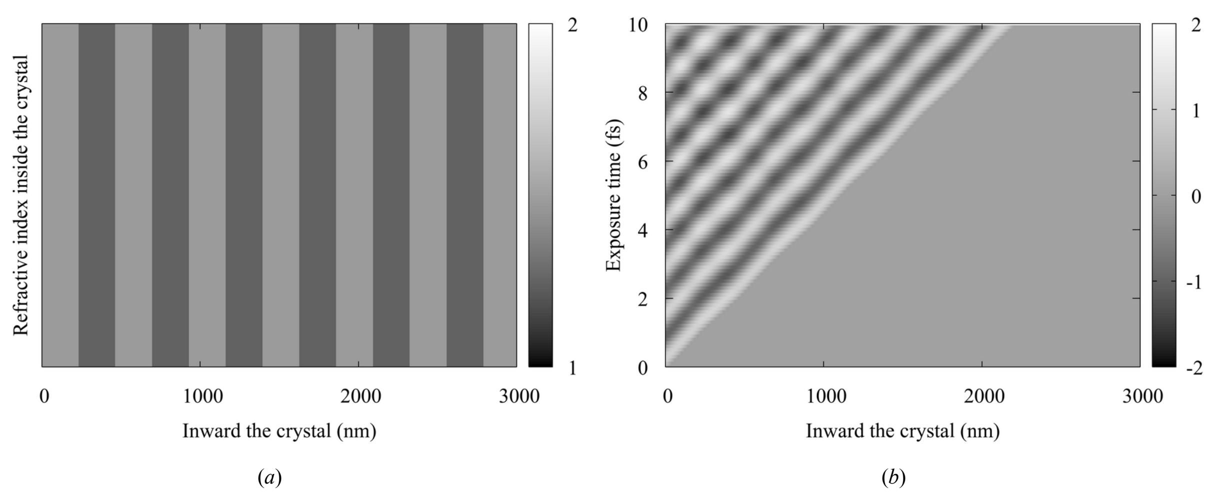

FIGURE 3. FDTD simulation for a light propagation in the photonic crystal: simulation geometry (*a*) and local field E/E_0 during first 10 *fs* of exposition by $\lambda = 400$ *nm* light source (*b*). Note the electromagnetic field begins to localize into a kind of "drops" what is the polaritonic Bose-condensate

EXPERIMENT

At the experiment photonic crystal was irradiated by the laser matched to the photonic bandgap. When laser was turned off, there was a long afterglowing of the crystal at wavelength of photonic bandgap edge (what confirms the extremely slow light, i.e. v = 0, predicted in (3) for BEC), fig. 4.

(*a*) (*b*)

FIGURE 4. Photonic crystal is irradiated by a laser (*a*) and its several seconds afterglowing because of polaritonic BEC (*b*). To longer BEC lifetime, the crystal is placed into a cuvette with liquid nitrogen (pictures are from [14])

DISCUSSION

The results demonstrate the simplicity of obtaining BEC of light in photonic crystal. Let's point out possible applications.

Light Storage Devices. Zero group speed of light can be used to store information optical way.

Enhanced Raman Scattering. Optical Tamm states of BEC allow to resonantly enhance Raman scattering in objects placed at the photonic crystal.

Photocatalysis. The giant surface electromagnetic field can be used for optical-driven chemical reactions. Since the BEC wavelength is the photonic bandgap edge one, it can be tuned for the molecule's required internal oscillation to amplify it resonant way. This also can be used to destroy viruses by detuning of the RNA.

Lasing. Microcavity's BEC in the photonic crystal is ideal for lasing at tunable wavelength.

Liquefaction of Light. During BEC light acts as a superfluid liquid that is a new phase state of a light.

High-Energy Physics (HEP). BEC's giant electromagnetic field is promising for various HEP applications, e.g. fusion.

New Particles Factory. Giant density of states for photons of the same wavefunction in BEC is favourable to observe photon-photonic processes, e.g. photon coupling to the axion-like biphoton: $\gamma + \gamma \rightarrow a$. Therefore photonic crystal can be a factory for the long-expected photon-based chameleon particles (paraphotons).

CONCLUSION

The results demonstrates a simple way to obtain high-temperature Bose-Einstein condensation of light in photonic crystals. This opens opens wide prospects for both fundamental and commercial applications [15-16].

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