「様式３」

プロジェクト番号　P-59

Development of Infrared sensor based on 3D photonic crystal

[1] Organization

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[2] Research progress

Operation of optical detectors relies on the absorption of electromagnetic radiation in a photosensitive element, where its energy is converted into an electronic signal. Hence, detection efficiency is directly related to the efficiency of the optical absorption process. The intrinsic efficiency of stand-alone photosensitive cells, determined by the atomic/molecular structure of the absorber, cannot be easily tailored. The need for high efficiency detectors driven by the demands of modern science, technology and industry has led to an intense search on new efficient photosensitive materials, such as carbon nanotubes, graphene, and others. On the other hand, recent developments in micro/nano-photonics have also opened new possibilities to concentrate the optical field into the photosensitive region and thus extrinsically improving the total absorption (e.g., plasmonic nano-antennas). A particularly attractive, and not yet implemented idea is to exploit a gradually slowing-down of the wave propagation in artificially structured materials the so-called Photohic Crystals (PhCs). Such materials have the ability to tailor the wave propagation properties eventually reaching trapped or "stopped" light, thus increasing light intensity, i.e. spatially localizing energy. Moreover, since the position of trapped light depends of wavelength, the spatial distribution of field enhancement can be colour-resolved.

This project continues our efforts to develop better theoretical understanding and practical applications of photonic crystal structures for optical detection and sensing. A special emphasis of our research efforts is the possibility to realize very small, micro-scale devices for applications in integrated optical circuits, and micro-opto-mechanical systems (MOMS). In addition, near infra-red (NIR) and infra-red (IR) spectral regions are specifically targeted, since art these wavelengths traditional detectors based on narrow-band semiconductors still have many disadvantages, such as low response speed, and need for cryogenic conditions for high sensitivity operation. Thus, we aim to develop super-compact optical detectors and sensors based on photonic crystals which would ensure both high sensitivity at room temperature and fast response time.

The proposed structures exploit slowing-down and stopping of optical waves in engineered micro-photonic structures, which can result in a substantial enhancement of the optical field intensity at a certain depth inside the structure, and correspondingly, enhanced absorption by a photosensitive cell embedded in the PhC. The key factor in realizing such local field enhancement is use of a chirped-period PhC (ChPhC), whose lattice period slowly varies varies along the direction parallel to the propagation of the incident wave. Photosensitive cells are embedded in the structure at the positions of maximum light concentration which, in turn, depends on the wavelength. This scheme is expected to be especially fruitful, since it allows field localization at separate depths for different wavelengths, thus potentially allowing for "colour vision" functionality, even in the NIR/IR spectral ranges. Thus, not only the detector sensitivity is enhanced, but also chromatic resolution is added.

[3] Results

(3-1) Research results

Practical realization of devices based on the above principles requires coordinated studies in several areas of research, such as nanophotonics, micro-/nano-fabrication, thermal imaging, and polymer science, represented by the participants of this project and their respective resreach groups. The first steps along this direction were taken during the financial year 2013, and further steps followed during the financial year 2014. This year, a mini workshop was organized on November 13, 2014 at the Research Institute of Electronics, Shizuoka University. The workshop was attended by several participants of the project, experts in the relevant fields, as well as some guests participants. The workshop was open for students and researchers interested in these fields of study.

Presentations and discussions during the workshop were centered on the following topics:

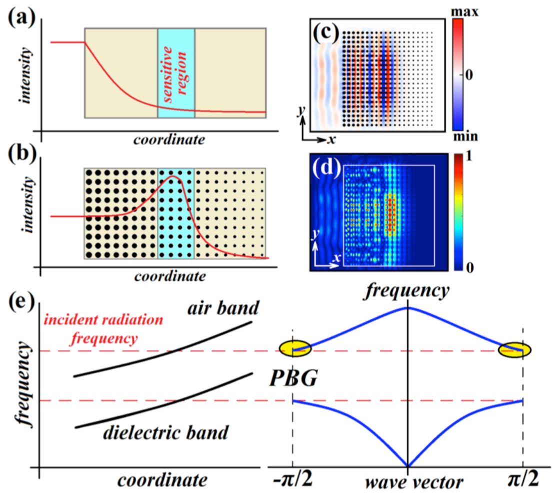

Fig. 1. Physical principles of optical field enhancement using ChPhC structures, (a) typical layout of a photodetector, (b) formation of field intensity peak within the structure, (c,d) numerically simulated intensity distribution inside the ChPhC structure, (e) spatial variation of photonic band gap frequency along the ChPhC structure (left), and local photonic band diagram at a certain depth, with slow-light regions emphasized by ovals (right).

Reports on material-related topics:

1) Sugar alcohol based materials for seasonal energy storage applications - metastability, nucleation, crustallization, A. Godin, M. Duquesne, E. Palomo del Barrio, Univ. Bordeaux, France.
2) Estimation of thermo physical properties of heterogeneous materials A. Godin, M. Duquesne, E. Palomo del Barrio, Univ. Bordeaux, France.

Reports on device-related topics:

3) Perfect absorber based on electromagnetic metamaterials, I. Fanyaeu, Research Institute of Electronics, Shizuoka University.
4) Signal superimpose system of micro-scale thermal imaging applied to un-cooled infrared cameras, J. Morikawa, Tokyo Institute of Technology.
5) Plastic surfaces for sensing, S. Juodkazis, Swinburne University of Technology, Australia.

Below we describe the main object of this project in more detail. Operation of ChPhC structure for local enhancement of optical field is illustrated schematically in Fig. 1. In conventional optical detection schemes, for instance those using photodiodes (PD), a thin photosensitive region containing p-n junction is embedded into a thicker absorbing homogenous material as illustrated in Fig. 2(a). Intensity of the incident light wave penetrating the structure decreases exponentially according to Lambert-Beer law, $I(x) = I_0(1\text{-}R)e^{-\alpha x}$, where I_0 is the intensity of incident light, R is the reflection coefficient, α is the absorption coefficient and x is the propagation direction. For such configuration, only a fraction of exponentially decaying incident radiation reaches the photosensitive region, where it can be converted into electrical signal. Decreasing the thickness of the surrounding non-photosensitive regions can alleviate the situation only partially, since absorption efficiency is limited by the small thickness of photosensitive layer.

The main idea of using ChPhC structure is explained in Fig. 1(b-e). Essentially, here we aim art obtaining a field intensity distribution radically different from that dictated by the Lambert-Beer law, and similar to that illustrated qualitatively in Fig. 1(b). In this case, the field intensity increases with penetration depth within the structure instead of exponential decay, with a local intensity peak achieved at the penetration depth controllable by the ChPhC design. A thin p-n junction or other photosensitive element embedded at the corresponding location will detect stronger signal due to the field enhancement. Computer-simulated temporal snapshot of a monochromatic field intensity is shown in Fig. 1(c), while steady-state intensity distribution is depicted in Fig. 1(d) demonstrating that ChPhCs can indeed concentrate light of a given wavelength at a specific depth along the propagation direction. The underlying physical mechanism for local field enhancement is schematically explained in Fig. 2(e). Adiabatic variation of the PhC lattice period along the propagation direction results in the corresponding variation photonic band gap frequency range (light cannot propagate through the structure at these frequencies). Therefore, the ChPhC structure is engineered to be transparent at the surface, but becomes strongly reflective at a certain where PBG range is gradually tuned to the frequency of the incident wave. In addition, low group velocity occurs at the edges of the PBG, resulting in the slow-light phenomenon. At one particular depth (for a particular frequency) the group velocity approaches zero, and the light reverses its propagation direction, slowing-down to zero at the overturning point. At such "soft reflection" point, there is a local enhancement of the average optical field intensity, as illustrated in Fig. 1(d). As a consequence, optical absorption rate in a photosensor embedded near the peak field position will be increased in comparison to that in a homogeneous material. Moreover, position of the intensity peak depends on the wavelength, which can be exploited for spectrally-resolved detection of polychromatic radiation by embedding photosensitive components at different depths in the ChPhC structure.

This project is aimed at implementation of these basic principles in infra-red optical sensors and detectors. To achieve this goal, three-dimensional (3D) ChPhC structures with lattice period allowing PBG at NIR wavelengths were prepared, and are currently undergoing characterization. In dielectric PhCs, Bragg resonant condition requires that the lattice period is comparable to approximately half of the light wavelength, therefore 3D structuring with a spatial resolution on the order of 1μm is required. This is not an easy task using traditional planar micro-/nano fabrication technologies. To circumvent this obstacle, we are using 3D Direct Laser Writing (DLW) technique, which is a relatively new, non-traditional method allowing high resolution 3D structuring of materials. In this approach, ultra short (femtosecond or picosecond) laser pulses are tightly focused into sub-micrometric spot in the bulk of transparent dielectric, and arbitrary 3D pattern is drawn by spatial scan of the focus position. This is possible to achieve with current capabilities of DLW techniques available to the participants of this project (Prof. Mizeikis and Dr. Malinauskas at Shizuoka and Vilnius Universities, respectively). Practical work on fabrication of ChPhC structures was carried out in close collaboration with Prof. Staliunas (on theory and basic operation principles of PhC based detectors), Prof. Morikawa (on thermal properties of homogeneous and structured polymers), Prof. Juodkazis (on properties and embedding of photodetectors and sensors). This collaboration will be continued to improve quality of ChPhC structures even further.

(3-2) Ripple effects and further developments

Exchange of scientific expertise between the participants was very helpful for coordination of experimental and theoretical work towards the goal of this project. Also, it has contributed to strengthening of domestic and international collaboration at Research Institute of Electronics (RIE) of Shizuoka University. In addition, one participant of the workshop (Prof. S. Juodkazis,) also attended the 2014 Takayanagi Kenjiro Memorial Symposium organized by RIE on November 11-12, 2014, where he contributed an invited talk.

Another important ripple effect of this collaboration is preparation of joint funding application entitled "High-Efficient Color-Resolved Infrared Photosensors based on Stopped Light" to NATO for Peace and Security Programme in 2015. Work on this application is currently in progress and will likely involve more researcher groups from different research institutions and companies worldwide.

In conclusion, the joint work of all participants and the mini-workshop conducted within the present project has broadened existing domestic and international research collaborations at RIE, and opened new venues for future collaborations.

[4] Achievements

Conference presentation:

(1) S. Juodkazis, "Sensor Surfaces", The 16th Takayanagi Kenjiro Memorial Symposium 2014, Nov. 11-12, Hamamatsu Campus, Shizuoka University (2014).

Travelling report

Name:	Prof. Saulius Juodkazis
Affiliation:	Centre of Microphotonics, Swinburne University of Technology, Melbourne, Australia
Period of time:	2014.11.11-11.14
Destination:	Shizuoka University, Japan
Purpose:	To carry out a joint research, plan the future collaboration, participate and report previously obtained results. To attend Cooperative Research Workshop " Development of Infrared Sensors Based on 3D Photonic crystals" and The 16th Takayanagi Kenjiro Memorial Symposium 2014.
Name of receiver:	Prof. Vygantas Mizeikis

Name:	Prof. Junko Morikawa
Affiliation:	Tokyo Institute of Technology
Period of time:	2014.11.13
Destination:	Shizuoka University, Japan
Purpose:	To plan the future collaboration, participate and report previously obtained results. To attend Cooperative Research Workshop "Development of Infrared Sensors Based on 3D Photonic crystals".
Name of receiver:	Prof. Vygantas Mizeikis