# First year report and second year work plan for the project

**1. Title:** Design and fabrication of robust photonic crystals

**2. Grant No:** FA2386-08-1-4078 AOARD 084078 (June 23, 2008 contracted)

**3. Principal investigator:** Professor Dr Toshio Katsuyama

## 4. Abstract of the project

The photonic crystal structure, that is robust for the structural fluctuation caused by the inevitable incompleteness of the fabrication process, will be studied. The final goals include (1) optimization of the deeply etched 1-D (one-dimension), 2-D, and 3-D photonic crystal structures, that are robust for the inevitable fabrication incompleteness, and (2) establishment of the generalized rule of the robustness for all kinds of photonic crystals, which is the key technology for realizing actual optical devices. The total research period is assumed to be three years.

## 5. First year achievement (from June 2008 to June 2009)

(1) Overview

In the first year, we have mainly studied the robust structures of the photonic crystals by using several simulation methods. In particular, 3-D planar-type photonic crystals composed of air columns and 1-D/2-D slab-type photonic crystals are the main targets of the research. In both structures, we have successfully obtained the guideline for the structure, that is robust for the structural fluctuation caused by the incompleteness of the fabrication process.

In addition, an actual fabrication process of the photonic crystals has been studied. One milestone is the successful fabrication of the periodically aligned $SiO_2$ micro plates formed on the Si pedestal. Those were fabricated by etching process, providing deeply etched 1-D photonic crystals. Since the photonic crystals are formed of silica glass, these are applicable to a wide spectral range from ultraviolet to near infrared. So far, photonic crystals capable of such wide spectral range operation have never been realized. Thus, the first year plan has been successfully achieved, which offers the definite schedule for the next year. Detailed achievement is described as follows.

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14. ABSTRACT
**The photonic crystal structure, that is robust for the structural fluctuation caused by the inevitable incompleteness of the fabrication process, will be studied. The final goals include (1) optimization of the deeply etched 1-D (one-dimension), 2-D, and 3-D photonic crystal structures, that are robust for the inevitable fabrication incompleteness, and (2) establishment of the generalized rule of the robustness for all kinds of photonic crystals, which is the key technology for realizing actual optical devices. The total research period is assumed to be three years.**

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(2) Simulation and optimization for robust structures

(2.1) 3-D planar-type photonic crystals composed of air columns

These photonic crystals are so-called woodpile structures composed of air columns. Since such structures can be fabricated by a simple technique based on 45-degree dry etching, various planar-type optical elements can be basically introduced into the flat wafers. Thus, fabricated photonic crystals can be easily combined with conventional electronic and optical elements, such as Si waveguides and switches.

At first, we have clarified the relation between the bandgap and shape of the air column cross section, assuming that the cross section is rectangular and that the wafer is Si. Thus, the large bandgap is obtained when the ratio of the lateral and longitudinal widths of cross section is 1.60-1.84. In addition, a resonant defect state can be obtained by introducing twin air columns with small cross sections instead of corresponding mother air columns. The robust defect, that is less influenced by the parameter fluctuation, is obtained when the longitudinal width and lateral width are 0.5 and 0.16, respectively, compared with the mother column widths. Therefore, we have obtained one potential candidate for robust 3-D photonic crystals.

(2.2) 1-D/2-D slab-type photonic crystals

Slab-type photonic crystals are the most popular structure among the various photonic crystals. We have examined the robust structures for two types of slab-type photonic crystals, i.e., the 1-D slab-type photonic crystals composed of aligned lateral columns, and the 2-D slab-type photonic crystals composed of triangular hole lattice.

The simulation results indicate that the 1-D Si photonic crystals give the robust characteristics when the Si column width is 480 nm for the 1.5 µm operation. The robustness for the 2-D Si photonic crystals can be obtained when the hole radius and lattice constant are 0.19µm and 0.5µm, respectively. Thus, the systematic study using simulation offers the candidates for the robust structures for typical slab-type photonic crystals.

(3) Fabrication of photonic crystals

Periodically aligned $SiO_2$ micro plates formed on the Si pedestal have been fabricated.

The fabrication process began with the deep etching of a Si substrate, followed by oxidation of the etched Si structure. This deep Si etching was performed using an inductively coupled plasma (ICP) etching procedure using a mixture of $SF_6$ and $O_2$ gases as the plasma source. The high-aspect-ratio Si etching was achieved using a cryogenic process, where the Si substrate was cooled with liquid nitrogen. This low-temperature process produced a very steep etching profile, because an oxide/fluoride thin layer formed on the sidewalls and blocked from ion attacks. The deviation of the sidewall surface from the perpendicular line was less than 0.5 degrees. Next, we oxidized the etched Si structure. Even though the process is quite simple, the oxidized structure can still retain its original shape. No damages or fractures could be observed in the structure. The typical aspect ratio for the etched space is 16, and the width and height for each $SiO_2$ plate are 1 μm and 12.5 μm, respectively. The height of the Si pedestal is 6 μm.

The important feature obtained in this year is that the $SiO_2$ structure is fabricated on the pedestal composed of different material such as Si. This structure provides deeply etched 1-D photonic crystals composed of $SiO_2$ formed on the pedestal constructed on the Si substrate. This configuration is useful for the monolithic integration for conventional electronic and optical elements composed of Si.

**6. Second year approaches and schedule (from July 2009 to June 2010)**

We have clarified the appropriate candidates for robust photonic crystals by using a simulation performed in the first year. In addition, we have established the fabrication process for some kinds of photonic crystals. Then, we proceed to the next research stage, which should be done in the second year, in order to obtain the final goal.

(1) Simulation and optimization for robust structures (second stage)

By considering the simulation results performed in 3-D planar-type photonic crystals with air columns and 1-D/2-D slab-type photonic crystals, we will extract the individual structural parameter whose fluctuation considerably influences the degradation of the characteristics of the photonic crystal, especially the degradation of the Q-factor (quality factor) of the resonant state. Thus, we will consider the structural parameters systematically, combining the results obtained in different types of photonic crystals. Then, we can discuss the guideline for the generalized rule for obtaining the robust structures for all kinds of photonic crystals. (from July 2009 to December 2009)

(2) Fabrication and evaluation of the robust photonic crystals

At first, we will fabricate the robust structure of deeply etched 1-D photonic crystals composed of Si and $SiO_2$ by using the guideline obtained by simulation. In addition, we will study the fabrication process for two types of slab-type photonic crystals, i.e., the 1-D slab-type photonic crystals composed of aligned lateral columns, and the 2-D slab-type photonic crystals composed of triangular hole lattice. Since we have already obtained the robust structures for these photonic crystals by using simulation, we will fabricate the actual photonic crystals with robust characteristics. (from July 2009 to December 2009)

In the next step, we will study the relation between the structural fluctuation and the characteristics of the photonic crystal by measuring the actual structural fluctuation of each photonic crystal. In this case, we should notice the structural parameters that are much influenced by the fabrication process. Thus, we can redesign the structure of the photonic crystal that is robust for such parameter fluctuation. Such feed-back process leads to the optimum structure that is robust even if the incompleteness of the fabrication process cannot be eliminated. Thus, we will discuss the guideline for the generalized rule for obtaining the robust structures in the viewpoints of both simulation and measurement. (from December 2009 to June 2010)

**7. Publications (during the contracted period from June 2008 to June 2009)**

1. M. Sagawa, S. Goto, K. Hosomi, T. Sugawara, T. Katsuyama, and Y. Arakawa, “40-Gbit/s operation of ultracompact photodetector-integrated dispersion compensator based on one-dimensional photonic crystals”, Japan. J. Appl. Phys. 47, No.8, 6672-6674 (2008)
2. Yoshiaki Nakajima, Hajime Inaba, Feng-Lei Hong, Kazumoto Hosaka, Masami Yasuda, Atsushi Onae, Kaoru Minoshima, Toshio Katsuyama, Sakae Kawato, Takao Kobayashi, Hirokazu Matsumoto, “Phase noise suppression in an octave-spanning fiber-based frequency comb by using wide-bandwidth phase-locking”, The 55$^{th}$ Spring Meeting of The Japan

Society of Applied Physics and Related Societies, 29a-ZX-11, Funabashi, Japan, March 2008

3. Kenji Hiruma, Kei-ichi Haraguchi, Masamitsu Yazawa and Toshio Katsuyama, “Growth and properties of GaAs, InAs nano whiskers”, Surface Science, 736-739, No.12, Vol. 29, 2008

4. Toshio Katsuyama, “Highly sensitive and extremely small sized optical evaluation system using photonic crystals”, FUNTEC Forum, Fukui, Japan, Jan. 2009

5. Yoshiaki Nakajima, Hajime Inaba, Kazumoto Hosaka, Atsushi Ihara, Masami Yasuda, Takuya Kohno, Atsushi Onae, Kaoru Minoshima, Takao Kobayashi, Sakae Kawato, Toshio Katsuyama, Feng-Lei Hong, “A narrow linewidth, and octave-spanning optical frequency comb generated by a mode-locked fiber laser with an intracavity electro-optic modulator”, The 55th Spring Meeting of The Japan Society of Applied Physics and Related Societies, 31p-ZM-6, Tsukuba, Japan, March 2009

6. Yoshiaki Nakajima, Hajime Inaba, Kazumoto Hosaka, Atsushi Ihara, Ken-ichi Watabe, Atsushi Onae, Kaoru Minoshima, Sakae Kawato, Takao Kobayashi, Toshio Katsuyama and Feng-Lei Hong, “A low-noise, octave-spanning optical frequency comb generated by a mode-locked fiber laser with an intracavity electro-optic modulator”, CMN2, The Conference on Lasers and Electro-Optics (CLEO) and The International Quantum Electronics Conference (IQEC), Baltimore, USA, May 2009

7. Yoji Kuwamura, Ahmad Nizamuddin, Mitsutaka Hattori and Toshio Katsuyama, “Correlation of electric-field-induced phase shift and luminescence in GaAs quantum well waveguides”, The 70th Autumn Meeting of The Japan Society of Applied Physics, Toyama, Japan, September 2009, to be presented

8. Ahmad Nizamuddin, Yoji Kuwamura, Mitsutaka Hattori and Toshio Katsuyama, “Cryogenic characteristics of Mach-Zehnder interference devices composed of GaAs quantum-well waveguides”, The 70th Autumn Meeting of The Japan Society of Applied Physics, Toyama, Japan, September 2009, to be presented

9. Toshio Katsuyama, Keisuke Shimizu and Mohd Saifizi bin Saidon, “Optimization of the 3D photonic crystals composed of air columns”, J. Appl. Phys. to be published