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Control of Light Emission and Propagation in Semiconductor Photonic Nanostructures

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Semiconductor photonic nanostructures, i.e. photonic crystals (PCs) and high index contrast structures (HICs), have become worldwide topics in this decade. They strongly control light emission and propagation, and so allows novel phenomena and device applications. Particularly in these years, they were discussed with various topics, e.g., nanolaser, slow light, negative index optics, and Si photonics. This presentation shows some of our recent activities on these topics.

The PC nanolaser is expected to be a high efficiency light source with the controlled spontaneous emission. Key issues are to obtain a small modal volume V_m and a high cavity Q. The latter particularly attracts attention these days. However, the former is more crucial, because the high Q is invalidated by the homogeneous broadening whose equivalent Q is less than 1000 in QWs and 10^5 in QDs at room temperature. To reduce the V_m, we employed the point-shift nanocavity consisting of only the shift of two neighboring holes in a PC slab, as shown in Fig. 1 [1,2]. The FDTD calculation predicted an extremely small V_m of $2(\lambda/2n)^3$. We fabricated it into GaInAsP QW slab and obtained the room temperature cw lasing by photopumping with an effective threshold power of 500 nW. Experimental modal behaviors well agreed with theoretical ones. It suggests that the extremely small V_m was really obtained. For this cavity, we measured the spontaneous emission decay lifetime to be of 100 ps order even below threshold [3]. Reasons for this are thought to be the strong Purcell effect (enhancement of spontaneous emission rate), nonradiative effects, and carrier diffusion effects, but they are still under investigation. In photonic integrated circuits, the nanolaser must be integrated with passive components. To realize this, we fabricated the active/passive buttjointed PC slab by using MOCVD regrowth technique, as shown in Fig. 2 [4]. A line defect laser and output waveguide were formed in a 1.55-μm-GaInAsP QW active region and a 1.30-μm-GaInAsP bulk passive region, respectively. The lasing operation as well as a practical external quantum efficiency of 8% were obtained.

Slow light in a PC line defect waveguide is of great interest due to its potential for optical buffering and enhancement of light-matter interaction [5]. However, a narrow bandwidth and large group velocity dispersion (GVD) are serious issues that disturb its practical use. We have proposed a chirped PC structure for wideband operation and a photonic band with an inflection point for GVD compensation. Various parameters such as hole diameter and slab index can be chirped parameters. The photonic band with an inflection point is obtained by the following three structures: 1) simple line defect with some structural tuning [6], 2) coupled waveguide [7] and 3) directional coupler of two different waveguides A and B with opposite dispersion [8]. Their wideband slow light was confirmed in FDTD simulation. Recently, we fabricated the directional coupler with the hole diameter chirping into SOI

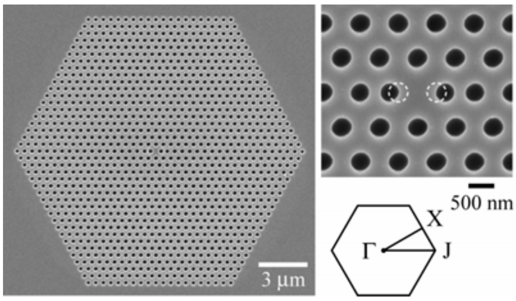

Fig. 1 PC nanolaser and Brillouin zone.

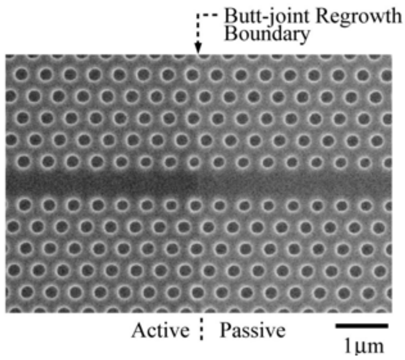

Fig. 2 Active/passive integrated PC slab laser.

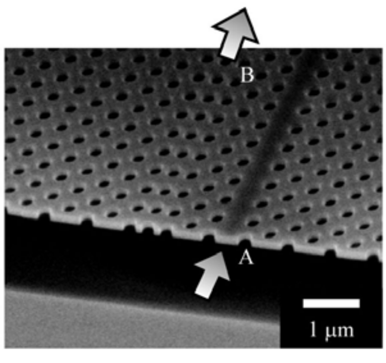

Fig. 3 PC directional coupler slow light device.

substrate, as shown in Fig. 3, and observed the expected light propagation [9]. Using frequency-domain and time-domain methods, the average group index (= slowdown factor) was evaluated to be 35 – 40 in a wide wavelength range of 35 nm. Even in the chirped structure, the group index is restricted by the bandwidth. A useful advantage of the chirped structure is the controllability of the delay and delay-band product.

The negative index optics attracts attention recently with the topics of metamaterials. But that based on PCs is advantageous at lightwave frequencies as it is free from absorption loss. We recently succeeded in demonstrating the superlens effect in a SOI PC slab [10]. Here, the second photonic band of the square lattice PC slab was used, in which the dispersion surface indicates the superlens effects. I/O ends of the PC were optimized so that the reflection loss was minimized [11]. Fig. 4 shows the near field pattern of focused light in the PC at λ = 1.36 μm. The superlens is very unique because it focuses light at the flat surface, and forms not a virtual image but a real image inside the PC. This means that the focusing characteristics are independent of the input position of light. It will be applicable to a compact demultiplexer [11], parallel optical coupler, imaging system, and so on.

The Si photonics is increasing importance for intra-chip optical interconnections in LSIs. However, it is also expected to be the next era PLC technologies because of the strong optical confinement of HIC Si photonic wire waveguides. We have demonstrated μm-size bends, branches, and some components in this waveguide [12]. In addition, a very compact AWG demultiplexer was realized [13-15], as shown in Fig. 5. For a channel spacing of 10 nm, the device size can be less than 100 × 100 μm^2. By carefully optimizing the connection between elements, the sidelobe level and device loss were reduced to less than –20 dB and 1.5 dB, respectively. If the polarization-insensitive characteristics are obtained, it will be a practical device for course WDM. By reducing the phase fluctuation in the arrayed waveguides, a narrower channel width and sensing applications will be available.

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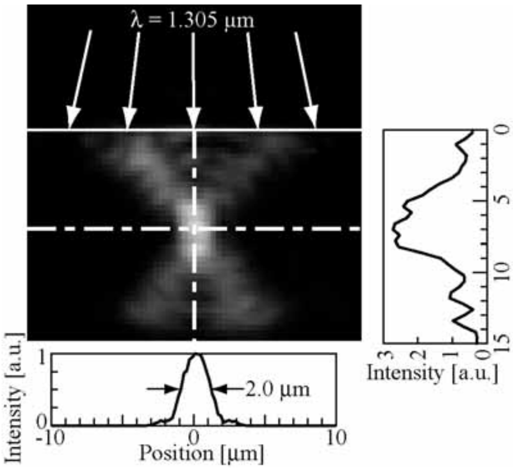

Fig. 4 Near field pattern of focused light in PC.

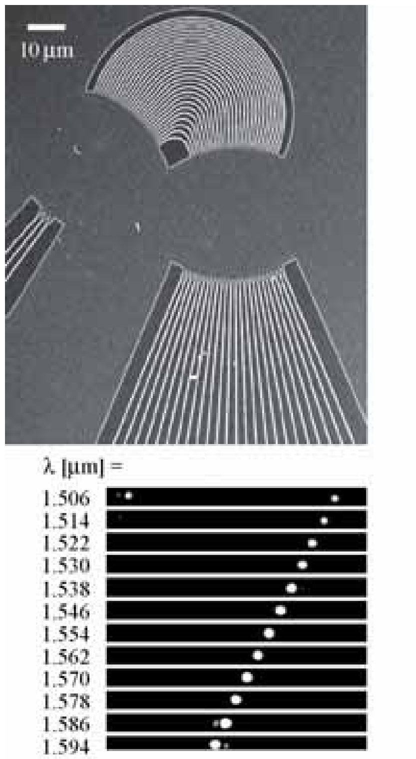

Fig. 5 Si wire AWG and output light.

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