Japanese Journal of Applied Physics **REGULAR PAPER**

Fabrication of two - color surface emitting device of a coupled vertical cavity structure with InAs QDs formed by wafer - bonding

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We fabricated the two color surface emitting device of a coupled cavity structure which is applicable to terahertz light source. GaAs/AlGaAs vertical multilayer cavity structures were grown on a (001) and (113)B GaAs substrates and the coupled multilayer cavity structure was fabricated by wafer-bonding of them. The top cavity contains self-assembled InAs quantum dots (QDs) as optical gain materials for two-color emission of cavity-mode lights. The bonding position was optimized for the equivalent intensity of two-color emission. We formed a current injection structure, and two-color emission was observed by current injection, although lasing was not observed.

1. Introduction

Terahertz light sources based on semiconductor materials have been studied for a wide range of possible application fields including wireless communication, spectroscopy, and transmission imaging.1–5) Several types of semiconductor devices, such as quantum cascade lasers (QCLs),6–9) resonant tunneling diodes (RTDs),10, 11) and photo-mixers,12, 13) have been studied and developed as continuous-wave (CW) terahertz light sources. Although there has been significant progress on terahertz QCLs, there still remain various problems in each type of device, such as insufficient emission power, for higher frequency operation of RTDs, or low operation temperatures of QCLs.

Efficient wavelength conversion based on difference frequency generation (DFG) in group III-V compounds semiconductors is attractive for terahertz light sources operating at room temperature because of the large second-order nonlinearity. Terahertz DFG was demonstrated using a GaP crystal excited by two individual lasers,14–16) and DFG from QCL was also reported recently.17)

We have proposed a terahertz emission device of a coupled multilayer cavity structure

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utilizing DFG of the two cavity modes.[18,19] A GaAs/AlAs coupled multilayer cavity structure, which had two equivalent cavity layers coupled by an intermediate distributed Bragg reflector (DBR) multilayer, was grown on a (113)B GaAs substrate by molecular beam epitaxy (MBE). Epitaxial growth on a non-(001) substrate is essential for terahertz DFG of the two cavity modes because the frequency mixing through the second-order nonlinear process is forbidden on a (001) substrate owing to crystal symmetry.[20] Strong sum-frequency generation (SFG) in the near-infrared region[21–23] and DFG in the terahertz region[24–27] were successfully demonstrated by simultaneous excitation of the two cavity modes in the coupled cavity structure using femtosecond laser pulses with a wide spectral width of ~35 nm. From the viewpoint of device applications, the two modes should be generated inside of the coupled cavity structure by current injection, which enable terahertz emission through the DFG process without external light sources. Figure 1 shows the schematic structure of THz wave emitting device. Recently, we fabricated GaAs/AlAs coupled multilayer cavities with InAs quantum dots (QDs) on a (001) GaAs substrate by MBE, and two-color emission by optical pumping was successfully demonstrated at room temperature under CW operation.[28] We have shown equivalent two-color emission intensities when the optical thicknesses of two cavity layers were exactly same as each other.[29] When we grow the coupled cavity structure with InAs QDs on the (113)B substrate, terahertz DFG should be generated without external lights. However, terahertz emission will be weakened because the radiated terahertz fields in the two cavity layers largely cancel each other out when both cavity layers have the same nonlinear susceptibility. Such cancellation can be significantly eliminated when we introduce susceptibility inversion in the middle of the structure. This situation is realized that the coupled cavity structure is fabricated by direct wafer-bonding of two single-cavity structures. In fact, the signal enhancement due to the susceptibility inversion was confirmed by the simulation and experimental observation of terahertz DFG for the wafer-bonded coupled cavity sample fabricated using two (113)B epitaxial wafers.[26]

In this paper, we fabricated a GaAs/AlGaAs coupled multilayer cavity structure with InAs QDs by the surface-activated bonding method[30,31] of two cavity structures grown individually. We found that the wafer-bonding position affected optical property of the bonded coupled cavity, and realized that two-color emission of equivalent intensity from them. We fabricated a current injection structure of the bonded epitaxial wafer and observed two-color spontaneous emission by current injection.

2. A coupled multilayer cavity structure formed by wafer-bonding

2.1 Fabrication of a coupled multilayer cavity structure formed by wafer-bonding

A coupled cavity structure with InAs QDs formed by wafer-bonding at the middle of center DBR shows in Fig. 2 inset. Two single multilayer cavity structures were grown on (001)- and (113)B-oriented undoped GaAs substrates, by MBE. Each structure contains a double -wavelength-thick ($2\lambda \sim 729nm$) cavity layer. On the (113)B substrate, the bottom(28-period) and top(6.25-period) GaAs/$\mathrm{Al_{0.9}Ga_{0.1}As}$ $\lambda/4$-DBR multilayer were undoped. On the (001) substrate, we grew at first an AlAs/$\mathrm{Al_{0.5}Ga_{0.5}As}$ (5nm/98nm) etch-stopper structure. This structure is used for the selective removal of the (001) GaAs substrate after the wafer-bonding. The 2λ cavity of the (001) epi-wafer consists of three layer of self - assembled InAs QDs embedded in $\mathrm{In_{0.15}Ga_{0.85}As}$ wells and GaAs spacer layers. InAs QDs were expected to apply to equivalent gain for two modes, because QDs has wide gain range. The 2λ cavity of the (001) has a lateral thickness variation by without substrate rotation during the growth. The bottom (28-period) and the top (6.25-period) GaAs/$\mathrm{Al_{0.9}Ga_{0.1}As}$ $\lambda/4$-DBR multilayers were doped by Be and Si, respectively. These GaAs/$\mathrm{Al_{0.9}Ga_{0.1}As}$ DBR layer had graded structures at the interfaces between GaAs and $\mathrm{Al_{0.9}Ga_{0.1}As}$ layers, in order to decrease resistance of the DBR layers. The two epitaxial wafers were directly bonded by a conventional surface-activated bonding method. In this method, two wafer surface were conducted treatment by Ar beam. Both epitaxial wafer's surface had GaAs layer which has $\lambda/8$ thickness. After bonding, the (001) GaAs substrate was completely removed by mechanical polishing and selective wet etching using a citric acid-based etchant and BHF etchant.

2.2 Consideration for bonding position

Figure 2 shows the surface emission spectrum observed at an excitation power of 398 mW at room temperature. The excitation source for PL measurements was a multimode semiconductor laser with a nominal wavelength of 920nm, which was operated in cw mode. This semiconductor laser's nominal wavelength was located outside the high reflection band. The laser beam was focused on the sample surface with a diameter of about 250 μm. Two peaks were observed at 1284.7 nm and 1296.7 nm. The intensity of the short wavelength peak was smaller than the long one.

We calculated the internal electric fields. When the optical thicknesses of two cavity layers were exactly same as each other, the ratio of the internal electric field intensity at the QD layers was unity and frequency difference became minimum. In previous report, we reported that the ratio of the two peak intensities by photo luminescence fitted with the ratio of the internal electric field intensity by calculated as shown in Ref. 29. Figure 3 shows the ratio of the electric field intensities at the QD layer versus the optical frequency difference (broken line). The experimental results of the peak intensity ratio of the two-colors versus the optical frequency difference that depending on the wafer position are also shown in the figure (closed circle). The ratio of the two peak intensities was not unity when frequency difference was minimum, although optical thicknesses of the two cavity layers are equivalent. Assuming that the bonding interface has absorbance layer: 2.5 nm (absorption coefficient: $\alpha = 15000cm^{-1}$), two color emission ratio fit with solid line in Fig. 3.

Figure 4 (a) shows the distribution of electric fields and refractive indices at the case when two epitaxial wafers were bonded at center of middle DBR. Position is a distance from a surface. A short wavelength's electric field had maximum at bonding interface, while a long wavelength's electric field had almost minimum at the bonding interface. Assuming optical loss at the bonding interface, the short mode may have loss. Therefore, two epitaxial wafers were bonded where the distribution of electric fields of two modes had minimum. Figure 4 (b) shows the distribution of electric fields and refractive indices at the just above 2λ cavity on (113)B substrate. The first neighboring for $\lambda/4$ GaAs to a cavity layer is replaced with $3\lambda/4$ GaAs layer for the bonding interface. Electric fields of the both modes had minimum at near bonding interface. In the case, the optical losses are considered negligible small.

Figure 5 shows the surface emission spectrum of the sample bonded at the layer near the cavity layer. This structure contained nine layers of InAs QDs at the top cavity layer Top- and bottom-DBR layer also increased 28-pairs and 32-pairs, respectively. The laser beam diameter was about 250 μm and excitation power was 158 mW. Two mode emissions were clearly observed at 1282.2 and 1293.9 nm. The mode frequency difference between the two emission modes was 2.1 THz, which was almost the same as the designed value. We observed two-color emission with equivalent intensities, resulting from that two epitaxial wafers were bonded at the position where the electric fields of the both modes were minimum.

3. Two-color surface emitting device by a current injection

We fabricated a device structure for current injection, using the bonding wafer which was bonded at near (113)B side cavity as shown in Fig. 4 (b). The processes are shown below.

A p-type metal (Ti/Au) electrode was deposited on the surface of the p-type DBR. Ti and Au were 5nm and 100nm, respectively. A mesa shape was formed on the substrate by wet etching. The p-type DBR was etched by phosphoric acid, the topside cavity layer was etched by citric acid, and the n-type AlGaAs of the first layer of the middle DBR was etched diluted phosphoric acid. The current confinement layer was formed by selective oxidation of an AlAa layer, which was grown just above the topside cavity layer, from the side wall of the mesa structure. An n-type metal (AuGe/Ni/Au) electrode was deposited on the GaAs surface of the n-type DBR. AuGe, Ni and Au were deposited 50 nm, 12.5 nm and 50 nm, respectively. Annealing was performed in N_2 atmosphere at 703 K for 45 seconds. At the end, passivation layer was coated.

We investigated the optical property by current injection at room temperature. The spontaneous emission spectrum of two color emitting device was shown in Fig. 6 left side. The injection current versus light output (I-L) curve was shown in Fig. 6 right side. Injection current source was pulsed operation with a duty of 0.20%(Period: 5 $msec$, Width: 10 μsec). The I-L measurement range was 0 mA − 100 mA. In this measurement system, light output has bias power at pulsed current 0mA. An emission image is shown in Fig. 6 inset. In emission image, two color emitting device operates CW mode. We succeeded to observe the two color spontaneous emission with nearly equivalent intensities by current injection, although lasing was not observed.

4. Conclusions

We fabricated a GaAs/AlGaAs coupled multilayer cavities with InAs QDs formed by wafer-bonding. Topside cavity layer included InAs QDs layers as optical gain materials. We found that two color emission intensities were not equivalent when the bonding interface was the center of middle DBR. We investigated distribution of the electric fields, and optimized bonding position to improve the optical property of the coupled cavity. Two color emission with equivalent intensities was demonstrated. Using the bonded wafer, we fabricated a device structure for current injection. We successfully observed two color emission with nearly equivalent intensity by current injection, although lasing was not observed.

Acknowledgment

This work was partly supported by SCOPE (Strategic Information and Communications R & D Promotion Programme) from the Ministry of Internal Affairs and Communications, Japan.

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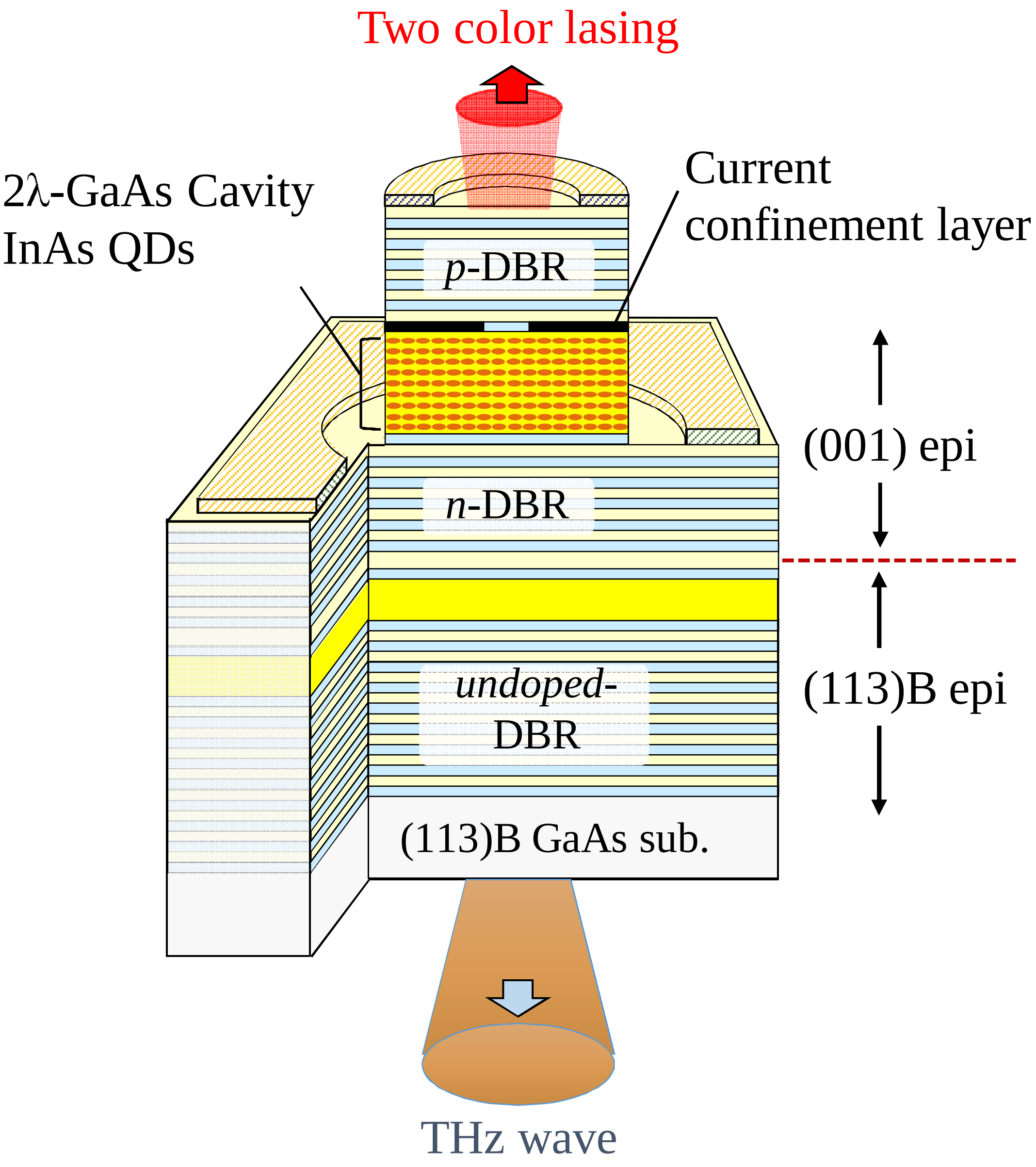

Fig. 1. (Color online) The schematic structure of THz wave emitting device.

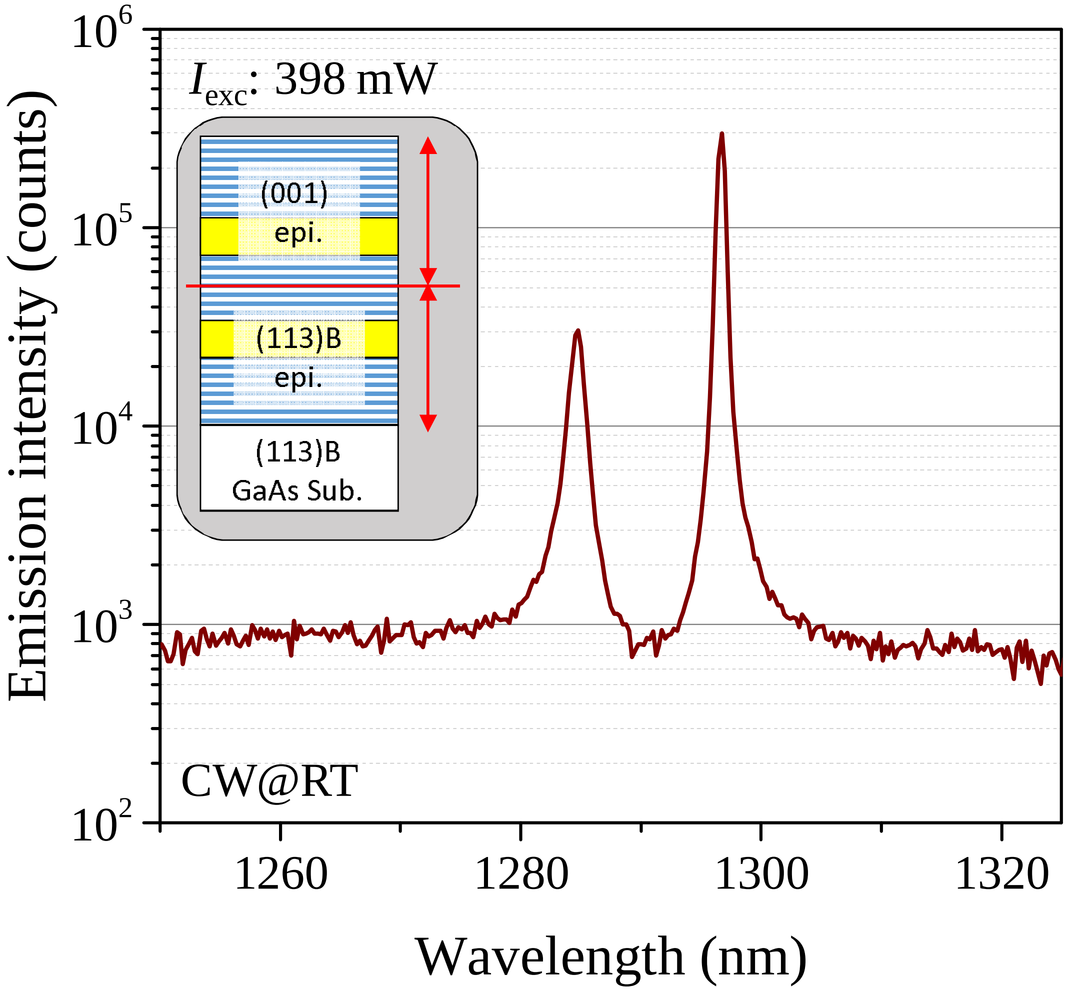

Fig. 2. (Color online)Surface emission spectrum of the coupled cavity that bond at center of middle DBR. The emission intensity is plotted on a log scale. A couple cavity structure, which was bonded at the center of middle DBR, is shown inset.

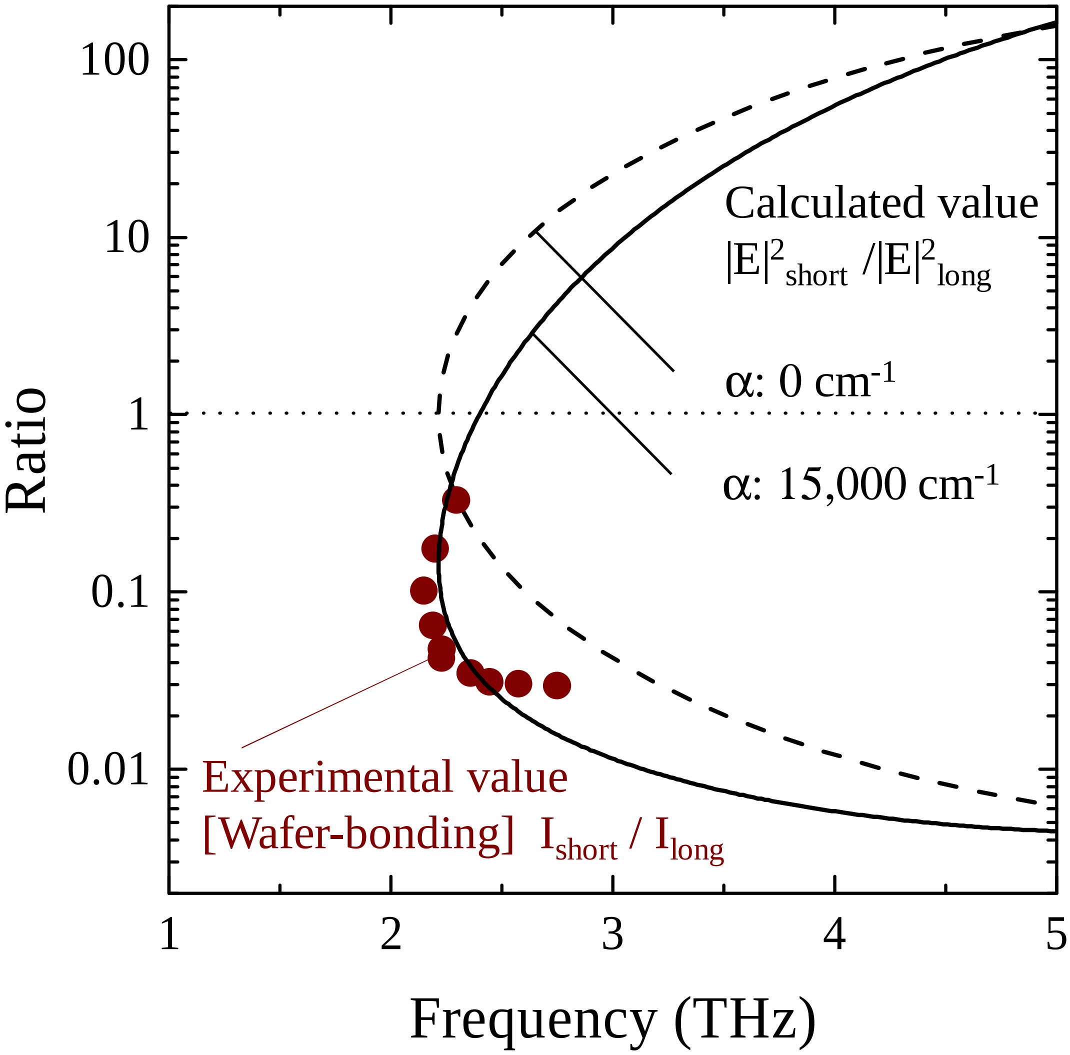

Fig. 3. (Color online) The closed circle shows relationship between peak intensity ratio of the experimental two color emissions on the vertical axis and the frequency difference on the horizon axis. The broken line shows the ratio of the simulating internal electric field intensity at the QD layers versus the optical frequency difference. The solid line shows the same one when the bonding interface has absorbance layer : 2.5 nm (absorption coefficient: α = 15000 cm^{-1}).

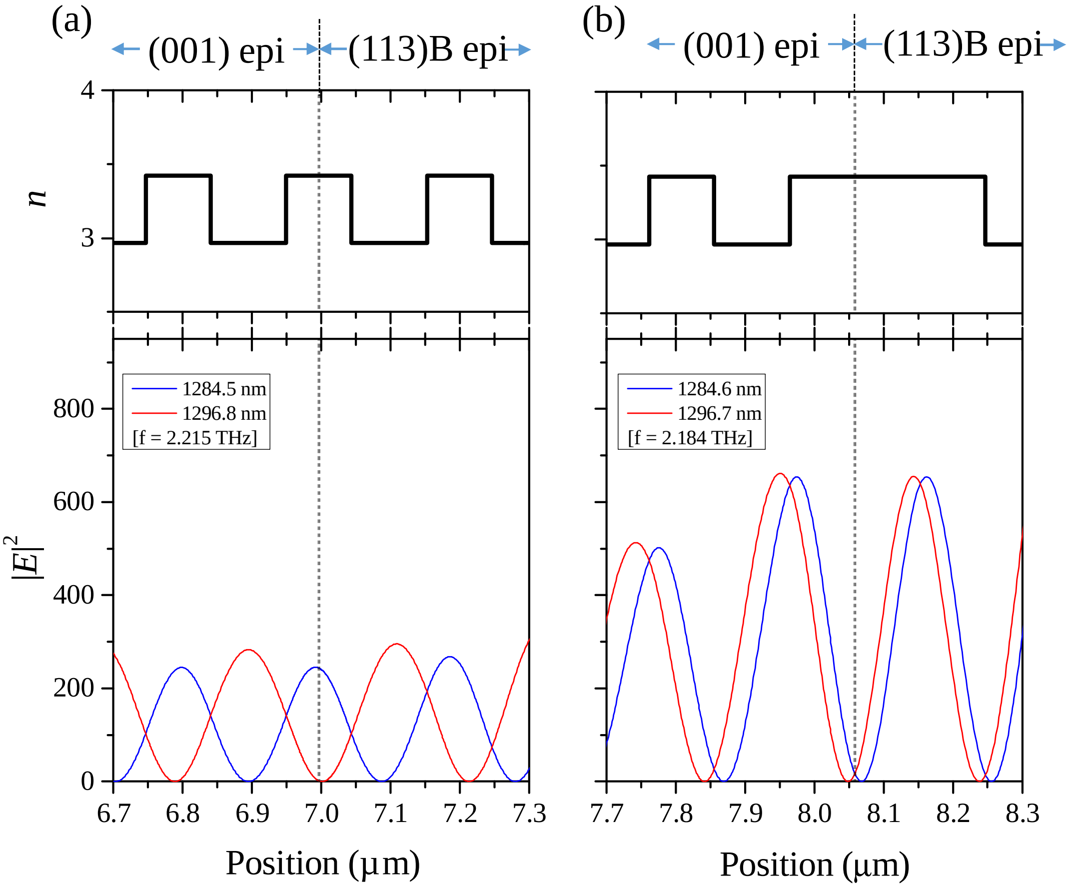

Fig. 4. (Color online) Distribution of the optical intensities for two color and refractive indices at (a) the center of middle DBR and (b) the just above the 2λ cavity on (113)B substrate. Position is a distance from a surface.

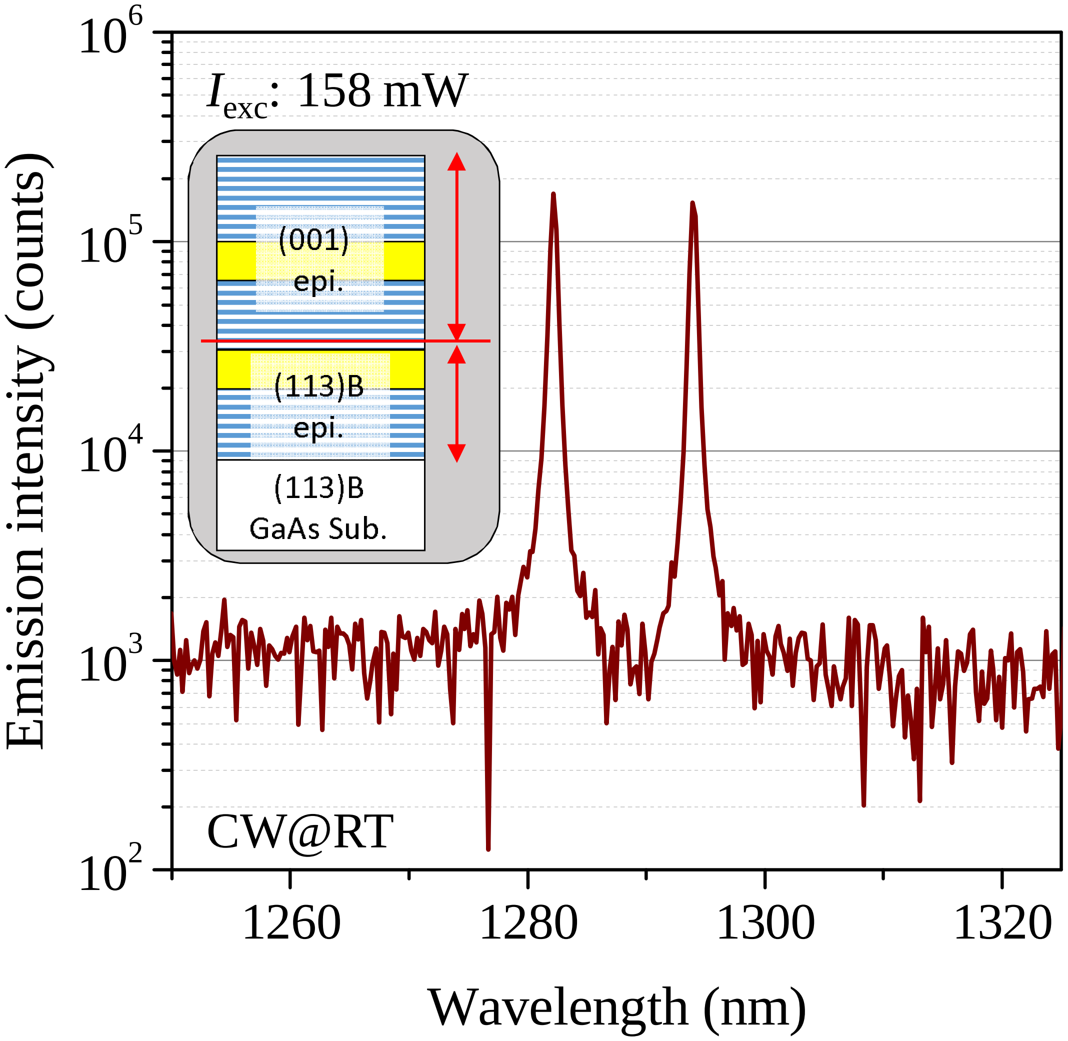

Fig. 5. (Color online) Surface emission spectrum of the coupled cavity by optical pumping. The emission intensity is plotted on a log scale. A couple cavity structure, which was bonded at the just above (113)B-side cavity layer, is shown inset.

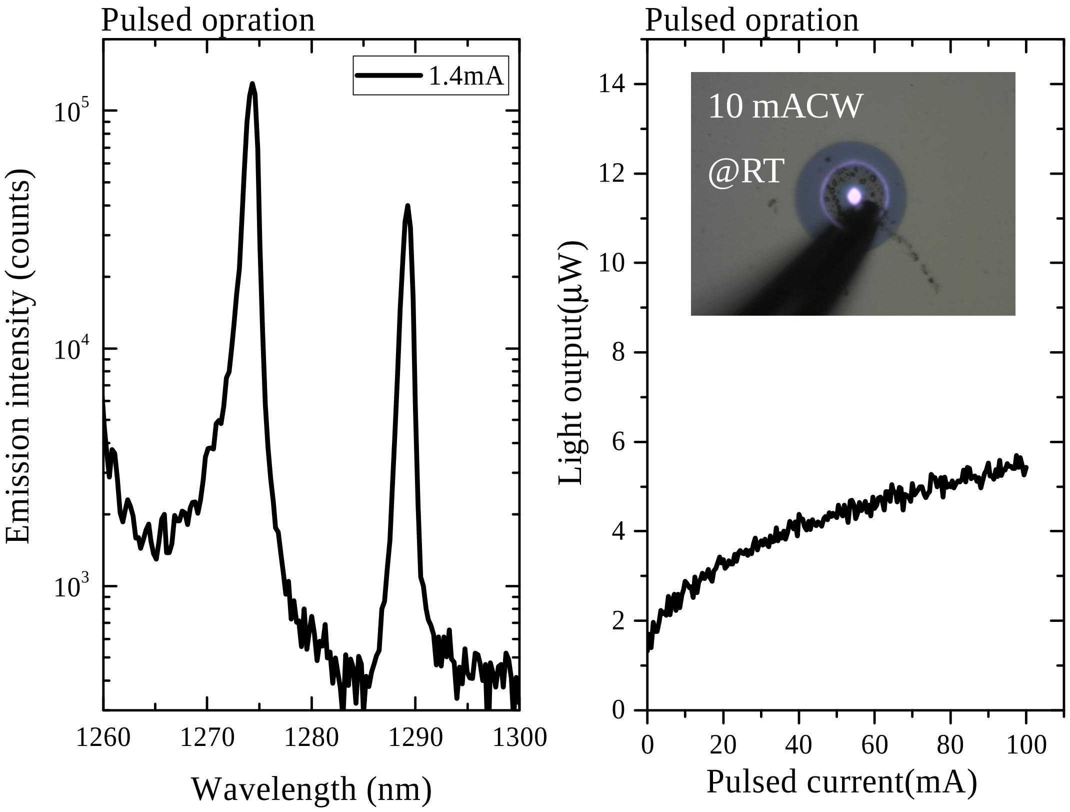

Fig. 6. (Color online) The emission spectrum of two color emitting device (left side). The injection current dependences of the light output (right side). The emission image of two color emitting device which operates CW mode (right side inset).