Design of Low-Threshold Photonic Crystal Surface-Emitting Lasers

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***Abstract*— We have investigated the influence of various thicknesses on different layers in GaAs-based photonic crystal surface-emitting lasers (PCSELs), by using the transfer matrix and coupled wave methods to increase the vertically optical confinement factor and to reduce the threshold gain. In addition, the relationship between the threshold gain and the filling factor has been considered. This letter provides an efficient calculation method for designing square-lattice-type PCSEL structures, which shall be useful for the fabrication of low-threshold PCSELs in the near future.**

***Index Terms*— Coupled wave, photonic crystal, surface-emitting laser.**

I. INTRODUCTION

OVER the past decade, photonic crystal (PC) has been widely manipulated and researched in many optoelectronic devices. In particular, two-dimensional (2D) photonic crystal surface emitting lasers (PCSELs) have been attracted much attention because of their many superior characteristics, such as the single mode operation, ultra-small divergence angle and high output power [1-4]. By adjusting the normalized frequency at the photonic band edges and the PC period of PCSELs rigorously, the specific Bragg diffraction will occur to achieve the surface emission condition [5-7]. GaAs-based materials have been used in production of red and infrared lasers, widely applied in the optical storage, pumping sources, medical treatments and various applications. In previous reports, several groups have demonstrated GaAs-based PCSELs [8, 9], but the impact of the vertically optical confinement factor in the device structure has not been carefully considered yet. Here, we have calculated the vertically optical confinement factor in the device structure by using the transfer matrix method [10] and the threshold gain by using the coupled wave theory [11] for square-lattice PC patterns. This simulation strategy not only can be applied to the air-hole type but also applied to the dielectric-rod type PC. By varying the thickness of the PC layer, inner cladding and optical confinement layers in PCSEL structures, the optical confinement factor has been optimized and the relationship between the threshold gain and the filling factor of the PC is also analyzed by the coupled wave theory in the PCSEL structures.

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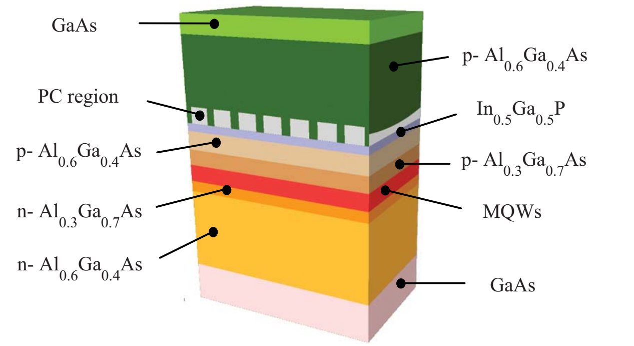

Fig. 1. Schematic of a GaAs-based PCSEL. The structure includes a GaAs substrate, an n-type AlGaAs bottom cladding layer, three-pair InGaAs/GaAs MQWs sandwiched between n-type and p-type AlGaAs optical confinement layers, an inner cladding layer and an outer cladding layer formed by p-type AlGaAs, separated by the PC layer and an InGaP etch stop layer, and a GaAs contact layer.

II. KEY DESIGN CONSIDERATIONS

The schematic of a GaAs-based PCSEL is shown in Fig. 1. The full structure is composed of a [100] GaAs substrate, a n-type 1.5 μm-thick $Al_{0.6}Ga_{0.4}As$ bottom cladding layer, a three-pair $In_{0.2}Ga_{0.8}As$/GaAs (6 nm/6 nm) multiple quantum wells (MQWs) sandwiched between the n-type and p-type 100 nm-thick $Al_{0.3}Ga_{0.7}As$ optical confinement layers, a 100 nm-thick inner cladding layer and a 1.4 μm-thick outer cladding layer formed by p-type $Al_{0.6}Ga_{0.4}As$, separated by the 100 nm-thick PC layer and an $In_{0.5}Ga_{0.5}P$ etch stop layer (10 nm), and a 100 nm-thick GaAs contact layer. The PC layer consists of SiO_2 and p-type $Al_{0.6}Ga_{0.4}As$, and the filling factor of PC (radius divided by period) is set to be 0.2 in this design. The dimension of the PC area is 240 μm × 240 μm.

In this letter, we want to establish a fast and accurate optimization method to successfully find the lowest threshold gain of laser structures in order to achieve the purpose of low power consumption. Based on the transfer matrix method and coupled wave theory, we can obtain the optical field distribution and the effective refractive index (n_{eff}) of fundamental mode with the structures. Then, we can estimate the fraction of the optical field within the PC region to access the vertically optical confinement factor. Next, the effective index can be calculated by the following approximated formulas [10]: $n_{eff}^2 = ff \times$

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$\varepsilon_a + (1 - ff) \times \varepsilon_b$ and $\Delta\varepsilon = \Gamma_{PC} \times (\varepsilon_{bulk} - \varepsilon_{rod})$, where ff is the filling factor, Γ_{PC} is the vertically optical confinement factor of the PC layer, $\Delta\varepsilon = \varepsilon_b - \varepsilon_a$ and $(\varepsilon_{bulk} - \varepsilon_{rod})$ is the difference between two materials composing the photonic crystal layer. Through the ways, we can obtain the dielectric constant for the circular rod (ε_a) and the background (ε_b) with the PC region, which are used in the calculation of the coupled wave theory [10].

We first modify the thickness of PC layer in order to decide the best overlapping between the optical field and the PC layer. Then, we determine the thickness of inner cladding layer to find out the relatively best results of vertically optical confinement factor in MQWs to reduce the value of threshold gain by using the coupled wave method. Third, we vary the filling factor of photonic crystal basis, which can affect the effective refractive index to determine the threshold gain of our design. Finally, we optimize the thickness of optical confinement layers to adjust the relative position including MQWs and PC layer within the structure.

III. Result and Discussion

Since the main lasing mechanism of PCSELs bases on the 2D distributed feedback effect, the spatial overlap between the optical field and the PC layer is crucial to the coupling strength. While the thickness of PC layer is increased from 0 to 100 nm, the vertically optical confinement factor of the PC layer is increased obviously from zero to 5.5%. Then, the vertically optical confinement factor of the PC layer saturates at 100 nm. The contribution from increasing of the PC thickness after 100 nm is relatively negligible since the extra extended PC thickness covers most of the tail of optical field. Therefore, the thickness of embedded PC layer is set to be 100 nm.

To enhance the optical confinement factor of MQWs, the thickness of optical confinement layers and inner cladding layer are varied simultaneously. The calculated result by using the coupled wave method shows that with the increasing of thickness of the inner cladding layer, values of threshold gain are presented with an increasing trend. In addition, the threshold gain curves as a function of the thickness of the optical confinement layer are parabolic-like distribution and the threshold gain can be reduced effectively while removing the inner cladding layer. Based on the coupled wave method, the lowest threshold gain is obtained while adopting 80 nm-thick optical confinement layers as shown in Fig. 2. The threshold gain of the optimized structure is calculated to be 155 cm^{-1}. In the overall PCSELs structure, the vertically optical confinement factor of PC region is calculated to be 7.3%. It exhibits that the PC effect could be dramatically enhanced in the vertical direction so that the threshold gain could be reduced.

The relationship between the threshold gain and the filling factor is also calculated as shown in Fig 3. As the result, the values of threshold gains exhibit two minima values, locating at 0.08 and 0.54, respectively. Along with the variation of the filling factor, the strength of coupling between the light and the PC is also distinct. The filling factor at 0.08 for the lowest threshold gain, calculated to be 54 cm^{-1}, could be interpreted as the best condition of light coupling to effectively reduce the threshold gain of the PCSEL.

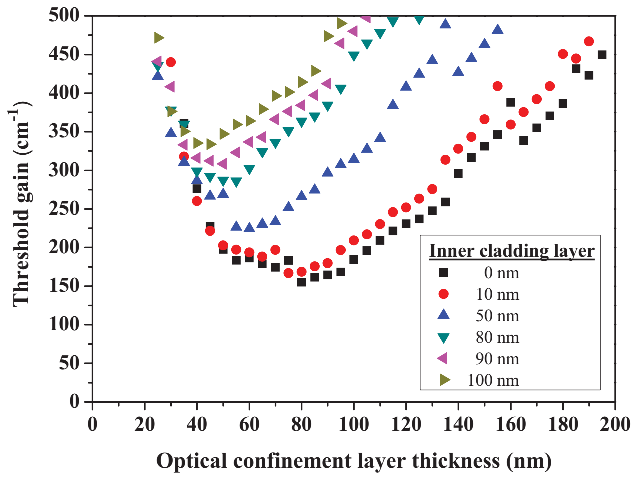

Fig. 2. Threshold gain as a function of the thickness of the optical confinement layer for various thicknesses of the inner cladding layer.

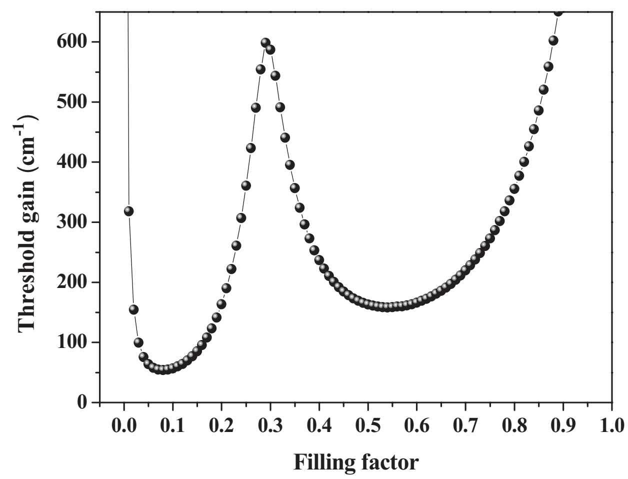

Fig. 3. Threshold gain as a function of the filling factor utilized the optimal results in Fig. 2.

Finally, we study the individual impacts of p-type and n-type optical confinement layers. Since the optical field is mainly distributed around MQWs region, the spacing between MQWs and PC layer should be reduced to enhance vertically optical confinement factor. Comparing with n-type optical confinement layer, the location of p-type one has a decisive impact on the optical confinement of the photonic crystal layer.

In order to obtain the ultimately optimal result, we gradually tune the thickness of n-type and p-type optical confinement layers separately. It is obvious that the best result of the thickness for the p-type and n-type optical confinement layer are 30 nm and 70 nm as shown in Fig. 4(a). The threshold gain is calculated to be about 50 cm^{-1}. On the other hand, we find the wide range of low-threshold condition with respect to the p-type and n-type optical confinement layer. It indicates that the p-type and n-type optical confinement layer could be designed with high tolerance for fabrication. Fig. 4(b) shows the threshold gain varied with n-type optical confinement layer when the p-type optical confinement layer is 30nm, the values of threshold gain are presented in the form of exponential decreasing function. Besides, through the above

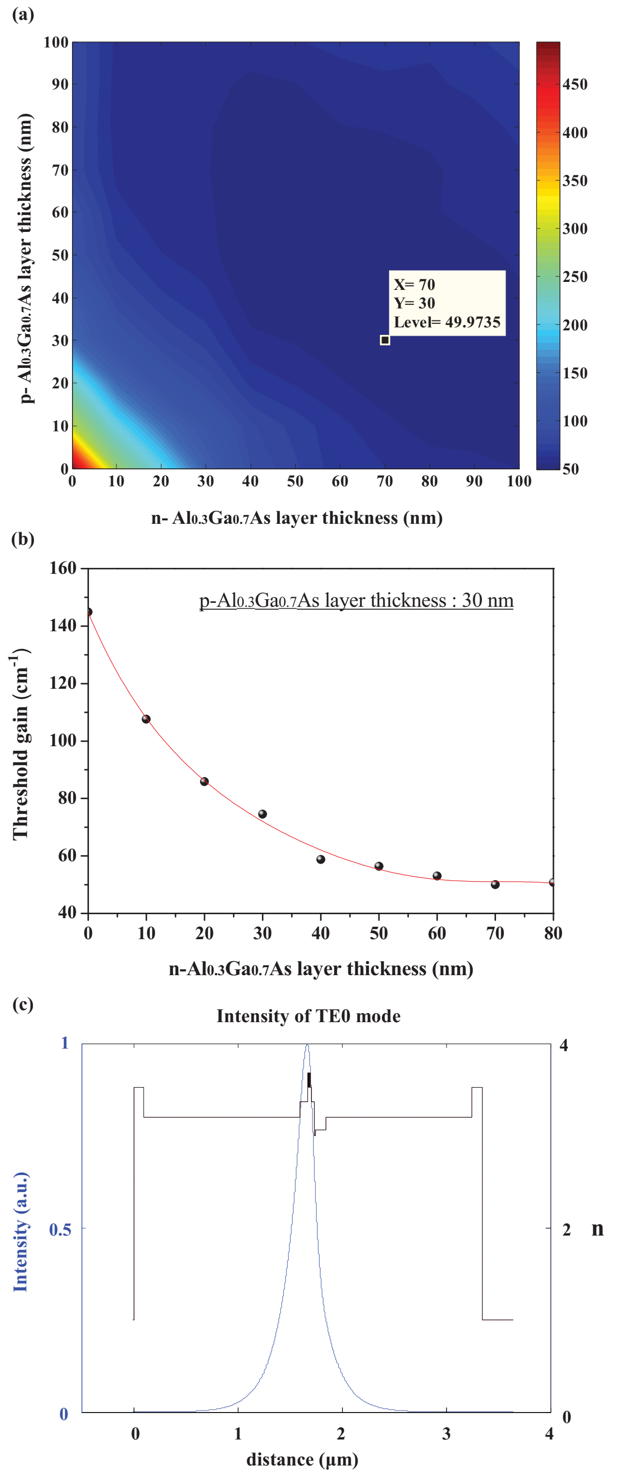

Fig. 4. (a) Threshold gain as a function of the thickness of the n-type and p-type optical confinement layers. The color alteration means the variation of threshold gain. (b) Detailed information captured from Fig. 4(a). (c) Optical field distribution of the device. The blue and black lines represent the optical field distribution and the refractive index in the structure, respectively. The above simulation results are based on the optimal results in Fig. 3.

simulation, the vertically optical confinement factor of PC region can be enhanced as large as 12.6%. The optical field distribution of the optimized structure is shown in Fig. 4(c). It clearly shows the optical field distribution is indeed more concentrated in the MQWs and PC layer by using this asymmetric confinement layer design. That is a key point to design the lowest threshold gain of PCSELs and we anticipate that by utilizing our systematic strategy on structure design and fabrication, a high efficient and low power consumption device could be easily realized.

IV. Conclusion

In summary, we have investigated the influence of various thicknesses on the inner cladding and optical confinement layers by the transfer matrix method, and also simulated the threshold gain of the optimized structure by the coupled wave theory. The relationship between the threshold gain and filling factor has been considered. The optimized filling factor of PC could be calculated to be 0.08. Moreover, the influence between p-type and n-type optical confinement layers is discussed. The results show the vertically optical confinement factor of PC could dramatically enhanced when the n-type and the p-type optical confinement layer are calculated to be 70 nm and 30 nm. Finally, the best value of vertically optical confinement factor of PC in the optimized GaAs-based PCSELs is calculated to be 12.6% and the threshold gain is reduced to 50 cm^{-1}. This study provides a fast calculation method in designing of PCSEL structures and we believe it is useful for fabrication of the low threshold PCSELs in the near future.

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