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Etching depth dependence of the effective refractive index in two-dimensional photonic-crystal-patterned vertical-cavity surface-emitting laser structures

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A vertical-cavity surface-emitting laser (VCSEL) having a two-dimensional (2-D) photonic crystal structure on its surface has been investigated for single-lateral-mode operation. We evaluated the effective index change of a VCSEL cavity introduced by a 2-D pattern. Our experimental results showed good agreement with a theoretical model in which the influence of a finite etching depth was taken into consideration. The etching-depth dependence parameter γ, which can be explained by the optical power distribution inside a VCSEL structure, will be helpful for controlling the lateral mode of VCSEL devices. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1556562]

Lateral-mode control of vertical-cavity surface-emitting lasers (VCSELs) is one of the key issues in realizing high-performance optical communication systems, in which single-mode operation is necessary for long and short wavelength regions. High-power single-mode operation is also required for free-space data communication applications. Recently, a two-dimensional photonic crystal (2-D PhC) structure formed on a VCSEL surface has been investigated as a lateral-mode control method.[1–3] The most attractive feature of this structure is the enlargement of the emission area, thereby permitting higher power output. The large area can be realized because of strong wavelength dependence of the refractive index in the 2-D PhC structure, analogous to the situation in a photonic crystal fiber.[4] Although good single-mode operation has been reported for a specific structure,[2] the optimized design of 2-D PhCs was not clear, especially when considering a finite etching depth. Since the mode control mechanism utilized in this technology is the effective refractive index control achieved by forming a 2-D PhC structure,[4] a parameter representing this control must have a strong dependence on the etching depth. We have investigated the etching depth dependence, both theoretically and experimentally, of the effective index change in a VCSEL structure.

To examine the effective index variation experimentally, we made 2-D PhC air holes with a triangular lattice configuration on the surface of an 850-nm-VCSEL wafer and measured resonant wavelengths for different etching depths. The VCSEL structure has $Al_{0.9}Ga_{0.1}As/Al_{0.2}Ga_{0.8}As$ distributed Bragg reflectors (DBRs) below and above an active region. The top DBR consists of 25 pairs and the bottom one consists of 35.5 pairs. Two-dimensional PhC patterns without any defects in the structure were delineated by electron-beam lithography and fabricated using an inductive coupled plasma reactive ion etching technique, with $SiCl_4$ as the etching gas. Since the etching depth will be affected by the hole diameter, the etch depth was evaluated by using a scanning electron microscope. A PhC pattern covers an area of 500 μm$\times$500 μm, with 500-μm-wide unpatterned areas between adjacent PhCs. The effect of material thickness variation across the wafer can be canceled by measuring the resonant wavelength at the unpatterned adjacent flat regions.

We used a multimode optical fiber to irradiate the PhC patterns, with a halogen lamp as a broadband light source. The reflection back from the pattern was then collected through the same fiber, which was split so that the spectra could be evaluated. The gap between the edge of the fiber and the sample was less than 100 μm. Figure 1 shows a typical sequence of reflectivity spectra obtained. The three solid lines are from the 2-D PhC patterned areas, and the data from the flat adjacent areas are shown as dotted lines. These 2-D PhC structures all have the same lattice constant (Λ) of 5 μm, but have different hole diameters (d) of 0.5, 1.5, and 3.0 μm. These structures were etched for an equivalent period of time, resulting in respective hole depths of approximately 9, 13, and 16 pairs of the top DBR. The etching depths are strongly affected by the hole diameters. Resonant dips can be seen clearly in the reflectivity spectra at around

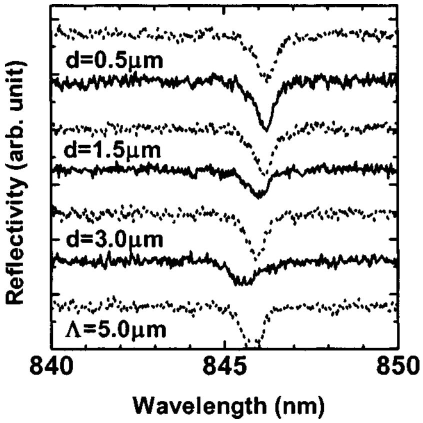

FIG. 1. A typical sequence of reflectivity spectra obtained is shown. The three solid lines are from the 2-D PhC patterned areas and the data from the flat adjacent areas are shown as dotted lines.

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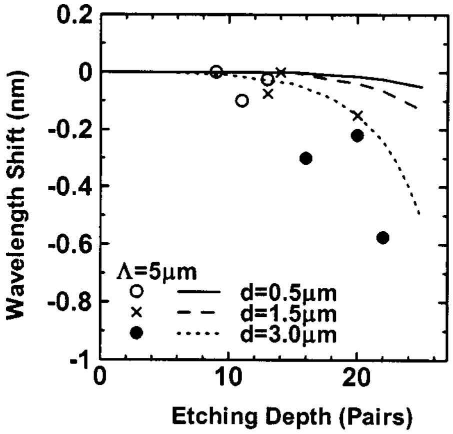

FIG. 2. The etching depth dependence of the wavelength shift in the structure having Λ of 5 μm is summarized.

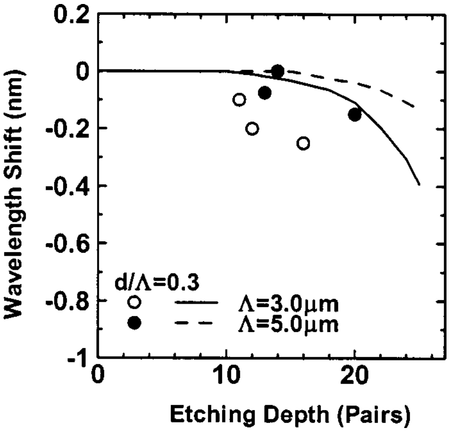

FIG. 3. Lattice-constant dependence of the wavelength shift in the structure having d/Λ of 0.3 is shown.

846 nm. The resonant wavelength of nearby unetched regions changes only slightly across the area of measurement. The structure with the larger hole diameter exhibits a larger blueshift, due to the substantial refractive index modification as well as the etching depth enhancement.

The refractive index of a 2-D PhC patterned semiconductor can be calculated from a band diagram analysis of out-of-plane propagation modes.[5] The relationship between the normalized frequency and k-vector along the air-hole direction of the lowest energy level available in the PhC structure gives the equivalent refractive index for the light propagating along that direction.[4] The term "effective index" is used in Ref. 4, but we define it here as the equivalent refractive index because the effective index represents the index of a VCSEL cavity at the resonant wavelength, as will be discussed later. We used the plane-wave expansion method with an infinite structure both in the plane and out of the plane to calculate the band structure.[6]

The effective index of a VCSEL structure with a PhC pattern is assumed to be defined as follows. Each DBR layer that has been penetrated by etched holes, assumed to be infinite in extent in the lateral direction, can be modeled by a single layer of constant refractive index, even though it is actually a complex structure because of the presence of etched holes. The material refractive index of a DBR layer n_m is assumed to be modified to the equivalent refractive index as $n_m - \Delta n_m$ by making the periodic photonic crystal structure, where Δn_m is the index reduction deduced by a band diagram calculation. Since Δn_m is small compared to the material index (it is on the order 0.01 or less), the same value of Δn_m can be applied to high and low index materials in the DBR for simplicity. The reflectivity spectrum from the entire structure, including the etched top DBR region (which has the altered material indices), the rest of the DBR, the optical cavity, and bottom DBR, was calculated to obtain the resonant wavelength of the structure. By changing the number of etched pairs in the top DBR, we can estimate the etching depth dependence of the resonant wavelength, or in other words, the effective refractive index, which is defined by $\Delta n/n_{\text{eff}} = \Delta\lambda/\lambda$.[7] The etching depth dependence of the wavelength shift in the structure having Λ of 5 μm is summarized in Fig. 2. Three lines shown in the figure are theoretical estimations of this dependence, where etching depth was assumed, pair by pair, to have no phase mismatch at the top surface; that is, a quarter-wavelength-thick $Al_{0.2}Ga_{0.8}As$ layer is assumed to be at the top of the etched surface. Experimental wavelength shifts are shown as circles and crosses in the figure. In the actual sample, the etching stopped at a random point along the phase curve, and the contribution of the phase mismatch might change the resonance wavelength slightly. The vertical shape of the holes is also different from the theoretical model. In spite of these difficulties and the fact that the thickness of each layer is too thin for the fundamental model of infinite PhCs to be applicable, the magnitude of the wavelength shift has very good agreement with our theoretical model.

Lattice constant dependence of the wavelength shift is shown in Fig. 3. If the reduction of the refractive index is simply related to the filling factor of air holes, rather than by the PhC effect (which requires a wavelength dependence of refractive index variation), these structures would have the same wavelength shift. In our results, PhCs with a smaller lattice constant resulted in a larger wavelength shift, as shown in Fig. 3. This is consistent with the band diagram calculation, in which the smaller lattice constant, or the larger k-vector in the propagation direction, exhibits the larger reduction of the refractive index. If we translate the theoretical curves shown in Figs. 2 and 3 into the effective refractive index change Δn normalized by the material index

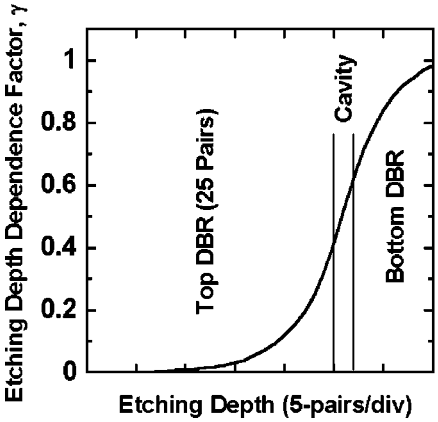

FIG. 4. The etching depth dependence factor γ, calculated for the experimental structure.

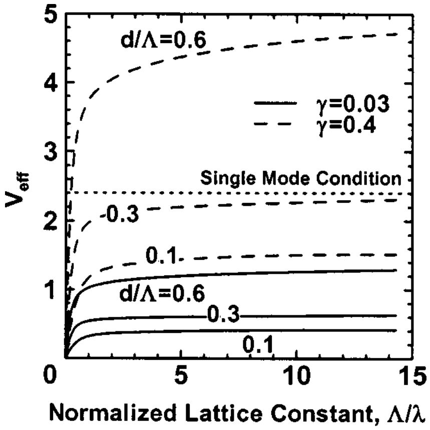

FIG. 5. V_{eff} parameters for γ of 0.03 and 0.4, which correspond to etching depths of 15 and 25 pairs, respectively, are calculated.

reduction Δn_m, all of them have the same etching depth dependence. The result is shown in Fig. 4 as an etching depth dependence factor γ. By using the γ-factor, the effective index of the VCSEL structure can be written as $n_{\mathrm{eff}}=n_m-\gamma\Delta n_m$. γ varies from 0 to 1 depending on the etching depth and structure. This parameter is explained qualitatively by the optical power distribution inside the VCSEL structure. To enhance the effective index reduction by a PhC structure, the etching depth should be large enough to overlap the optical power distribution. The number of guided modes supported by a single point defect structure buried in a 2-D PhC can be evaluated by the V_{eff}-parameter:[4]

$$V_{\mathrm{eff}}=\frac{2\pi\Lambda}{\lambda}\sqrt{n_m^2-n_{\mathrm{eq}}^2}, \tag{1}$$

where n_{eq} is the equivalent refractive index of the PhC cladding region. If V_{eff} is less than 2.405, the structure is considered to be a single-mode waveguide. We can introduce the γ-parameter to Eq. (1) by replacing n_{eq} by $n_{\mathrm{eff}}=n_m-\gamma\Delta n_m$. Typical results of V_{eff} calculations for γ of 0.03 and 0.4, which correspond to etching depths of 15 and 25 pairs, respectively, are shown in Fig. 5. As is evident from the figure, V_{eff} is strongly affected by γ. To obtain stable single-mode operation, V_{eff} should be large enough to overcome any external perturbations, such as carrier-injected thermal effects. At the same time, we have to pay attention that the structure maintains the single mode condition even if there are perturbations.

In summary, we have investigated the effective index change of a VCSEL structure introduced by creating a 2-D PhC pattern on the surface and have found strong etching depth dependence. The etching depth dependence factor γ will be helpful in designing an appropriate PhC structure to control the lateral mode of VCSEL devices.

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[1] H. J. Unold, M. Golling, R. Michalzik, D. Supper, and K. J. Ebeling, *Proceedings of the 27th European Conference on Optical Communications*, 2001, Amsterdam, Netherlands, Paper Th.A.1.4.
[2] D. S. Song, S. H. Kim, H. G. Park, C. K. Kim, and Y. H. Lee, Appl. Phys. Lett. **80**, 3901 (2002).
[3] N. Yokouchi, A. Danner, and K. D. Choquette, *2002 LEOS Summer Topical Meetings*, Quebec, Canada, Paper TuP2.
[4] T. A. Birks, J. C. Knight, and P. St. J. Russell, Opt. Lett. **22**, 961 (1997).
[5] A. A. Maradudin and A. R. McGurn, J. Mod. Opt. **41**, 275 (1994).
[6] J. D. Joannopoulos, R. D. Meade, and J. N. Winn, *Photonic Crystal-Molding the Flow of Light*, (Princeton University Press, Princeton, NJ, 1995).
[7] G. R. Hadley, Opt. Lett. **20**, 1483 (1995).