Low-Loss Bragg-Reflector Lateral-Transverse-Mode Confinement in AlGaInP Red Laser

Yoshiyasu Ueno

***Abstract*—A low-loss Bragg-reflector-waveguide (BRW) structure is proposed for AlGaInP red lasers. This BRW laser uses (AlGaInP/GaAs)$_n$ Bragg-reflector (BR) block layers in place of conventional GaAs block layers. Propagating-mode calculations reveal that an aluminum content (x) lower than 0.2 for $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ in the BR block layers is sufficient for reducing mode loss together with confining the lateral transverse mode. Mode loss in the (AlGaInP/GaAs)$_n$ BR region is reduced resonantly to one-third that of a conventional GaAs block region. This reduction originates from a combination of Bragg reflection and the low absorption loss in the AlGaInP crystal. The refractive-index step, formed at the edge of a ridge stripe by the BR block layers, is around 1×10^{-2}.**

I. Introduction

MUCH research has focused on AlGaInP lasers for use in optical-disk memory systems and laser printers, because their laser wavelengths are significantly shorter than those of conventional AlGaAs lasers. For practical applications, mode confinement is necessary in stabilizing the laser-beam shape. Earlier, a refractive-index-guided AlGaInP laser structure with GaAs block layers was reported [1], where the GaAs block layers were selectively grown outside a ridge stripe. This structure has been used for both high-power lasers [2]–[7] and lasers with wavelengths below 640 nm [8]–[11]. Its mode loss is large, however, because the GaAs block layers absorb much of the propagating laser light along the cavity.

Replacement of the GaAs block layers with transparent $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ block layers is believed to reduce this loss. An aluminum content (x) of at least 0.6 is needed to stabilize the fundamental transverse mode. It is difficult, however, to selectively grow AlGaInP crystals with such a high aluminum content. Several other refractive-index-guided laser structures have been developed reducing the mode loss [12]–[14]. These structures, however, are likely to have problems regarding crystal quality and stress induced by electrodes.

In order to develop a practical low-loss laser structure, the author turned his attention to an AlGaInP block layer with an aluminum content lower than 0.2. This block layer, which is almost transparent for 630- to 690-nm laser light, should be easier to grow selectively. The problem is that a laser structure with these block layers will not guide the propagating-mode light because their refractive index is higher than that of the cladding layers.

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The author is with the Opto-Electronic Device Research Laboratory, Opto-Electronics Research Laboratories, NEC Corporation, 34 Miyukigaoka, Tsukuba, Ibaraki 305, Japan.
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This paper introduces a new Bragg-reflector-waveguide (BRW) laser structure which can be used to overcome this problem. In this structure a reflection function is added to the low-aluminum AlGaInP block layers to guide the propagating-mode light. GaAs is used in the alternate Bragg-reflector (BR) block layers because it is easy to grow selectively. Even though absorptive GaAs is used, propagating-mode calculations reveal a significant reduction in resonant mode loss. A laser structure with block layers consisting of alternating AlGaInP layers with different aluminum contents has already been reported by I. Kidoguchi *et al.* [15]. The alternating layers, however, were not designed quarter-wave thick, and the structure formed a negative refractive-index step. In contrast, the BRW structure forms a sufficient positive index step and therefore the laser should emit a fundamental-transverse-mode light without any side lobes. The concept behind the BRW laser structure is also applicable to II-VI blue-green lasers and AlGaAs lasers.

II. Laser Structure

Fig. 1 shows a waveguide structure of a BRW laser. This BRW structure is similar to a conventional self-aligned-structure refractive-index-guided AlGaInP red laser [1], [2] except that conventional GaAs block layers are replaced with BR block layers. The BR block layer consists of several pairs of (Al)GaInP and GaAs layers. The thickness of each of these (Al)GaInP and GaAs layers is tuned to a quarter of the transverse wavelength in each layer, as defined in (8) in Section III, to satisfy the Bragg-reflection condition. The aluminum content (x) needed for the $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ layers is 0 to 0.2, and depends on the laser wavelength. For a 680-nm laser, (GaInP/GaAs)$_n$ BR block layers are used as shown in Fig. 1. No aluminum is used, because the GaInP layer is almost transparent for a 680-nm light. So, this BR block layer should be very easy to selectively grow by using MOVPE. For a 630-nm laser, an aluminum content (x) of 0.2 is needed. More details on the aluminum content are discussed in Section V.

The laser cavity of a 680-nm BRW laser consists of a 60-nm-thick $Ga_{0.5}In_{0.5}P$ active layer sandwiched by 1.0-μm-thick $(Al_{0.6}Ga_{0.4})_{0.5}In_{0.5}P$ cladding layers, and cleaved mirrors. The optical confinement factor (Γ) for the active layer is 0.18. The cladding layer sandwiched by the BR layer and the active layer is 200-nm thick. For this laser cavity, the optimum quarter-wavelength layer thicknesses of GaInP and GaAs in the BR block layers are 146 nm and 92 nm, respectively. Attempts to equalize the heights of the top surfaces of the cladding layer and the BR layers determined

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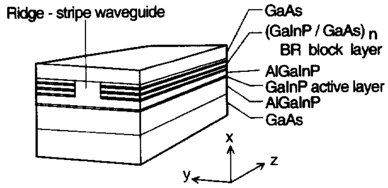

Fig. 1. Waveguide structure for a Bragg-reflector-waveguide (BRW) AlGaInP red laser. A pair of (AlGaInP/GaAs)$_n$ Bragg-reflector (BR) block layers are formed outside a ridge stripe. BR block layers for a 680-nm laser consist of GaInP and GaAs layers, without aluminum, as shown in this figure. Those for a 630-nm laser consist of $Al_{0.2}Ga_{0.8})_{0.5}In_{0.5}P$ and GaAs layers. The thickness of each of these (Al)GaInP and GaAs layers is tuned to a quarter of the transverse wavelength in each layer to satisfy the Bragg-reflection condition.

TABLE I
MATERIAL PARAMETERS USED FOR THE CALCULATION. AN ABSORPTION COEFFICIENT FOR $Ga_{0.5}In_{0.5}P$ IN A BR BLOCK LAYER IS DISCUSSED IN SECTION V.

	Refractive Index	Absorption Coefficient (cm^{-1})
$Ga_{0.5}In_{0.5}P$ (for an active layer)	3.530	0.
$Ga_{0.5}In_{0.5}P$ (in a BR block layer)	3.530	500.
$(Al_{0.6}Ga_{0.4})_{0.5}In_{0.5}P$	3.321	0.
GaAs	3.790	20000.

that the BR layers have three periods. These surfaces are covered with a GaAs cap layer to form an ohmic contact with an electrode. Results of propagating-mode calculations on this 680-nm BRW laser are shown in Section IV, where the dependencies of mode confinement and mode loss on BR layer thickness are presented.

III. Propagating-Mode Calculation

The mode loss and mode distribution for the propagating mode in a BR block region were calculated, using wave equations in an 11-layer slab waveguide [16]. Material parameters are listed in Table I. The absorption coefficient for these $Ga_{0.5}In_{0.5}P$ layers is assumed to be 500 cm^{-1}, which is discussed in Section V. The refractive indexes for $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ [17] are slightly modified to fit the radiation angles measured for our lasers. The refractive index and the absorption coefficient of GaAs at 680 nm are extrapolated using data from a previous report [18].

The lateral y-direction component of the electric-field distribution in the ith layer for a propagating transverse-electric mode is expressed as

$$E_i^y(x) = u_i e^{k_i x} + v_i e^{k_i x},\ (i = 1, 2, \cdots, 11), \tag{1}$$

where

$$k_i \equiv \sqrt{\beta^2 - k_0^2 \varepsilon_i} \tag{2}$$

$$\varepsilon_i \equiv (n_i + j\frac{\alpha_i}{2k_0})^2 \tag{3}$$

$$k_0 \equiv \frac{2\pi}{\lambda_L}. \tag{4}$$

n_i and α_i are the refractive index and the absorption coefficient for the ith layer, respectively. λ_L is the laser wavelength. The complex propagation constant (β) and distribution coefficients (u_i and v_i) are obtained after numerically solving a system of equations consisting of boundary conditions at the ten interfaces and at positive- and negative-infinite distances. Thus, the mode loss (α_{BR}) is obtained as two times the imaginary part of the propagation constant,

$$\alpha_{BR} = 2\text{Im}(\beta). \tag{5}$$

The mode loss approximately equals the sum of absorption losses in all layers

$$\alpha_{BR} \approx \sum \Gamma_i \alpha_i, \tag{6}$$

where Γ_i is the confinement factor for the ith layer.

The important structural parameters are the thicknesses of the GaInP (t^a) and GaAs (t^b) intermediate layers in the BR block layer. They are tuned to quarter wavelengths in the vertical x direction in these two kinds of layers. Therefore, thicknesses normalized by these wavelengths are useful. In this paper, it is assumed that

$$\frac{t^a}{\lambda_a} = \frac{t^b}{\lambda_b} \equiv t_p. \tag{7}$$

The t_p-dependencies of the mode confinement and mode loss are shown in Section IV. The x-direction wavelengths for GaInP (λ_a) and GaAs (λ_b) are expressed as

$$\lambda_l = \frac{2\pi}{|\text{Im}k_l|} = \frac{2\pi}{\text{Re}\sqrt{n_l^2 k_0^2 - \beta^2}},\ (l = a, b). \tag{8}$$

These wavelengths for GaInP (584 nm) and GaAs (368 nm) are longer than the laser wavelength in the waveguide in the longitudinal z direction ($2\pi\beta \approx 200$ nm).

To consider lateral-transverse-mode confinement in a two-dimensional BRW laser structure, effective refractive indexes were calculated from the standpoint of the equivalent-refractive-index approximation. An effective refractive index (n_{eff}) for a slab waveguide is expressed, using a propagation constant (β), as

$$n_{eff} = \text{Re}\frac{\beta}{k_0}. \tag{9}$$

A refractive-index step is defined as the difference of effective refractive indexes for inside and outside the ridge stripe.

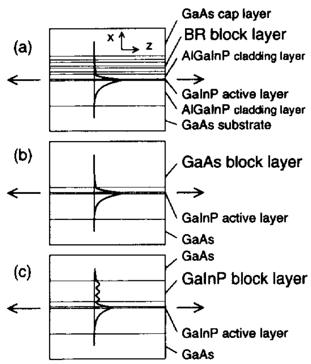

Fig. 2. Comparison of power distributions of the propagating-mode light in block regions outside ridge stripes for three kinds of lasers. In a GaAs block region for a conventional laser (b), the propagating mode is confined by the strong absorption of GaAs. A less-absorptive GaInP block layer does not confine the mode (c). In contrast to the GaInP block layer, the $\lambda/4$ -thick-(GaInP/GaAs)$_3$ BR block layer (a), whose average absorption coefficient is still lower than GaAs, confines the mode as much as the conventional GaAs block layer does.

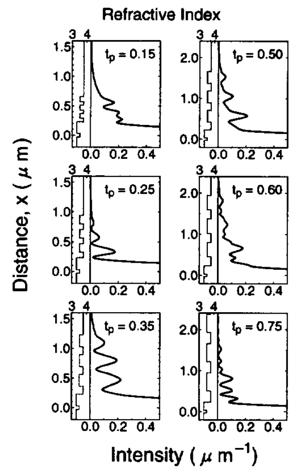

Fig. 3. BR-layer-thickness dependency of a mode distribution magnified in the vicinity of the BR block layer. The layer thickness t_p is defined in (7), where the layer-thickness ratio between GaInP and GaAs layers is kept constant. Mode leakage into the BR block layer is suppressed the most at a quarter-wavelength thickness $t_p = 0.25$. The origin of the x axis is the center of the active layer.

IV. Results

A. Mode Confinement

Fig. 2 shows a calculated power distribution of a propagating mode in the vertical x direction in the (GaInP/GaAs)$_3$ BR block region, as compared to distributions in a conventional GaAs block region and in a GaInP block region. The arrows indicate the laser-light propagating directions. This figure qualitatively shows the mode confinement caused by the BR block layer in the BRW laser. In a conventional GaAs block region, the mode is confined by the strong absorption of GaAs, although the refractive index of GaAs is higher than that of the cladding layers [Fig. 2(b)]. A less-absorptive GaInP block layer, whose refractive index is also higher than that of the cladding layers, does not confine the mode [Fig. 2(c)]. In contrast to the GaInP block layer, the quarter-wavelength-thick-GaInP/GaAs BR block layer, whose average absorption coefficient is still lower than GaAs, confines the mode [Fig. 2(a)] as much as the conventional GaAs block layer does.

Fig. 3 shows the BR-layer-thickness (t_p) dependency of a mode distribution. The details of the mode distributions are magnified in the vicinity of the BR block layer. The layer thickness t_p is defined in (7), where the layer-thickness ratio between GaInP and GaAs layers is kept constant. The origin of the x axis is the center of the active layer. The dashed lines show the refractive-index profiles for those layer structures. Leakage of the mode into the BR block layer is the most suppressed at a quarter-wavelength thickness $(t_p = 0.25)$. this means that a mode is the most confined at $t_p = 0.25$. This layer-thickness dependency of mode confinement proves that the confinement originates not from absorption, but from Bragg reflection.

Mode confinement caused by the BR block layer produces a sufficient refractive-index step at the edge of the ridge stripe. Fig. 4 shows an effective refractive index for the BR block region (solid line), together with an index for the active region inside the ridge stripe (dashed-and-dotted line). The index for a conventional GaAs block region (dashed line) is also shown for comparison. As shown in the figure, the index for the BR block region differs from that inside the stripe by about 1×10^{-2} at the Bragg-reflection condition $(t_p = 1/4)$ and the layer-thickness dependency is not large. This refractive-index difference (Δn) in the y direction is sufficient for the fundamental transverse mode.

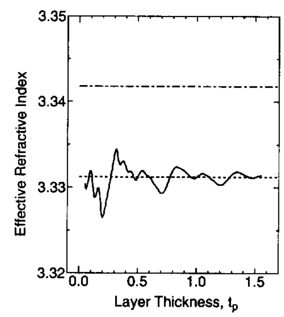

Fig. 4. Effective refractive index for the BR block region (solid line), together with that for the active region inside the ridge stripe (dashed-and-dotted line). An index for a conventional GaAs region (dashed line) is also shown for comparison. The BR block region forms a refractive-index step around 1×10^{-2}.

B. Mode Loss and Waveguide Loss

Fig. 5 shows mode loss in the BR block region, where the absorption coefficient for $Ga_{0.5}In_{0.5}P$ layers in the BR block layer is assumed to be 500 cm^{-1}. The mode loss shows clear resonance at

$$t_p = \frac{2N-1}{4}, (N = 1, 2, \cdots). \tag{10}$$

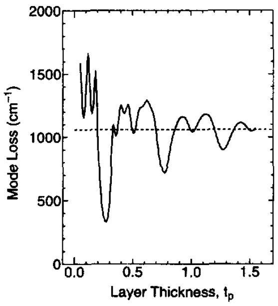

Fig. 5. Mode loss in the BR block region. The mode loss shows clear resonance at layer thicknesses (t_p) of $(2N-1)/4$, where N indicates a positive integer. At a quarter-wavelength thickness $(t_p = 1/4)$, the mode loss drastically decreases to 31% of that in the conventional GaAs block region shown by the dashed line.

This resonance proves that Bragg reflection plays an important role. At a quarter-wavelength thickness $(t_p = 1/4)$, the mode loss decreases drastically to 31% of that in the conventional GaAs region shown by the dashed line. This mode-loss decrease should lead to large improvements in differential quantum efficiency, threshold current, output power, etc.

It should be noted that the (real) refractive-index ratio of 1.074 between $Ga_{0.5}In_{0.5}P$ and GaAs layers in the BR block layer is not as large as the ratio of 1.21 [19] between AlAs and GaAs. BR mirrors for vertical-cavity surface-emitting lasers consist of the latter [20], [21]. So, the mode-loss decrease to 31% resulting from BR block layers might seem surprisingly large. A function of the Bragg reflection is further discussed in Section V.

Fig. 6 shows mode losses in the BR block region, where the absorption coefficient for $Ga_{0.5}In_{0.5}P$ layers in the BR block layer is assumed to be from zero to $2 \times 10^4\,\mathrm{cm}^{-1}$. The dashed line shows mode loss in the conventional GaAs block region. This figure shows that the mode loss decreases as much as that shown in Fig. 5, if the absorption for GaInP is smaller than $1000\,\mathrm{cm}^{-1}$. It also shows that the resonance of the mode loss at $t_p = 1/4$ is nsot very steep; about a 10% error from the optimum value for a layer thickness is permissible. Consequently, the author believes that this BRW structure is practical.

A decrease in waveguide loss (α_w) for the fundamental transverse mode with a decrease in mode loss in the block region (α_B) is estimated as follows. The waveguide loss for an AlGaInP laser is approximately the sum of mode loss in the block region and free-carrier absorption in the active layer

$$\alpha_w = \alpha_B \Gamma^B + \alpha_{act}^{fc} \Gamma^{act} \Gamma_a. \quad (11)$$

Lateral confinement factors for the block region (Γ^B) and the active region (Γ^{act}), together with a vertical confinement factor for the active layer (Γ_a), are obtained from the propagation-mode calculation. For a conventional laser with a 3- μm-wide stripe, the waveguide loss is estimated to be $40\,\mathrm{cm}^{-1}$, which consists of mode loss in the GaAs block region $(\approx 30\,\mathrm{cm}^{-1})$ and free-carrier absorption $(\approx 10\,\mathrm{cm}^{-1})$. In contrast, mode loss in the BR block region decreases to one third, as shown in Fig. 3. As a result, the waveguide loss decreases to $20\,\mathrm{cm}^{-1}$, consisting of mode loss in the BR block region $(\approx 10\,\mathrm{cm}^{-1})$ and free-carrier absorption. Thus, waveguide loss for a BRW laser is estimated to decrease to half that for a conventional laser.

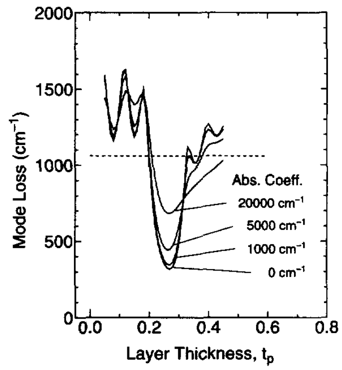

Fig. 6. Mode losses in the BR block region, where the absorption coefficient for GaInP layers in the BR block layer is assumed to be from zero to $2 \times 10^4\,\mathrm{cm}^{-1}$. The mode loss decreases as much as that shown in Fig. 5, if the absorption coefficient is smaller than $1000\,\mathrm{cm}^{-1}$.

V. Discussion

A. Aluminum Content for AlGaInP in a BR Layer

The absorption coefficient of $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ layers in a BR block layer for laser light plays an important role in decreasing mode loss, as shown in Fig. 6. Here, the absorption coefficient of $Ga_{0.5}In_{0.5}P$ for a 680-nm light is first discussed in relation to its bandgap energy (E_g). It is well known that the E_g of $Ga_{0.5}In_{0.5}P$ lattice-matched to GaAs depends on the growth conditions due to group-III-sublattice ordering [22], [23]. When a BR block layer is n-type Si-doped, in order to confine the injected current like a conventional GaAs block layer, the E_g for GaInP layers increases to 1.93 eV at an electron density of $10^{18}\,\mathrm{cm}^{-3}$ [23], [24]. This E_g increase originates partly from Si-induced sublattice disorder and partly from Burstein shift which results from high-density free electrons. This E_g value is 0.11 eV higher than the photon energy of a 680-nm light (1.82 eV). Thus, the absorption coefficient for a Si-doped GaInP layer is estimated to be below $500\,\mathrm{cm}^{-1}$, by referring to measured absorption spectra for n-type-doped GaAs [25]. Based on this estimation, we proposed to use $Ga_{0.5}In_{0.5}P$, without aluminum, in BR layers for 680-nm AlGaInP lasers.

For a 630-nm laser, the author proposes a BRW structure with $((Al_{0.2}Ga_{0.8})_{0.5}In_{0.5}P/GaAs)_n$ BR block layers. The photon energy for a 630-nm laser light is 1.97 eV. The E_g for a Si-doped $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ layer increases from 1.93 to 2.07 eV by increasing the aluminum content (x) from zero to 0.2. Consequently, the absorption coefficient for $(Al_{0.2}Ga_{0.8})_{0.5}P$ is estimated to be below $500\,\mathrm{cm}^{-1}$ for a 630-nm light. Similar to the 680-nm BRW laser mentioned above, quarter-wavelength-thick $((Al_{0.2}Ga_{0.8})_{0.5}In_{0.5}P/GaAs)_n$ BR block layers should reduce the mode loss for a 630-nm laser. The quarter-wavelength thickness for a 630-nm laser is derived from (8).

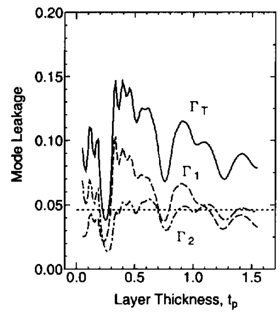

Fig. 7. Mode leakage into the BR block region. The dashed line shows leakage into GaInP layers in the BR block layer (Γ_1). The dashed-and-dotted line shows leakage into GaAs layers in the BR block layer and into the GaAs cap layer (Γ_2). The solid line shows total leakage into the BR block layer ($\Gamma_T = \Gamma_1 + \Gamma_2$). Leakage into the BR layer (Γ_T) is minimized at a quarter-wavelength thickness ($t_p = 1/4$), as expected. The minimum value is slightly smaller than leakage into the conventional GaAs block layer shown by the dashed line (Γ_B). Bragg reflection suppresses mode leakage into GaAs layers (Γ_2) to 30% of that into a GaAs block layer (Γ_B), which results in the mode-loss decrease.

B. Origin of Loss Decrease

The results of the mode calculation in Section IV showed that the mode-loss decrease for a BRW laser originates from a combination of Bragg-reflection and the low absorption loss of (Al)GaInP layers in BR block layers. This section discusses the function of Bragg reflection in order to clarify the origin of the loss decrease.

Fig. 7 shows mode leakage into the BR block layer. The dashed line shows leakage into GaInP layers in the BR block layer (Γ_1). The dashed-and-dotted line shows leakage into GaAs layers in the BR block layer and into the GaAs cap layer (Γ_2). The solid line shows total leakage into the BR block layer ($\Gamma_T = \Gamma_1 + \Gamma_2$). The dashed line shows mode leakage into the conventional GaAs block region (Γ_B) for comparison. Mode leakage into the BR block layer (Γ_T) is minimized at a quarter-wavelength thickness ($t_p = 1/4$), as expected. The minimum value is slightly smaller than the leakage into the conventional GaAs block layer (Γ_B). This means that the optimized Bragg reflection compensates for the mode-confinement decrease caused by absorptive-layer-thickness decrease in the BR block layer, so that mode confinement is approximately the same as with a conventional GaAs block layer. Consequently, the Bragg confinement suppresses mode leakage into the GaAs layers (Γ_2) to 30% of that into a conventional GaAs block layer, and results in a mode-loss decrease. The mode-leakage decrease agrees well with the mode-loss decrease of 31%.

VI. Conclusion

A new low-loss 630–680-nm BRW AlGaInP laser structure was proposed. This BRW laser uses $(\mathrm{AlGaInP/GaAs})_n$ BR block layers in place of conventional GaAs block layers. An aluminum content (x) lower than 0.2 for $(\mathrm{Al}_x\mathrm{Ga}_{1-x})_{0.5}\mathrm{In}_{0.5}\mathrm{P}$ in the BR block layers is sufficient for decreasing mode loss together with confining the fundamental transverse mode. The mode calculations revealed that mode loss for a BRW laser decreases to 31% of that for a conventional laser with GaAs block layers. Waveguide loss decreases to approximately one half. The BR block layers confine the propagating-mode light as much as conventional block layers do, and create a sufficient refractive-index step around 1×10^{-2}.

The advantage of this structure is that BR block layers with low aluminum content are easier to grow selectively than high-aluminum-content AlGaInP block layers. In particular, a BR block layer for a 680-nm laser needs no aluminum.

The mode-loss decrease originates from a combination of Bragg reflection and the low absorption loss for an AlGaInP crystal. The $(\mathrm{Al}_x\mathrm{Ga}_{1-x})_{0.5}\mathrm{In}_{0.5}\mathrm{P}$ crystal ($0 \leq x \leq 0.2$) is almost transparent for laser light due to sublattice disorder and Burstein shift. The optimized $\lambda/4$ Bragg reflection prevents the mode-confinement from decreasing with decrease in the absorptive-layer thickness in BR block layers. As a result, Bragg reflection suppresses mode leakage into GaAs layers to one third. This suppression decreases the mode loss.

The BRW laser structure is also applicable to II-VI blue-green lasers and AlGaAs lasers.

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Yoshiyasu Ueno received the B.S. and M.S. degrees in physics from the University of Tokyo in 1985 and 1987, respectively, where he studied resonant Raman scattering in tetragonal red-HgI_2 crystals.

In 1987 he joined the Opto-Electronics Research Laboratories, NEC Corporation, and has been engaged in the design, characterization, and MOVPE crystal growth of AlGaInP lasers. To improve these lasers, he has researched carrier confinement, degradation, window facets, strain-induced effect in QW's, and sublattice-order-induced recombination in GaInP active layers. In 1992, he and his coworkers successfully developed a 30-mW high-power AlGaInP red laser for high-density optical-disk memories. His research interest is optical phenomena around semiconductor lasers, aiming at functional opto-electronic devices for advanced information processing.

Mr. Ueno is a member of the Japan Society of Applied Physics and the Physical Society of Japan.