Reduced loss and improved mode discrimination in resonant optical waveguide arrays

D.F. Siriani and K.D. Choquette

Coherent laser arrays designed using resonant optical waveguides (ROWs) have proven to offer one of the most promising methods of monolithic beam combining in diode lasers. However, the high lateral transmission that provides strong optical coupling also leads to increased loss – a detriment to laser efficiency and performance. Presented is a derivation of additional design rules to eliminate lateral radiation loss from ROW arrays while still maintaining all the strong coupling properties. Additionally, it is speculated that improved mode discrimination and enhanced field uniformity should result from the proposed design modifications.

Introduction: In the pursuit of high power diode lasers with high brightness, coherent beam combining approaches based on monolithic arrays have proven to be some of the most promising and challenging. Since their introduction [1, 2], anti-guiding resonant optical waveguide (ROW) arrays have demonstrated some of the best coherent array performance in both edge-emitting lasers [3, 4] and vertical-cavity surface-emitting lasers (VCSELs) [5–7]. However, ROW arrays can be limited by high lateral radiation losses, which reduce efficiency and output power, and insufficient mode discrimination, which leads to degraded beam quality.

Recently, it has been suggested that these detrimental effects can be avoided by incorporating a cladding structure around the exterior of the array [8]. This Letter presents a derivation of augmented design rules to introduce a cladding around the array that simultaneously eliminates radiation loss and maintains the resonance condition. Numerical calculations demonstrate the effectiveness of this method, as well as reveal potentially improved mode discrimination and enhanced field uniformity.

Design rules: The proposed structure is illustrated in Fig. 1, which shows a typical ROW array with additional array edge waveguides and cladding layers at both ends. In anticipation of reducing the layered structure to a single reflective surface in future steps, we have labelled the reflections r_1 and r_2 in the left edge waveguide. As in a Fabry-Pérot cavity, a mode is required to satisfy the round-trip criterion

$$r_1 r_2 e^{i2kL} = 1 \tag{1}$$

where k and L are the wavevector and thickness of the edge waveguide, respectively. The left reflectivity is just the reflection from the cladding, given in a scalar approximation by (for TE and TM expressions see [9])

$$r_1 = \frac{k - i\alpha}{k + i\alpha} \tag{2}$$

where α is the decay constant in the cladding.

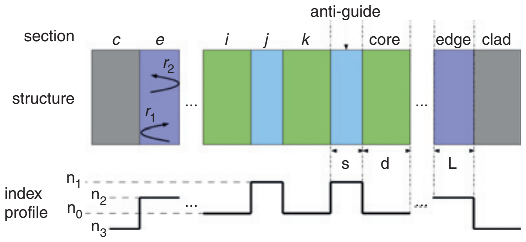

Fig. 1 *Specific array structure under consideration with sections, refractive indices, and reflections labelled*

To analyse the layered structure to the right of the edge waveguide, the transfer matrix method is used [9]. In the left edge waveguide and with transmission occurring to the right, the amplitudes of the forward- and backward-travelling waves are given by the vector elements of

$$\begin{bmatrix} E_0 \\ r_2 E_0 \end{bmatrix} = \mathbf{T}_{01}\mathbf{T}_{12}\ldots\mathbf{T}_{(N-1)N}\begin{bmatrix} tE_0 \\ 0 \end{bmatrix} \tag{3}$$

where **T**'s are the transfer matrices. Now, for a ROW array, the design conditions given previously [1, 2] cause the products of many of these matrices to reduce to the identity matrix. The reduction to identity matrices is indicative of perfect transmission and is the reason for strong coupling in ROW arrays. The reduced matrix equation is

$$\begin{bmatrix} E_0 \\ r_2 E_0 \end{bmatrix} = \pm\mathbf{T}_{01}\mathbf{T}_{(N-2)(N-1)}\mathbf{T}_{(N-1)N}\begin{bmatrix} tE_0 \\ 0 \end{bmatrix} \tag{4}$$

where it can be shown that

$$\begin{aligned} \mathbf{T}_{01}\mathbf{T}_{(N-2)(N-1)} &= \begin{bmatrix} e^{-ikL} & 0 \\ 0 & e^{ikL} \end{bmatrix}, \\ \mathbf{T}_{(N-1)N} &= \frac{1}{2}\begin{bmatrix} k+i\alpha & k-i\alpha \\ k-i\alpha & k+i\alpha \end{bmatrix} \end{aligned} \tag{5}$$

From these expressions, the reflection coefficient can be found to be

$$r_2 = \frac{k - i\alpha}{k + i\alpha} e^{i2kL} \tag{6}$$

Thus, the round-trip equation becomes

$$\begin{aligned} e^{i(4kL - 2\varphi)} &= 1, \\ \varphi &= 2\tan^{-1}\left(\frac{\alpha}{k}\right) \end{aligned} \tag{7}$$

(Note that this scalar expression for the reflection phase φ can be adjusted for TE or TM polarisation as in [9]). The resulting design rule puts a restriction on the thickness of the edge waveguide according to

$$L = \frac{p\pi + \varphi}{2k} \tag{8}$$

where p is an integer. Combining this with the previously derived ROW array equations [1, 2] gives the collection

$$\begin{aligned} s &= \frac{m\lambda_1}{2}, \\ \lambda_1 &= \frac{\lambda}{\sqrt{n_1^2 - n_0^2 + (\lambda/2d)^2}}, \\ L &= \frac{(p\pi + \varphi)\lambda_2}{4\pi}, \\ \lambda_2 &= \frac{\lambda}{\sqrt{n_2^2 - n_0^2 + (\lambda/2d)^2}}, \\ \varphi &= 2\tan^{-1}\left(\frac{\sqrt{n_0^2 - (\lambda/2d)^2 - n_3^2}}{\sqrt{n_2^2 - n_0^2 + (\lambda/2d)^2}}\right) \end{aligned} \tag{9}$$

where λ is the free-space wavelength, and the distances (d, s, and L) and refractive indices (n's) are labelled in Fig. 1.

Results: Having established the new design criteria for the lossless arrays, we can now investigate the influence of the modifications. In this example, the design is a ten-element array with parameters $d = 3$ µm, $n_1 = 3.4$, $n_2 = 3.424$, and $n_3 \simeq 3.397$ (which is chosen to be at cutoff for modes of higher order than the resonant mode). From (9), the remaining design parameters are $s \simeq 1$ µm and $L \simeq 0.5$ µm. Calculations of the cold-cavity mode losses and field profiles are performed via the finite difference method with perfectly matched layer boundary conditions.

Fig. 2 shows the resonant mode (mode 18) intensity profile for this waveguide structure for both the conventional leaky array and the proposed confined array. In both cases, there is high field uniformity, which is characteristic of resonant anti-guide modes. In fact, owing to the lack of edge radiation losses, the field is more uniform for the confined array structure. Enhanced field uniformity could help improve beam quality, mitigate problems with spatial hole burning, and improve the mode confinement factor.

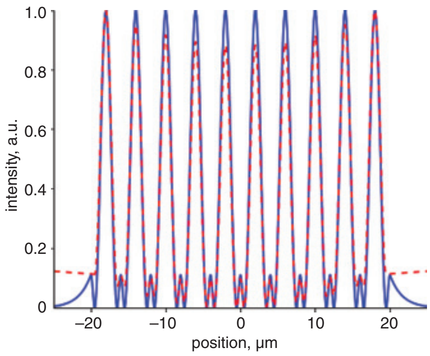

Fig. 2 *Mode 18 (resonant) for leaky (dashed) and confined (solid) structures. Modes exhibit very similar features*

By defining the confinement factor to be the fraction of the total power within the array overlapping the core guides, it is possible to explore whether or not there is enhanced confinement. Fig. 3 plots the confinement factor calculated for both leaky and confined cases. Overall, the situation for both designs is very similar, although again the confined structure exhibits slightly better performance. As a result, it should still be possible to use previously employed spatial mode filtering methods in the confined structure to support singlemode operation.

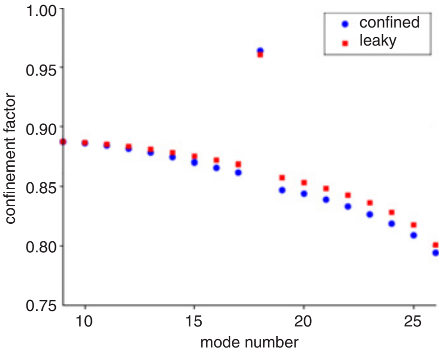

Fig. 3 *Confinement factor for modes 9–26 for leaky and confined structures. For both, resonant mode has highest confinement*

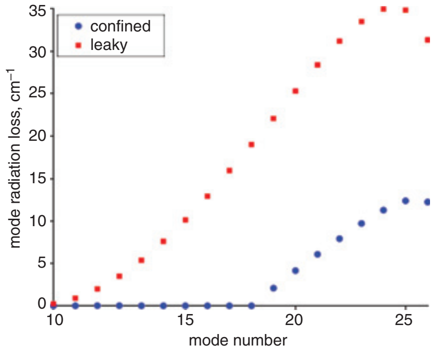

Fig. 4 *Radiation loss for modes 9–26 for leaky and confined structures. In confined case, mode 18 (resonant) is last mode without loss*

Finally, the mode radiation loss for modes 9 through 26 is plotted in Fig. 4. It is apparent that there is a very significant difference between the leaky and confined structures. For the resonant mode, the leaky structure experiences nearly 20 cm^{-1} of loss, while the confined structure experiences none. This has several important implications. The most apparent is that there should be a significant reduction in threshold and increase in efficiency owing to the reduced intrinsic loss via radiaiton. Moreover, the mode discrimination should improve against both higher- and lower-order modes. For lower-order modes, the losses are equal to that of the resonant mode, which means that gain and loss discrimination via the confinement factor should be more effective. For higher-order modes, the same is true with the added benefit that these modes can experience significant radiation loss. Therefore, it is expected that higher powers should be achieved owing to the reduced intrinsic loss, and better beam quality and mode stability should result from the increased mode discrimination.

Conclusion: We have described a method for improving the performance of anti-guided ROW arrays by incorporating a cladding structure. New design rules for maintaining the resonance condition have been derived. Numerical results show that the confined structure has many advantages over its leaky predecessor. These include lower losses, improved mode discrimination, and enhance field uniformity. Since these have been some of the most significant drawbacks of leaky ROW laser arrays, it is expected that significantly improved performance could result from the modified design.

28 February 2012
doi: 10.1049/el.2012.0558
One or more of the Figures in this Letter are available in colour online.

D.F. Siriani and K.D. Choquette (*Micro and Nano-technology Laboratory, Department of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA*)

E-mail: dominic.siriani@ll.mit.edu

D.F. Siriani: Now with MIT Lincoln Laboratory, Lexington, MA, USA

References

1 Botez, D., Mawst, L.J., and Peterson, G.: 'Resonant leaky-wave coupling in linear arrays of antiguides', *Electron. Lett.*, 2002, **24**, (21), pp. 1328–1330

2 Botez, D., Mawst, L.J., Peterson, G.L., and Roth, T.J.: 'Phase-locked arrays of antiguides: modal content and discrimination', *IEEE J. Quantum Electron.*, 2002, **26**, (3), pp. 482–495

3 Botez, D., Mawst, L., Hayashida, P., Peterson, G., and Roth, T.J.: 'High-power, diffraction-limited-beam operation from phase-locked diode-laser arrays of closely spaced "leaky" waveguides (antiguides)', *Appl. Phys. Lett.*, 1988, **53**, (6), pp. 464–466

4 Botez, D., Jansen, M., Mawst, L.J., Peterson, G., and Roth, T.J.: 'Watt-range, coherent, uniphase powers from phase-locked arrays of antiguided diode lasers', *Appl. Phys. Lett.*, 1991, **58**, (19), pp. 2070–2072

5 Serkland, D., Choquette, K., Hadley, G., Geib, K., and Allerman, A.: 'Two-element phased array of antiguided vertical-cavity lasers', *Appl. Phys. Lett.*, 1999, **75**, (24), pp. 3754–3756

6 Zhou, D., and Mawst, L.: 'Two-dimensional phase-locked antiguided vertical-cavity surface-emitting laser arrays', *Appl. Phys. Lett.*, 2000, **77**, (15), pp. 2307–2309

7 Bao, L., Kim, N., Mawst, L., Elkim, N., Troshchieva, V., Vysotsky, D., and Napartovich, A.: 'Near-diffraction-limited coherent emission from large aperture antiguided vertical-cavity surface-emitting laser arrays', *Appl. Phys. Lett.*, 2004, **84**, (3), pp. 320–322

8 Siriani, D.F., and Choquette, K.D.: 'Lossless anti-guided arrays with improved mode discrimination'. IEEE Photonics Conf., Arlington, VA, USA, 2011, pp. 761–762

9 Chuang, S.L.: 'Physics of optoelectronic devices' (John Wiley & Sons, Inc., New York, 1995)