Extremely Small Vertical Far-Field Angle of InGaAs–AlGaAs Quantum-Well Lasers with Specially Designed Cladding Structure

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Abstract— **We report on a very small vertical far-field angle achieved by lasers with a specially designed structure. For an InGaAs–AlGaAs quantum-well laser with a 2.5-μm-wide ridge waveguide, the far-field pattern has a vertical far-field angle of 13° and a lateral far-field angle of 8°. Meanwhile, the threshold current remains acceptably low ($\approx$36 mA for a 500-μm-long cavity). The slope efficiency of the *L–I* characteristic is high ($>$0.9 W/A) compared to that of the conventional laser.**

I. INTRODUCTION

HIGH-POWER semiconductor lasers emitting at 980-nm wavelength have emerged as a key component for Er^{3+}-doped fiber amplifier (EDFA) systems. The key issue for practical application of EDFA systems is to achieve high optical power coupled into a single-mode fiber. For conventional laser structures, the vertical far-field angle is usually large ($\approx$40°) and reducing the far-field angle merely by a thin-waveguide design leads to unacceptably high threshold currents. This makes it difficult to efficiently couple the optical power to the fiber using a conventional laser structure. To overcome this difficulty, much attention has recently been focused on the engineering of the cladding layer structures [1]–[7]. By doing so, the intensity profile of the lasing mode can be ingeniously tailored so that a small beam divergence can be achieved while the threshold current remains acceptably low. Vertical far-field angles smaller than 20° have been obtained and the optical coupling efficiency has therefore been improved to be higher than 60% [4] and [5]. As the calculated results of Yen and Lee [7] showed, it is not difficult to obtain a vertical far-field angle smaller than 15° using a specially designed structure. To the best of our knowledge, however, a vertical far-field angle of $<$15° without serious side lobes has not yet demonstrated experimentally using an unconventional cladding structure.

In this letter, we report on a small vertical far-field angle of 13° achieved by a specially designed laser structure. Due to the special laser structure, the threshold current can remain acceptably low. The design strategy for this purpose is to widely expand the optical mode without significantly affecting the confinement factor of the quantum-well region. This can be achieved by the structure schematically shown in the inset of Fig. 1. Different from the conventional graded-index separate confinement heterostructure (GRINSCH), there are two low-index layers inserted between the graded-index layers and the cladding layers. Because of these two layers, the optical field in the active region is tightly confined. Meanwhile, outside the low-index layers, the optical field widely spreads since the lasing mode index is lowered by the two low-index layers to be close to the refractive index of the cladding layers. This situation is illustrated in Fig. 1(a), which shows the calculated near-field profile of the new structure with low-index layers and that of a conventional GRINSCH. The confinement factor is intentionally designed to be the same for both structures. The new structure has, nevertheless, a much more widespread mode profile. As a result, the far field angle of the new structure is greatly reduced compared with that of the conventional one [see Fig. 1(b)] although the threshold currents of both structures are the same.

II. CALCULATED RESULTS

The calculated results of the far-field angle and the threshold current for lasers with low-index layers are presented in this section. The laser structure is assumed to be composed of a 65 Å $In_{0.2}Ga_{0.8}As$ single quantum well, two 120 Å GaAs barriers, two 1000 Å graded-index layers (graded from GaAs to $Al_{0.8}Ga_{0.2}As$), two $Al_{0.8}Ga_{0.2}As$ low-index layers, and then two thick $Al_xGa_{1-x}As$ cladding layers. This kind of lasers has been theoretically analyzed in detail by Yen and Lee [7]. Fig. 2(a) shows the vertical far-field angle versus the Al content of the cladding layers with the low-index layer thickness as a parameter. From the figure, we can see that the vertical far-field angle is reduced with decreasing the Al content of the cladding layers. The reason is clear that as the cladding index increases to be closer to the lasing mode index, the lasing mode becomes more expanded, leading to a smaller far-field angle. Further decreasing the Al content of the cladding layers is dangerous since the cladding index can exceed the fundamental mode index. As a result, there is no guided mode in the waveguide. From the figure, one can find that a far-field angle $<$15° can be easily achieved. However, as can be seen in Fig. 2(b), when the Al content of the cladding layers decreases, the threshold current rises. Fortunately, comparing Fig. 2(a) and (b), one can find that a

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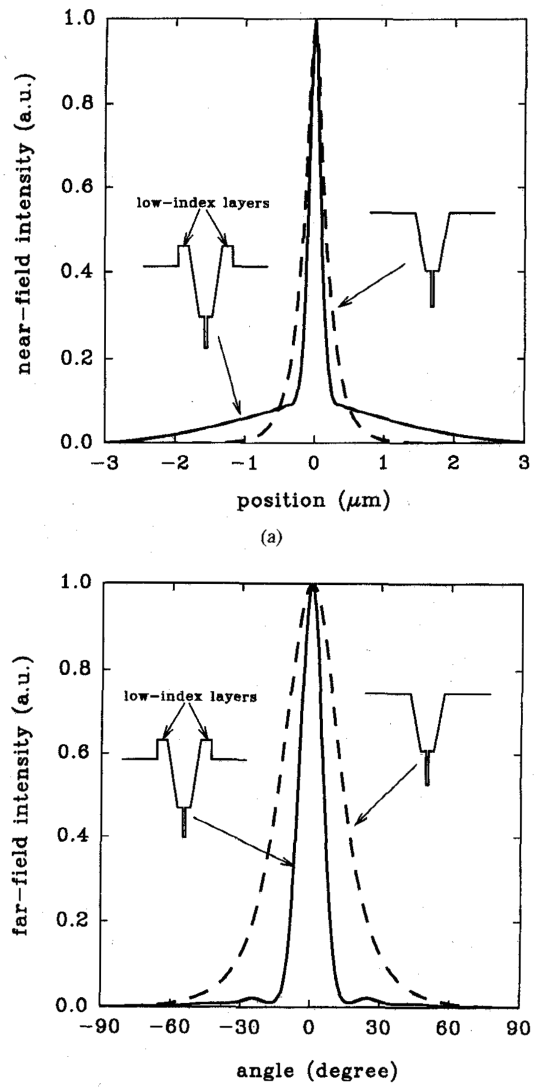
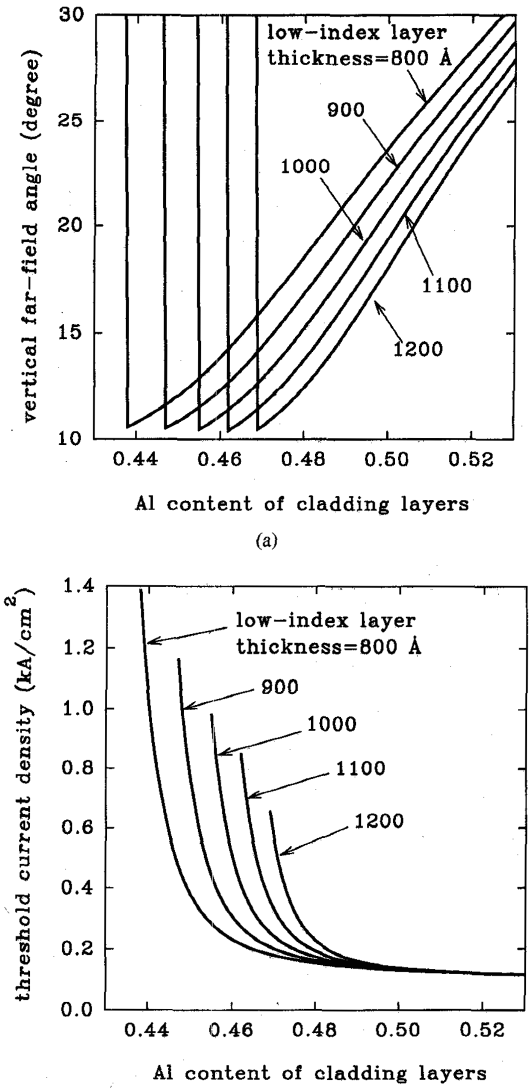


(a)

(b)

Fig. 1. (a) The calculated near-field profiles and (b) the calculated vertical far-field patterns for the structure with two low-index layers and the conventional GRINSCH.



(a)

(b)

Fig. 2. (a) The calculated vertical far-field angle and (b) the calculated threshold current density versus the Al content of the cladding layers with the low-index layer thickness as a parameter.

far-field angle <15° can be achieved by paying only a slight increase of the threshold current density (<400 A/cm^2).

III. Device Fabrication

Based on the theoretical results given in the last section, an InGaAs–AlGaAs strained single-quantum-well laser structure was grown by MBE on an n-GaAs substrate. The grown layer structure consists of (from the substrate): 1) an n-GaAs buffer layer (0.5 μm, Si = 3 × 10^{18} cm^{-3}), 2) an n-Al$_x$Ga$_{1-x}$As graded buffer layer (x = 0–0.48, 0.2 μm, Si = 3 × 10^{18} cm^{-3}), 3) a thick n-Al$_{0.48}$Ga$_{0.52}$As cladding layer (3 μm, Si = 1 × 10^{18} cm^{-3}), 4) an n-Al$_{0.8}$Ga$_{0.2}$As low-index layer (0.1 μm, Si = 1 × 10^{18} cm^{-3}), 5) an undoped Al$_x$Ga$_{1-x}$As graded-index layer (x = 0.8–0.15, 0.1 μm), 6) an undoped active region composed of a 60-Å In$_{0.25}$Ga$_{0.75}$As quantum well sandwiched by two 120-Å GaAs barrier layers, 7) an undoped Al$_x$Ga$_{1-x}$As graded-index layer (x = 0.15–0.8, 0.1 μm), 8) a p-Al$_{0.8}$Ga$_{0.2}$As low-index layer (0.1 μm, Be = 1 × 10^{18} cm^{-3}), 9) a thick p-Al$_{0.48}$Ga$_{0.52}$As cladding layer (3 μm, Be = 3 × 10^{18} cm^{-3}), 10) a p-Al$_x$Ga$_{1-x}$As graded layer (x = 0.48–0, 0.1 μm, Be = 3 × 10^{18} cm^{-3}), and 11) a p$^+$-GaAs ohmic contact cap layer (0.2 μm, Be = 1 × 10^{19} cm^{-3}). Since the wide expansion of the optical mode is expected, the cladding layers 3) and 9) are designed to be thick enough to avoid the undesired loss due to the leakage of the optical field out of the cladding layers.

After growth, a SiO$_2$ layer was deposited by plasma-enhanced chemical vapor deposition (PECVD). A 2.5-μm ridge pattern was then defined and the SiO$_2$ outside the ridges was removed by dry-etching. Subsequently, reactive ion etching (RIE) with BCl$_3$/Ar as the etching gas was used to remove the cap layer and part of the p-Al$_{0.48}$Ga$_{0.52}$As cladding

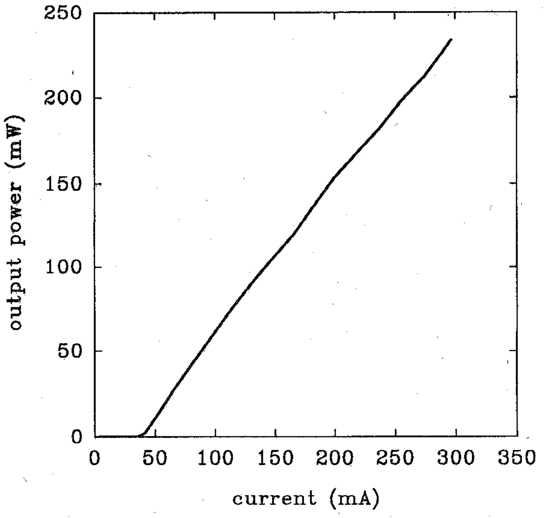


Fig. 3. The measured light-current characteristic of the laser with a 2.5-μm-wide ridge and a 500-μm —long cavity.

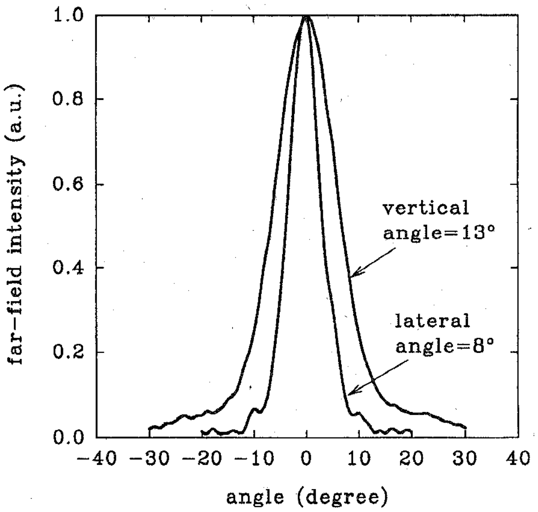


Fig. 4. The measured far-field patterns for the laser with a 2.5-μm-wide ridge and a 500-μm-long cavity. The vertical far-field angle is 13° and the lateral far-field angle is 8°.

layer. As a result, vertical sidewalls of the ridges were obtained and the thickness of the remaining cladding layer outside the ridge was 0.3 μm. Passivation oxide was then deposited on the etched regions by self-aligned process. The resulting sample was then processed into uncoated facet ridge-waveguide lasers by the conventional method.

IV. MEASURED RESULTS

Fig. 3 shows the typical light-current characteristic for the laser with a 500-μm-long cavity. The lasers were probed directly on a copper heat sink at room temperature under pulsed operation (pulse width: 1 μs, repetition rate: 150 Hz). As can be seen from the figure, the threshold current is $\approx$36 mA and the slope efficiency is >0.9 W/A. The slope efficiency is superior to that of the conventional laser since the transmissivity through the mirror facet is higher for an optical mode of wider expansion. Although the measured threshold current is acceptably low, it is significant higher than the calculated one shown in Fig. 2(b). This is mainly because the current spreading, which is not considered in the calculation, is serious in lasers with a narrow ridge waveguide. Fig. 4 shows the measured far-field patterns. The vertical far-field angle ($\Theta_{\perp}$) is as small as 13° and the lateral far-field angle ($\Theta_{//}$) is 8°. The measured vertical far-field angle is slightly smaller than the theoretical result ($\approx$15°). We attribute the slight difference to the slight deviation of the grown structure from the designed one. The aspect ratio ($\Theta_{\perp}/\Theta_{//}$) of the far-field angles is about 1.6. These results are excellent compared with those of conventional lasers. The measured series resistance of the diode ($\approx$5.5 Ω) is not significantly larger than that of a conventional laser with the same size ($\approx$4 Ω), implying that the very thick cladding layers and the high-Al low-index layers does not significantly affect the device electrical property.

V. CONCLUSION

We have demonstrated an extremely small vertical far-field angle of 13° using a specially designed laser structure. By properly designing the laser structure, a small far-field angle can be easily obtained while the threshold current remains acceptably low. The performance of this kind of lasers is excellent for application in the EDFA system compared with the conventional laser. The slope efficiency of the *L–I* characteristic is high (>0.9 W/A) and the aspect ratio of the far-field angles is reduced to 1.6.

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