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A 970 nm strained-layer InGaAs/GaAlAs quantum well laser for pumping an erbium-doped optical fiber amplifier

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We report the performance of a 970 nm strained-layer InGaAs/GaAlAs quantum well laser and its application for pumping Er-doped optical fiber amplifiers. The laser was grown by molecular beam epitaxy and has three $In_{0.2}Ga_{0.8}As$/GaAs quantum wells. For a 5-μm-wide and 400-μm-long ridge-waveguide laser, a cw threshold current of 20 mA and an external quantum efficiency of 0.28 mW/mA per facet were obtained. Maximum output power exceeds 32 mW/facet. With antireflection coating, even higher external quantum efficiency (0.40 mW/mA) was achieved, and more than 20 mW of power was coupled into a single mode fiber. Preliminary experiments of pumping the Er-doped fiber amplifier gave 15 dB of gain at 1.555 μm for a pump power of 14 mW into the Er fiber.

Erbium-doped optical fiber amplifiers have attracted a great deal of interest recently as they offer many advantages for amplifiers operating at 1.53 μm, including high gain, low noise, polarization independence, and fiber compatibility.[1] Although the Er-doped fiber amplifiers have been demonstrated using argon ion lasers[2] (514.5 nm), dye lasers [665 nm (Ref. 3) or 980 nm (Ref. 1)], frequency-double YAG lasers[1] (532 nm), or color center laser[4] (1.49 μm) as pump sources, a more practical pump source is semiconductor diode lasers. Semiconductor lasers operating at 807 nm (Ref. 5) or 1.49 μm (Ref. 6) are readily available in GaAlAs/GaAs or InGaAsP/InP material systems. On the other hand, the 980 nm band was identified as the ideal pump wavelength because it is free of excited-state absorption and thus has very high pumping efficiency.[1] Therefore, the semiconductor lasers operating at 980 nm are highly desirable for pumping Er-doped fiber amplifiers. A 978 nm diode laser pumped fiber amplifier was recently reported,[7] where a total of 6.2 mW pump power was coupled into the amplifier fiber.

Semiconductor lasers with lasing wavelength longer than 870 nm were made possible by combining strained-layer InGaAs quantum wells with the lattice-matched GaAlAs/GaAs double heterostructure.[8,9] With the advances of the crystal growth techniques, room-temperature continuous-wave (cw) operations of the strained-layer InGaAs quantum well lasers have been demonstrated.[10–14] The application for pumping Er-doped fiber amplifiers, however, requires accurate control of the lasing wavelength around 980 nm and single lateral mode under high output power for efficient coupling into optical fiber. Lateral index guiding can be achieved with buried heterostructure,[12] channeled substrate,[15] impurity-induced layer disordering,[13] or ridge waveguide.[16] The ridge waveguide structure is preferred for this application because the lasing wavelength is not sensitive to the processing steps (e.g., no high-temperature processes) and allows systematic control of the lasing wavelength by crystal growth. In this letter, we report the performance of an InGaAs/GaAs strained-layer quantum well laser grown by molecular beam epitaxy (MBE), which lases at 970 nm and can couple more than 20 mW into a single mode fiber. Preliminary results of pumping Er-doped optical fiber amplifiers are also discussed.

Graded-index separate-confinement quantum well structure[17] is used for the laser, as shown in Fig. 1. The active region consists of three $In_{0.2}Ga_{0.8}As$/GaAs quantum wells, sandwiched between two composition-graded GaAlAs confining layers. The laser was grown by MBE on an n^+-GaAs substrate. The growth sequence is described as follows: a 1-μm-thick n^+-GaAs buffer layer, a 1-μm-thick N-$Ga_{0.6}Al_{0.4}As$ lower cladding layer, a 0.15-μm-thick N-$Ga_xAl_{1-x}As$ composition-graded layer (x changes from 0.6 to 1), three 65-Å-thick $In_{0.2}Ga_{0.8}As$ quantum wells and four 120-Å-thick GaAs barriers, all p doped to 5×10^{17} cm^{-3}, a 0.15-μm-thick P-$Ga_xAl_{1-x}As$ composition-graded layer (x changes from 1 to 0.6), a 1-μm-thick P-$Ga_{0.6}Al_{0.4}As$ upper cladding layer, then followed by a 0.1-μm-thick GaAs cap layer ($N_D = 10^{19}$ cm^{-3}), and a 200-Å-thick n^+-GaAs contact layer ($N_D = 5\times10^{19}$ cm^{-3}).

After growth, ridge waveguides of 5 μm width were etched by a 1:1:20 ratio of $NH_4OH:H_2O_2:H_2O$ solution along the $[01\bar{1}]$ direction. To ensure single transverse mode operation, the etching was controlled to stop within 0.1 μm above the upper composition-graded layer. Lasers etched below the composition-graded layer resulted in higher threshold current and lower differential quantum efficiency. Then SiO_2 was deposited over the entire surface by thermal chemical vapor deposition. A 3-μm-wide window was opened on top of the ridge waveguide. After thinning down the wafer to about 100 μm thick, Au/Be/Ti/Au and Au/Sn/Au were evaporated for p and n contacts, respectively. The contacts were sintered at 450 °C for 15 s. Then the wafer was cleaved into individual lasers of 400 μm length. The

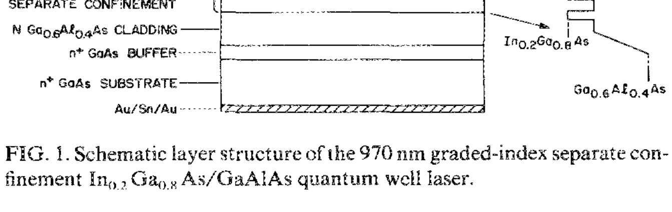

FIG. 1. Schematic layer structure of the 970 nm graded-index separate confinement $In_{0.2}Ga_{0.8}As$/GaAlAs quantum well laser.

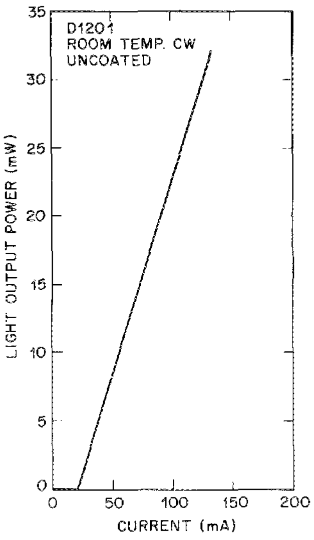

FIG. 2. Room-temperature cw light vs current characteristics of the 970 nm ridge-waveguide ($5\times400\,\mu m$) InGaAs quantum well laser. The cw threshold current is 20 mA and the external quantum efficiency is 0.28 mW/mA per facet. Maximum power exceeds 32 mW/facet for uncoated laser.

resultant diode has a forward series resistance of 4 Ω and a reverse breakdown voltage of 6.5 V. The laser was tested at room temperature under cw operation. Figure 2 shows typical light-versus-current characteristics of an uncoated laser bonded p side up. It has a threshold current (I_{th}) of 20 mA and an external quantum efficiency of 0.28 mW/mA per facet. The slope efficiency is constant up to $7I_{\text{th}}$. Maximum output power before catastrophic damage of facets was greater than 32 mW. With antireflection-coated facet, an external quantum efficiency of 0.40 mW/mA/facet can be achieved.

Figure 3(a) shows the cw spectrum of the laser light coupled into a single mode fiber as measured by the Anritsu spectrometer. At 100 mA pumping current, the laser has a dominant mode at 970.5 nm, and a total of 12.8 mW was launched into the fiber. At 140 mA drive current, more than 20 mW was measured in the single mode fiber. Figure 3(b) shows the lasing wavelength versus the quantum well thickness. Experimental data are shown by dots and triangle. The three lasers represented by the dots have identical structures except for the thickness of the quantum wells: $d_{\text{well}} = 90$ Å for D-1188, $d_{\text{well}} = 79$ Å for D-1194, and $d_{\text{well}} = 65$ Å for D-1201. All these lasers have similar threshold currents: I_{th} (pulse) = 18 mA and I_{th} (cw) = 20 mA. The laser represented by the triangle (D-1195) has similar waveguide structures; however, the active region consists of five quantum wells of 79 Å width. The threshold current of D-1195 is slightly higher, about 25 mA in pulsed operation. The solid curve in Fig. 3(b) is the calculated photon emission energy from the first electron level to the first heavy hole level. A finite-square well model[18] is used. The energy gap of $In_{0.2}Ga_{0.8}As$ (1.12 eV) is corrected for hydrostatic compression and shear stress (1.19 eV). A 70/30 split for the conduction/valence band discontinuity is assumed,[18] though the results are very insensitive to this parameter. Reasonable agreement between experiments and theory was obtained.

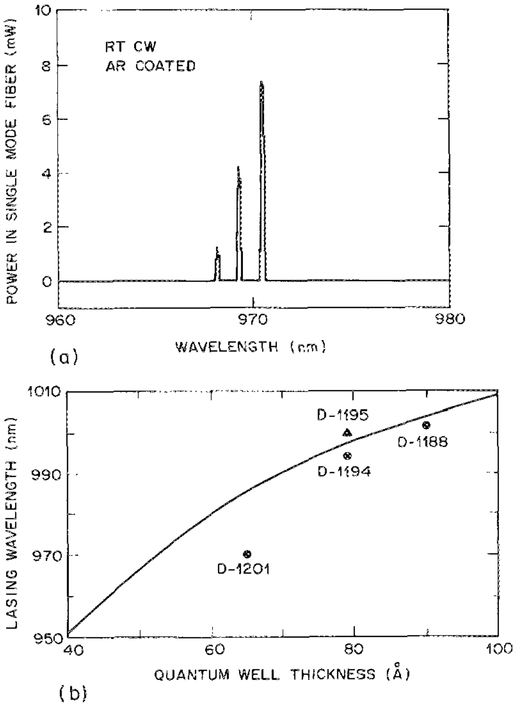

FIG. 3. (a) cw spectrum of the AR-coated InGaAs quantum well laser coupled into a single mode fiber at a pumping current of 100 mA. The laser has a dominant mode at 970.5 nm. A total of 12.8 mW was launched into the single mode fiber. (b) The lasing wavelength vs the thickness of the InGaAs quantum well. The dots (D-1188, D-1194, D-1201) and the triangle (D-1195) are experimental data of three-quantum well and five-quantum well lasers, respectively, and the solid line is the calculated result.

Preliminary experiments of pumping the Er-doped optical fiber amplifier using the 970 nm diode laser are also performed. The amplifier characteristics were tested with co-propagating signal and pump light, which were launched into the amplifier fiber via a dichroic coupler. Figure 4 shows the output light spectrum from the fiber amplifier for an input signal of − 30 dBm at 1.555 μm for various diode pump current. The output powers at the signal wavelength were − 23.8, − 20.8, − 18, − 16, − 13.8 dBm for diode currents of 110, 120, 130, 140, 160 mA, respectively. A signal gain of 16.2 dB was obtained at 160 mA. At 15 dB gain,

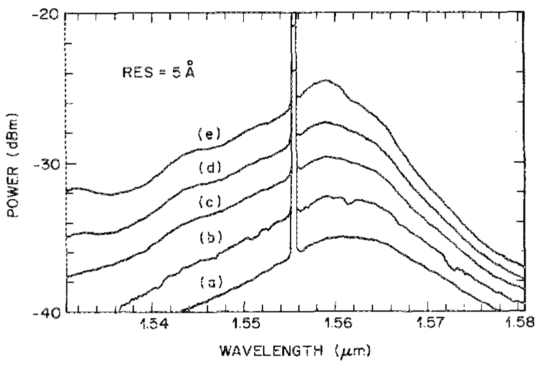

FIG. 4. Spectrum of the output light from the Er-doped optical fiber amplifier pumped by the 970 nm InGaAs quantum well laser. The input signal wavelength is 1.555 μm and the power is − 30 dBm. The amplified signal intensities are (a) − 23.8 dBm for $I_{\text{pump}} = 110$ mA, (b) − 20.8 dBm for $I_{\text{pump}} = 120$ mA, (c) − 18 dBm for $I_{\text{pump}} = 130$ mA, (d) − 16 dBm for $I_{\text{pump}} = 140$ mA, and (e) − 13.8 dBm for $I_{\text{pump}} = 160$ mA.

the pump power in the Er fiber is measured to be 14 mW. More detailed results of the fiber amplifier will be published separately.

In conclusion, we have fabricated a ridge-waveguide, graded-index separate confinement InGaAs/GaAlAs quantum well laser lasing at 970 nm. The cw threshold current of 20 mA and the external quantum efficiency of 0.28 mW/mA per facet were obtained for an uncoated laser. Maximum output power of uncoated lasers exceeds 32 mW/facet. With antireflection coating, the external quantum efficiency increased to 0.40 mW/mA per facet, and 20 mW of power was launched into a single mode fiber. Preliminary experiments of pumping Er-doped optical fiber amplifier showed a signal gain of 15 dB at 1.555 μm for a diode pumping power of 14 mW into the Er fiber.

[1] R. I. Laming, M. C. Farries, P. R. Morkel, L. Reekie, D. N. Payne, P. L. Scrivener, F. Fontana, and A. Righetti, Electron. Lett. **25**, 12 (1989).

[2] E. Desurvire, J. R. Simpson, and P. C. Becker, Opt. Lett. **12**, 888 (1987).

[3] R. J. Mears, L. Reekie, I. M. Jauncey, and D. N. Payne, *Proceedings of Optical Fiber Communications Conferences* (Optical Society of America, Washington, DC, 1987).

[4] E. Desurvire, C. R. Giles, J. R. Simpson, and J. L. Zyskind, *Proceedings, Conference of Lasers and Electro-Optics*, PD-20 (Optical Society of America, Washington, DC, 1989).

[5] T. J. Whitley, Electron. Lett. **24**, 1537 (1988).

[6] M. Nakazawa, Y. Kimura, and K. Suzuki, Appl. Phys. Lett. **54**, 295 (1989).

[7] R. I. Laming, V. Shah, L. Curtis, R. S. Vodhanel, F. J. Favire, W. L. Barnes, J. D. Minelly, D. P. Bour, and E. J. Tarbox, *Proceedings, International Conference on Integrated Optics and Optical Fiber Communication*, 20PDA-4, Japan (Japanese Society of Applied Physics, Tokyo, Japan, 1989).

[8] M. J. Ludowise, W. T. Dietze, C. R. Lewis, M. D. Camras, N. Holonyak, Jr., B. K. Fuller, and M. A. Nixon, Appl. Phys. Lett. **42**, 487 (1983).

[9] W. D. Laidig, P. J. Caldwell, Y. F. Lin, and C. K. Peng, Appl. Phys. Lett. **44**, 653 (1984).

[10] Y. J. Yang, K. Y. Hsieh, and R. M. Kolbas, Appl. Phys. Lett. **51**, 215 (1987).

[11] W. Stutius, P. Gavrilovic, J. E. Williams, K. Meehan, and J. H. Zarrabi, Electron. Lett. **24**, 1493 (1988).

[12] P. K. York, K. J. Beernink, G. E. Fernandez, and J. J. Coleman, Appl. Phys. Lett. **54**, 499 (1989).

[13] J. S. Major, Jr., L. J. Guido, K. C. Hsieh, and N. Holonyak, Jr., Appl. Phys. Lett. **54**, 913 (1989).

[14] S. D. Offsey, W. J. Schaff, P. J. Tasker, H. Ennen, and L. F. Eastman, Appl. Phys. Lett. **54**, 2527 (1989).

[15] J. N. Baillargeon, P. K. York, C. A. Zmudzinski, G. E. Fernandez, K. J. Beernink, and J. J. Coleman, Appl. Phys. Lett. **53**, 457 (1988).

[16] S. E. Fischer, D. Fekete, G. B. Feak, and J. M. Ballantyne, Appl. Phys. Lett. **50**, 714 (1987).

[17] W. T. Tsang, Appl. Phys. Lett. **40**, 217 (1982).

[18] See, for example, R. M. Kolbas, N. G. Anderson, W. D. Laidig, Y. Sin, Y. C. Lo, K. Y. Hsieh, and Y. J. Yang, IEEE J. Quantum Electron. **QE-24**, 1605 (1988).