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A novel edge-emitting periodic index separate confinement heterostructure (PINSCH) semiconductor quantum well laser is proposed and demonstrated for the first time. Periodic semiconductor multilayers are used as optical confinement layers to simultaneously reduce the transverse beam divergence and increase the maximum output power. Self-aligned ridge-waveguide InGaAs/GaAs/AlGaAs PINSCH quantum well lasers emitting at 980 nm are fabricated. The 5×750 μm device has far-field angles of 10° by 20°, a threshold current of 45 mA, an external differential quantum efficiency of 1.15 mW/mA (90%), and an output power exceeding 620 mW, all measured at room temperature under CW operation. A record high fiber coupling efficiency of 51% and maximum coupled power of 130 mW has been achieved with a lensed fiber of 5 μm core diameter.

High-power semiconductor lasers with symmetric and narrow optical beam divergence are of great interest for applications in fiber optics, optical data storages and free-space optical interconnects. Conventional graded-index separate confinement heterostructure (GRINSCH) quantum well (QW) lasers have produced lasers with low threshold currents and high quantum efficiencies.[1] However, the tight optical confinement of GRINSCH structure results in a large beam divergence in the direction perpendicular to the junction (e.g., $\sim$50° for typical InGaAs/AlGaAs lasers).[2] Such large transverse beam divergence leads to highly elliptical far-field patterns and low coupling efficiency into optical fibers. The beam divergence can be reduced by expanding the transverse mode size in the laser cavity. Previous approaches to reduce the beam divergence include the use of large optical cavities[3] and vertically coupled active/passive waveguides.[4,5] However, care must be taken to ensure sufficient electrical carrier confinement and suppression of high-order transverse modes while expanding the optical mode size.

In this letter, we demonstrate a novel periodic index separate confinement heterostructure (PINSCH) quantum well laser, which utilizes the periodic-index confining layers to expand the optical mode size and to achieve the electrical carrier confinement at the same time. The expanded transverse mode size further reduces the optical power density in the cavity. Therefore, much higher output power can be obtained before it is limited by catastrophic optical damage (COD). In our experiments, the transverse beam divergence of the InGaAs/AlGaAs PINSCH QW laser is drastically reduced to 20°. The maximum output power of a 5-μm-wide self-aligned ridge-waveguide[6] PINSCH laser exceeds 620 mW at room temperature under continuous-wave (CW) condition. The external differential quantum efficiency is as high as 1.15 mW/mA (90%). The narrow beam divergence leads to a record high coupling efficiency of 51% into a lensed fiber with a 5 μm core diameter. More than 130 mW of power is coupled into the single mode fiber. The emission wavelength of this PINSCH strained quantum well laser is designed to be 980 nm, which is the most efficient and the lowest noise pump band for Er-doped fiber amplifiers.[7]

The schematic layer structure and the calculated near-field distribution of the PINSCH laser are shown in Figs. 1(a) and 1(b), respectively. The PINSCH structure consists of three parts: a quantum well active region in the center, a *p*-doped and an *n*-doped PIN (periodic-index) confinement layers. Each PIN confinement layer consists of eight pairs of $Al_{0.4}Ga_{0.6}As/GaAs$ heterostructures. The active region comprises three 70-Å-thick $In_{0.2}Ga_{0.8}As$ wells and four 200-Å-thick GaAs barriers.

The use of periodic layered waveguide (Bragg reflection waveguides) was previously proposed[8] and applied to surface waveguides.[9] For optical waves propagating parallel to a semi-infinite PIN layered media, the transverse propagation constant, β_T, has allowed bands and forbidden bands. In the forbidden bands, β_T is complex and the optical field decays evanescently in the transverse direction. Therefore, the PIN layers can be used as transverse optical confinement layers. Here, we integrate the Bragg reflection waveguides with semiconductor quantum well lasers. As shown in Fig. 1(b), the optical mode size is much expanded in the PINSCH structure ($\sim$1 μm) compared with that in the conventional GRINSCH structure. The optical field decays quickly within the first few periods of the PIN layers, and only a finite number of periods are needed to implement the PINSCH lasers.

The suppression of high-order spatial modes is very important for many applications which require diffraction-limited beam profile and high light collection efficiency. In a properly designed PINSCH laser, all the high-order transverse modes are totally suppressed. The strong discrimination against high-order modes comes from the selection of β_T by the PIN structure. The principle of the single transverse-mode operation is similar to that of the single longitudinal-mode operation in a quarterwave-shifted distributed feedback (λ/4-DFB) laser widely used in optical communication systems.[10,11] In the λ/4-DFB lasers the optical waves propagate along the direction of the periodicity and the Bragg reflection condition applies to the longitudinal modes, while in the PINSCH lasers the optical waves propagate in the direction perpendicular to the periodicity and the Bragg condition applies to the transverse modes.

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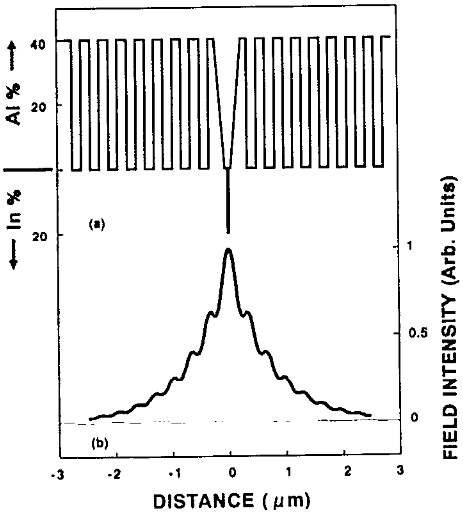


FIG. 1. (a) The layer composition of the PINSCH quantum well laser. (b) The calculated optical field distribution of the PINSCH laser.

The main feature of the PINSCH laser is that the transverse optical mode profile can be independently synthesized and expanded, while the electrical carrier confinement is as good as that of the conventional GRINSCH structure. Electrons and holes are confined in the active region by the first adjacent wide-band gap layers of the PIN confining layers. These wide-band gap layers are linearly graded towards the active region to produce a built-in electric field, which forces the injected carriers into the quantum wells. The PINSCH laser structure is a good example of combining index engineering for optical confinement and band gap engineering for electrical carrier confinement using advanced molecular beam epitaxial technology.

The precise control of the layer composition and thickness in the PINSCH laser structures is realized by a novel temperature-modulation molecular beam epitaxial (TM-MBE) growth technique.[12] The growth of the PIN multilayers is solely controlled by modulating the Al and the Ga cell temperatures without any shutter operations. Each $Al_{0.4}Ga_{0.6}As/GaAs$ hetero-interface in the PIN layers is linearly graded to reduce the barrier height for the injected carriers. Without resorting to the high doping concentrations, the graded hetero-interfaces provide low resistance and low optical loss at the same time. The composition grading is achieved by ramping the Ga and the Al cell temperatures simultaneously. For a 5×750 μm PINSCH laser, a series resistance as low as 2 Ω is achieved even though 16 pairs of moderately doped $Al_{0.4}Ga_{0.6}As/GaAs$ confining layers are employed in the structure. The growth rates of GaAs and AlGaAs are calibrated by reflection high-energy electron diffraction (RHEED) oscillations, high-resolution x-ray diffraction, and optical reflectivity measurements to a precision within 5%. The substrate temperature during growth is kept constant at 600 °C. A broad-area lasing threshold current density of 500 A/cm^2 is obtained despite the low optical confinement factor associated with the expanded mode size.

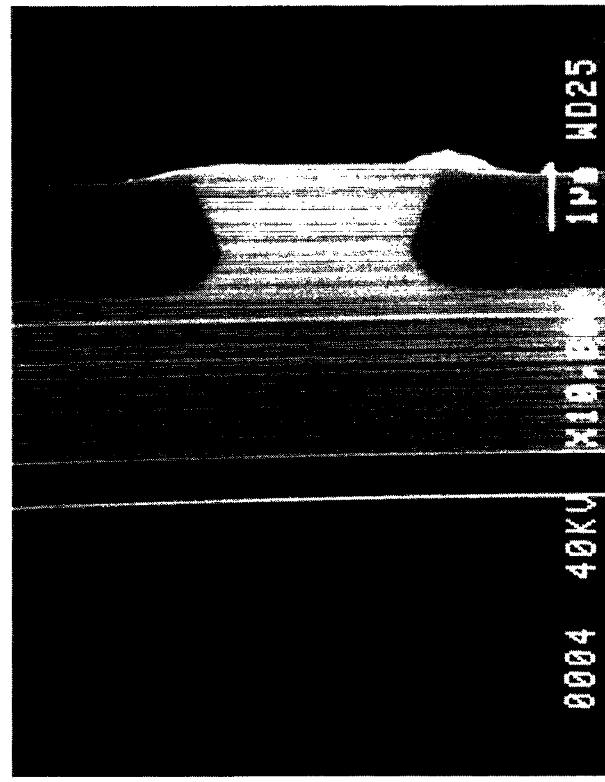
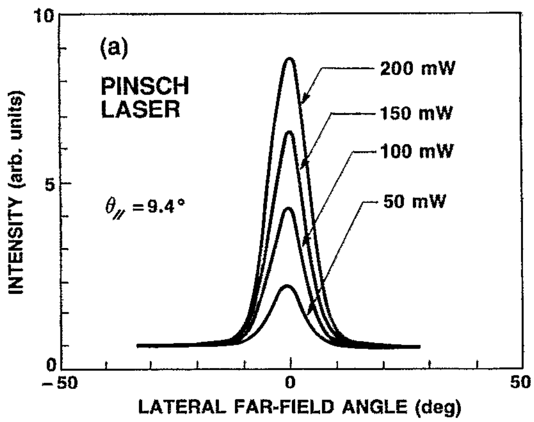


FIG. 2. The cross-sectional SEM micrograph of the self-aligned PINSCH ridge-waveguide laser. The polyimide which planarizes the ridge structure is also shown.

Ridge-waveguide PINSCH lasers are fabricated using a self-aligned process reported elsewhere.[6] A 5-μm-wide ridge waveguide is formed by wet chemical etching. The thickness of the remaining upper PIN layers outside the ridge is 0.45 μm above the active quantum wells. Figure 2 shows the scanning electron micrograph (SEM) of the cross section of the PINSCH laser. The ridge structure is planarized by polyimide, as also shown in Fig. 2. No regrowth or other high-temperature process is used so that accurate lasing wavelength can be reproducibly achieved.

The lateral and transverse far-field patterns of a coated 5×750 μm PINSCH laser are shown in Figs. 3(a) and 3(b), respectively. The reflectivities of the front and back facets are 10% and 90%, respectively. Single transverse-mode operation with full-width-at-half-maximum (FWHM) far-field angle of $\theta_\perp = 20°$ is observed at all output power levels. Stable single lateral mode with $\theta_\parallel = 9.4°$ (FWHM) is obtained up to 200 mW of output power. The $\theta_\perp/\theta_\parallel$ ratio of 2.1 is two to three times better than those of the conventional InGaAs/AlGaAs GRINSCH lasers. The more symmetric beam profile greatly increases the optical coupling efficiency into optical fibers.

Figure 4 shows the room-temperature CW light-versus-current (L-I) curves of the 750-μm-long coated PINSCH laser. A threshold current of 45 mA and an external differential quantum efficiency as high as 1.15 mW/mA (90%) are achieved. The CW output power into free space exceeds 620 mW at a pump current of 700 mA, which is



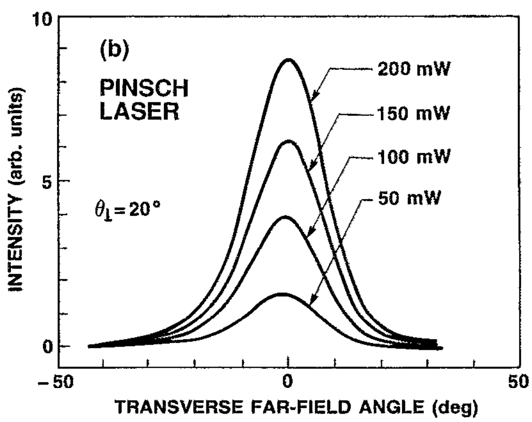


FIG. 3. The (a) lateral and the (b) transverse far-field patterns of the PINSCH laser at 50, 100, 150, and 200 mW. The FWHM angles are $\theta_{\parallel} = 9.4°$ and $\theta_{\perp} = 20°$, respectively.

not limited by COD yet. The kinks in the *L-I* curve above 400 mW are due to the high-order lateral modes. As a final test of the optical beam profile and its stability with pump current, a fiber coupling experiment is performed. The output light is collected by a lensed single mode fiber with 5 μm core diameter. Then the power in the fiber is measured versus the pump current without changing the fiber position. A fiber coupling efficiency as high as 51% is obtained. Furthermore, the coupling efficiency is constant from the threshold up to 175 mA of pump current, which indicates that the far-field pattern is very stable with pumping current. At higher pump current, high-order lateral modes start to show up because of the wide ridge width, and the fiber coupling efficiency gradually degrades. Nevertheless, a record high 130 mW of power at 980 nm wavelength is coupled into the single mode fiber at a bias current of 400 mA. In addition to the high coupling efficiency, the low beam divergence allows the use of lenses with lower numerical aperture for more relaxed alignment tolerance.

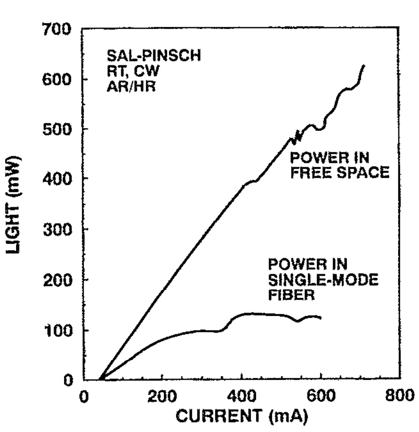


FIG. 4. The room-temperature CW *L-I* curves of a 5 μm$\times$750 μm PINSCH laser for output power in free space and output power coupled into a single mode fiber with 5 μm core diameter. The maximum powers in free space and in the fiber are 620 and 130 mW, respectively.

In conclusion, we have proposed and demonstrated, for the first time, an edge-emitting periodic index separate confinement heterostructure (PINSCH) laser. The PINSCH structure expands the fundamental transverse mode size while totally suppressing the high-order modes and efficiently confining the injected electrical carriers. A transverse beam divergence of 20° is measured with a moderate increase of the threshold current density. With a self-aligned ridge-waveguide structure, the 5-μm-wide and 750-μm-long PINSCH laser has a CW threshold current of 45 mA, an external quantum efficiency of 1.15 mW/mA (90%), and a CW output power exceeding 620 mW at the 980 nm pump band for erbium-doped fiber amplifiers. Stable far-field patterns of 10° by 20° and a record high coupling efficiency of 51% into single mode fiber are achieved. More than 130 mW of power is coupled into the fiber, the highest value ever reported at this wavelength.

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[1] W. T. Tsang, Appl. Phys. Lett. **40**, 217 (1982).
[2] S. Uehara, M. Okayasu, T. Takeshita, O. Kogure, M. Yamada, M. Shimizu, and M. Horiguchi, Optoelectronics **5**, 71 (1990).
[3] H. F. Lockwood, H. Kressel, H. S. Sommers, and F. Z. Hawrylo, Appl. Phys. Lett. **17**, 499 (1970).
[4] R. G. Waters, M. A. Emanuel, and R. J. Dalby, J. Appl. Phys. **66**, 961 (1989).
[5] Y. C. Chen, R. G. Waters, and R. J. Dalby, Electron. Lett. **26**, 1348 (1990).
[6] Y. K. Chen, M. C. Wu, W. S. Hobson, S. J. Pearton, A. M. Sergent, and M. A. Chin, Photon. Tech. Lett. **3**, 406 (1991).
[7] 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).
[8] P. Yeh, A. Yariv, and C. S. Hong, J. Opt. Soc. Am. **67**, 423 (1977).
[9] P. Yeh, A. Yariv, and A. Y. Cho, Appl. Phys. Lett. **32**, 104 (1978).
[10] H. Kogelnik and C. V. Shank, J. Appl. Phys. **43**, 2328 (1972).
[11] S. Wang, IEEE J. Quantum. Electron. **QE-10**, 413 (1973).
[12] M. Hong, J. P. Mannaerts, J. M. Hong, R. J. Fischer, K. Tai, J. Kwo, J. M. Vandenberg, Y. H. Wang, and J. Gamelin, J. Cryst. Growth **111**, 1071 (1991).