Demonstration of high-brightness-mode propagation in a compound waveguide structure

J. A. Patchell, F. P. Logue,[a)] J. O'Gorman, and J. Hegarty
Optronics Ireland, Trinity College, Dublin 2, Ireland

B. A. Usievich and V. A. Sychugov
General Physics Institute of Russian Academy of Sciences, 117942, Moscow, Russia

(Received 22 March 1999; accepted for publication 17 May 1999)

We demonstrate the existence of an unusual and useful high-brightness guided mode of a multimode AlGaAs/GaAs heterostructure compound slab waveguide. This mode has a narrow near-field single lobe confined to the low-index regions of the waveguide. This mode was selectively probed by optically exciting quantum wells optimally placed in the waveguide. By pumping in a stripe geometry, lasing is observed above a threshold of 80 kW/cm^2 indicating efficient lasing in the highest-order waveguide mode. The near-field emission pattern of the waveguide was imaged to provide a direct measurement of the intensity profile of the higher-order mode. © *1999 American Institute of Physics.* [S0003-6951(99)02128-2]

An important and as yet unresolved problem in the onward development of laser diodes is that of raising the power extracted while not compromising the source brightness. Brightness is defined as the power emitted into a unit solid angle per unit emitting area from a single spatial mode.[1] Conventional semiconductor lasers emitting in a single spatial mode have small (μm scale) apertures. This small emission aperture size limits the maximum emitted power prior to the onset of catastrophic facet degradation.

Typically, the maximum power extracted from high-power, narrow stripe lasers is in the region of ~200 mW.[2] Using the simple expedient of increasing the emitting aperture area results in increased power but at the expense of the source brightness due to the onset of filamentary emission and/or lasing in high-order modes. Unfortunately, source brightness is key to many applications since this quantity determines the minimum spot size to which the emission can be focused. The ability to focus high-power laser diode light to small spots (~1 μm) is key to many uses such as efficient coupling to single-mode fiber, for fiber amplifier applications and the production of high-power densities for cutting, welding, and soldering applications.

While the waveguide geometry created both by the semiconductor layer structure and the surface processing of a laser diode impact on characteristics such as laser threshold and emission efficiency, they can also be used to tailor the device modal emission. Waveguide engineering can be used effectively to improve laser diode characteristics such as output power[3,4] and emission spatial coherence.[1] However, in many cases it is difficult to increase both the emitted power and its spatial coherence in tandem; i.e., it is often difficult to achieve an increase in brightness even if the output power is maximized. A particular example of this is where high-efficiency launching of light is required from a high-power laser diode into a single-mode optical fiber for rare-earth-doped fiber amplifier pumping. Existing large aperture laser diodes can emit at high powers, but due to poor source brightness, only a fraction of this light is useful for fiber coupling.

Reference 5 describes a compound waveguide structure which supports a higher-order "supermode." We show numerically in a separate publication[6] that this mode considerably increases the guided-mode brightness over that of conventional laser diode waveguides of equivalent dimension. Furthermore, we demonstrate the brightness increase by comparing the coupling efficiency of the emission from a 61 μm aperture compound waveguide, which we call a LO-GUIDE, to a single-mode fiber with that of a conventional high-power multimode ridge waveguide structure. Coupling efficiency improvements of up to 5× and as high as 20% are expected for butt coupling. The exceptional nature of this result was highlighted when we computed the coupling efficiency between the single-mode fiber and a single-mode ridge waveguide with a ridge width of 3 μm. In this case the coupling efficiency was 13%, a figure in keeping with what is commonly experimentally observed for butt coupling of single-mode fiber to ridge waveguide laser diodes.

Our primary aim in this work is to examine a closely related waveguiding structure and to demonstrate experimentally the existence of the higher-order guided mode which is proposed in Refs. 5 and 6. This we achieve by examining the emission characteristics of a photopumped AlGaAs/GaAs-based LO-GUIDE in which InGaAs quantum wells (QWs) have been placed at the antinode of the LO-GUIDE mode. Even though our initial calculations concerned lateral waveguiding solutions, our experimental approach involves implementation of the waveguide geometry in the transverse (growth) direction in order to facilitate waveguide realization by exploiting the tighter control that current semiconductor epitaxial growth techniques allow over surface processing.

The structure studied in this experiment was grown by metal–organic vapor-phase epitaxy. The waveguide core of our structure was grown on a GaAs substrate and consisted of a 3.4 μm GaAs high-index region, followed by a 0.6 μm $Al_{0.27}Ga_{0.73}As$ low refractive index layer. The waveguide

[a)]Electronic mail: fplogue@tcd.ie

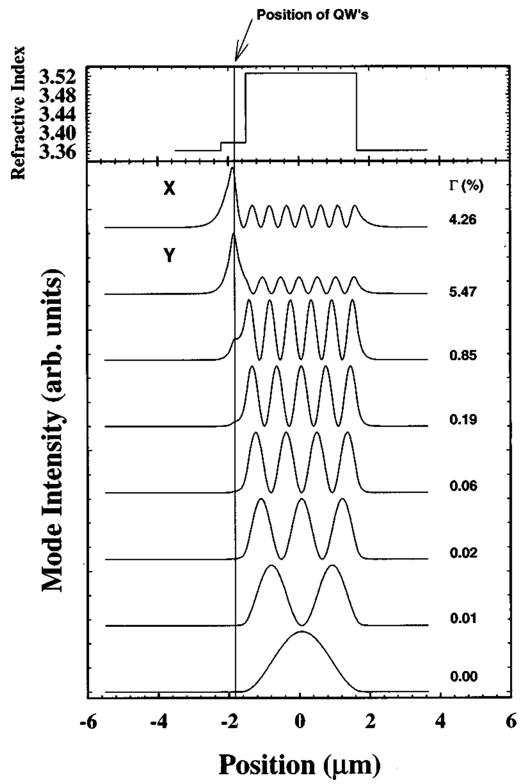

FIG. 1. Calculated guided modes for the LO-GUIDE waveguide structure operating at $\lambda = 980$ nm. Also shown is the transverse-index profile of the sample and the overlap of the quantum wells with each mode (Γ).

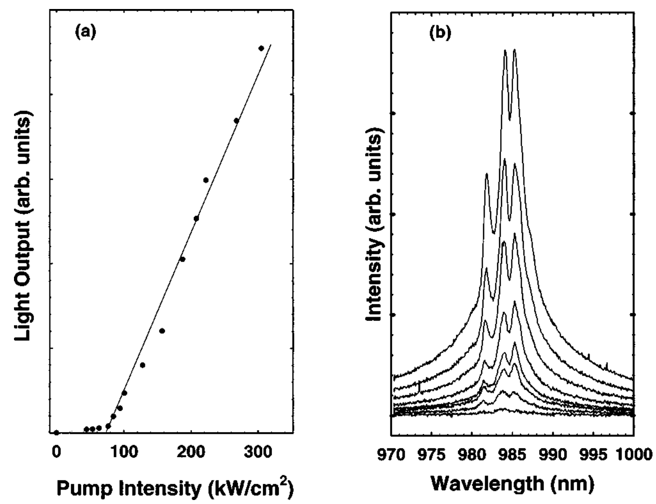

FIG. 2. (a) Edge emission power vs 532 nm pump power for the LO-GUIDE sample. There is a clear threshold at a pump power of approximately 80 kW/cm^2. (b) Emission spectrum for increasing pump power.

core was surrounded by top and bottom $Al_{0.32}Ga_{0.68}As$ cladding layers of 1.3 and 2.0 μm. Using the refractive index data of Adachi,[7] this layer structure produces a refractive index profile as shown in Fig. 1 at a wavelength of $\lambda = 980$ nm. This refractive index profile corresponds to half of the waveguide geometry introduced in Ref. 5. Due to band structure and absorption considerations, this is the optimal structure for optical pumping measurements. However, the results reported in this work are equally valid for the full waveguide structure introduced in Refs. 5 and 6.

Figure 1 also shows all of the calculated guided modes of the slab waveguide structure illustrated at the top of Fig. 1. These modes were calculated using standard waveguide theory.[8] Obviously, the waveguide supports many modes. However, the two highest-order confined modes (*X* and *Y*) are striking. They are effectively confined to the low-index region of the waveguide. Second, although these are the highest-order guided modes, the optical power is confined in a narrow lobe in each case. The aim of this work is to show that these counterintuitive results are not mere artifacts of the theory but are in fact stable, guided modes of the waveguide.

Due to the inherent difficulties in probing an individual higher-order mode of a multimode waveguide by purely passive means such as optical transmission measurements, our approach involved incorporation of quantum wells into the waveguide which emit light when photopumped. Five InGaAs quantum wells with a peak luminescence of $\lambda = 980$ nm were positioned in the center of the $Al_{0.27}Ga_{0.73}As$ layer facilitating excitation of spontaneous emission directly inside the structure which coupled directly into the waveguide modes. To determine the optimum position for excitation of the higher-order ''supermodes'' (*X* and *Y* in Fig. 1), we modeled the overlap of the quantum wells with the optical modes of the cavity.[9] Our modeling results indicated that, for this purpose, the optimum position of the QWs was at the peak of the supermode. We also have given the calculated optical confinement factor for the quantum wells for each mode in Fig. 1. The supermode (*Y*) has the highest confinement factor for this QW position, and consequently, the natural experimental verification of the existence of this mode is to measure the near-field pattern of the waveguide emission when the sample is pumped in a stripe geometry above the lasing threshold. Since the mode with the largest confinement factor will reach the threshold first, it will dominate the near-field emission pattern of the sample near the threshold.

Samples were cleaved to a cavity length of approximately 1 mm and optically pumped using a *Q*-switched, frequency-doubled Nd:YAG with emission at $\lambda = 532$ nm, a pulse length of 5 ns, and a repetition rate of 20 Hz. The laser emission was focused to a 50-μm-wide stripe on the sample surface with care being taken to ensure that the stripe was of uniform intensity along the full length of the sample. The pump intensity was measured using a calibrated energy meter and controlled with a variable neutral density filter. The light emission versus pump power characteristic was obtained by focusing the filtered edge emission of the sample onto a silicon photodiode and is shown in Fig. 2(a). A clear threshold can be seen in this curve indicating the onset of lasing at an intensity of approximately 80 kW/cm^2. A narrowed spectral linewidth of 6 nm full width at half maximum (FWHM) was observed above threshold [Fig. 2(b)] as compared to the subthreshold linewidth of about 30 nm FWHM.

The observation of lasing with a reasonably low-threshold pump intensity[10] is strong evidence that the transverse mode of the structure has a high-confinement factor as predicted using our modal analysis in Fig. 1. We measured the structure's near-field emission pattern to unambiguously confirm the structure of the transverse mode. The laser emission was magnified and captured using a 40×0.6 numerical aperture objective and charge-coupled device camera combination. The magnification of this optical system was cali-

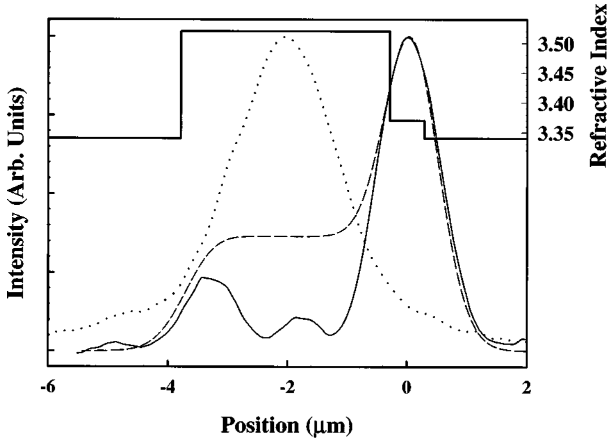

FIG. 3. Comparison between measured (solid) and calculated (dashed) near-field patterns for the compound waveguide structure, account having been taken of system resolution. Also shown is the near-field transmission spectrum of the waveguide (dotted line).

brated by imaging a calibration target of known dimensions. In Fig. 3 we show the measured intensity profile in the transverse direction (solid line). The near-field profile is strongly peaked in the low-index $Al_{0.27}Ga_{0.73}As$ layer while it has an oscillatory tail stretching into the high-index 3.4-μm-thick GaAs layer. Also shown is the calculated intensity profile (dashed line) of the highest-order mode, taking into account the 1 μm system resolution. There is excellent agreement between the measured and calculated profiles. The agreement with the main lobe of the mode is excellent while there is also reasonable agreement in the profile tail. A possible source of deviation in the tail is interference from the other waveguide modes, which although not above lasing threshold still emit spontaneous emission and contribute to the near-field profile primarily in this region. As a final check on our results we show the near-field pattern obtained by transmitting monochromatic light at $\lambda = 980$ nm through the same sample. In this case the light was coupled into the waveguide using another 40× microscope objective. Now, however, the transmitted light coincides with the high-index GaAs layer and our calculations again indicate that in the case of launching light from external to the waveguide, guiding occurs, as is conventional, in the high-index layer and that in this case it is guided in the fundamental waveguide mode.

In a separate report[6] we show that guided modes such as the one observed in this work significantly enhance the brightness characteristics of guided wave optical components. Because of the narrow emission lobe of this mode, narrower even than the lowest-order (fundamental) guided mode, single-mode fiber coupling can be significantly increased.

In conclusion, we have demonstrated experimentally the existence of a higher-order guided mode which is predominately confined to the low-index region of a compound AlGaAs/GaAs heterostructure waveguide. This mode was selectively excited by optically pumping QWs placed to enhance the supermode emission under lasing conditions. The moderately low-threshold pump intensity (80 kW/cm^2) and narrow spectral emission width indicate that the structure is lasing in a well-confined mode. Our modal calculations showed that for this structure the low-threshold lasing modes were strongly confined in the low-index part of the compound waveguide. On measuring the near-field profile excellent agreement was obtained between the calculated near-field profile and that measured from the waveguide structure. Emission into this mode has predominantly a single lobe in the near field and is narrower than the lowest-order waveguide mode demonstrating the increased brightness possibilities of the LO-GUIDE concept.

This work was performed under the European Union ESPRIT Project TRUE-BLUE (Project No. 22,666).

[1] J. N. Walpole, Opt. Quantum Electron. **28**, 623 (1996).
[2] J. Heerlein, M. Grapherr, R. Jager, and P. Unger, IEEE Photonics Technol. Lett. **10**, 498 (1998).
[3] L. J. Mawst, D. Botez, C. Zmudzinski, and C. Tu, IEEE Photonics Technol. Lett. **4**, 1204 (1992).
[4] L. J Mawst, A. Bhattacharya, J. Lopez, D. Botez, D. Z. Garbuzov, L. DeMarco, J. C. Connolly, M. Jansen, F. Fang, and R. F. Nabiev, Appl. Phys. Lett. **69**, 1532 (1996).
[5] S. J. Krivoshlykov, U.S. Patent No. 5574818.
[6] F. P. Logue, J. A. Patchell, J. O'Gorman, J. Hegarty, B. A. Usievich, and V. A. Sychugov (unpublished).
[7] S. Adachi, J. Appl. Phys. **58**, R1 (1985).
[8] D. Marcuse, *Theory of Dielectric Optical Waveguides*, 2nd ed. (Academic, San Diego, CA, 1991).
[9] H. C. Casey, Jr. and M. B. Panish, *Heterostructure Lasers, Part A: Fundamental Principles* (Academic Press, New York, 1978).
[10] F. P. Logue, P. Rees, J. F. Heffernan, C. Jordan, J. F. Donegan, J. Hegarty, F. Hiei, S. Taniguchi, T. Hino, K. Nakano, and A. Ishibashi, J. Opt. Soc. Am. B **15**, 1295 (1998).