High-power GaAs/AlGaAs quantum fountain unipolar laser emitting at 14.5 μm with 2.5% tunability

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We demonstrate operation of a high-power quantum fountain unipolar laser relying on intersubband emission in optically pumped GaAs/AlGaAs quantum wells. The collected power per facet is as large as 2.3 W at 20 K and 1.5 W at 120 K, which translates into 6.6 W optical power per facet at low temperature accounting for collection efficiency. The maximum operating temperature is 135 K. We also demonstrate that the lasing wavelength can be tuned by as much as Δλ/λ~2.5% simply by tuning the pump wavelength. © 1999 American Institute of Physics. [S0003-6951(99)03511-1]

There is a strong interest in the development of semiconductor lasers for infrared applications such as trace gas analysis. The recent demonstration of quantum cascade (QC) unipolar lasers is already challenging the currently available technology relying on electron–hole radiative recombination in narrow-gap semiconductors.1 Unlike conventional diode lasers, the infrared emission of a QC laser arises from an intersubband transition in a quantum well or superlattice active region and only involves one type of carrier. QC lasers are current injection devices based on the well-mature InP or GaAs technology.2 They can deliver tens to hundreds milliwatts of optical power in the 3–17 wavelength region and pulsed operation above room temperature has been reported at wavelengths as long as 11.5 μm.3 Very recently, an alternate type of unipolar laser relying on intersubband emission, the so-called quantum fountain intersubband laser (QF) has been proposed and demonstrated.4,5 The active region consists of periods of two GaAs/AlGaAs-coupled quantum wells exhibiting three bound electron states. Electrons are optically excited from the ground state to the upper state. The radiative intersubband transition to the intermediate state gives rise to the infrared emission. Population inversion, as well as fast recycling of electrons into the ground state, is provided by insuring a short lifetime of electrons in the intermediate state through an enhanced scattering with LO phonons.4 Although their operation imposes an external pumping source, QF lasers offer the advantages of a simplified design and of less stringent material requirements as compared to QC lasers. With no current flow, doping of the cladding layers and metal contacts are not necessary, which results in low internal losses at long wavelengths due to free-carrier absorption. Another advantage of optical pumping is that the laser can be operated far above threshold with much less thermal penalty than in a current injection device. QF lasers are then expected to exhibit better performances in terms of output power than QC lasers at long wavelengths above 10 μm. In a recent letter, we have reported on the operation of a QF laser emitting at λ = 15.5 μm with 0.6 W optical power per facet and a maximum operating temperature of 110 K.5

In this letter, we report on an optimized QF laser emitting at 14.5 μm under optical pumping by a pulsed CO2 laser. The collected power per facet is as large as 2.3 W at 20 K, which corresponds to ~6.6 W optical power per facet accounting for collection efficiency. The maximum operating temperature is 135 K. We also demonstrate that the lasing wavelength can be tuned by as much as Δλ/λ~2.5% simply by tuning the pump wavelength.

The design of the waveguide sample is basically the same as in Ref. 5, but with two modifications aimed at enhancing the modal gain of the laser. The number of active quantum well structures has been increased from 100 to 150 and the waveguide design has been optimized to achieve a large 81.1% overlap of the TM mode within the active region. The sample has been grown by molecular beam epitaxy on an n-doped GaAs substrate. The active structures separated by 20 nm thick Al0.35Ga0.65As barriers, are asymmetrically coupled quantum wells formed by a 7.9 nm thick GaAs wide well, a 1.13 nm thick Al0.35Ga0.65As barrier, and a 5.1 nm thick GaAs narrow well. The quantum wells are modulation doped resulting in a measured sheet carrier density of 2 × 1011 cm−2. The transition energies are calculated to be 127 and 86.8 meV for e1→e3 and e2→e3 transitions, respectively. In growth order, the waveguide structure consists of a 5 μm thick Al0.9Ga0.1As cladding layer, followed by a 0.75 μm thick GaAs core layer, the 5.1 μm thick multiquantum well layer, and a 1.75 μm thick GaAs cap layer. The waveguide is designed to be single mode for the TM emission at 14.5 μm. The waveguide losses at this wavelength are deduced to be ~20 cm−1 using Fourier transform infrared (FTIR) waveguide transmission measurements.

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The experimental arrangement is shown in the inset of Fig. 1. The laser samples are cleaved in 2.15 mm long bars and mounted on the cold finger of a variable temperature cryostat. The pump beam from an Edinburgh MTL-3 mini-TEA CO$_2$ laser operated at 10 Hz repetition rate is focused using a cylindrical lens onto the 2.15 mm long side facet with a $5 \times 0.4 \text{mm}^2$ spot size. It should be noticed that in the present configuration, less than 1.5% of the pump energy is coupled into the 11.8 $\mu$m thick waveguide. The emission is collected from one of the cleaved facets perpendicular to the side facet with a f/1.2 ZnSe lens. Time-resolved detection is performed by a helium-cooled quantum well infrared detector (QWIP) with a cutoff wavelength of 18 $\mu$m and a sensitive area of $0.45 \times 1.5 \text{mm}^2$. The QWIP detector offers the advantage of a linear response even under intense irradiation. Part of the incident pump beam is detected by a room-temperature HgCdTe photoconductor for reference purposes. The spectral response of the detectors and of the various optics have been carefully calibrated using a FTIR spectrometer.

Figure 1 shows typical oscilloscope traces of the pump and laser pulses. The QF laser is optically pumped at 9.6 $\mu$m and is operated at 20 K. The multimode pump pulse consists of micropulses with a 2.6 ns full width at half maximum (FWHM) in a macropulse with 110 ns FWHM. As seen in Fig. 1, the laser emission follows the pump signal above some threshold. The rise time of the QWIP signal is limited by electronics at 5 ns, which is too slow to fully resolve the multimode beatings. For temperatures between 20 and 77 K, the pump threshold is of the order of 33 kW at 9.46 $\mu$m and decreases to 12 kW as the pump wavelength gets in closer resonance with the $e_1-e_3$ intersubband absorption near 9.6 $\mu$m. At 120 K, the minimum threshold $\approx 18$ kW is achieved at a longer wavelength of 9.66 $\mu$m due to the redshift of the intersubband resonance with temperature. The slight increase of the minimum threshold with temperature is a consequence of the thermal population of the $e_2$ subband which reduces available gain. Above 120 K, the intersubband resonance wavelength shifts to $\lambda > 9.7 \mu$m, which is outside the tuning range of our CO$_2$ laser. Thus, a maximum operating temperature of 135 K has been achieved under optical pumping at 9.68 $\mu$m.

Figure 2 shows the collected power per facet versus incident pump power at temperatures ranging from 20 up to 120 K. The pump wavelength was 9.6 $\mu$m at 20 K and 9.68 $\mu$m at 120 K. The curves are constructed from the time-resolved evolution of the pump and laser pulses after calibration of the detector response. The collected power at 20 K reaches a record value of 2.3 W when the laser is operated at seven times above threshold. The evolution with pump power is similar at 20 and 77 K. At 120 K, the collected power is of the order of 1.5 W when the laser is operated four times above threshold. Note that the power curve slope above threshold is smaller at 120 K than at 20 K, which stems from a lower differential gain due to the increased thermal population of the $e_2$ subband. To estimate the collection efficiency, we have performed separate beam divergence measurements of the QF laser emission. The divergence angle in the plane of the layer is found to be 26°, which corresponds to a beam waist at the output facet of the order of 10 $\mu$m. The divergence angle $\theta_2$ in the plane parallel to the growth axis could not be measured due to the limited aperture of the cryostat windows but is larger than 50°. Based on our calculations of the TM mode profile at the output facet, we estimate $\theta_2$ to be 60.4° following Ref. 9. The collection efficiency is then deduced to be 35%.

Figure 3 presents normalized emission spectra of the QF laser operated two times above threshold at 20 K for different pump wavelengths.
laser operated at 20 K two times above threshold. The pump wavelength is varied between 9.458 and 9.676 μm. The resolution of the 60 cm long infrared spectrometer used for measurements is 0.4 cm\(^{-1}\). As seen, the laser spectrum is typical of multimode operation with a mode spacing of 0.69 cm\(^{-1}\). The major result of Fig. 3 is the large tunability of the peak lasing wavelength between 14.25 and 14.61 μm achieved by tuning the pump wavelength. This result is not the signature of a near-resonant Raman emission process\(^{10}\) since the shift of the laser photon energy respective to the pump is 0.72 instead of 1. The tunability of the QF laser is, in fact, attributed to layer thickness fluctuations during the long growth of the multiple quantum well layer. We have simulated the peak gain spectral position accounting for a 1 ML thickness fluctuation of each of the quantum well layers and assuming a Gaussian distribution centered at the nominal thickness. The model predicts a relative energy shift of 0.7 in agreement with experiments. The tunability range is maintained at 77 K. Also seen in Fig. 3, the emission spectrum gets narrower as the emission wavelength is shifted to 14.2 μm. This is a consequence of the gain spectrum narrowing as the pump wavelength is tuned out of resonance. However, we cannot exclude the effect of increased internal losses as the emission wavelength gets closer to the mixed-mode Al–Ga two-phonon absorption band at 14.0 μm in the AlGaAs alloy cladding layer.\(^{11}\)

In conclusion, we have reported on a high-power unipolar laser relying on intersubband emission in optically pumped GaAs/AlGaAs quantum wells. Tunable emission in the 14.2–14.7 μm region has been achieved by tuning the pump wavelength. By operating the laser seven times above threshold, the optical power per facet is of the order of 6.6 W at low temperatures. In the present side-facet pumping configuration, the efficiency of the QF laser is low of the order of 10\(^{-4}\) at 20 K due to a poor coupling of the pump beam into the active region. Accounting for a conservative value of 1.5% for the coupling efficiency, the internal quantum efficiency is at least 0.6%. Much larger output powers could be achieved by using a better coupling geometry such as grating coupled waveguides.

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