High efficiency beam combination of 4.6-μm quantum cascade lasers

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The quantum cascade laser (QCL), a potential laser source for mid-infrared applications, has all of the advantages of a semiconductor laser, such as small volume and light weight, and is driven by electric power. However, the optical power of a single QCL is limited by serious self-heating effects. Therefore, beam combination technology is essential to achieve higher laser powers. In this letter, we demonstrate a simple beam combination scheme using two QCLs to extend the output peak power of the lasers to 2.3 W. A high beam combination efficiency of 89% and beam quality factor of less than 5 are also achieved.

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Quantum cascade lasers (QCLs) operating at room temperature have become desirable laser sources in the mid-infrared wavelength region for many applications, including chemical sensing, environment measurements, free-space telecommunications, infrared countermeasures, etc.[1−3]. Instead of recombinations of electrons and holes observed in the bandgap of traditional semiconductor lasers, QCLs use only electrons that jump between quantized energy levels to create photons, and one electron can produce several tens of photons[4]. This QCL principle achieves high electro-optical conversion efficiency but also results in serious heat accumulation in the device, which limits the enhancement of optical power. New structures or techniques have been proposed to improve the optical power of QCLs[5,6], but the brightness of QCLs is insufficient for high-power applications.

To exceed the optical power limit of a single laser, beam combination technology is necessary for practical applications. Beam combination technology has been successfully applied in near-infrared semiconductor lasers, demonstrating a high-beam quality, high-power laser system[7,8]. The technology has also been used in mid-infrared QCLs. Complex beam combination schemes that produce high beam quality using different types of gratings have been demonstrated in recent years[9−14]. However, these high-cost schemes produce beam combination efficiencies ranging from only 50% to 81% and are difficult to assemble. In most applications, a simple and low-cost mid-infrared beam combination approach that produces high beam combination efficiency is preferred.

In this letter, we demonstrate a simple beam combination scheme to produce 4.6-μm QCLs. A peak optical power of 2.3 W, a maximum efficiency of 89%, and a beam quality factor M^2 of less than 5 are achieved using this scheme. The scheme further provides high power in the mid-infrared region easily and effectively.

In our scheme, superposition of multiple beams in the fast axis direction is used to combine the beams and achieve high output powers. The light path of this scheme is simulated by Zemax, as shown in Fig. 1(a). The QCLs are placed at different heights, and a single aspheric lens instead of a complex collimating system is applied to each QCL to compress the beam divergence of both fast and slow axes. However, since QCL beams feature astigmatism, which means that the beam waists of the fast and slow axes are misaligned in the propagation direction, a single collimator lens can only compromise the divergence of both axes. The beams obtained after collimation are reflected by planar mirrors to superimpose one beam onto the adjacent beam in the direction of the fast axis. Therefore, the aspheric lens should be adjusted to compress the divergence of the fast axis preferentially so that the beams could be placed more closely to each other. Near- and far-field beam spots produced after beam combination are shown in Figs. 1(b) and (c), respectively. This scheme can be extended to beam combinations for multiple QCLs.

QCLs with a wavelength of 4.6 μm were used. The QCL epitaxial wafer was grown on an indium phosphide substrate by solid-source molecular beam epitaxy. The active region is based on strain-compensated InGaAs/In-

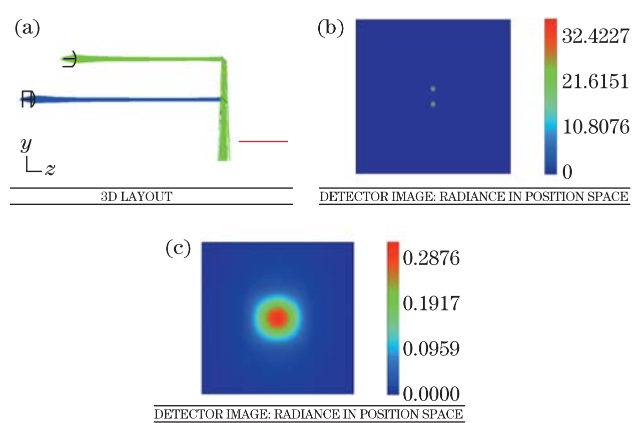

Fig. 1. Zemax simulation of the experimental scheme. (a) The scheme structure. (b) Near- and (c) far-field beam images.

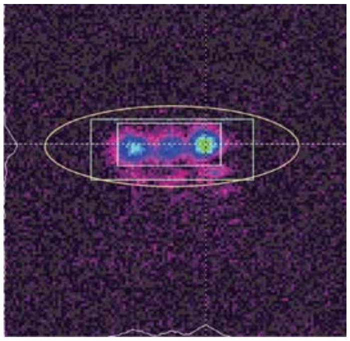

Fig. 2. A light beam obtained from a single QCL.

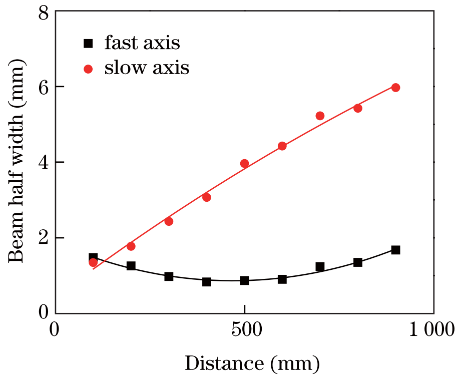

Fig. 3. Laser beam width measurement of one QCL.

AlAs quantum wells and barriers. The epiwafer was etched into a double-channel waveguide and subsequently cleaved into 14-μm-wide, 3-mm-long QCL chips after evaporation of the highly reflective (HR) coating. The QCL chips were indium-bonded with the epilayer side facing down on copper heat sinks and subsequently wire-bonded to an external contact pad. A laser driver provided a 2.0-A pulsed peak current and approximately 12-V peak voltage with a 2-μs pulse width and a 2-kHz repetition frequency. The light beam was observed and measured by a CCD beam analyzer, and the optical power was measured by a power meter.

Figure 2 shows the image of a laser beam emitted from one QCL after collimation by the aspheric lens. Results indicate that the lasing mode occurs in fundamental mode at the fast axis and high-order mode at the slow axis. Measurement results of the beam half width versus the propagation distance are shown in Fig. 3. After calculation, the M^2 of the fast and slow axes are less than 3.8, respectively.

Two QCLs were employed for beam combination. QCLs with heat sinks were mounted on a pedestal with a height difference. Light beams from the QCLs were collimated by corresponding aspheric lenses fixed to the pedestal and then reflected by planar mirrors coated with gold and fixed with a proper height difference. The beam image obtained after combination is shown in Fig. 4. Beams from two QCLs are superimposed in the fast axis direction with about 3-mm spacing. The beam width obtained after combination was measured, and results are shown in Fig. 5 as a function of the propagation distance. The obtained M^2 of the fast and slow axes are both less than 5. Figure 6 shows the output optical power obtained after beam combination. The peak power increases with increasing driving current of the QCLs and reaches 2.3 W at a peak driving current of 2 A. The efficiency of beam combination was calculated, and the results are shown in Fig. 7. The beam combination efficiency increases with the driving current, and a maximum efficiency of 89% is obtained at a peak driving current of 2 A. Power loss occurs because of lens and mirror losses as well as beam propagation losses. Beam divergence and the stability of QCLs improve slightly when the driving current exceeds a threshold value, thereby reducing beam propagation loss and increasing the beam combination efficiency.

In conclusion, the high-efficiency beam combination of QCLs is demonstrated. Beams from multiple QCLs are superimposed in the fast axis direction after collimation. A peak optical power of 2.3 W, an M^2 of less than 5, and a maximum efficiency of 89% are achieved after beam combination. This simple and effective method can be

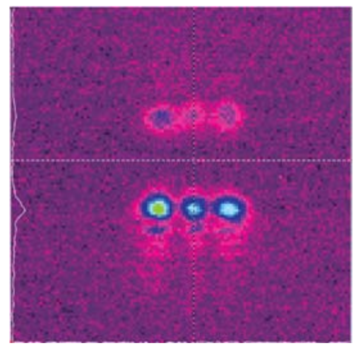

Fig. 4. Image of a light beam after beam combination.

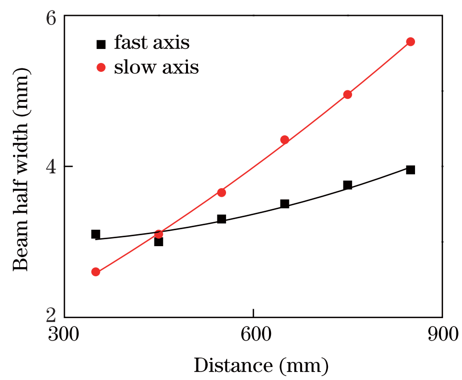

Fig. 5. Laser beam width measurement after beam combination.

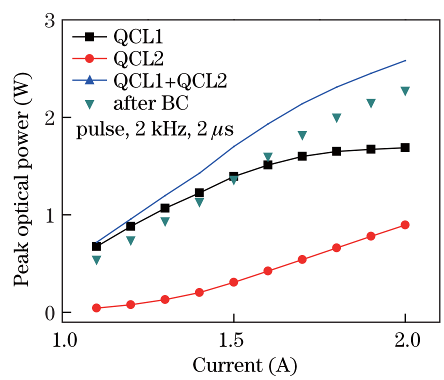

Fig. 6. Optical power measurements obtained after beam combination.

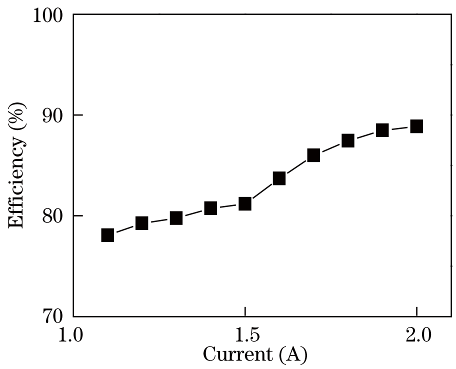

Fig. 7. Efficiency curve of beam combination.

used to achieve high power in mid-infrared lasers, and the results of this experiment will contribute to the development of high-power, high-beam quality mid-infrared lasers.

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