High power semiconductor lasers make mid-infrared wavelengths accessible

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The availability of compact semiconductor lasers that emit in the mid-infrared (from 3μm to 8μm) has always been limited. Sources in this spectral region are useful for a number of industrial and military applications, but significant physical challenges exist to creating semiconductor, limiting available output power and operating temperature. This article discusses recent technological improvements that have led to high-power room-temperature diode lasers in this important wavelength range.

Diode lasers that emit at mid-infrared (from 3μm to 8μm) wavelengths may one day have a dramatic impact on applications such as biological and chemical spectroscopy systems, directed infrared military countermeasure systems, and free space optical communication systems. Diode lasers are intrinsically compact, durable, and potentially mass-producible: that make them easier than non-diode lasers to integrate into systems. Unfortunately, standard diode laser technology is not easily extendable to wavelengths longer than 3μm due to an unfavorable electronic band structure and increased non-radiative recombinations. Until recently, lead-salt lasers were the only commercially-viable diode lasers for this spectral region based on interband recombination. These lasers operated only at cryogenic operating temperatures around 80K and produced only low output powers of about 1mW.

Many groups attempted to develop alternative heterostructures that bypass some of the intrinsic inefficiencies of low-bandgap semiconductors. Most applications for mid-IR lasers need a device that can emit a continuous wave (CW) at or near room temperature with output powers higher than 100mW. Research groups followed several different paths including the use of Type II heterostructures (in which optical gain occurs due to interband transitions) and quantum cascade heterostructures (in which optical gain occurs due to intersubband transitions). The main difference between a quantum cascade laser (QCL) and traditional interband lasers is that, for a QCL, the emission wavelength is determined primarily by the thickness of layers within the device. For an interband laser, the emission wavelength is determined by the natural bandgap of the constituent semiconductors (see Figure 1).

While both approaches can create lasers in the 3 to 4μm wavelength range, no Type II structure has yet achieved CW operation at room temperature. Further, the potential for room-temperature operation at wavelengths longer than 4μm is even more limited, with consistently lower performance compared to intersubband techniques.

The idea of fabricating an infrared laser based on intersubband transitions within semiconductor quantum wells was first proposed by Kazarinov and Suris in 1971. The quantum cascade

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laser (QCL) is a variant of this approach, and was first demonstrated at Bell Laboratories in 1994.\(^5\)

Because the QCL’s wavelength depends on structure, rather than the semiconductor, it can have a very wide wavelength range as the emission energy approaches zero. Quantum-cascade-type terahertz lasers have already been demonstrated at wavelengths as long as 159\(\mu\)m at cryogenic temperatures.\(^6\) The main material limitation occurs at shorter wavelengths, at which point the emission energy is limited by the intrinsic energy depth (in other words, by the conduction band offset) of the quantum-well heterostructure.

Unfortunately, lattice-matched InP-based materials, which are the most extensively developed for the QCL, have a limited offset of about 510meV. We have increased this band offset using strain-balanced InP-based heterostructures. In this system, the quantum wells are compressively strained and the quantum barriers are tensilely strained. This allows for a much larger change in bandgap and conduction band offset at each interface than is possible in unstrained systems. We engineered the net strain in the device to be zero, which allows us to grow thick structures without significant strain-induced material defects. In general, this system is predicted to be able to demonstrate an offset of up to about 1eV, which should allow for emission down to wavelengths of roughly 3\(\mu\)m.

Our group demonstrated high-power CW operation throughout the 4.0 to 9.5\(\mu\)m wavelength range.\(^7\)\(^8\) Individual, room temperature, CW devices have produced output powers as high as 640mW with wavelengths near 6\(\mu\)m. Another recent result includes more than 100mW CW output power at wavelengths as short as 4\(\mu\)m (see Figure 2). The shortest wavelength demonstrated by a strain-balanced laser at room temperature is 3.66\(\mu\)m.\(^9\) Although this laser doesn’t operate in CW mode at present, recent work allowed demonstration of average powers near 160mW at this wavelength, with peak powers near 1W.

In addition, this technology is compatible with many of the advanced fabrication technologies used to make InP-based telecommunication lasers. Buried heterostructure strain-balanced QCLs have been demonstrated, which allow for a significant enhancement of laser performance.\(^10\) Further, distributed feedback (DFB) gratings allow for selective filtering of the output wavelength. While some power decrease is inevitable when using DFBs, we still observed more than 100 mW of continuous output at room temperature from a 4.8\(\mu\)m laser operating in a single spatial and spectral mode.\(^11\) Lastly, we improved the performance of our lasers by applying packaging techniques (used for high-power pump laser diodes at wavelengths of 808nm and 980nm) such as epilayer-down die bonding and the use of heat spreaders.\(^12\)

In conclusion, by leveraging the well-understood InP material system with an intersubband emission scheme, we created room-temperature diode lasers that emit at relatively high powers in the mid-infrared spectral region. At present, it is still difficult to access wavelengths shorter than 4\(\mu\)m but, as we continue to optimize material quality and laser design, we hope to achieve high power output at wavelengths as low as 3\(\mu\)m in the future. This would bridge the gap between existing interband and intersubband technology, and allow for seamless integration of potentially inexpensive laser diode technology throughout the visible and infrared spectral regions.

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