Direct liquid cooling of room-temperature operated quantum cascade lasers

J.Z. Chen, Z. Liu, Y.S. Rumala, D.L. Sivco and C.F. Gmachl

A compact packaging module for direct liquid cooling of room-temperature quantum cascade lasers is implemented. The light was coupled out of the hermetically sealed package through a mid-infrared fibre epoxy-bonded to the laser. The threshold current reduces by ~10%, compared to convectional substrate-side cooled lasers when using low boiling temperature (boiling point (b.p.) = 34°C) 3M HFE-7000 coolant. No reduction was observed with high boiling point 3M FC-77 (b.p. = 97°C) coolant.

Introduction: Cooling of quantum cascade lasers (QCLs) is a central issue for the development of room-temperature continuous-wave operated lasers [1, 2], long-term reliability, and the spectral and power stability of the laser output. Several methods have been used to improve heat dissipation of QCLs, such as episide downmounting [1], InP regrowth [2], and thick electroplated Au coatings [3, 4]. Direct liquid cooling of electronic devices or central processing units (CPUs) has been widely implemented since the heat dissipation efficiency of CPUs has reached the limit of air convective cooling [5, 6]. As for the liquid cooling of high-power semiconductor lasers, the liquids are usually not in direct contact with the lasers [7, 8]. To our best knowledge, direct liquid cooling from the surface of semiconductor lasers has not been reported before. One reason may be the ensuing need to couple the laser light out through the liquid, e.g. via a directly bonded fibre. In this Letter, we present the implementation of a compact direct liquid cooling packaging module including optical fibre pig-tailing for QCLs. In addition to cooling with a thermoelectric (TE) cooler from the substrate, it offers additional heat dissipation mechanism from the top of the laser ridges, which were exposed to the cooling liquid. Cooling from the surface in this way can be especially advantageous for cooling of dense large area laser arrays.

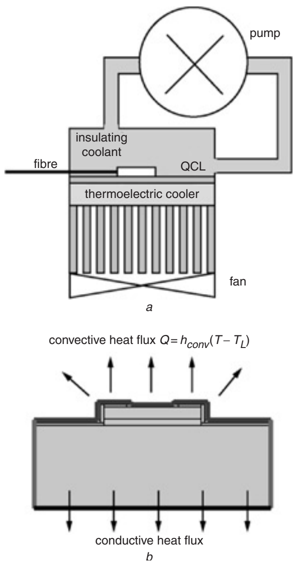

Fig. 1 *Schematic of QC laser (QCL) packaging module for direct liquid cooling, and schematic of heat transfer mechanisms involved in direct liquid cooling packaging*

a QCL packaging module for direct liquid cooling
b Heat transfer mechanisms involved in direct liquid cooling packaging

Design of packaging module: Fig. 1*a* depicts the design of this cooling module. The laser light is guided by a clad silver halide fibre (core/cladding diameter = 400/500 µm, numerical aperture (NA) = 0.25, purchased from JT Ingram Inc.) to prevent scattering as well as absorption due to the coolant. Although this clad silver halide fibre has a smaller NA than an unclad one, the clad fibre is chosen for this package module to prevent evanescent-wave absorption which could severely attenuate the output power at this wavelength range [9, 10]. The details about QCL-fibre coupling efficiency and fibre preparation were described in [9]. Direct laser/fibre coupling was applied to this module and the fibre was bonded with epoxy to the laser. Coupling with a Ge ball lens was attempted but had lower coupling efficiency compared to direct coupling. The fibre was bonded onto the machined copper block with 353ND epoxy purchased from Epoxy Technology Inc. and the fibre feed through the package was sealed by the same epoxy.

Heat transfer analysis and selection of coolants: To first order, the core temperature of the active region of a QCL, T_Q, can be given as

$$T_Q = T_L + R \cdot P_Q \qquad (1)$$

where T_L is the liquid surface temperature, P_Q is the power dissipated; R is the thermal resistance, which depends on the flow speed, conductivity of liquid and solid, and convective coefficients. Reduction of T_Q can therefore be achieved by reducing R, i.e. by increasing the convective heat transfer coefficient h_{conv}, which reaches highest value when convective boiling/condensation occurs [11].

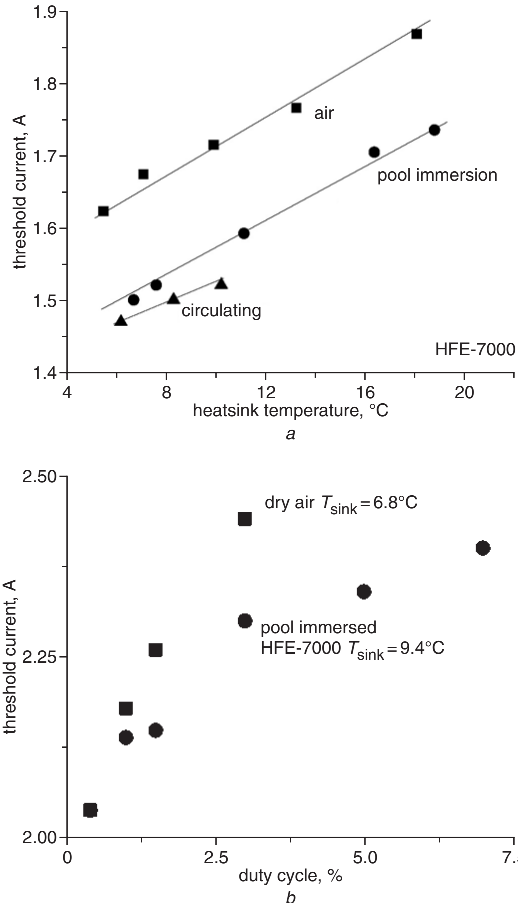

Fig. 2 *Threshold currents against heatsink temperatures; and against duty cycles with two different cooling fluids, air and HFE-7000*

a Threshold currents against heatsink temperatures
Three cases are plotted, air-cooled, pool-immersed and circulated HFE 7000. Lasers operated at 0.4% duty cycle
b Threshold currents against duty cycles with two different cooling fluids, air and HFE-7000
Threshold currents measured up to maximum operational duty cycle

The two heat dissipation mechanisms active in this laser package are illustrated in Fig. 1*b*. The liquid cools the laser ridge convectively from the top in addition to the conductive cooling from the substrate with a solid state TE cooler. The liquid flowing over the surface of the TE cooler is cooled to the same temperature; no extra cooling is applied to the liquid. Two different types of electrically insulating coolants, 3M Novec Engineered Fluid FC-77 and 3M Fluorinert Electronic Fluid HFE-7000, were tested. HFE-7000 has lower boiling point (b.p. = 34°C) and larger heat of vaporisation (h.v. = 142 J/g) than FC-77 (b.p. = 97°C and h.v. = 89 J/g) [12]. It is expected that the convective boiling condition is easier to achieve with HFE-7000 owing to its low boiling temperature. For *Biot number* ($Bi = h_{conv}\Delta x/k$) ~ 1, the heat dissipating into the liquid from the laser ridge becomes comparable to that which dissipates into the heatsink. With a Δx

(substrate thickness) $\sim$100 μm and a k (substrate thermal conductivity)$\sim$100 W/m K, h_{conv} needs to be around 100 000 in order to have $Bi \sim 1$, which is about the maximum value achievable.

Reduction of threshold current: The quantum cascade lasers tested in this cooling experiment are D2616 and D3028 structures [13, 14]. The active region designs of D2616 and D3028 are based on three-well and four-well two-phonon structures, respectively. Both can be operated in pulsed mode at room temperature without assistance of the cooling mechanism.

The pulsed threshold currents were determined from the L-I curves of a light-current-voltage (LIV) measurement. In our experiment with FC-77, no significant threshold current reduction was observed. In contrast, there was about 10% threshold current reduction using HFE-7000, as plotted in Fig. 2*a*, with a smaller difference between pool-immersion and liquid circulation. In both cases, no significant difference was observed with or without circulation. Using HFE-7000, bubbles were rapidly forming at the operated laser ridge once the laser was operated over $\sim$1% duty cycle operation. This indicates that the liquid is locally boiling and h_{conv} is increased due to the phase transition. We further tested the packaged laser at higher operating duty cycles. Comparison between the liquid-cooled and dry air-cooled lasers is plotted in Fig. 2*b*. The threshold currents were reduced by using HFE-7000 coolant and the maximum operated duty cycle is improved from $\sim$2.8 to $\sim$7.5%.

Conclusion: A direct liquid cooling package for QCLs was implemented. The room-temperature threshold current was reduced by about 10% for a pulsed operated QCL using an insulating coolant 3M HFE-7000, with a boiling point of 34°C, indicating the improved convective and evaporative cooling. This method can be especially advantageous for cooling a large array of high-power semiconductor lasers.

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