Intracavity resonant quantum-well photodetection of a vertical-cavity surface-emitting laser

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Indexing terms: Vertical cavity surface emitting lasers, Photodetectors

The authors demonstrate the first intracavity quantum-well photodetector within a VCSEL. Minimal spontaneous emission is detected by the internal detector. The effective responsivity is as high as 9A/W, the dark current is <1nA, limited by the noise floor the instruments used.

As vertical-cavity surface-emitting lasers (VCSELs) become more prominent in many applications, the need arises to be able to monitor the lasing power in a compact and cost-effective manner [1–3]. Conventional power detection utilises an external photodetector that usually entails bulky optical components to collimate the output light. Furthermore, an integrated detector structure is essential for simultaneous monitoring of laser arrays. Previous works have addressed this issue with a monolithically integrated $p$-$n$ bulk detector grown on top of a VCSEL [1, 2]. Ideally, an integrated detector should detect virtually no spontaneous emission, show high responsivity to laser emission, receive minimal stray light, and have low dark current. In this Letter, we present experimental results of a VCSEL with an intracavity quantum-well photodetector that meets all the above requirements for the first time. By placing the quantum well detector layer at a peak of the VCSEL internal optical intensity distribution, the quantum well resonance at only the Fabry-Perot wavelength minimizes the detection of the inherently broadband spontaneous emission. Furthermore, this resonance maximizes the detectivity of laser emission. With its embedded position, the quantum well prevents stray light from interfering with the power detection and monitoring while the thin active region minimizes the dark current. We demonstrate that the photodetector response matches that of an external detector very well.

80Å In$_{0.2}$Ga$_{0.8}$As quantum well as the detector, and 24.5 $n$-doped Al$_{0.2}$Ga$_{0.8}$As/GaAs DBR pairs as well as a phase-matching layer on top. The fabrication involved etching down to oxidise the AlAs layer, evaporating the top $n$-contact, etching down to just below the detector spacer, then evaporating an annular gold $p$-contact. The devices tested had ~15 μm diameter oxide-defined apertures. The $p$-contact is used to forward bias the active region while the $n$-contact is used to control the voltage across the quantum-well detector.

Fig. 2a shows light-current (L-I) traces as measured by the internal and external detectors for an internal detector bias of ~0.5V. Both responses match very closely to each other. Note that the internal detector response to spontaneous emission is at most as sensitive as the external detector. In Fig. 2b closer inspection shows that the internal detector actually senses less spontaneous emission below threshold. This feature is highly important for clear determination of threshold as well as near-threshold modulation. Effective responsivity (internal detector current/output power) is ~9A/W, a very high value compared to that of a typical external silicon detector (~0.5A/W).

**Fig. 2** Responses of internal and external photodetectors against pump current for detector $v$-bias of ~0.5V and magnified view of near threshold to show responses to spontaneous emission

a Responses of internal and external photodetectors against pump current

b Magnified view

**Fig. 3** Internal detector response against pump current for different reverse bias voltages across detector

--- 2V
--- 0V
--- ~0.5V
Fig. 3 shows the device L-I characteristics for different bias voltages of the internal detector. Based on observed changes in the differential quantum efficiency and threshold current for detector biases above and below the detector quantum-well transparency, the absorption introduced by the internal detector is estimated to be 5.6 cm⁻¹, much smaller than the total loss (sum of the mirror loss and internal loss) of 83 cm⁻¹. This result agrees well with our theoretical analysis. By similar calculation from experimental data, the absorption introduced by the internal detector under different biases is estimated to be 2.1 cm⁻¹, also much smaller than the total loss. The dark current is measured to be <1 nA and is limited by the noise floor of our instruments (not shown here).

We also fabricated some top-emitting lasers with similar geometry and integration of an intracavity quantum-well detector. Fig. 4 shows the L-I characteristic for a typical device measured by an external silicon detector. Peak output powers average ~1.4 mW. This clearly demonstrates that this novel integration does not adversely affect the VCSEL performance in terms of output power. The threshold current for the top-emitter is higher than that of the bottom-emitter because (i) the top-emitting device aperture is larger (~26 μm diameter), and (ii) we have discovered that owing to wafer growth, the top-emitter has a mismatch between the gain peak and the Fabry-Perot wavelength. This mismatch can be easily remedied.

In conclusion, we have demonstrated a novel intracavity resonant quantum-well detector within a VCSEL. The embedded nature of the quantum well detector as well as its resonance at the Fabry-Perot wavelength result in low sensitivity to spontaneous emission and a very high effective responsivity for the first time.

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References


Type-II interband quantum cascade laser at 3.8 μm

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The authors have demonstrated the first stimulated emission from Sb-based type-II quantum cascade configuration. Laser emission at 3.8 μm has been observed for temperatures up to 170 K. The device was composed of 20 periods of active regions separated by digitally graded quantum-well injection regions.

Recently, there has been intensive research in mid-infrared (MIR) semiconductor diode lasers emitting from 3 to 5 μm for many military and commercial applications. MIR lasers utilising Sb-based materials are showing steady progress [1-4]. The recent demonstrations of a room-temperature quantum cascade (QC) laser at 5 μm [5] and a long wavelength IR (~11 μm) QC laser operating up to 200 K [6] indicate a great potential for the QC configuration. The QC lasers utilise photon emissions between subbands in a staircase of coupled type-I InGaAs/InAlAs quantum wells (QWs). However, the type-I intersubband QC lasers still have a relatively low radiative efficiency (<10⁻³) owing to a fast non-radiative phonon relaxation between subbands, which leads to a high threshold current density and substantial heating.

Fig. 1 Schematic diagram of n-type QC laser based on type-II QWs

The type-II QC laser, as originally proposed in [7], is based on interband transitions where the phonon relaxation is intrinsically suppressed due to the opposite curvatures of the conduction and valence band structures, and the Auger recombination could be significantly suppressed through bandgap engineering owing to the unique nature of type-II structures. Therefore, the type-II QC lasers are suitable for obtaining high output power [8-10]. Fig. 1 shows a schematic diagram of an n-type QC laser based on InAs/InGaSb/InAlSb type-II QWs. Under a forward bias, electrons are injected from an injection region into the level E₁, which is in the bandgap region of the adjacent InGaSb layer, reducing the leakage current. Since the electrons are effectively confined in the InAs well with the InGaSb, AlSb, and GaSb barrier layers, they tend to relax to the hole state E₂ in the adjacent valence band QW, and emit photons as indicated in Fig. 1. Electrons at state E₂ will then cross the thin AlSb barriers and GaSb well by tunnelling and scattering into the conduction band of the next injection region because of a strong spatial interband coupling, and are ready for being injected into the next active region. Since the relaxation time...