Single-angled-facet laser diode for widely tunable external cavity semiconductor lasers with high spectral purity

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External cavity semiconductor lasers are demonstrated using a single-angled-facet semiconductor laser diode that does not require anti-reflection coating. A wide tuning bandwidth (7%, λ = 980 nm), large side-mode suppression ratio (50 dB, λ = 1590 nm), narrow linewidth (50 kHz), and high output power (13.5 mW) are achieved with conventional external cavity configurations.

Introduction: External cavity semiconductor lasers (ECSLs) with grating feedback provide tunable, narrow-linewidth, single-frequency sources for visible and near-IR wavelength applications. ECSLs typically consist of an edge-emitting semiconductor laser with one facet anti-reflection (AR) coated to suppress Fabry-Perot resonances. The quality of this AR coating determines many critical ECSL operating properties. Recent analysis, for example, has shown that the AR coated facet reflectivity must be less than $R = 1.5 \times 10^{-4}$ to prevent axial-mode instability [1]. This represents a challenging manufacturing requirement which limits the performance of commercial ECSLs and adversely contributes to their cost and reliability.

Alternatively, low facet reflectivity ($R \simeq 10^{-5}$) can be achieved with an angled-facet structure [2]. Angling the facet prevents reflected light from coupling back into the waveguide mode, providing an inherently broadband reduction in facet reflectivity compared with AR coating. ECSLs based on angled-facet travelling wave amplifiers have been demonstrated, however the external cavity is more complex, requiring either precision coupling to two device facets rather than one [3] or a ring-laser configuration [4]. A more promising approach consists of using a curved waveguide device having only one angled facet, as has been demonstrated for broadband superluminescent diodes [5], modelocked external cavity lasers [6], and fibre grating semiconductor lasers [7]. We implement ECSLs based on a single-angled facet laser diode (SAF-LD) and demonstrate for the first time that wide tuning and high spectral purity can be achieved using the SAF-LD in conventional external cavity configurations.

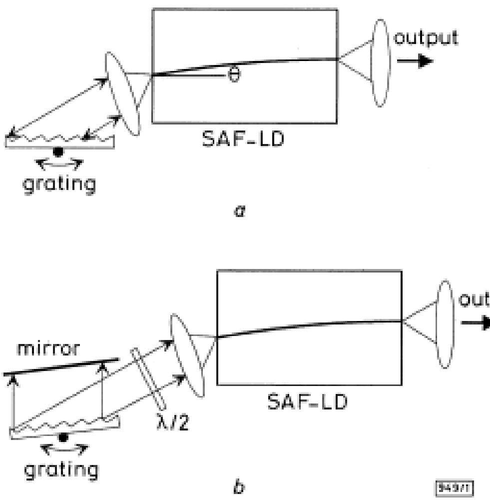

Fig. 1 *Schematic diagram of SAF-LD external cavity semiconductor laser*

a Littrow configuration
b Littman configuration

Device fabrication: The SAF-LD is comprised of a curved ridge waveguide that intersects the facet cleavage plane at normal incidence on one facet and at an angle on the other facet, as shown in Fig. 1*a*. The ridge waveguide traverses an arc along the 1 mm length of the device, with a constant radius of curvature of ~9.5 mm, intersecting the angled-facet at an angle θ relative to the facet normal.

Two SAF-LD devices were fabricated: (i) a single-quantum well (SQW) InGaAs/GaAs device and (ii) a four-quantum-well (MQW) InGaAsP/InP device. Both compressively strained separate confinement heterostructures were grown using molecular beam epitaxy (MBE) and in each case the individual quantum well thickness was 10 nm. A 5 μm wide singlemode ridge waveguide was defined by wet etching to an etch stop layer. Angled facets of θ = 7 and 6° were formed in the InGaAs and InGaAsP devices, respectively, owing to slightly different waveguide radii of curvature in the two devices. The SAF-LDs were mounted on copper heat sinks and operated CW. Measurement of the angled facet reflectivity obtained $R = 2 \times 10^{-5}$ which agrees well with values achieved previously [2].

Experimental setup: The InGaAs SAF-LD was mounted in a standard Littrow configuration external cavity as shown in Fig. 1*a*. The low-reflectivity angled facet was coupled to a diffraction grating (1800 lines/mm) and angled so that the first-order diffracted beam was retro-reflected back into the SAF-LD. The grating lines were oriented perpendicular to the TE polarised (junction plane) output light from the SAF-LD. Output power from the ECSL was taken from the SAF-LD normal facet which served as a moderate reflectivity ($R \simeq 30\%$) output coupler.

The InGaAsP SAF-LD was mounted in a Littman configuration external cavity as shown in Fig. 1*b*. The external cavity consisted of a diffraction grating (1100 lines/mm), angled such that the first-order diffracted beam was reflected by a mirror and re-diffracted back into the SAF-LD. The grating was oriented with the grooves parallel to the SAF-LD junction plane with a λ/2-plate included to maximise the grating reflectivity [8]. The lasing wavelength of both ECSL configurations was adjusted by rotating the diffraction grating.

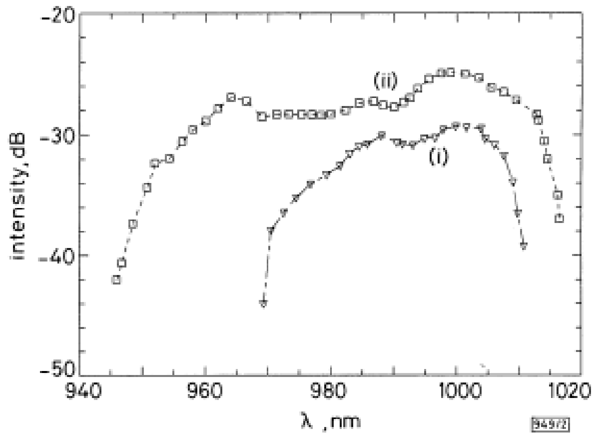

Fig. 2 *Tuning range of SAF-LD external cavity semiconductor laser*

(i) I = 90 mA
(ii) I = 190 mA

Experimental results: The threshold current for the InGaAs ECSL was ~35 mA at an emission wavelength of λ = 980 nm. This compares well with the threshold current for a comparable 1 mm long straight waveguide normal facet laser diode (I_{TH} = 25 mA). The tuning range of the InGaAs ECSL is shown in Fig. 2. At a low bias current (I = 90 mA), the tuning range was ~40 nm. Increasing the bias extends the tuning range as the gain spectrum broadens due to population of the second (n = 2) quantum-well state. A tuning range of 70 nm was achieved at a bias current of 190 mA corresponding to a 7% tuning bandwidth (λ = 980 nm).

The tuning range continued to increase with bias current and was ultimately limited by device damage rather than facet reflectivity. Under pulsed operation, the amplified spontaneous emission (ASE) spectrum of the solitary SAF-LD revealed no laser threshold, even at I = 850 mA, corresponding to a bias current 34 times larger than Ith of a straight waveguide laser diode. The broadband, low reflectivity of the angled facet enables operation at high pump current, which in turn promotes wideband ECSL operation.

The output power and spectral purity of the InGaAsP ECSL was measured. An output power of 13.5 mW (λ = 1590 nm) was obtained at I = 160 mA with a threshold current of 50 mA. The optical spectrum was measured using an optical spectrum analyser with a resolution of 0.1 nm. Owing to the low reflectivity of the angled facet, the side modes of the solitary SAF-LD were suppressed by 50dB at I = 100mA (Fig. 3). The laser linewidth was measured using the self-delayed homodyne method and was found to be < 50kHz.

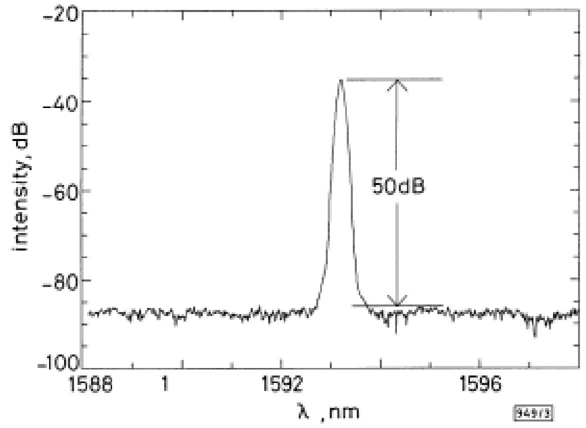

Fig. 3 *Output spectrum of SAF-LD external cavity semiconductor laser*

I = 100mA

A tuning range of 66 nm was measured at I = 110mA, corresponding to a 4% tuning bandwidth (λ = 1590nm). This tuning bandwidth was less than that obtained with the SQW InGaAs SAF-LD and is consistent with the narrower ASE spectrum observed for the MQW InGaAsP SAF-LD. A much larger tuning range is anticipated with proper optimisation of the MQW region [9].

Conclusion: We used SAF-LD devices in two conventional ECSL setups and demonstrated a 7% tuning bandwidth, 50dB side-mode suppression ratio, 50kHz linewidth, and 13.5mW output power. These results were obtained without any AR coating. In addition to not requiring AR coating, the angled facet provides a broader bandwidth low-reflectivity facet than an AR coating. Therefore, the SAF-LD has the potential to both improve the performance and lower the cost of widely tunable, high-spectral purity ECSL sources.

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