Extended cavity ridge waveguide lasers
operating at 1.5 μm using a simple damage induced quantum well intermixing process
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The authors report extended cavity ridge waveguide lasers in InGaAs/InGaAsP, intermixed by damage induced via a silica sputtering process, with selective intermixing achieved through photolithographic masking. Laser threshold currents indicate positive waveguide losses of 4.4 cm⁻¹.

Introduction: The requirement for future high data rate telecommunications systems has led to the development of several quantum well (QW) intermixing techniques for the fabrication of photonic integrated circuits in 1.55 μm laser material [1, 2]. We have recently reported a new approach which relies on the damage induced during sputtered silica (SiO₂) deposition on the surface of a semiconductor laser wafer [3]. After subsequent annealing, the diffusion of the generated point defects introduces significant bandgap blue-shifts in both the short wavelength GaAs/AlGaAs and GaInP/AlGaInP systems, and the material systems of InGaAs/InGaAsP and InGaAs/InAlGaAs which cover the low loss fibre optic communications windows. This enables monolithic integration of active and passive waveguides to form extended cavity lasers. Such a geometry allows the realisation of diode laser cavities of up to several mm in length, useful in mode-locked applications, without the corresponding high threshold current which normally seriously inhibits CW performance at room temperature [4].

Processing: Extended cavity ridge waveguide lasers were fabricated in standard five QW lattice-matched InGaAs/InGaAsP laser material grown by MOVPE. From the p+ Si-doped InP substrate up, the layer specifications were as follows: a 1 μm InP p-type lower cladding layer Si doped at 6×10²⁰ cm⁻³; an intrinsic 0.36 μm waveguide core; a 1.4 μm InP upper cladding layer p+doped with Zn at 7×10²⁰ cm⁻³ (first 200 nm left undoped); a 50 nm InGaAsP resistance reduction layer (λₚ = 1.18 μm), and finally a p+ InGaAs contact layer Zn-doped at 6×10²⁰ cm⁻³. The waveguide core contained five 65 Å InₓGa₁₋ₓAs QWs with six 120 Å InGaAsP (λₚ = 1.26 μm) barriers surrounded in both directions by a step graded index region of 50 nm InGaAsP (λₚ = 1.18 μm) and 80 nm InGaAsP (λₚ = 1.1 μm).

Fig. 1 PL wavelength shifts against RTA temperature (60s) after 200 nm deposition of sputtered silica with samples

- □ unmasked
- × capped with 200 nm of PECVD silica
- ○ capped with 200 nm of PECVD silica plus 1.8 μm photoreactive layer

The material was intermixed by deposition of 200 nm of silica directly on to the p-side of the sample via an RF sputtering process using a 9:1 Ar/O₂ gas mixture, an RF power of 100 W, and a DC self bias of 1000 V. When annealed, point defects produced during the sputtering process diffuse through the material and cause varying degrees of quantum well intermixing. This process was characterised by measuring the 77K photoluminescence (PL) spectra of samples after treatment in a rapid thermal annealer (RTA) for 60 seconds at temperatures ranging from 625 to 700 °C. Fig. 1a shows that PL shifts of > 140 nm are obtainable in this way. In fabrication of extended cavity lasers, selective suppression of the intermixing process in order to define both active and passive regions is of vital importance. As can be seen from Fig. 1b, significant PL shifts are still observed for samples capped with 200 nm of PECVD silica prior to the sputtering process. However, full suppression of the intermixing process is obtained when a further 1.8-μm photoreactive layer is deposited before sputtering, with the PL shifts shown in Fig. 1c corresponding to the shift of as-grown material when annealed at these temperatures.

For extended cavity lasers, the samples were initially covered in 200 nm of PECVD silica. The passive regions were then defined by HF etching using a photoreactive mask. With the photoreactive mask remaining to suppress the intermixing, 200 nm of silica was sputtered onto the samples. After resist removal, the sample was annealed for 60 s at 650 °C to produce a PL shift of 110 nm with the intermixing in the masked region completely suppressed. Photoreactive was then used to define the 5 μm wide ridge waveguides which were wet-etched to 200 nm above the waveguide core. Silica was deposited on the sample with the resist mask still in place. After deposition, the silica was lifted-off from the top of the ridge in acetonitrile leaving self-aligned current injection windows. Finally, after contact evaporation (p-side metal on suppressed areas only), the p+ contact layer was etched from the passive section to ensure electrical isolation.

Fig. 2 Light/current curves for active and extended cavity lasers

- - - - - - - - 500 μm AAL
- - - - - - - - 500 μm/150 μm ECL
- - - - - - - - 200 μm AAL

Results: Individual devices were cleaved to the following lengths: 500 μm all-active lasers (AAL), 2000 μm AALs and 500 μm active/1500 μm passive extended cavity lasers (ECL). Typical light/current curves for the devices are shown in Fig. 2. Pulsed current testing conditions were used to eliminate thermal effects. The threshold current Iₜₚ for the 500 μm device increased to Iₜₚ = 76 mA with the addition of passive section losses. This increase of ~50% in threshold current is extremely favourable when compared to the increase of ~200% to 150 mA for the 2000 μm AAL. Assuming the logarithmic gain current density relationship for QW material [5] and a coupling coefficient of 100% between active and passive sections, the following relationships can be derived between the threshold currents of active and extended devices and the extended cavity losses [6]:

\[ \frac{I_{ECL}}{I_{AAL}} = \exp \left( \frac{\alpha_{ECL}}{nL_{ECL}} \right) \]

where Lₚ = 500 μm, Lₚ = 1500 μm, αₑ is the absorption coefficient in the passive waveguide, nₑ is the modal overlap factor for the five QW active region, and g₀ is the gain saturation parameter. From eqn. 1, αₑ is calculated to be 4.4 cm⁻¹ which is consistent with the decrease in slope efficiency from 6.1% for the 500 μm AAL to 4% in the ECL.

In Fig. 3, the lasing spectrum of a 2000 μm ECL is shown. Devices fabricated from the as-grown material operate close to 1.55 μm in wavelength, hence there is an apparent shift in the lasing wavelength to ~1.53 μm. The spectrum underwent a red shift.
to 1.545 μm when the passive section was cleaved off and the remaining 500 μm AAL was tested, thus confirming that the intermixing is effectively suppressed in the active layer region, and suggesting that the passive cavity induces the laser to operate at a slightly shorter wavelength.

![Lasing spectra of 500 μm active/150 μm passive extended cavity laser device and of device with extended cavity cleaved off](image)

**Conclusion:** We have reported the operation of extended cavity ridge waveguide lasers around 1.55 μm fabricated using an extremely simple and widely applicable sputtered silica intermixing technique. Total suppression of the intermixing can be achieved through the use of photoresist masking, which results in the ability to use standard UV photolithography along with this technique to define sophisticated integrated device geometries easily.

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References


**Green, holmium-doped upconversion fibre laser pumped by red semiconductor laser**

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Pumping of a green (λ ≈ 549 nm) Ho-doped fluorozirconate glass fibre laser with a high power (~30 mW) singlemode red diode laser is demonstrated. CW output powers exceeding 1.2 mW have been generated from a 22 cm long Ho:ZBLAN fibre for ~24 mW of incident pump power (10.5 mW launched) at 643 nm and a cavity output coupling of 24%. The threshold pump power, 3.5 mW launched (2.1 mW absorbed), is the lowest reported for any upconversion fibre laser. The maximum slope and optical conversion efficiencies measured to date are 18.5 and 12%, respectively, with respect to launched pump power. These results represent the first demonstration of a fibre laser driven by a red semiconductor diode laser.

**Introduction:** The CW power commercially available from red semiconductor diode lasers (630–650 nm) has risen steadily over the past several years and is now sufficient to drive low threshold visible and infrared oscillators. Both solid state (Cr-doped alexandrite and LiSAF) [1, 2] and dye [3] lasers pumped by 670–690 nm semiconductor lasers have been reported by Scheps and co-workers [1–3]. Pump power thresholds for the diode-pumped Cr:BeAl2O4 and DCM (dye) lasers, for example, are 12 and 6.6 mW, respectively [1, 3]. This Letter reports the demonstration of a visible upconversion fibre laser pumped by a red (λ < 650 nm) semiconductor diode laser. Specifically, the Ho-doped fluorozirconate glass (ZBLAN) fibre laser (544 ± λ ≈ 549 nm) has been pumped by a high power (~30 mW) diode laser operating at 643 nm in a single spatial mode. More than 1 mW of output power at 544 nm has been obtained for 24 mW of incident power (6 mW of absorbed power) and 24% cavity output coupling. To our knowledge, this is the first report of any fibre laser pumped by a red diode laser. Also, the threshold pump power reported here is the lowest for an upconversion fibre laser by more than a factor of 3. In 1993, Pfiehler et al. [4] reported two colour pumping of a co-doped Pr:Yb:ZBLAN fibre with diodes, and obtained lasing in both the red and green regions. Since then, diode-pumped upconversion fibre lasers have been demonstrated for Er and Tm in the green and blue regions, respectively, and further work with Pr:Yb co-doped fibres has yielded single pump wavelength operation on red, green, and blue transitions of Pr3+ [5–9]. Two distinct advantages of upconversion fibre lasers over other approaches to generating coherent visible radiation from diode lasers operating at longer wavelengths are the relative insensitivity of the gain medium to the pump wavelength (pump acceptance bandwidths of 5 nm are typical) and the absence of phase matching.

**Experiment:** The fibre for these experiments is 22 cm in length and its core has a diameter, numerical aperture NA, and Ho doping concentration of 1.7 μm, 0.39, and 1000 ppm by weight, respectively. After polishing, the fibre ends were butt-coupled to thin flat mirrors. The mirror through which the pump radiation was coupled into the resonator has 74% transimission at the pump wavelength and > 99.9% reflectivity at 549 nm. Two output couplers have been tested to date. Most of the data presented here were obtained with a mirror having 24% transmission at 549 nm and a reflectivity of 68% at 643 nm. An attractive aspect of the Ho:ZBLAN fibre laser pumped in the red is that the pump and laser wavelengths are sufficiently close so that a single-stack, dielectric coating may be engineered to have optimal reflectivities at both pump and laser wavelengths. This allows multiple-pass pumping of the fibre which results in reduced threshold pump powers. The InGaAsP pump diode, fabricated by SDL, Inc., produces ~30 mW for a drive current of 80 mA and operates at 643 nm. Although all experiments reported here were conducted at room temperature, the diode itself was mounted on a thermo-electric cooler and maintained at a temperature of 17°C. The pump beam was launched into the fibre by a 20× microscope (0.4 NA) with a measured efficiency of 43%. Radiation emerging from the output coupler was collimated by a second 20× microscope objective having an NA of 0.35. Power measurements were made with a calibrated, pin silicon