current density after irradiation is, however, quite different: the value for the QW laser worsens by about twice as much as for the QD laser, 950A/cm^2 and 550A/cm^2, respectively. From these results we conclude that in the regime of spontaneous emission incorporated defects introduced by the proton irradiation result in non-radiative relaxation channels. These defects in or in the vicinity of the active region are much more critical in the QW case owing to the higher in-plane diffusion of the carriers, contrasted to QDs. The localised carriers in the QDs have a reduced interaction with the defects. Once the devices lase, the differential quantum efficiency is reduced owing to leakage currents in the barrier that are similar for QWs and QDs. The fast stimulated emission in the active media bypasses non-radiative recombination of localised carriers, resulting in similar differential quantum efficiencies for QWs and QDs.

From the external differential quantum efficiency for both cavity lengths of the QW device, the internal quantum efficiency and the internal optical losses before and after irradiation can be estimated. Before irradiation an internal quantum efficiency η_{int} of 95% and an internal optical loss of 2.9cm^{-1} are found to be in agreement with results obtained from a larger set of samples (η_{int} = 84% with a 10% error, α_{int} = 5cm^{-1}). After irradiation, 56% and 3.3cm^{-1} are found, respectively. Since the internal optical loss has a similar value before and after irradiation, we attribute the reduction in external differential quantum efficiency after irradiation to the reduced internal quantum efficiency.

Conclusion: We have presented the effect of high energy proton irradiation on the device characteristics of QW and QD lasers. QW and QD lasers with identical structures except for the active region allow a direct comparison of the radiation hardness. In the spontaneous emission regime QD lasers demonstrate an enhanced radiation hardness in contrast to the QW device owing to reduced interaction of localised carriers with defects in the vicinity of the active region, leading to a comparable lower threshold. However, in the regime of lasing, both devices show similar degradation owing to barrier leakage currents leading to reduced internal efficiency. These findings indicate that the QD approach is promising for lasers with increased lifetime, operating in a radiation environment or with an active zone in defect-rich materials.

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High-speed response of optically-pumped InGaAs/InGaAsP microdisk lasers

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Transient step-response and small-signal response of intensity-modulated InGaAs/InGaAsP microdisk lasers have been measured for the first time at room temperature. Microdisk lasers operating at room temperature have a measured turn-on delay of 100ps and a –3dB small-signal bandwidth in excess of 1.4GHz.

Microdisk lasers are of interest for use in small photonic integrated circuits. A prerequisite for these applications is a demonstration of high-speed response in such devices. In this Letter we report results of measuring at room temperature the step-response and small-signal response of InGaAs/InGaAsP microdisk lasers.

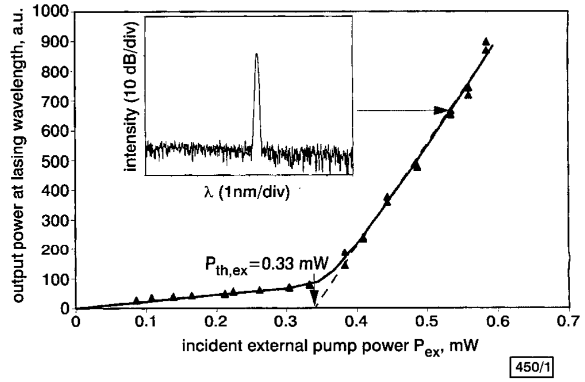

Fig. 1 *Measured optical power at lasing wavelength P_{out} at room temperature, T = 300K, against continuous incident pump power at λ_{pump} = 980nm, P_{ex} for radius R = 2.0μm microdisk*

A clear change in slope at threshold pump power $P_{th,ex}$ = 0.33mW is seen
Inset: Measured room temperature luminescence spectra at P_{ex} = 1.69 × $P_{th,ex}$ = 0.56mW and lasing at wavelength λ_0 = 1554nm. Linewidth of lasing resonance is limited by the 0.1nm resolution of the spectrometer. Wavelength span is from λ = 1550nm to λ = 1558nm

Light from a pump laser operating at an emission wavelength λ_{pump} = 980nm is used to inject carriers into microdisk lasers which are fabricated using methods similar to those described previously [1]. Optical emission from the multiple quantum well active region of a microdisk laser is collected perpendicular to the plane of the disk and substrate. The collected lasing intensity near wavelength λ = 1554nm is amplified using an erbium-doped fibre amplifier (EDFA). To improve signal-to-noise ratio, spontaneous emission from the EDFA is suppressed using a filter with a free spectral range FSR = 56nm and a –3dB bandwidth of 10GHz (0.08nm). Step-response is measured by directly modulating the pump laser optical output between a low value, P_{low}, and a high value, P_{high} = P_{low} + P_{mod} with a pulse period of 500ns and a pulsewidth of 10ns.

Fig. 1 shows the measured continuous optical power output at the lasing wavelength P_{out} against external incident optical pump power P_{ex} for a microdisk laser of radius R = 2.0μm. Laser threshold occurs at $P_{th,ex}$ = 0.33mW. The inset to Fig. 1 shows a strong lasing resonance above threshold (P_{ex} = 1.69 × $P_{th,ex}$ = 0.56mW) at λ_0 = 1554nm.

Fig. 2*a* shows the measured optical pump step-input at wavelength λ_{pump} = 980nm. The measured transient step-response of a typical R = 2.0µm and $P_{th,ex}$ = 0.33mW microdisk laser when the pump power is modulated between a low value, P_{low}, and a high value, $P_{high} = P_{low} + P_{mod}$ is shown in Fig. 2*b*. The rise time shown in Fig. 2*a* is limited by the 1.67GHz bandwidth of the detection scheme used.

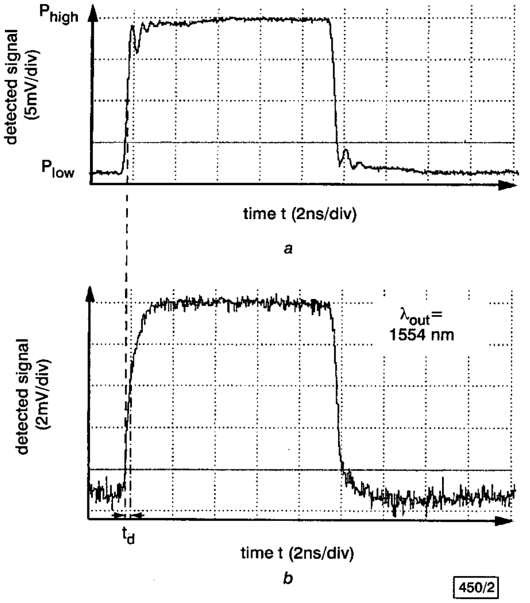

Fig. 2 *Pump power, transient-response and turn-on delay*

a Pump power, which excites carriers in microdisk, against time
Pump power at wavelength λ_{pump} = 980nm is switched from low value, P_{low}, and high value, $P_{high} = P_{low} + P_{mod}$ (always $P_{high} > P_{th,ex}$)
b Measured transient response of microdisk laser's optical output at T = 300K for step-change in incident pump power

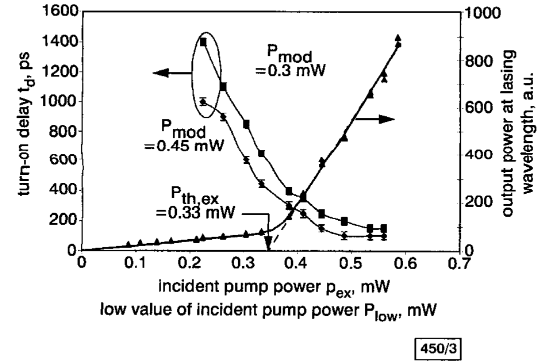

Fig. 3 *Measured turn-on delay t_d against P_{low} for R = 2.0µm and indicated values P_{mod}*

Measured P_{out} against P_{ex} characteristic is also shown, indicating a threshold pump power of $P_{th,ex}$ = 0.33mW. Turn-on delay is larger for on-off modulation ($P_{low} < P_{th,ex}$) than for on-on modulation ($P_{low} > P_{th,ex}$) and shows negligible dependence on P_{low} for on-on modulation

Turn-on delay, t_d, is the time delay between the rising edge of the pump pulse and the rising edge of the microdisk optical output power at the lasing wavelength and is indicated in Fig. 2*b*. Fig. 3 shows measured t_d against P_{low} for the indicated values of P_{mod} for an R = 2.0µm device. The measured optical power in the lasing line P_{out} against the incident pump power P_{ex} is also shown in Fig. 2*b*. For above-threshold 'on-on' modulation ($P_{low} > P_{th,ex}$), t_d = 100ps and shows a negligibly small dependence on P_{mod} and P_{low}. This is similar to a conventional edge-emitter or a vertical cavity surface-emitting laser (VCSEL) where the stimulated emission rate determines the turn-on delay for above-threshold modulation. For below-threshold 'on-off' modulation ($P_{low} < P_{th,ex}$), t_d decreases monotonically with an increase in P_{low} and shows a strong dependence on P_{mod}. For a given P_{low}, t_d is larger for a smaller P_{mod}. Similar to a conventional edge-emitting laser or a VCSEL [2], the turn-on delay for the R = 2.0µm device is dominated by stimulated emission lifetime for on-on modulation and by carrier lifetime for on-off modulation.

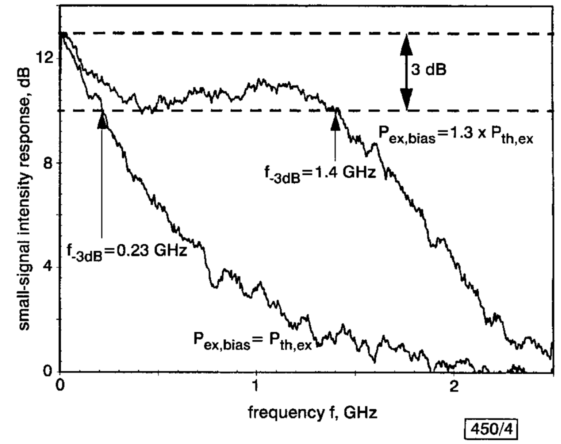

Fig. 4 *Small-signal intensity response for typical R = 2.0µm microdisk for indicated values of incident pump power bias, $P_{ex,bias}$, and modulation power of P_{mod} = 0.02mW*

When microdisk laser is biased at threshold, $P_{ex,bias} = P_{th,ex}$, small-signal response is limited by carrier lifetime and shows an LED-like behaviour. Measured –3dB bandwidth is 0.23GHz. However, when device is biased at $P_{ex,bias} = 1.3 \times P_{th,ex}$, –3dB bandwidth increases to 1.4GHz and a relaxation oscillation peak (although severely damped) is seen at 1.1GHz. This behaviour is similar to that of a conventional singlemode laser

Fig. 4 shows the measured small-signal intensity response of a typical R = 2µm microdisk laser at the indicated bias pump powers, $P_{ex,bias}$. An incident optical modulation power of P_{mod} = 0.02mW is used. In this case, the measured small-signal intensity response of the pump laser is limited by a 2.25GHz detector bandwidth. At an incident pump power $P_{ex,bias} = P_{th,ex}$ the carrier lifetime dominates the small-signal intensity response and leads to an LED-like behaviour with a measured –3dB bandwidth of 230MHz. However, at an incident pump power $P_{ex,bias} = 1.3 \times P_{th,ex}$, the measured –3dB bandwidth is 1.4GHz and the small-signal intensity response behaves similarly to a conventional singlemode laser with a damped relaxation oscillation peak at 1.1GHz. Since the relaxation oscillation peak is strongly damped, we do not observe ringing in the transient step-response. Other devices with –3dB bandwidths of 1.8GHz have been measured.

In summary, microdisk lasers operating at room temperature have a measured small-signal –3dB frequency in excess of 1.4GHz and large signal turn-on delay of less than 100ps.

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