inserted between them to suppress spontaneous emission light [5, 6]. A stable tilt splice of 25° with a loss of less than 0.2dB was attained between the PDF and the high-NA silica fibre by using the V-groove connection technique. Reflectivity of less than –60dB was achieved using the tilted V-groove connection. The signal source was a DFB laser operating at 1302nm and its output power was 6.5dBm. 40ch carriers ranging from 91.25 to 403.25MHz directly modulated the DFB laser with a modulation depth of 5.6%/ch. The DFB laser output was amplified by the PDFA and attenuated with a variable optical attenuator. CNR and distortion characteristics were measured for three carrier frequencies, 91.25, 211.25, and 403.25 MHz.

Fig. 3 shows the CNR at 403.25MHz as a function of loss budget with and without a PDFA.The CNR was the same in the measured three channels. The loss budget improvement for 52dB CNR was 10dB. The NF was 9.8dB as estimated from the CNR degradation. We believe that the NF improvement from previous reports is due to selecting low loss PDF and that further NF improvement can be expected by suppressing PDF scattering.

Table 1: Distortion characteristics and measured carrier frequency

	Without PDFA	With PDFA
CSO	66.5dB (403.25MHz)	67dB (403.25MHz)
CTB	67.7dB (211.25MHz)	65.5dB (211.25MHz)
XM	63.2dB (403.25MHz)	64.1dB (403.25MHz)

The worst measured distortion values are summarised in Table 1. Distortion values almost met the CATV trunk line specification.The picture quality was also evaluated. Degradation in picture quality before and after PDFA amplification was imperceptible in subjective tests.

Summary: PDFA performance in multichannel AM-VSB video signal transmission has been examined. The loss budget was improved by 10dB for 52dB CNR and distortion characteristics almost met the CATV trunk line specifications. The picture quality degradation due to PDFA use was confirmed to be 'imperceptible'. The improved PDFA configuration presented in this Letter offers great potential for practical use in 1.3µm transmission systems. The proposed PDFA will be used in various practical optical systems after confirming its long-term reliability.

Acknowledgment: The authors thank E. Yoneda for fruitful discussions and Y. Terunuma, Y. Ohishi, and S. Sudo for their help in fibre preparation.

16 September 1994
Electronics Letters Online No: 19941389

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Low threshold voltage vertical-cavity lasers fabricated by selective oxidation

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Indexing terms: Vertical cavity surface emitting lasers, Oxidation

Novel vertical-cavity surface emitting lasers fabricated using selective oxidation to form a current aperture under a top monolithic distributed Bragg reflector mirror are reported. Large cross-sectional area lasers (259µm²) exhibit threshold current densities of 150A/cm² per quantum well and record low threshold voltage of 1.33V. Smaller lasers (36µm²) possess threshold currents of 900µA with maximum output powers greater than 1mW. The record performance of these oxidised vertical-cavity lasers arises from the low mirror series resistance and very efficient current injection into the active region.

Vertical-cavity surface emitting lasers (VCSELs) have received attention over the past few years, due in part to their potentially low power consumption and low threshold current. The 'conventional' gain-guided VCSEL relies on high energy proton implantation to compensate the material around the laser cavity to funnel current into the active region [1]. This scheme requires that the implanted region must be sufficiently far away from the active region to avoid damage, and thus results in undesirable current spreading. In addition the VCSEL diameter using implantation is limited to ≥ 5µm, due to lateral ion straggle during implantation. We report VCSELs fabricated using selective oxidation of a buried AlGaAs layer immediately adjacent to the quantum well active region to define the lateral extent of the laser cavity. This oxidised VCSEL structure minimises current spreading, eliminates implantation damage, and should enable fabrication of ultrasmall VCSELs. Our present lasers have aperture areas as small as 36µm² exhibiting 900µA threshold currents, while larger devices have threshold current densities of 150A/cm² per quantum well and 1.33V threshold voltage, the latter value being the lowest reported to date.

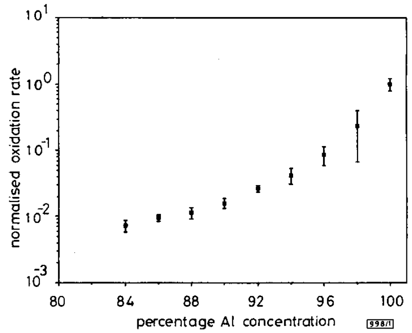

Fig. 1 *Average oxidation rate of AlGaAs at 425°C, normalised to average AlAs oxidation rate*

Oxidation of AlGaAs has previously been used to fabricate edge emitting lasers [2] and VCSELS [3, 4]. For the latter, oxidised AlAs has been used as a current aperture under a top hybrid dielectric distributed Bragg reflector (DBR) [3], and to make high reflectivity broad bandwidth DBRs [4, 5]. In the present work we exploit the high oxidation selectivity of AlGaAs to fashion a buried oxide current aperture within an all-semiconductor monolithic VCSEL structure. In Fig. 1 we show the nonlinear lateral oxidation rate of 50nm thick $Al_xGa_{1-x}As$ layers sandwiched between GaAs layers. Note that there is greater than two orders of magnitude variation in the oxidation rate for $1.0 \le x \le 0.84$, providing a high degree of oxidation selectivity. We have designed the top DBR mirror such that the low index layer of the first period adjacent to the active region has a higher Al concentration and thus lateral oxidation rate than the remaining periods. Hence, in comparison with a conventional gain-guided VCSEL, a current aperture in an oxide layer approximately 100nm from the quantum wells defines the lateral extent of the laser cavity, rather than an implanted region.

Our MOVPE grown wafer has a 25 (38) period top (bottom) DBR mirror employing uniparabolic grading and carbon doping [6], with three InGaAs quantum wells in the active region. We chose $Al_{0.98}Ga_{0.02}As$ for the oxidised current aperture layer, and $Al_{0.9}Ga_{0.1}As$ as the composition of the low index layers used in the remainder of the top DBR stack, resulting in a 15:1 oxidation rate ratio. Square mesas 105µm on a side are fashioned by reactive ion etching using an SiN_x mask. The etch depth is >5µm to expose the $Al_{0.98}Ga_{0.02}As$ oxidation layer at the mesa sidewall. Immediately after etching, the sample is oxidised at 425°C under nitrogen gas bubbled through water at 85°C for 3–6h to produce the current apertures which vary from 60 to 5µm on a side. We find that the oxidation process is isotropic, and thus the apertures have roughly the geometry of the etched mesas. After oxidation and striping the SiN_x mask, Ti/Au and AuGe/Ni/Au contacts are deposited and annealed.

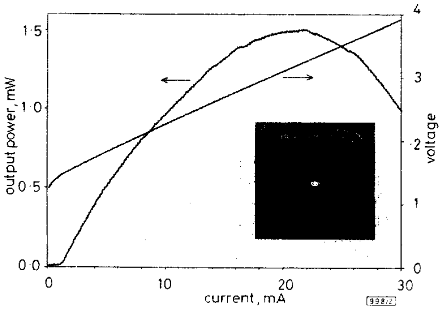

Fig. 2 *Light output and voltage against current for small oxidised VCSEL*

I_{th} = 900µA, V_{th} = 1.42V

Inset: 4.5 × 8µm² lasing aperture within electrode aperture

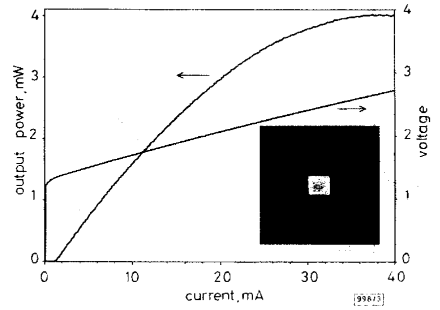

Fig. 3 *Light output and voltage against current for large oxidized VCSEL*

I_{th} = 1.16mA, V_{th} = 1.33V

Inset : 14.4 × 18µm² lasing aperture within electrode aperture

In Figs. 2 and 3 we show light output and voltage against current for two oxidisedVCSELs; the insets are top views of these devices, showing lasing within the current apertures inside of the metal contact openings. The smallVCSEL (area = 36µm²) in Fig. 2 has a threshold current of 900µA, a threshold voltage of 1.42V, and emits at 986nm. The maximum power is 1.5mW, significantly higher than previously reported oxidised hybridVCSELs [3]. The largerVCSEL (area = 259µm²) in Fig. 3 has a threshold current of 1.16mA, a threshold voltage of 1.33V, and emits at 969nm. The threshold current density corresponds to 448A/cm [2]. Notice that the record low threshold voltage of this device is only 50mV greater than the photon energy. This low threshold voltage arises due to the low DBR series resistance [6] both laterally and vertically, as well as very efficient current injection into the active region as manifested by the low current density.

For all oxidisedVCSELs tested, the operating characteristics were constant, showing no 'burn-in' effects during testing. In addition, the size of the metal contact opening had no effect on the threshold current, voltage or maximum power, unless the contact opening was smaller than the oxidised current aperture, thus obscuring the output. The record low threshold voltage and low current densities achieved in these devices establishes the effectiveness of this selective AlGaAs oxidation fabrication approach and demonstrates the viability of our design for realising high performance ultrasmall VCSELs.

Acknowledgment: This work is supported by the US Department of Energy under contract No. DE-AC04-94AL85000.

18 October 1994
Electronics Letters Online No: 19941421

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Packaged 1.55µm DFB laser with 25GHz modulation bandwidth

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Indexing terms: Distributed feedback lasers, Semiconductor quantum wells

25GHz modulation bandwidth is achieved from a fully packaged 1.55µm DFB laser, using devices with *p*-doped compressively strained MQW active regions and large negative wavelength detuning. Devices on submounts show a record bandwidth of 26 GHz, limited by device and bonding parasitics. Resonance frequencies of over 26GHz are measured.

Introduction: High bandwidth singlemode semiconductor lasers operating in the low loss and low dispersion regions of optical fibres are required for high capacity digital and analogue transmission systems. Applications also include narrow bandwidth mixed format signal transmission on microwave carriers such as for satellite remoting. Operation at 1.55µm allows the use of erbium fibre amplifiers to boost signal level. Previous unpackaged high bandwidth lasers have achieved modulation bandwidths of 25GHz for Fabry-Perot devices [1], and 22.5GHz for 1.55µm DFB lasers [2, 3]. The use of external cavity [4] and monolithic devices [5] has been reported for providing narrow bandwidth microwave chan-