turbid spectra above and below threshold, and showed that a mode suppression of 7dB is possible, even below threshold due to the modulation of the roundtrip gain. This is a major mechanism for the enhanced mode seen below threshold, and may be augmented by enhanced spontaneous emission coupling into some modes.

Conclusion: In this Letter we have shown that:

(a) Focused ion beam etching is a successful technique for mode sculpturing without leading to large rises in threshold current.

(b) Mode sculpturing is a method by which quasi-singlenode lasers can be engineered.

(c) Etch pits give rise to optical losses, through scattering and reflection, and introduce recombinant sites.

(d) Annealing partially recovers threshold current.

(e) Etch pits give rise to reflections which modulate the roundtrip gain causing one mode to have a gain closer to unity even below threshold.

Numerical modelling [6] shows that it is possible, using mode sculpturing on short cavity lasers, to produce quasi-singlenode lasers with negligible rises in threshold current.

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References

Suppression of polarisation hole burning in an EDFA using an unpolarised source

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Suppression of polarisation hole burning in the erbium-doped fibre amplifier (EDFA) is demonstrated by converting a polarised signal into an unpolarised signal using a Michelson interferometer which consists of a polarisation beam splitter and two Faraday rotator mirrors.

Introduction: In a long-haul transmission system where many erbium-doped fibre amplifiers (EDFAs) are included, the degradation of the Q-factor due to polarisation-dependent gain (PDGs) in the EDFA is a serious problem [1]. The PDGs result from polarisation-selective pumping and polarisation hole burning (PHB) which occur when a linearly polarised strong signal is amplified [2]. PDGs due to polarisation-selective pumping are not important since pump polarisations are not correlated between EDFAs. However, PDGs due to the PHB increase the average noise figure of the EDFA [3], which directly impairs the system performance. Scrambling the signal polarisation state faster than the response time of the PHB (~0.2ms) has been shown to eliminate the PHB. Several active polarisation scrambling methods have been proposed and demonstrated [1, 4, 5]. In this case, amplitude modulation in the received signal can be induced by combination of polarisation scrambling and polarisation-dependent loss of the optical link, which leads to fluctuations in the Q-factors [6, 7]. In this Letter we demonstrate a simple passive PHB suppression method by converting a polarised signal to an unpolarised signal using a Michelson interferometer which consists of a polarisation beam splitter and two Faraday rotator mirrors. Using this method, amplitude modulation due to polarisation modulation may be eliminated.

Unpolarised source generation: Generation of an unpolarised source is accomplished by using the setup shown in Fig. 1. A polarisation beam splitter (PBS) separates the input signal from the laser diode into two orthogonal components that propagate into arms 2 and 3, respectively. Powers in each arm are adjusted to be equal using the polarisation controller (PC). The extinction ratio of the PBS used in the experiment is ~15dB. Signals in each arm are reflected by Faraday rotator mirrors with change of their polarisation states orthogonally. Reflected beams are combined at the PBS again and propagate into path 4 regardless of birefringence in the fibre at 2 and 3. Ideally, the insertion loss of this interferometer is zero, different from conventional Michelson interferometers. The optical path length difference between arms 2 and 3 is 20m, which is far longer than the coherence length (4m) of the signal source. The output signal is the sum of orthogonally polarised coherent lights, i.e. an unpolarised light. Power fluctuations and the degree of polarisation of the generated unpolarised source are nearly zero. Thus the transmitted power through some devices is nearly constant, regardless of the magnitude or the direction of the polarisation-dependent loss.

Experimental results and discussion: To demonstrate that the unpolarised source can compress the PHB, we compare the amount of PHB induced by the polarised signal and the unpolarised signal. The experimental setup is shown in Fig. 2. The saturating signal and probe signal are combined through the 90/10 directional coupler. Both the saturating and the probe signal wavelengths are 1548nm. The power of the probe signal is kept at ~40mW during the measurement. The probe signal is chopped with a frequency of 500Hz using an acousto-optic modulator. At the input port of the EDA, the polarisation angle between the saturating signal and the probe signal is 45°. After the amplification of these signals, the
probes is divided by the polarization beam splitter (PBS). One is polarized along the pump polarization direction and the other is orthogonal to it. The differences between the PBS outputs are measured using photodetectors and the lock-in amplifier. Without the saturating signal, the offset of the lock-in amplifier is initially adjusted so that the effect of the PDG due to polarization-selective pumping and the polarization-dependent loss is eliminated in the output of the lock-in amplifier. Fig. 3 shows the measured gain and PDG against saturating signal power. When the saturating signal is linearly polarized, well-known polarization-dependent gain behaviour is observed. The amount of PDG is maximum when the saturating signal power is 10dBm. For a gain compression larger than 10dB, the amount of PDG is decreased because the gain is decreased seriously, as commented on in [6]. When the saturating signal is replaced by the unpolarized source, PDG is reduced considerably. PDG in the entire gain region of the EDFA is compressed to be nearly equal to PDG in the small-signal gain region. The transmission of information can be accomplished by inserting a polarization-independent external modulator after the unpolarized source generator.

Conclusion: In conclusion, we have demonstrated a new method to suppress the polarization-dependent gain due to polarization hole burning in EDFA by converting a polarized signal into an unpolarized signal using a Michelson interferometer, which consists of a polarization beam splitter and two Faraday rotator mirrors. The suppressed PDG is very close to the PDG of the EDFA operating in the linear region.

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References

Tapered InGaAs/GaAs MQW lasers with carbon modulation-doping and reduced filamentation

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Indexing terms: Semiconductor doping, Modulation doping, Semiconductor junction lasers

Highly localised carbon doping is demonstrated within the active region of strained InGaAs/GaAs MQW lasers. As predicted by numerical beam propagation simulations, the smaller linewidth enhancement factor arising from the combination of strain and p-doping leads to reduced filamentation in tapered laser structures, as compared to devices fabricated from otherwise identical epilayer structures containing undoped active regions.

Reduction of the linewidth enhancement factor α in semiconductor laser structures is of great interest for both high-speed and high-power applications. We have shown experimentally that the combination of strain and p-doping in the active region leads simultaneously to enhanced modulation bandwidths [1, 2] and a substantial reduction of α [3, 4] in GaAs-based MQW Fabry-Perot lasers. Furthermore, we have recently shown theoretically that similar low α-factor epilayer designs should lead to reduced filamentation in tapered waveguide amplifiers, and thus allow good beam quality to be maintained up to substantially higher output powers [5].

The stability of the p-dopant in the active region, both during epitaxial growth and during device operation, is an important issue for the practical application of the above device concepts. In previous investigations of high-speed devices fabricated using localised Be-doping in the active region, we have observed that Be diffusion during molecular-beam epitaxial (MBE) growth leads to QW doping at the expense of high p-type background concentrations throughout the entire core region [6]. Additional unintentional core doping also arises due to Be diffusion from the p-type cladding layer during epitaxial growth [7]. Laser-operation-induced migration of Be due to recombination-enhanced diffusion at the mirrors of GaAs/AlGaAs QW lasers has also recently been identified as a source of minor heating and device failure [8]. In this Letter we demonstrate the ability to achieve highly localised p-type doping within the active region of MBE-grown strained InGaAs/GaAs MQW lasers by replacing Be with carbon. Reduced filamentation is demonstrated for the first time in tapered laser structures with such p-doped active regions, as compared to devices fabricated from otherwise identical epilayer structures containing undoped active regions.