The EDFA input power was increased while the EDFA output power did not significantly increase; this was to prevent fibre nonlinearity from being detrimentally enhanced. The large signal output power level made the EDFAs saturate. Fig. 4 shows the measured optical spectrum and electrical SNRs after 5678 km transmission. These measured electrical SNRs were larger than 16.8 dB, this corresponds to bit error rates better than $3 \times 10^{-4}$, which could be reduced to below $10^{-10}$ by forward error correction with a Reed-Solomon code [255,239].

**Fig. 4** Optical spectrum and electrical SNR (ESNR) after 5678 km transmission

**Conclusion:** We have shown that Raman amplification in combination with conventional EDFAs improves both optical and electrical SNRs for long distance 20 Gbit/s signal transmission. It is also noted that the existence of fourth-order dispersion becomes significant in a transmission line with low third-order dispersion, and managing it properly yields a wide available optical bandwidth. We used these results to achieve Raman-assisted 48x20 Gbit/s WDM transmission over 5678 km.

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References


**Upstream traffic transmitter using injection-locked Fabry-Perot laser diode as modulator for WDM access networks**

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An upstream traffic transmitter based on a Fabry-Perot laser diode (FP-LD) as modulator is proposed and demonstrated for wavelength division multiplexed (WDM) access networks. By injection-locking the FP-LD with the downstream wavelength at the optical network unit (ONU), the original downstream data can be largely suppressed while the upstream data can be transmitted on the same injection-locked wavelength by simultaneously directly-modulating the FP-LD.

**Introduction:** The application of wavelength division multiplexing (WDM) in local access networks [1] is a promising approach to meeting increasing bandwidth demand from enterprises and households. For better wavelength management, network architectures with centralised light source at the central office (CO) and data remodulation of the downstream signal for the upstream traffic at the optical network unit (ONU) were proposed. The blank time slots from the downstream signal were modulated with upstream data at the ONU via either an optical modulator [2] or a semiconductor optical amplifier [3], thus eliminating any wavelength-registered source at the ONU. In [4], an amplified spontaneous-emission (ASE) injected Fabry-Perot laser diode (FP-LD) was proposed as a WDM source at the remote ONU to transmit the upstream data traffic. However, it required completely unmodulated ASE wavelengths from the central office and thus could not support downstream traffic with the same set of wavelengths.

In this Letter, we propose and demonstrate a novel upstream traffic transmitter, based on injection-locking of an FP-LD with the downstream wavelength carrying high-speed downstream data. The proposed transmitter requires only an FP-LD at the ONU and thus is potentially low-cost. Experimental results showed that, under suitable operation conditions, the injection-locking of the FP-LD largely suppressed the original 10 Gbit/s downstream data stream, allowing reuse of optical power and simultaneous direct modulation of 1 Gbit/s upstream data. The injection-locked FP-LD offered singlemode operation and thus greatly reduced the fibre-dispersion-induced penalty. We have demonstrated that the upstream signal could be transmitted over a 20 km fibre spool with error-free operation.

**Upstream traffic transmitter with remodulation:** Fig. 1 shows the architecture of a typical WDM local access network. A wavelength grating router (WGR) is employed to route different wavelength channels to different ONUs. Our proposed upstream traffic transmitter employs an FP-LD at the ONU (see inset of Fig. 1). At the ONU the downstream wavelength channel is partially tapped off for down-
stream data reception while the rest of the wavelength power is injected into the FP-LD for injection-locking. The injected-locked FP-LD exhibits a greatly improved sidemode suppression ratio (SMRR), which is necessary in a dense WDM environment. The improved SMRR also increases the tolerance to fibre chromatic dispersion and thus enhances the network transmission span. Under the condition that the power levels of both one and zero bits in the injected downstream signal are above a certain power threshold, the injection-locked FP-LD will emit the same wavelength as the downstream signal with the original data content largely suppressed, as shown in Fig. 2a. Thus, by directly-modulating the injected-locked FP-LD with the upstream data simultaneously (Fig. 2b) a potentially low-cost upstream data transmitter with improved signal quality can be realised.

Experimental demonstration: Fig. 3 shows the experimental setup to demonstrate our proposed upstream traffic transmitter, to perform data remodulation, for simplicity, on one particular downstream wavelength channel. At the central office, a DFB laser at 1546.2 nm was externally modulated with a 10 Gbit/s NRZ, $2^{21} - 1$ pseudorandom bit stream (PRBS) data to form the downstream signal, which was then transmitted over a fibre span of 50 km to the ONU. The extinction ratio of the downstream signal was adjusted to −29 dB so that the power of ones and zeros was well above the locking threshold (measured to be −15.2 dBm) before the FP-LD at the ONU. At the ONU, 50% of the downstream signal was tapped off for downstream data reception via a 10 Gbit/s optical receiver while the rest of the signal power (at −6.1 dBm) was injected into a FP-LD, which was simultaneously directly-modulated with a 1 Gbit/s NRZ, $2^{21} - 1$ PRBS upstream data. An optical circulator was used to separate the reflected and injection-locked upstream signal from the downstream signal. The injection-locking improved the SMRR of the FP-LD from 2 to 29.7 dB (see inset of Fig. 4) and the output signal was observed to have 1.7 dB power gain. The remodulated upstream signal was then transmitted over another 50 km fibre span and was received at the central office. Fig. 4 shows the BER performance of the 10 Gbit/s downstream signal and the 1 Gbit/s remodulated upstream signal, measured at ONU and CO, respectively. The eye diagrams for both signals are also shown in insets of Fig. 4. Both measurements showed error-free operation and proved the effectiveness of our proposed scheme.

Conclusion: We have proposed and demonstrated a novel upstream traffic transmitter for a WDM access network (10 Gbit/s downstream signal and 1 Gbit/s upstream signal) with a centralised light-source approach. The FP-LD replaces the local laser source and optical modulator in a conventional ONU, thus resolving the problem of wavelength mismatch between the downstream and upstream wavelengths in a low-cost regime. The ‘re-writing’ of the downstream signal by injection-locking of the FP-LD is promising in an access network since it works for both symmetric and asymmetric two-way traffic, thus eliminating the complicated synchronisation process. In addition, better bandwidth utilisation is achieved as no blank time slots in the downstream signal are reserved for the upstream signal. The injection-locking method enables the FP-LD to achieve much better tolerance to the fibre chromatic dispersion, thus enhancing the network transmission span.

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References
High-power, highly reliable 1.05 μm InGaAs strained quantum well laser diodes as pump sources for thulium-doped fibre amplifiers

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High output power of about 500 mW in chips without kink and having stable operation for over 5500 h under auto-power-control of 225 mW at 50°C have been achieved in 1.05 μm InGaAs strained quantum well laser diodes for pump sources of thulium-doped fibre amplifiers. Low-temperature growth of the InGaAs well layer enabled the lasing wavelength to be extended to 1.05 μm.

Introduction: The remarkably huge increase in transmission capacity of wavelength division multiplexed (WDM) optical networks demands development of thulium-doped fibre amplifiers (TDFAs) for 5-1.48-1.51 μm and 5-7 band (1.45-1.48 μm). Since a T DFA for a signal around 1.47 μm was first demonstrated using upconversion pumping at 1.064 μm of a Ti : sapphire laser [1], the wavelength of around 1.05 μm has been used for pumping the T DFA. To extend the gain to S-band, dual wavelength pumping with both a 1.05 μm Yb fibre laser and 1.56 μm laser diode (LD) [2], and a high concentration Tm doping technique with simple one-colour pumping using a 1.087 μm Nd : YLF laser [3] have also been proposed. For all-LD pumping, more recently a 1.4-1.56 μm pumping scheme has been proposed [4]. We are aiming at the development of a 1.05 μm LD as a replacement for solid-state-laser pump sources.

InGaAs strained quantum well (QW) laser diodes successfully operate at 0.98 μm wavelength. To extend their lasing wavelength beyond 1 μm, the In content of the QW has to be increased. However this gives rise to higher strain in the QW layers and consequently prevents us from realising the high-quality LDs [5, 6]. LDs with strain-compensated QWs of InGaAs/GaAsP or InGaAs/InGaAsP have been reported for 1.064 μm wavelength [7, 8]. Conversely, we previously reported highly reliable 1.02 μm wavelength InGaAs strained QW lasers [5, 9] and recently have been trying to make the lasing wavelength longer.

In this Letter, we report high-power and highly reliable 1.04-1.05 μm InGaAs strained quantum well LDs that have kink-free output power of about 500 mW in chips. The LDs have operated stably for 5500 h in an ageing test under the condition of 225 mW at 50°C. LD modules with output power beyond 200 mW have also been demonstrated. Low-temperature growth of the active layer has enabled us to form highly strained QWs, which make it possible to extend the operation wavelength of InGaAs strained QW lasers to 1.05 μm.

Photoluminescence for QW: A separate confinement heterostructure (SCH) with InGaAs strained QW active layers was grown on n-GaAs substrates by metal organic vapour phase epitaxy [10]. The InGaAs double QW layers were grown at a temperature 100°C lower than the other layers. Lasing wavelengths were controlled by changing the In content and the thickness of the strained QWs. The dependence of the QW photoluminescence (PL) peak intensity on the peak wavelength is shown in Fig. 1 for the low-temperature growth and conventional growth of the well layers. PL measurement was performed at room temperature with Ar laser excitation. The intensities decrease gradually with increasing wavelength, and then abruptly decrease at the critical wavelength, where the quantum layer seems to degrade. It is found that the critical wavelength in the low-temperature growth is 20 nm longer than that in the conventional growth. This may have its origin in the dependence of growth mode transition or critical layer thickness on growth temperature [11, 12].

LD characteristics: Ridge waveguide structures with a ridge width of ~2 μm were fabricated by using electron-cyclotron-resonance reactive ion etching. The cavity length (L) was 900 or 1200 μm. An anti-reflecting film (2%) was coated onto the front facet, and a highly reflecting film (80-90%) onto the rear facet. A pump laser module coupled with a singlemode fibre (SMF) was also fabricated.

Fig. 2 shows the typical continuous wave (CW) optical light output power against driving current (I-L) characteristics and the lasing spectrum at 25°C. For the LDs with L = 1200 μm the peak lasing wavelength is 1.05 μm. The maximum free-space lasing output power is beyond 600 mW, and kink-free operation is observed up to about 500 mW. The threshold current is 33 mA, and the slope efficiency is 0.9 W/A. The vertical and horizontal divergence angles are 14.7° and 8.0°, respectively. For the 900 μm cavity length, the kink power is over 350 mW and the maximum output power is about 450 mW. Fig. 3 shows the ageing test results obtained under auto-power-control (APC) of 225 mW at 50°C for the LDs with L = 900 μm. Thirteen lasers were tested. Stable operation has been observed for over 5500 h. The increase in operating currents in CW measurement is within a few per cent at 50°C.

Modules were fabricated with the LDs having L = 900 μm. The LD chips were coupled with tapered singlemode fibres. Coupled optical powers beyond 200 mW at the driving current of 400 mA have been obtained without kink. Higher output power of about 300 mW is expected for LDs with L = 1200 μm.