The optical power launched into the EDFA's was changed with a variable attenuator whose attenuation dependence on wavelength was < 0.1 dB in the wavelength range of 1540 to 1560 nm. The EDFA's used a two-stage configuration as shown in Fig. 5a to improve the noise figure. The lengths of EDF1 and EDF2 were optimised so as to obtain flat amplification with a signal input power of -15 dBm/channel and the smallest noise figure. The noise figure measured by the polarisation extinction technique was 3.9 dB at 1.55 μm. The gain excursion with six-stage amplification is 0.9 dB in the signal bandwidth after six-stage amplification.

Conclusion: We studied the common amplification characteristics of EDFA's with high Al concentration for WDM signals. The gain tilt at 1.55 μm changes continuously with the total input power of WDM signals. By optimising the EDFA length in accordance with the total input power, extremely flat common amplification can be realised for WDM signals ranging from 1540 to 1557 nm. We demonstrated gain and S/N excursion within 0.02 dB/nm/stage for six-stage amplification. These results show the possibility of long haul transmission of WDM signals with gain equalisation.

Acknowledgement: The authors thank Dr. Matsumoto of this laboratory for his encouragement.

Low repetition rate master source for optical processing in ultrahigh-speed OTDM networks

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Indexing terms: Distributed feedback lasers, Electro-absorption modulators, Q-switching

A simple technique for the generation of transform-limited pulses with durations of a few picoseconds at low repetition rates is reported. This is demonstrated experimentally and 6 ps pulses are generated at 1 and 2 GHz. These pulse trains have very low duty cycles and background levels.

As data transmission rates continue to increase it is important not only to develop ultrahigh frequency pulse sources, but also lower frequency short pulse sources for applications such as all-optical switching and demultiplexing, and as master sources suitable for optical time division multiplexing (OTDM) up to bit rates of 40 Gbit/s and beyond. The application of direct modulation techniques is potentially very attractive for the creation of such sources. Directly modulated schemes have the advantages over conventional mode-locked lasers in that they are simple, compact, robust, stable, can operate at flexible data rates and do not require active stabilisation techniques such as regenerative mode-locking [1]. The two direct modulation techniques that have attracted the most attention recently are gain switching of semiconductor laser diodes and the modulation of a CW laser diode with an electroabsorption (EA) modulator.

Gain-switched semiconductor DFB laser diodes typically produce pulses with a duration of ~20 ps, powered with a DC bias and RF modulation [2]. Although pulses can be generated at relatively low repetition rates (~1 GHz) through the use of a step recovery diode to produce a comb-like RF drive, the pulse quality is generally poor. This is because pulses generated in this way tend to have large nonlinear chirp which cannot be completely compensated using a linear dispersive delay line. Even after linear chirp compensation and spectral filtering, such pulses tend not to be transform-limited and are accompanied by a significant pedestal component owing to incomplete chirp compensation [3]. EA modulators, on the other hand, can produce much higher quality pulses and we have recently demonstrated the generation of transform-limited (ΔνΔτ = 0.32) 5.2 ps sech⁴ pulses at 10 GHz with a duty ratio of ~5% [4]. Such short pulse durations can only be achieved in this way by employing a relatively high modulation.
In this Letter, we propose and demonstrate the combination of low frequency gain switching of a DFB laser with synchronous high frequency EA modulation. In this way we have combined the superior pulse quality available from EA modulators with the low repetition rates and zero background levels associated with gain-switched lasers.

The gain-switched pulses were reshaped and shortened by the EA modulator. When driven at 10GHz with 1W of RF power (into 50Ω) and a 7V DC bias, the modulator generated pulses of ~18ps, therefore extracting only the central part of the input 80ps pulse. As well as pulse shortening, the EA modulator provided spectral filtration of the chirped input pulses, suppressing the nonlinearly chirped wings. As a result of this, the pulses at the output of the EA modulator had a linear chirp imparted dominantly by the modulator. This was then compensated for in a dispersive transmission filter, which was preceded by an erbium amplifier to boost the signal power. The dispersive transmission filter consisted of a polarisation controller, a polarisation-division multiplexing coupler and a tuneable chirp fibre Bragg grating, described in detail in [4]. Effectively transform-limited, pedestal free pulses were generated at the output. The autocorrelation trace of these pulses is shown in Fig. 1b and the corresponding spectrum is shown in Fig. 2b. These pulses were measured to have an FWHM duration of ~6.6ps, assuming a sech² intensity profile, and the spectral width was 0.4nm, yielding a time-bandwidth product of 0.32.

Fig. 4a and b shows the pulse trains as measured with the sampling optical oscilloscope for the gain-switched DFB and the total system, respectively. In this technique, it is important that the baseline duration of the pulses at the input to the EA modulator are considerably shorter than 200ps, to avoid the formation of pulse sidelobes due to the presence of light in the prior and consecutive modulation cycles. Unfortunately, the minimum pulse duration which we could attain from our gain-switched DFB laser was ~80ps FWHM. This was limited by the frequency response of the device packaging. These pulses were slightly longer than was ideal, resulting in the generation of small sidelobes (5% of main pulse intensity) that can be seen in Fig. 4b. These sidelobes would disappear if a laser in a higher bandwidth package generating shorter pulses of ~50ps was used. Alternatively, spectral filtering of the gain-switched pulses prior to coupling into the EA modulator may provide sufficient pulse shortening to overcome this problem [5]. Neglecting these sidelobes, the background level at times in the drive cycle when the DFB emitted light was determined by the extinction ratio of the modulator used, which was 25dB in this case. As the DFB does not emit light between pulses, the background level during the dark time of the cycle is essentially zero. This low background level and pedestal suppression is important if such pulse trains are to be optically multiplexed to higher repetition rates.

In conclusion, we have demonstrated the generation of transform-limited 6.6ps pulses at 1 and 2GHz using only direct modulation techniques. These pulse trains had duty ratios of 0.66 and 1.32%, respectively, and negligible background levels, indicating the suitability of such a source for applications which require high quality short pulses at relatively low repetition rates. This technique is not limited to the repetition rates demonstrated here. For lower frequencies in the megahertz range, a step recovery diode could be used, as we demonstrated in our experiment. The pulse duration is determined by the EA modulator. If even shorter pulses were required, nonlinear pulse compression could be used, as we have already demonstrated at 10GHz generating pulses as short as 200fs [6].

Acknowledgments: This work was partly funded by the EPSRC. We would like to thank IRE-POLUS Co. for the loan of the erbium-doped fibre amplifiers used in these experiments.
Subcarrier multiplexing with dispersion reduction

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A novel dispersion-reduction technique using subcarrier multiplexing and optical prefiltering is described. Measured results from a link demonstration indicate that a pair of 2.5-Gbit/s data channels can be transmitted over 2100 km of ordinary single-mode fibre with negligible dispersion.

Introduction: Future fibre-optic networks will demand the use of transmission methods that offer flexibility and the efficient exploitation of bandwidth of existing network assets, such as installed single-mode fibre. Subcarrier multiplexing (SCM) is one of the few techniques that can accommodate the multiformat array of transmission protocols and modulation formats that will be carried on future networks.

Various experimental high speed SCM systems have been presented in technical journals, but have depended on dispersion-shifted fibre [2]. We offer a novel approach to the problem, which allows baseband detection [3] and incorporates dispersion reduction in the SCM system. Using microwave mixers and a lithium niobate external modulator, sidebands are produced several gigahertz apart on the principal laser optical carrier. Digital data streams are independently impressed on these sidebands for transmission over ordinary singlemode fibre.

Experimental setup: A block diagram of our SCM system is shown in Fig. 4. Independent 2.5-Gbit/s data streams are upconverted to 6 and 15.5 GHz. A solid state 1550 nm laser carrier is externally modulated with the two microwave subcarriers using a Mach-Zehnder interferometric modulator. The optical signal is sent over 100 km of ordinary singlemode fibre, with the aid of two erbium-doped fibre amplifiers (EDFAs). At the receiving end, the desired subcarrier is optically preselected using a fibre Fabry-Perot (FFP) filter. This process is illustrated in Fig. 2a. The ideal filtered optical spectrum is shown in Fig. 2b. An optical detector converts the selected optical signal into a baseband electrical 2.5 Gbit/s data stream.

We offer a novel approach to the problem, which allows baseband detection [3] and incorporates dispersion reduction in the SCM system. Using microwave mixers and a lithium niobate external modulator, sidebands are produced several gigahertz apart on the principal laser optical carrier. Digital data streams are independently impressed on these sidebands for transmission over ordinary singlemode fibre.