A plot of the output power of the second fibre DFB laser against the pump power is shown in Fig. 3. In this MOPA configuration, the residual pump power is absorbed within the additional section of erbium doped fibre, separated from the laser by an isolator. A maximum output power of 5.4mW for 50mW of launched pump power was measured. The inset of Fig. 3 shows the lasing curve, without the amplifying section. For this configuration, the lasing threshold is as low as 8mW of launched pump power can be attributed to the strong spatial hole burning effect, which can easily be reached. Singlemode operation of both lasers was verified by a scanning Fabry-Pérot interferometer (Fig. 4). No mode-hops or sidemodes were observed within the temperature range 20–30°C. The delayed self-heterodyne method with a resolution of 1.7kHz was used to evaluate the linewidth of the second DFB laser [5]. A 3dB linewidth (FWHM) of 15kHz was measured, assuming a Lorentzian spectrum (inset of Fig. 4). The narrow linewidth is believed to be caused by the n/2 phase shift, extended along the grating. This broadens the intensity profile around the phase shift, and therefore reduces the strong spatial hole burning effect, which is characteristic of DFB lasers with an abrupt phase shift [1].

The nonlinear amplifying loop mirror (NALM) [1] has been extensively used as an intensity (phase) dependent transmission element in passively mode locked femtosecond and picosecond fibre lasers, with particular effect in the ‘figure of eight’ geometry [2]. Transmission, which requires a phase imbalance, is achieved in these fibre interferometers (which use a 3dB coupler and an offset lumped fibre amplifier in the loop), since the operations of dispersion and nonlinearity on the clockwise and counterclockwise pulses do not commute. The intensity-dependent transmission function mimics that of an ultrafast saturable absorber, where the response time is effectively infinitely fast (~few femtoseconds) i.e. that of the Kerr nonlinearity of the medium. Thus in association with soliton shaping, ultrashort pulse generation is possible from a fibre laser incorporating these elements. In order that stability is achieved with solitons in a periodically amplified geometry, the system must operate within the regime of the average soliton dynamics [3]. A required condition is that the periodic length of the laser Zp is substantially less than the characteristic scale of the soliton Z0. This condition can be generally met quite comfortably when operation is in the picosecond regime. However, with femtosecond pulses, since the soliton period Zp is proportional to t1/3, where t is the pulselength, it becomes reasonably difficult to meet the demands on the physical dimensions set by the average soliton requirements. As a result, the periodically perturbed (amplified) soliton sheds radiation and the interaction between the unstable soliton and this dispersive radiation gives rise to the now characteristic spectral sideband structure [4, 5]. Several approaches have been taken to reduce or eliminate the spectral sidebands. These have included operation in the region of strong normal dispersion, thus avoiding solitons and employing extracavity compression [6], the use of low anomalously dispersive fibre and short cavity lengths [7], or filtering effects [8]. If picosecond pulses are generated in the soliton fibre lasers, then the effect

Conclusions: We have demonstrated two robustly singlemode fibre DFB lasers with gradual and localised n/2 phase shifts, directly induced in non-centrosymmetric Er3+ doped fibre. A narrow linewidth of 15kHz was measured. The environmentally stable singlemode operation and high output power, combined with a low lasing threshold, makes the laser attractive for application in optical communication systems.

Acknowledgments: We are very grateful to C. Larsen and B. Pihlsdottir from Lycom for his support during the experiment.
of the periodic decomposition of the gain, i.e. the sidebands, is not apparent; however, some additional pulse compression technique must be applied to obtain femtosecond pulses. One method for soliton pulse compression which has received considerable attention lately has been adiabatic compression using dispersion decreasing (or tapered) fibre (DDF) [9, 10]. In this technique, solitons experience a quasi-amplification and consequently adiabatic pulse compression as a result of the slowly varying increasing power density/decreasing dispersion in the tapered fibre. Such a DDF fibre, within the NALM section of a figure of eight laser, could replace the doped fibre amplifier, permitting an intensity-dependent switching behaviour as a result of the non-reciprocal nature of the device, giving pulse compression, yet allowing overall operation in the long pulse regime to enable the reduction or possible elimination of the effects of sidebands in an optimised geometry. In this Letter we report the operation of a DDF in a femtosecond fibre laser.

A schematic diagram of the experimental configuration is shown in Fig. 1. The NALM section of this figure of eight laser was essentially constructed from a 3dB fibre coupler and a 100m length of tapered fibre. This DDF exhibited a group delay dispersion at 1535nm of 8.4ps/nm/km at input and -0.8ps/nm/km at the output. For a completely adiabatic process, a pulse compression of 10+ times would be expected. A polarisation controller PC2 permitted the phase biasing within the 104m long nonlinear loop to be set, while PC1 within the linear loop controlled the polarisation state of the feedback signal. Also in this uni-directional 14m long section was a diode-pumped Yb:Er gain fibre (IRE-Puls Amplifier EAM-60) and a polarisation-independent isolator (shown as the arrow). The compressed output was taken just after the lower dispersion end of the DDF using a 10% output fused fibre coupler. This coupler also permitted the input pulses to the nonlinear loop to be monitored.

![Fig. 1 Schematic diagram of experimental configuration](image1)

Modelocked operation was obtainable with the system as shown in Fig. 1. The operation was similar to that observed with the more common configuration which incorporates the Er amplifier offset within the nonlinear loop [2] in that the temporal output was periodic but random when pumped well above threshold, but on reduction of the pump power, a single pulse per round trip could be obtained. Typically in modelocked operation the average output power was 650mA.

![Fig. 2 Autocorrelation and (inset) corresponding spectrum of modelocked output pulses from fibre laser configuration](image2)

Fig. 2 shows a representative noncollinear second harmonic generation intensity autocorrelation of the modelocked output pulses together with the corresponding spectrum. It can be seen that pulses of 250fs were generated, but that a pedestal component was present. This is indicative that the compression mechanism was not completely adiabatic. It can also be seen that the associated spectrum which had a FWHM of 6.8nm (ΔΔτ = 0.31 indicating effectively transform limited operation assuming sech² profiles) exhibits a spectral modulation.

![Fig. 3 Autocorrelation and corresponding spectrum of input (transmitted) pulse to nonlinear loop mirror section of fibre laser](image3)

Fig. 3 shows the autocorrelation of the pulse which was switched (transmitted) by the nonlinear loop section of the fibre laser. This was monitored as the input to this section of the laser. It had a measured deconvolved FWHM pulsewidth of 1.25ps and a corresponding spectral width of 2.3nm, indicating near transform limited pulses (1.25ps requiring 2.0nm, assuming sech² profiles). This implies that at the input to the tapered fibre the characteristic soliton period was 75nm. An overall compression of 4 times was achieved. However, this compression is not completely adiabatic. This is evidenced by the pedestal component accompanying the compressed soliton pulse in Fig. 2. Interference between the soliton and the dispersive component gives rise to the structure observed on the output spectrum. One problem associated with the present configuration is that it is difficult to optimise the adiabatic compression process. This would be most conveniently carried out using a spectral filtering technique, both to predetermine the pulse duration of operation and to finely control the dispersion and corresponding compression factor, which is critical on the operational wavelength.

In summary, we have demonstrated femtosecond soliton generation through the compression of picosecond pulses in a dispersion decreasing fibre which was incorporated in the nonlinear section of a figure of eight fibre laser. This permitted intensity-dependent switching with picosecond pulse operation, which can negate the sideband spectra associated with periodically amplified solitons. Through optimisation of the operational parameters of the laser, in particular control of the wavelength and pulsewidth, complete adiabatic compression should be possible with no pedestal generation. This should eliminate the spectral modulation observed in the unoptimised geometry.

Acknowledgment: The overall support of the Engineering and Physical Sciences Research Council for this research is gratefully acknowledged. A. Boskovic acknowledges financial support of a studentship from the Conselho Nacional de Pesquisas (CNPq) Brazil.

© IEE 1995 7 July 1995
Electronics Letters Online No. 1995/0142
A. Boskovic, S.V. Chernikov and J.R. Taylor (Femtosecond Optics Group, Physics Department, Imperial College, Prince Consort Road, London SW7 2BP, United Kingdom)

References

Fluidic self-assembly of InGaAs vertical cavity surface emitting lasers onto silicon

J.K. Tu, J.J. Talghader, M.A. Hadley and J.S. Smith

Introduction: Vertical cavity surface emitting lasers (VCSELs) are an attractive candidate for optoelectronic integrated circuits (OEICs). Not only do these devices have low threshold currents and high wallplug efficiencies [1], but they are also compact in size and can easily be fabricated into dense 2-D arrays. By integrating VCSELs with Si circuitry, high performance OEICs can be attained. Recently, fluidic self-assembly (FSA) has been presented as a technique for high yield (> 80%) large volume optoelectronic integration [2, 3]. In this process, devices are grown on GaAs and fabricated into trapezoidal blocks which are freed from the substrate into a carrier liquid. This solution is then dispensed over an Si receptor wafer which has correspondingly-shaped holes etched into it. Under the ensuing fluid transport, blocks self-assemble into the holes. This technique has advantages over other processes such as epitaxial lift-off because it can perform rapid integration of large numbers of devices, make precise placement of discrete devices without alignment, make more efficient use of wafer material, and is compatible with a planar process flow. Until now, GaAs microstructures integrated in this manner have only been tested by direct probing [4, 5]. We present a planar process flow that includes device isolation, bonding and contacting [6], resulting in the first successful integration of VCSELs onto Si by FSA.

Device fabrication: The VCSELs were designed to operate at 0.98 μm and were grown by MBE with a Varian Gen-II machine. Thermal emission measurements [7] were used to provide in situ monitoring of the growth rates. The Al content in the mirrors was chosen to be x = 0.67 so that the total device thickness would be close to the 10μm depth of the hole. The laser structure (Fig. 1) was grown on top of a 1.3μm thick, AlAs sacrificial etch layer. These lasers were top emitting, with the n mirror placed on top to give a more uniform current injection. Since the device layers are integrated upside down onto Si, the n mirror, which consists of 23 quarter-wavelength pairs of GaAs/AlGaAs, was grown first. The active region consisted of 3 × 75Å In0.37Ga0.63As quantum wells centred in a one wavelength thick separate confinement heterostructure region. The p mirror was designed to terminate on a highly reflective interface and consisted of 40 quarter-wavelength GaAs/AlGaAs pairs. Linear grading with excess doping was used in the p mirror to reduce the series resistance. In both the n and p mirrors, the doping was lowered in the Bragg pairs nearest the active region to reduce the effects of free carrier absorption.

Following growth, the wafer was metallised with CrAu and ion milled down to the AlAs layer to form 40 × 40 μm2 trapezoidal blocks [2]. The wafer was then encased face-down in wax, and the substrate was removed using a combination of mechanical lapping and selective chemical etching (3:100 NH4OH:H2O2). The AlAs was removed with 5:1 BHF and the blocks were freed from the wax with acetone. The blocks were then transferred into the carrier liquid, ethanol.

Integration and processing of the receptor wafer is discussed in more detail in [6]. For the receptor wafer, 10μm deep holes were etched with a solution of KOH:H2O:IPA at a temperature of 80°C. A diffusion step was performed to provide electrical isolation and contact to the bottom of the hole. Gold was then evaporated and patterned to form an actual bottom contact. This contact also served to bond the block into the hole after integration.

Fig. 1 Schematic diagram of VCSEL structure
a. Doping
b. Energy band structure
c. Close-up of active region with normalised E-field imposed

Fig. 2 Process flow
a. Block formation
b. Receptor wafer formation
1. Integrated VCSEL after planarisation and final metallisation

FSA was then carried out using a modified recirculation scheme. The wafer was placed into the beaker with the block solution in it, and a pipette was used to create fluid flow. Following