was estimated to be less than 4ns. Although some bits were missing after frequency switching, clear eye openings were obtained except during a change of state. If duplex light source techniques employing an optical $LiNbO_3$ with two lasers [6] or a single laser and fibre delay line [7] were used in our system, we could overcome the switching time limitation and not miss the signal bits during a change of state. Fig. 4*c* shows the output signal while the signal was steady and the signal rate was 5Gbit/s. After a transitional response time of 8ns, a clear eye opening was obtained.

Conclusion: We have demonstrated optical switching of 16 optical ports at a data rate of 5Gbit/s by using an SSG DBR laser and an arrayed-waveguide grating multiplexer. The frequency spacing of each channel is 100GHz. The response time of the channel switching is 8ns. These results indicate that the system with our two devices is a practical scheme that can be applied to optical cross-connect systems.

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Figure-eight fibre laser with largely unbalanced central coupler

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Indexing terms: Fibre lasers, Laser mode locking, Nonlinear optical loop mirrors, Ring lasers

The authors describe the operation of a figure-eight fibre laser constructed with an asymmetrically located amplifier and a largely unbalanced central coupler. This laser experiences less loss and is more easily modelocked than figure-eight lasers constructed with balanced (50:50) central couplers.

Fibre figure-eight lasers have attracted considerable attention because they can produce ultrashort solitons at high repetition rates [1–7]. Thus far, these lasers have been constructed with balanced (50:50) central couplers. We report here that figure-eight lasers, when constructed with greatly unbalanced central couplers, can still produce subpicosecond pulses but are more easily modelocked and experience less loss during pulsed operation than do figure-eight lasers with 50:50 central couplers.

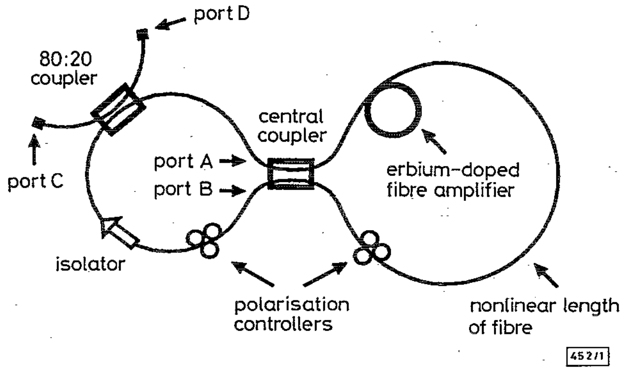

Fig. 1 *Schematic illustration of figure-eight fibre laser*

Fig. 1 gives a schematic illustration of a figure-eight fibre laser. The central coupler and the loop on the right had side of the laser form a nonlinear Sagnac interferometer. In the low-intensity limit, a fraction of the light incident on this device at port A is retroreflected; part of this reflected light exits the laser at port C and the rest is absorbed by the isolator. For a more intense input pulse, the counterpropagating pulses within the interferometer accumulate a relative nonlinear phase shift such that when the pulses interfere at the central coupler, more of the light exits at port B and less is absorbed by the isolator. In this way the combination of the nonlinear interferometer and the isolator acts as a saturable absorber and serves to passively modelock the laser.

Figure-eight lasers have been constructed almost exclusively with nonlinear Sagnac interferometers known as nonlinear amplifying loop mirrors (NALMs) [8]. These interferometers are constructed with a 50:50 coupler and an asymmetrically located amplifier that induces a relative nonlinear phase shift between the counterpropagating pulses. NALMs have the advantage of posessing exceedingly large extinction ratios that are limited only by the spectral and temporal overlaps and the uniformity of the nonlinear phase shifts of the two pulses that interfere at the central coupler. However, in the steady-state pulsed operation of figure-eight lasers, NALMs typically retroreflect tens of percent of the incident light and, because of the 50:50 coupler, they force the solitons within the laser to undergo very large amplitude changes. To minimise these perturbations and decrease the loss, another type of nonlinear Sagnac interferometer known as a nonlinear optical loop mirror (NOLM) might be used [9]. This device uses the asymmetry created by an unbalanced central coupler to generate the relative nonlinear phase shift between the pulses within the interferometer. By using a greatly unbalanced central coupler that couples more than 90% of the light in one direction, most of the energy in the incident pulse can traverse the loop mirror without significant, abrupt energy changes. Like NALMs, these devices can have a maximum energy transmission coefficient that approaches 100%, but the maximum percentage of light that the loop mirror can retroreflect is significantly less than 100%. Still, an NOLM with a 90:10 coupler can retroreflect as much as 36% of the incident light, which provides more than enough saturable loss to modelock a laser. One disadvantage of using an NOLM with a largely unbalanced coupler is that the nonlinear length of fibre required to generate ultrashort pulses is impractically short. We demonstrate here that the use of both a largely unbalanced central coupler and an asymmetrically located amplifier within the loop mirror of a figure-eight laser significantly improves the transmission of the loop mirror during pulsed operation, allows for the generation of subpicosecond pulses with reasonable lengths of fibre, and decreases amplitude perturbations of the solitons within the laser.

We constructed a figure-eight laser with a central coupler that couples 94% of the incident light into the nonlinear length of fibre and 4% into an asymmetrically located amplifier. By coupling the more energetic pulse first into the nonlinear length of fibre and then through the amplifier, we create a switching power that is sufficiently high to generate subpicosecond pulses with nonlinear lengths of fibre of the order of 1m. 4m of low dispersion fibre are used as the nonlinear length of fibre. Use of this dispersion shifted fibre prevents significant temporal spreading of the less energetic pulse as it propagates through the loop mirror. This improves the temporal overlap of the two pulses when they meet at the central coupler and therefore increases the maximum transmission of the loop mirror. The amplifier was constructed with 15m of erbium-doped fibre that was unidirectionally pumped with 40mW of 980nm light from a semiconductor laser.

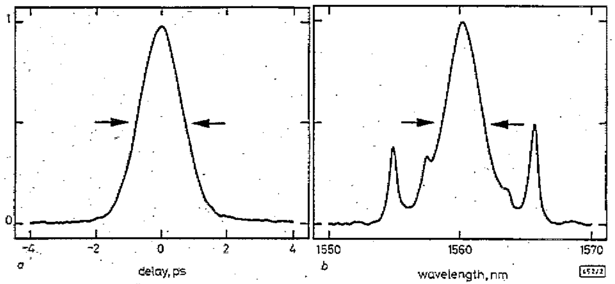

Fig. 2 *Autocorellation trace and spectrum of the output of fibre figure-eight laser with a 94:6 central coupler*

a Autocorrelation trace, $\tau_{auto} = 1.5$ps
b Spectrum $\Delta/\lambda = 3.2$nm

The autocorrelation trace and spectrum of the output of the laser are shown in Fig. 2. The full width at half maximum of the pulse is 970fs, assuming a hyperbolic secant pulse shape, and the spectral width is 3.2nm. The pulse is nearly transform-limited, having a time-bandwidth product of 0.38, as opposed to 0.32 for an ideal transform-limited pulse. With a coupling ratio of 94:6, it can be shown that as much as 20% of the light exiting the loop mirror can be retroreflected [9]. By measuring the output powers at ports C and D, (defined in Fig. 1) and by measuring the relative loss from the central coupler to ports C and D, we find that only 4% of the light exiting the loop mirror is retroreflected during pulsed operation. In contrast, we find that typically 10–40% of the light is retroreflected when a 50:50 coupler is used. A disproportionate amount of the 4% may be due to dispersive wave components (the sharp spectral features created by the periodic amplification of solitons). To our knowledge this 4% loss is the lowest nonlinear loss introduced by a loop mirror in a figure-eight laser. The laser produces pulses at coupling ratios as unbalanced as 97:3, but in this case a significant fraction of the output energy is in a continuous-wave component rather than in modelocked pulses.

A figure-eight laser with an unbalanced central coupler is basically a simple ring cavity where only a small percentage of the pulse is made to counterpropagate through the loop mirror in order to introduce some saturable loss. By reducing the loss and the perturbations to the solitons, this configuration should decrease the fraction of light coupled into dispersive wave components. In addition, this configuration decreases spatial holeburning in the amplifier during continuous-wave operation which may serve to frustrate the initiation of modelocking of the laser. In fact, we find that figure-eight lasers with greatly unbalanced central couplers are easier to modelock than are lasers constructed with 50:50 couplers in that they require little or no mechanical perturbation.

In conclusion, we have demonstrated that fibre figure-eight lasers constructed with largely unbalanced central couplers are in many ways superior to figure-eight lasers constructed with 50:50 central couplers. In pulsed operation, these lasers can still produce subpicosecond pulses, while more easily modelocking and experiencing less loss.

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High power, reliable 645nm compressively strained GaInP/GaAlInP laser diodes

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Indexing terms: Semiconductor junction lasers, Semiconductor quantum wells, Reliability

CW output powers in excess of 1W and reliable CW output powers of 250mW at room temperature from double quantum well compressively strained GaInP/GaAlInP laser diodes with an emission wavelength of 645nm were demonstrated. An anomalous dependence of threshold current density and wavelength on GaInP/GaAlInP laser diode stripe width was characterised.

High-power GaInP/GaAlInP visible laser diodes with emission wavelength of 630–650nm are promising for various applications such as illuminators, optical pumps for tunable solid-state lasers, radiation sources for photodynamic therapy, high definition projection displays and high-speed printers. Geels *et al.* demonstrated 900mW CW for 100μm-wide laser diodes with emission wavelength of 633nm that incorporate a tensile strained single quantum well (SQW) heterojunction [1]. Serreze *et al.* demonstrated 1W CW for 60μm-wide compressively strained laser diodes with emission wavelength of 670nm at 10°C [2]. However, reliable high power CW operation with emission wavelength shorter than 650nm at room temperature has not been reported. This is mainly due to the high thermal resistance of InAlGaP layers as well as the low conduction band offset between the cladding layer and active region. In this Letter, we demonstrated maximum CW output powers of 1W at room temperature and reliable 250mW CW from compressively strained GaInP/GaAlInP laser diodes with emission wavelength of 645nm. These results are encouraging because they represent the best performance from compressively strained GaInP/GaAlInP laser diodes with emission wavelength shorter than 650nm.

The devices used in these experiments consisted of double quantum well (DQW) graded-index separate confinement structures grown on an *n*-type GaAs substrate by a low pressure metal organic chemical vapour deposition (MOCVD). DQW gives rise to increasing catastrophic optical damage level with a minimal penalty in threshold current density. The device layer consists of an Si doped n-$(Al_{0.7}Ga_{0.3})_{0.5}In_{0.5}P$ cladding layer, a DQW-GRIN-SCH active layer, and a Zn doped p-$(Al_{0.7}Ga_{0.3})_{0.5}In_{0.5}P$ cladding