This work was supported under the United Kingdom National Measurement System Policy Unit's programme on optoelectronics.

4th September 1992

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MEASUREMENT OF GROUP BIREFRINGENCE AND DISPERSION OF POLARISATION MAINTAINING ERBIUM-DOPED SILICA FIBRE

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Indexing terms: Group birefringence, Polarisation dispersion, Erbium-doped fibres

The group birefringence and chromatic dispersion of a polarisation maintaining bow-tie erbium-doped silica fibre have been measured in the wavelength range 1·2–1·68 μm by an interferometric measurement technique without any polarisers. The group birefringence is lower than that of a conventional bow-tie fibre and the zero dispersion wavelengths of the two polarisation modes are shifted to 1·613 and 1·630 μm.

Introduction: High bit rate optical transmission systems have to overcome two major difficulties: attenuation and dispersion. The erbium-doped fibre amplifier (EDFA) seems to have the potential to overcome both. With small-signal gains of more than 30 dB and noise figures near the quantum limit the EDFA eliminates the attenuation problem [1]. Erbium-doped silica fibres have smaller core diameters and larger index differences compared to standard singlemode fibres [2] and may therefore be used to compensate for the dispersion of the latter. Together with a novel transmission scheme [3] all-optical long-distance multigigabit transmission using standard singlemode fibres and EDFAs is possible.

If optical isolators which are not polarisation independent are used [4] or if a polarisation maintaining active fibre is used in fibre ring lasers to overcome stability problems [5] the polarisation dispersion of the amplifying fibre has to be known. This Letter presents, for the first time to our knowledge, measurements of the group birefringence and the chromatic dispersions of a polarisation maintaining erbium-doped silica fibre in the wavelength range 1·2–1·68 μm.

Experimental results: The index differences Δn and core diameters $2a$ of the germano-alumina silicate fibre under investigation are 0·01643 and 2·5 μm for the x-polarisation mode and 0·0186 and 4·0 μm for the y-polarisation mode. This leads to a ratio $\rho = \Delta n/2a$ [2], defined as index difference to core diameter, of $6{\cdot}57 \times 10^{-3}\,\mu m^{-1}$ and $4{\cdot}65 \times 10^{-4}\,\mu m^{-1}$, respectively. The fibre core contains ~200 ppm Er^{3+} ions.

The group birefringence B_g is determined by an interferometric setup without any polarisers as

$$B_g(\lambda) := \Delta n_g(\lambda) = n_{gx} - n_{gy} = \frac{\Delta l(\lambda)}{l} \qquad (1)$$

where Δl is the length difference [6] between the interference patterns of the two polarisation modes, l is the fibre length and Δn_g is the group index difference. The indices x and y are used to distinguish between the two polarisation modes. Since the attenuation of erbium-doped silica fibres (~3 dB/m at 1·532 μm) is large compared to standard singlemode fibres, the interferometric measurement is the only possible technique for determining polarisation dispersion. However, the length difference Δl between the two interference patterns must be larger than twice the coherence length of the light source to distinguish between the interference patterns of the polarisation modes. Here the coherence length of the halogen lamp used was about 0·5 mm. Therefore, for a group birefringence of $\sim 2 \times 10^{-4}$ the fibre must be longer than 5 m. We chose a length of 10·13 m. By use of a highly sensitive photodetector with a transimpedance of 1 GΩ and a lock-in amplifier technique we overcame the problem of the high attenuation of the erbium-doped slica fibre in the wavelength range 1·45–1·60 μm.

Fig. 1 shows the group birefringence spectrum of the erbium-doped silica fibre and, for comparison, that of a conventional bow-tie fibre [6], in the wavelength range 1·2–1·68 μm. The spectral stepwidth of the measurement was

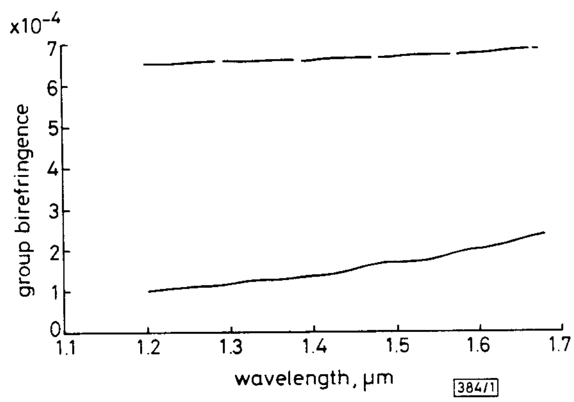

Fig. 1 *Group birefringence spectrum of erbium-doped bow-tie fibre and conventional bow-tie fibre* [6]

——— erbium doped
– – – – conventional

20 nm. The curves are interpolated by a third-order spline fit. The lower group birefringence of the erbium-doped bow-tie fibre, compared to the conventional bow-tie fibre, can be attributed to the smaller difference between its refractive indices for the x- and y-polarisation modes (see eqn. 1).

The chromatic dispersion spectra of the two polarisation modes have been calculated from a fourth order polynomial fit of the group delay spectra which have been measured with the same interferometric setup. They are indicated in Fig. 2. The zero dispersion wavelengths are shifted to 1·613 and 1·630 μm for the two polarisation modes. The slopes of the chromatic dispersion spectra at the zero dispersion wavelength are calculated to be 0·0562 and 0·0518 ps/km/nm². For the conventional bow-tie fibre the zero dispersion wavelengths have been calculated to be 1·385 and 1·386 μm with slopes of 0·0834 and 0·0821 ps/km/nm² [6]. It is not possible to directly attribute the two dispersion spectra to the polarisation modes because no polarisers are implemented in the measurement setup. However, since the zero dispersion wavelength is shifted to longer wavelengths with increasing ratio ρ, due to waveguide dispersion [2], we conclude that the x-polarisation mode has the higher zero dispersion wavelength. Such a large dispersion shift to positive group velocity dispersion at 1·55 μm would have implications if such fibres were to be used

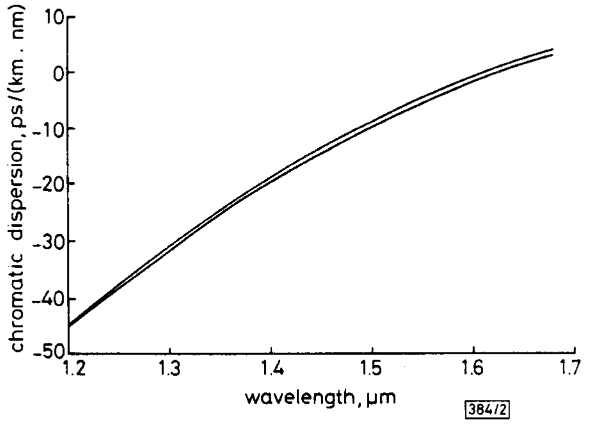

Fig. 2 *Measured chromatic dispersions of two polarisation modes of bow-tie erbium-doped silica fibre*

in passively mode locked erbium-doped fibre based soliton lasers which require an overall negative group velocity dispersion [7].

Conclusions: We have measured the group birefringence and the chromatic dispersions of a polarisation maintaining erbium-doped bow-tie fibre in the wavelength range 1·2–1·68 μm. Compared to standard single mode fibres, erbium-doped silica fibres are ordinarily fabricated with a larger index difference and a smaller core diameter in order to obtain an optimal overlap of the pump and signal modes. This results in the effect that the zero dispersion wavelengths are shifted to longer wavelengths with lower slopes for the two polarisation modes. In addition, the difference between the indices for the two polarisation modes of this fibre is smaller than for a conventional bow-tie fibre and results in a lower group birefringence. Such considerations need to be taken into account when designing such fibres for use in polarisation-maintaining mode-locked erbium-doped fibre soliton lasers.

Acknowledgments: York Technology is gratefully acknowledged for fabrication of the erbium-doped bow-tie fibre. Part of this work was performed within the RACE Project R2015 Artemis.

16th September 1992

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EFFICIENT HIGH-SPEED DIRECT MODULATION IN *p*-DOPED $In_{0.35}Ga_{0.65}As$/GaAs MULTIQUANTUM WELL LASERS

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Indexing term: Semiconductor lasers

The authors demonstrate *p*-type modulation-doped strained-layer $In_{0.35}Ga_{0.65}As$/GaAs multiquantum well lasers which achieve a 3 dB direct modulation bandwidth of 20 GHz at a low CW drive current of 50 mA in a simple $3 \times 200\,\mu m^2$ mesa structure. For the same device dimensions, a modulation bandwidth of 30 GHz was measured at a CW drive current of 114 mA. This is the highest direct modulation bandwidth reported for any semiconductor laser.

Recent experimental results have demonstrated the potential of molecular-beam epitaxially (MBE) grown strained $In_yGa_{1-y}As$/GaAs multiquantum well (MQW) lasers for direct modulation at frequencies exceeding 20 GHz, but drive currents in excess of 80 mA were required in all cases [1–3]. *p*-type modulation-doping has been shown to substantially enhance the relaxation frequency at a given drive current in GaAs/$Al_xGa_{1-x}As$ MQW lasers [4, 5]. Experimental results have confirmed both an increase in the differential gain and a decrease in the K factor with the doping level in InGaAs/InGaAsP MQW lasers [6]. The decrease in the K factor was attributed to an enhancement in the differential gain, in the absence of any corresponding increase in the nonlinear gain coefficient, ϵ. The magnitude of the increase in the differential gain due to the doping is still debated [4, 7]. The effect of *p*-type modulation-doping in strained $In_yGa_{1-y}As$ lasers has not yet been reported.

We compare the high-speed properties of undoped and *p*-type modulation-doped (MD) $In_yGa_{1-y}As$ MQW lasers with otherwise identical epilayer structures operating at wavelengths $\lambda = 1080–1090$ nm. The structures were grown by MBE with cracked arsenic. A vertically compact waveguide design [8, 9] was used both to improve the high-speed modulation and to simplify eventual monolithic integration. The layer sequence consists of: 1 μm n^- GaAs contact layer ($4 \times 10^{18}\,cm^{-3}$ Si-doped); 100 nm graded $Al_xGa_{1-x}As$, with $0 \leq x \leq 0.8$ ($3 \times 10^{18}\,cm^{-3}$ Si-doped); 800 nm $Al_{0.8}Ga_{0.2}As$ lower cladding region ($3 \times 10^{18}\,cm^{-3}$ Si-doped); 48 nm GaAs lower core region (undoped): four 5·7 nm $In_{0.35}Ga_{0.65}As$ QWs separated by 20 nm GaAs barriers; 48 nm GaAs upper core region (undoped); 800 nm $Al_{0.8}Ga_{0.2}As$ upper cladding region ($1 \times 10^{18}\,cm^{-3}$ Be-doped); 100 nm graded $Al_xGa_{1-x}As$, with $0.8 \geq x \geq 0$ ($8 \times 10^{18}\,cm^{-3}$ Be-doped); 200 nm p^{++} GaAs top contact layer ($8 \times 10^{19}\,cm^{-3}$ Be-doped). The $Al_{0.8}Ga_{0.2}As$ cladding layers are GaAs/AlAs binary short-period superlattices [8, 9]. Structures were grown both with undoped MQW active regions and with *p*-type modulation doping in the QWs. In the MD case, a 4·5 nm Be-doped region ($2 \times 10^{19}\,cm^{-3}$) was placed above each QW, separated by a 3 nm undoped GaAs spacer. Lasers were fabricated with 3 μm wide mesas in a coplanar ground-signal-ground contact geometry [10], suitable for on-wafer microwave measurements. The lasers were cleaved to a length of 200 μm and indium-soldered onto copper heatsinks.

All measurements were made at heatsink temperatures of 25°C. Typical threshold currents, I_{th}, were 19 mA for undoped and 17 mA for MD devices. The CW optical power-current characteristics were linear up to 100 mA, with slope efficiencies of 0·26 mW/mA and 0·18 mW/mA per facet for undoped and MD lasers, respectively.

Relative intensity noise (RIN) power spectra in the range 100 kHz to 26·5 GHz were measured using an HP 70209A spectrum analyser, an HP 70620 low noise preamplifier and a New Focus 1011 photodiode. An optical isolator was used to suppress the influence of optical feedback on the RIN power spectra. The RIN power spectral densities were corrected for the noise floor of the preamplifier and fitted to a standard