but at the important pump wavelength around 1.49 μm, the contribution from OH was estimated to be <0.1 dB/km.

The $^{4}I_{11/2} - ^{4}I_{13/2}$ absorption band peak was 33 dB/km, from which we estimate the Er$^{3+}$ concentration to be 1 ppm. The dopant concentration was uniform over the 6 km length to within ±2%. With this rare-earth concentration, fibre lengths in excess of 1 km can be used as high-gain amplifiers whilst incurring negligible excess loss of pump or signal. It seems possible to fabricate fibres with still lower concentrations of Er$^{3+}$ to extend the amplifying medium further.

The absorption and fluorescence spectra of the low-concentration fibres were measured to determine if there were differences compared with higher concentration fibres, brought about by further isolating the individual ion sites. No differences were observed in the spectra or in the radiative lifetime of the transition. When pumped using a Ti:Sapphire laser at 980 nm, a 5 km of the lightly doped fibre was seen to lase in a cavity formed by the cleaved ends imperfectly matched with paraffin. The single-pass gain was estimated to be in excess of 35 dB, confirming this fibre as a high-gain medium. Introducing an external cavity grating reduced the linewidth of the oscillation to 15 MHz, comprising of many unstable longitudinal modes separated by 60 kHz intervals equivalent to the round trip cavity spacing.

Summary: We have investigated the background loss of Er$^{3+}$ doped fibres, and found that with solution-doped fibres, particularly those incorporating Al$_2$O$_3$ in the core, an excess loss due to Fe$^{3+}$ is present. This could be undesirable in amplification systems using long lengths of doped fibre. With GeO$_2$-SiO$_2$ core fibre prepared by the volatile halide method, excess loss could be virtually eliminated, and a 6 km length of fibre was fabricated with a uniform Er$^{3+}$ concentration of 1 ppm and a total loss of 0.73 dB/km at 1.5 μm wavelength. This result means that an efficient distributed amplification medium in excess of 1 km can now be realised.

Acknowledgements: The authors thank T. J. Whitley for the fibre laser measurements, R. Cecil and R. Smith for excellent technical assistance and the Principle General Manager of Components and Materials Research Department, British Telecom, for permission to publish this letter.

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FEMTOSECOND SOLITON AMPLIFICATION IN ERBIUM DOPED SILICA FIBRE

Indexing terms: Optical fibres, Doping, High frequency amplifiers

We report on the amplification of soliton pulses of less than 200 femtoseconds in an erbium doped single mode fibre. A gain of 2.6 times (~4 dB) was obtained for input signal peak powers of 50 W in 200 femtosecond pulses.

Introduction: The renewed interest in rare earth doped optical fibres has been stimulated by the need for optical amplifiers which can be easily integrated into fibre communication networks. Due to their 1.53 μm peak gain wavelength, erbium doped amplifier systems have recently been the subject of intensive studies with a maximum gain of 34 dB having been recorded. At the highest modulation rates of 2 Gbit/s yet reported small signal gains of up to 17 dB were measured using an argon ion pump source. Recently, an erbium doped fibre amplifier has been demonstrated as a repeater providing 20 dB gain for 1.2 Gbit/s intensity modulated signals transmitted over 218 km of single mode optical fibre. It has been proposed that increased bandwidths can be obtained in communication systems through the use of optical solitons and Nakazawa et al. have investigated picosecond soliton pulse amplification and transmission using an erbium doped fibre repeater.

In this letter we report initial results on the amplification of femtosecond soliton pulses in erbium doped silica based single mode optical fibre.

Experimental: The source of test signal pulses was derived from an optimised, cascade Raman soliton fibre ring laser. This laser when fully optimised, operating on the second Stokes band and synchronously pumped at 1.32 μm by a CW mode locked Nd:YAG laser, gave outputs in excess of 150 mW average power in a broad band centred around 1.5 μm. Within this broad spectral band several single solitons exist, the number of which and their temporal separation are not particularly controllable, a result of the soliton evolution from the amplification of noise. The intensity autocorrelation of the output integrates all the pulses and a typical pulse duration is of the order of 200 fs, with minimal durations of 100-120 fs being obtained. Since the spectral extent is far from...
transform limited, spectral selection can allow the generation of femtosecond pulses at specific central wavelengths. Through selection around 1.53 μm, the source of test soliton pulses was derived, with durations of 200 fs and average powers of up to ~80 mW. The pulses were coupled into various lengths of erbium doped, silica-based single mode fibre. This fibre had an erbium concentration of 200 ppm, a core diameter of 4.56 μm and an outer diameter of 115 μm. The profile of the fibre as a step approximation had a Δn of 0.014.

Pumping of the fibre amplifier in a counter-propagating arrangement was provided by a low average power (~1 W) CW argon ion laser at 514 nm, which enabled a maximum average power coupling of 300 mW into the fibre. The input pulse width and signal power were continually monitored, as was the output pulse width and pump power. A scanning second harmonic generation autocorrelator with a temporal resolution of approximately 50 fs was used for the pulse width measurements.

Results and discussion: Fig. 1 shows an autocorrelation of the spectrally selected input signal pulses with a measured duration of 200 fs. The pedestal component of the background free autocorrelation of these soliton pulses was less than one half percent, indicating that more than 55% of the average power was in the soliton pulse. The measured amplified spontaneous emission spectrum from the erbium fibre, for excitation at 514 nm showed the normal peak of the emission at 1553 nm with a secondary peak at 1550 nm. Giles et al. have reported an 11 nm, 3 dB gain bandwidth in erbium doped fibre, while Whitley and Hodgkinson have measured a 5 dB gain bandwidth of 3 THz (~23.5 nm). For reference, a transform limited 200 fs pulse would have a spectral width of 12.3 nm. However, it should be noted that the signal pulses used had bandwidths in excess of two times this width, simply limited by the spectral filter used. In the time domain, several randomly spaced solitons were present under the broad spectral envelope.

In Fig. 2 the effect of varying the pump power in a 4 m length of erbium-doped fibre on the output soliton intensity can be seen. The pump power in Fig. 2a was at the threshold for lossless propagation of the signal, as was determined using direct average power measurements, monitoring input and output at the soliton pulse wavelength. Fig. 2b on the same intensity scale shows the clear increase in the signal and the retention of the input 200 fs soliton pulse width for the maximum average pump power of 250 mW launched into the erbium doped fibre.

Fig. 3 shows the measured gain as a function of average power in the soliton signal for the maximum average pump power of 300 mW in a 10 m length of the erbium doped fibre.

Fig. 3 Measured gain against average power

At the high signal levels used, up to 50 mW average power (corresponding to approximately 2.5 kW peak power) saturation of the amplifier was apparent. On reduction of the signal level to around 1 mW, a gain of 2-6 times was recorded. It was however necessary to operate with signal levels in this regime, since the fundamental soliton power for a 200 fs pulse in our fibre was 22.5 W, which is equivalent to an average power of 0.45 mW.

It is possible that even at the lowest soliton signal power levels, a reduction in gain would occur because of the wide spectral extent of the probe signal pulse, which was ~30 nm. Since this erbium fibre is unable to provide its maximum gain over such a bandwidth, a reduced overall gain would be expected, caused by gain saturation at the peak and reduced gain in the spectral wings of the pulse. However, some temporal reshaping of the amplified signal pulses should be associated with this. This was not observed, although improved temporal resolution of the autocorrelation measurement system may be required to reveal this feature. At the highest signal levels, the low gain was a result of gain saturation of the system.

Conclusion: We have observed gains of 2-6 times (~4 dB) for 200 fs soliton pulses in erbium doped single mode silica based fibres, for signal levels around 1 mW average power (~50 W peak power). Similar gains have been recorded when operating the system using 120 fs signal pulses. A contribution to the low gains may be a result of the broad spectral bandwidth of the signal source. Operating at much lower signal levels would probably give rise to higher gains, however power levels would then be sub soliton and significant temporal reshaping and broadening of 200 fs pulses would be expected in gain lengths of the order of 10 metres. To maintain solitons in the work reported here, signal launched average powers greater than 0.5 mW were required.

Acknowledgment: The overall financial support for this work by British Telecom and the Science and Engineering Research Council is gratefully acknowledged. P. G. J. Wigley is supported by a BT-SERC CASE Studentship. B. J. Ainslie and K. J. Blow thank the director of British Telecom Research Laboratories for permission to publish.
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FABRICATION OF DOMAIN REVERSED GRATINGS FOR SHG IN LiNbO₃ BY ELECTRON BEAM BOMBARDMENT

Ind-soy terms: Lasers and laser applications, Crystals, Electron beam lithography

A novel technique for the lithographic definition and the fabrication of domain reversed regions in LiNbO₃ is reported, with application to periodic structures for SHG. For the first time, to our knowledge, domain reversal has been achieved on the negative c-face of the crystal. Such a structure should be useful for quasiphasematched second harmonic generation of infra-red laser radiation.

Introduction: Second harmonic generation (SHG) of infra-red radiation in lithium niobate (LiNbO₃) optical waveguides has been the subject of much research. Many nonlinear optical devices have been demonstrated using a variety of phasematching techniques including birefringence, modal dispersion and Cerenkov radiation. An alternative method, known as quasiphasematching, has been demonstrated recently for SHG in integrated optical waveguiding structures. Quasiphasematched SHG is best achieved by periodic reversal of the sign of the nonlinear coefficient $\chi^{(2)}$ of the material and is potentially a very efficient method of achieving SHG. By appropriate choice of the period of the modulation, it is possible to phasematch for any arbitrary fundamental wave-length.

It is known that titanium indiffusion at temperatures near the Curie temperature of congruent LiNbO₃ (1140°C) can result in domain reversal on the positive c-face of LiNbO₃ but not on the negative c-face. Outdiffusion of LiO₂ can also lead to domain reversal on the positive c-face. Both of these techniques have been used to produce periodic domain reversed gratings for quasiphasematched SHG. It is, however, often the negative c-face which is preferred for waveguide fabrication. We report here, for the first time, periodic domain reversal on the negative c-face, which has been achieved by electron beam bombardment of the negative c-face at temperatures well below the Curie temperature. To realise the periodic structure it is necessary to use a periodic metallic mask to prevent the penetration of the electron beam into the crystal. This paper will report on the design and fabrication of such a mask and also on the technique for subsequent formation of a periodic domain reversed structure on the negative c-face of the crystal. This technique leads to a domain reversed grating, but avoids completely the titanium indiffusion or high temperature outdiffusion requirements of the other techniques.

Grating fabrication: There are three requirements that must be satisfied so that a domain reversed grating can be fabricated by electron beam bombardment and exploited successfully for SHG. These requirements are: the correct periodicity in the first order grating to compensate for the phase mismatch between the fundamental and the harmonic waves, a masking layer that can absorb the electrons efficiently in the regions where domain reversal is not desired and, finally, it must be possible to provide an electrical contact to the grating so that a poling field can be applied to the crystal. A schematic diagram of the required grating structure is shown in Fig. 1.

![Fig 1 Arrangement for domain reversal by electron beam bombardment](image)

The period required for a first order grating to obtain quasiphasematched SHG of 1.06 pm laser radiation was experimentally estimated to be 3.4 pm for a z-cut proton exchanged waveguide with a waveguide depth chosen to optimise the conversion efficiency for SHG. Gold was chosen for the mask since it is an efficient absorber of electrons and is compatible with standard photolithographic techniques. Using a Monte Carlo simulation of the Bethe relation, the depth of penetration of electrons in both LiNbO₃ and gold was calculated as a function of the incident electron energy. The Bethe relation is only strictly valid for electron ranges calculated in single elements. In the both model, the penetration depth is dependent on the atomic number and the mass number of the element and also on the ionisation potential of the element. To calculate the electron range in the LiNbO₃, the compound was treated as a single element, with the atomic number, the mass number and the ionisation potential being approximated by calculating a weighted average for each using the appropriate values of atomic numbers and atomic masses for lithium, oxygen and niobium respectively. Fig. 2 shows a graph of penetration depth as a function of incident electron energy. This calculation does not take account of the temperature of the substrate and it would be expected that, at the temperatures to be used for domain reversal, the electron energies required will be greater than those indicated by our analysis, due to increased scattering. The penetration depth of 1 pm in the LiNbO₃ was chosen to be greater than the depth of the waveguide to be