Multicore rare-earth doped fibres; application to amplifiers, filters and lasers

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FINAL REPORT

INTRODUCTION

Wavelength division multiplexing (WDM) is the preferred choice for expanding the capacity of optical communication systems. Using this technique bit rates exceeding 1 Terabits/s have been demonstrated. However to fully exploit the potential of WDM several key device developments are required. This report describes the results of an experimental program *Multicore rare-earth doped fibres; application to amplifiers, filters and lasers* funded under the ROPA scheme and targeted at new devices for WDM applications. The proposed program covered a three year program however funding was only awarded for two years. The key thrusts of the original submission were to introduce spatial hole burning into rare earth doped devices to controllably induce effective inhomogeneous broadening into the gain/loss medium. It was proposed to develop and optimise twincore erbium doped fibres to provide spatial hole burning and thus effective inhomogeneous broadening in the gain/loss medium. The development of channel equalising optical amplifiers, multi-wavelength and single frequency fibre lasers as well as passive tracking optical filters was targeted. These objectives were met. In addition multi-wavelength DFB fibre lasers have been developed as telecommunication sources and also applied to in-line pump a polarisation insensitive phase conjugator and as an active fibre temperature and strain sensor. Finally, a multi-wavelength (12 channel) Brillouin fibre laser has been demonstrated.

TECHNICAL PROGRESS

1. Twincore erbium doped fibres

A twincore erbium doped fibre device, in this case a twincore EDFA is shown schematically in figure 1. The signals (λ_1 & λ_2) and pump are input into one core however as they propagate they couple from core to core with different periods, proportional to λ^{-3}. As a result the two signals access a different subset of ions and their gain and saturation are partially decoupled. At the far end the output is taken from both cores by selecting the even mode of the structure.

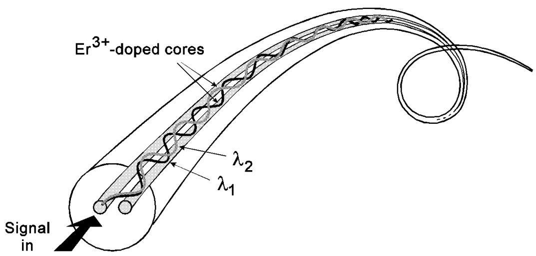

Figure 1: Schematic of twincore fibre

As a result of this work the fibre design has been optimised in several respects to enhance the device performance [1-5]. Key issues considered were input and output coupling, coupling period, device length (erbium concentration) and polarisation sensitivity. Figure 2 shows an end picture of an optimised twincore fibre. Here the outer fibre diameter is ~125 microns, the core NAs are 0.23 with 1.4 micron radii and 4.5 micron core separation. These fibre parameters resulted in a coupling period of 1.2 mm. The erbium concentration (8 dB/m) was optimised to give a short device length of several metres. Because the twincore fibre is an azimuthially

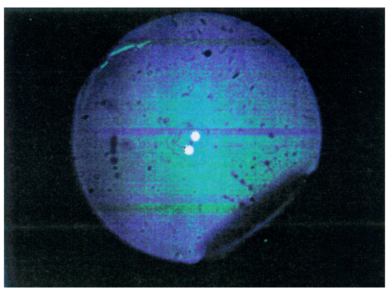

Figure 2: End picture of optimised twincore fibre

asymmetric structure it exhibits some inherent birefringence leading to polarisation sensitivity. However this was minimised by fibre design (increasing the core-to-core separation) and in addition preform spinning during fibre drawing was employed to eliminate birefringence. Two techniques, tightly bending the fibre or tapering were investigated and employed at the output of the twincore fibre to cutoff the odd mode and select only the even mode thus ensuring practical wavelength independent output coupling.

1.1 **Channel equalising amplifiers**

High capacity long distance and reconfigurable WDM optical networks are currently being installed. However, due to the combination of the non-uniform gain spectrum and the predominantly homogeneous properties of erbium ions in silica glass the different wavelength channels will diverge in signal strength after several stages of amplification along a link. Considerable progress has been made in broadening and flattening the gain spectrum of EDFAs by choice of material composition, incorporating filters and careful design optimisation. Even so, when link powers change, for example by adding or dropping signal powers this will change the gain of the amplifiers thus modifying their gain spectrum. Some form of active equalisation is required. In this project we have designed and optimised twincore EDFAs that induce inhomogeneous broadening in the gain medium at room temperature [1]. It is demonstrated that the TC-EDFA can passively compensate for the wavelength dependence of the erbium gain spectrum thus allowing non-divergent and self regulating propagation of individual channel powers in a 910km WDM link [1-4].

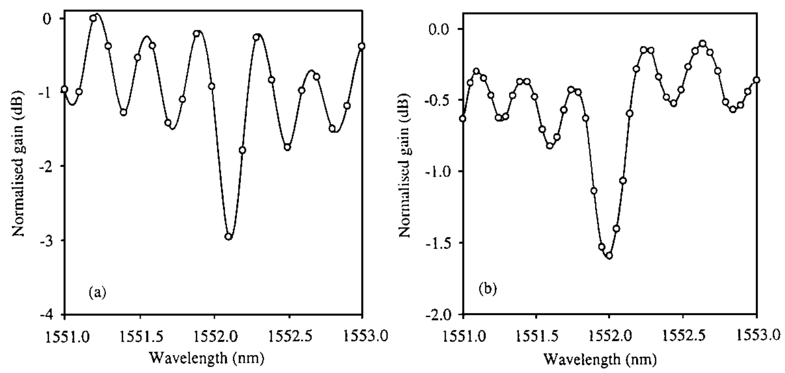

Figure 3(a,b): Spectral holes for co- and counter- pumped amplifiers

Spectral gain holes in the amplifier were characterised using a weak wavelength scanning probe in the presence of a strong saturating signal. Figure 3 shows measured spectral gain holes for co- and counter-pumped TC-EDFAs. Here the amplifier is pumped with ~100 mW at 980 nm and the saturating input signal 2 mW. The nominal gain is ~13 dB. It can be observed that strong gain holes upto ~3 dB are observed. Figure 4 illustrates the dependence of hole depth on input power from which it can be seen that the hole depth reduces with reducing signal power. These measurements were taken at room temperature and agree with the theoretical predictions (dashed line). These characteristics form the basis of spectral equalisation.

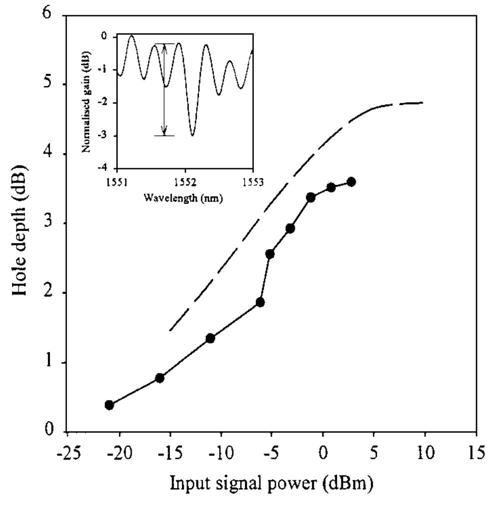

Figure 4: Dependence of gain hole strength on input power

Four multiplexed channels (1550, 1551, 1552 and

1553 nm) were launched into the TC-EDFA. To simulate a WDM link employing a cascade of identical TC-EDFAs a single stage amplifier and a feedback technique were used. The interstage loss is 13 dB corresponding to an amplifier spacing of 65 km assuming a fibre loss of 0.2 dB/m. For a comparison the same test was performed with conventional EDFAs operating under identical conditions.

Figures 5a and b show the output powers for the TC-EDFA and the conventional EDFA both at room temperature. The 14 stage link corresponds to a total distance of 910km. To demonstrate the self regulating properties of the TC-EDFAs, an extra 5 dB loss was introduced at 1553 nm after the fifth stage. In the case of the conventional EDFA, the different wavelength channels slowly spread as the number of stages is increased (figure 5b), where as in the case of the TC-EDFA the channels are self regulating (figure 5a). In figure 5c the powerspread is plotted showing that the TC-EDFA is self-healing with ~0.2 dB per stage clearly demonstrating the inhomogeneous properties of the TC-EDFA. This is in excellent agreement with theoretical predictions.

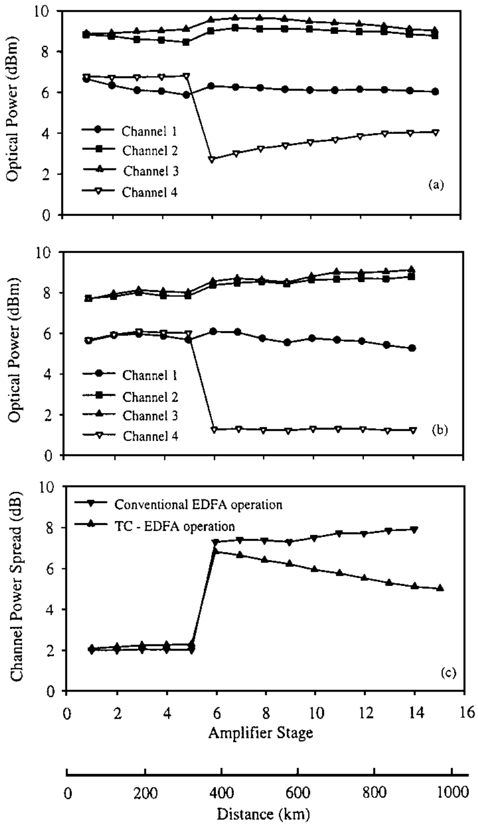

Figure 5 (a-c): Output powers for the TC-EDFA and conventional EDFA link

1.2 **Multi-wavelength and single-frequency fibre lasers**

Incorporation of TC-EDF into a unidirectional ring laser cavity allows the generation of multi-wavelength and single frequency laser operation. Figure 6(a,b) show schematically the operation of a TC-EDF and conventional EDF ring laser. Whereas the conventional EDF based laser operates on one mode at the peak of the gain, spectral hole burning in the TC-EDF allows multi-wavelength operation.

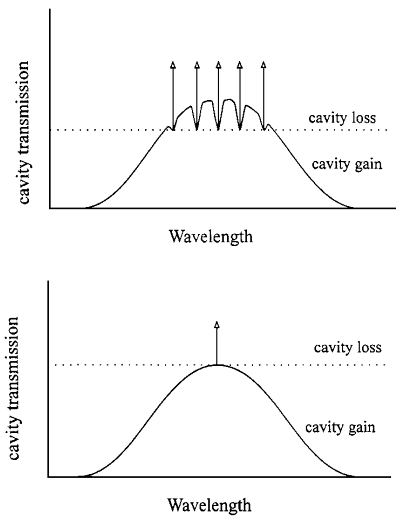

Figure 6: Schematic of operation of TC-EDF and conventional EDF ring lasers

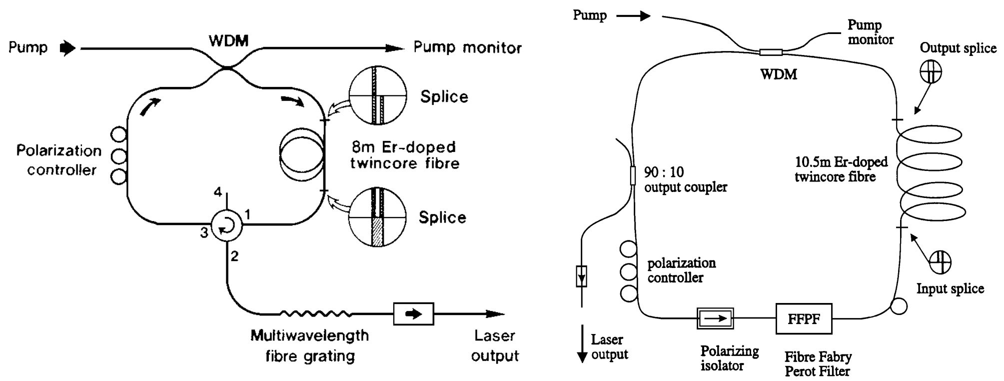

Figure 7 (a,b): Multichannel twincore EDF ring lasers

Figures 7(a,b) show two laser configurations tested employing either fibre gratings [5] or Fabry-Perot filters [1] to define the precise operating wavelength. Figure 8 shows that upto 8 lasing wavelengths were obtained. Separate measurements confirmed that these were each single frequency with linewidths of ~10 kHz.

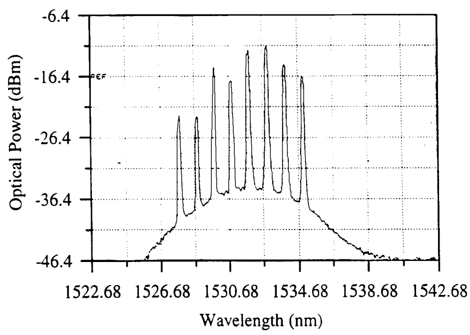

Figure 8: 8 channel output of TC-EDF laser

1.3 **Tracking optical filters**

By employing the TC-EDF as an unpumped saturable absorber rather than an amplifier a passive tracking filter can be created. Figure 9 shows typical filter characteristics. At the outset of the project it was envisaged that these would be employed as sliding filters in long distance soliton links. However parallel developments of partial dispersion compensated soliton systems in my group [*A.B.Grudinin, M.Durkin, M.Ibsen, R.I.Laming, A. Schiffini, P.Franco, E.Grandi, M.Romagnoli, Straight line 10Gbit/s soliton transmission over 1000 km of standard fibre with in-line chirped fibre grating for partial dispersion compensation, Electron. Lett. 1997 Vol.33 (18) pp.1572-3*] and others worldwide has led us not to pursue this technique farther.

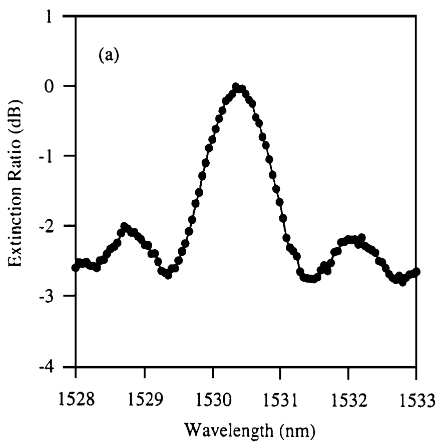

Figure 9: Twincore filter response

2. **DFB fibre lasers**

By combining erbium-Ytterbium co-doped fibre and fibre gratings technology we can create robust single frequency DFB fibre lasers. These lasers are typically 5 cm in length and currently exhibit output powers upto 20 mW with linewidths of a few kHz. DFB fibre lasers can employ polarisation dependent gain competition to cause dual polarisation operation. Alternatively, recently we have also achieved robust single polarisation operation by use of polarisation dependent grating strength achieved via optimising the grating writing conditions. Being defined by the fibre grating the wavelength of operation is extremely stable and suitable for use in WDM networks [6]. Although not included in the original proposal subsequent developments in fibre grating and DFB fibre laser technologies at the

Optoelectronics Research Centre (ORC) gave new opportunities to create multi-wavelength sources which were thus included in the program.

2.1 **Multi-wavelength sources**

Recent advances in our fibre grating fabrication technology has allowed overlaying of two or more fibre DFB gratings in the same doped fibre. In this way several wavelength operation is promoted since spatial hole burning and gain competition is established in the cavity. Figure 10 shows the output of the first two channel Moiré DFB. Both channels are now single frequency with precise wavelengths and separation defined by the grating structure.

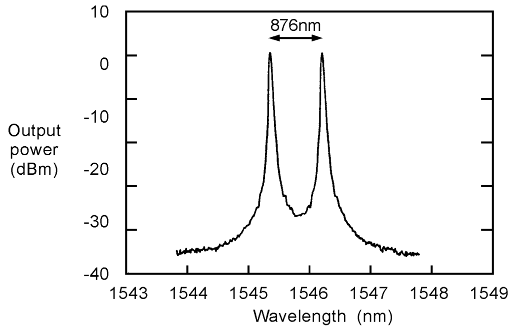

Figure 10: Dual wavelength fibre DFB

2.2 **In-line polarisation insensitive phase conjugators**

Dual polarisation DFB lasers have been used for the first time as in-line pumps for polarisation insensitive optical phase conjugators. A schematic of the system is shown in figure 11 [7-9]. Birefringence in the doped fibre ensures that the two orthogonally polarised laser outputs are also separated in wavelength. A 40 Gbit/s dispersion compensated transmission test over 204 km of standard fibre in collaboration with BT Labs confirms the potential of this type of scheme [10].

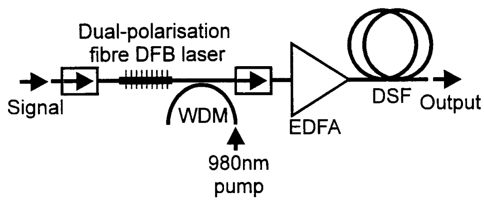

Figure 11: In-line polarisation insensitive phase conjugator

2.3 **Active fibre sensors**

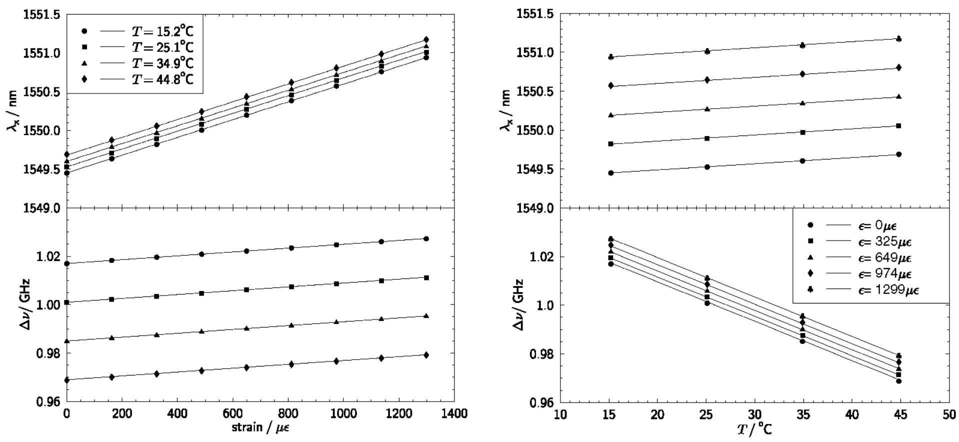

Figure 12: Stain and temperature sensitivity of active DFB sensor

By combining dual polarisation and dual wavelength (Moiré) technologies gives four laser outputs. Careful monitoring of the absolute wavelengths and RF beat signals between the different modes has allowed us to measure both the length change and birefringence change in the DFB fibre laser [11]. From this the applied strain and temperature can be computed. Figure 12 shows measurements of strain and temperature. Initial measurements indicate a high resolution of 0.04 degrees C and 3 micro strain are obtained due to the precision of the wavelength measurement via the active laser wavelength.

3. **Multi-wavelength Brillouin fibre laser**

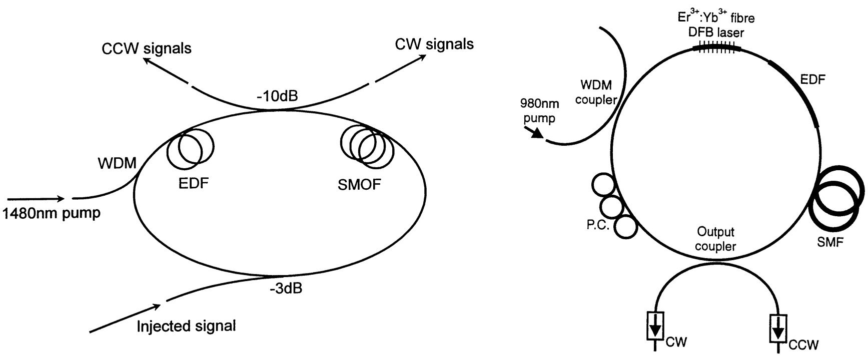

Figure 13 (a,b): Multi-wavelength Brillouin/erbium fibre ring lasers

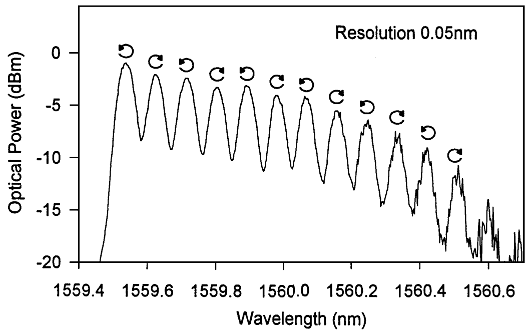

Figure 14: Multiple wavelength operation of BEFL source

Brillouin/Erbium fibre lasers (BEFL) have recently been demonstrated as a novel mode of operation of fibre lasers, using both the gain of an erbium doped fibre (EDF) and Brillouin gain in single-mode optical fibre. BEFLs can be configured to produce laser combs, with potential applications in dense wavelength division multiplexing. We have developed two novel BEFL sources. In the first (figure 13a) a laser is employed to injection lock the ring resonator, and which then seeds the BEFL modes [12]. In the second configuration (figure 13b) a DFB fibre laser is incorporated into the ring cavity seeding Brillouin laser operation [13,14]. Figure 14 shows a typical output where over 10 lasing modes are observed.

SUMMARY

The original objectives have been met in full. TC-EDFAs with reduced polarisation sensitivity and improved input and output coupling design have been developed. In addition demonstration of a self-regulating 910 km WDM link has confirmed their advantages. Employing TC-EDF in a ring laser allowed the generation of a multi-wavelength (8 channels) and single frequency fibre laser. An initial demonstration of a TC-EDF self-adjusted filter was performed but the concept not pursued further owing to other developments in the field of soliton control.

In addition advances in fibre grating fabrication at the ORC have facilitated the development of robust single-polarisation and multi-wavelength DFB fibre lasers. Spatial hole burning is again employed in the laser cavity to ensure multi-wavelength operation. These lasers have been developed and tested as telecommunication sources, applied to in-line pump a polarisation insensitive phase conjugator which was tested at 40Gbit/s at BT Labs and employed as an active fibre temperature and strain sensor. Finally multi-wavelength (12 channel) Brillouin fibre lasers were demonstrated employing fibre DFBs as pumps. These latter two multi-wavelength devices were not envisaged in the original proposal but were subsequently included as an alternative emerging technology due to advances in fibre gratings technology made at the ORC.

ACKNOWLEDGMENTS

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