Polarisation coupling between sections. The DGD elements generate electrically-driven polarisation controllers that generate uniform polarisation coupling across sections. The emulator has three variable DGD elements separated by two sections. The Q measurement is performed using the method presented in [6]. The Q measurement is accomplished by applying a biased DGD distribution to each section (chosen to emphasise the region of interest) and then appropriately weighting the results to obtain the proper probability density function (pdf). Instead of applying Maxwellian-distributed DGDs to each section (the conventional, unbiased case), an unbiased Manwellian (-750 ps average DGD) is applied to each section to cause the emulator to generate more events, we employed importance sampling (IS) is accomplished by applying a biased DGD distribution to each section (the conventional, unbiased case), with programmable DGD elements. Proc. of Conf. on Optical Fiber Communication (OFC), Atlanta, GA, USA, March 2003, Paper TuS.6.

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Suppression of temperature-dependent gain variation of conventional EDFA by hybrid connection of antimony-doped silica EDF

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A new technique to suppress temperature dependence of EDFA gain is proposed and experimentally demonstrated. A specially designed EDF, the glass host of which is Sb-doped silica, showed an opposite sign of temperature dependent gain coefficients in C-band compared to Al-doped silica EDFs. Concatenation of those two EDFs showed an improved gain variation less than ±0.37 dB for the saturated gain over 15 dB, within -40 to +80°C.

Introduction: As the technical concerns in optical communications move to metro access networks from the long-haul transmissions, one of the important issues for optical components has been suppression of temperature dependent deviations in their performances to provide cost-effective solutions. One of the solutions in the light sources is uncooled laser diode [1], which can eliminate temperature-control electrical circuits and consequently reduce power consumption.

In the case of erbium-doped fibre amplifiers (EDFAs), however, the gain characteristics have been always treated as temperature-dependent [2] and only a limited effort has been reported to provide ‘uncooled solutions’. A method to inherently compensate the temperature dependent gain has been suggested in theory using a serial connection of silica-based EDF to fluoride-based EDF [3].

This method, however, suffers from splicing between two different types of EDFs as well as the environmental durability of fluoride-based EDF. It is, therefore, highly desirable to develop a special EDF the temperature dependent gain coefficient of which could cancel out that of conventional EDFs and furthermore the fibre needs to be based on high silica in order to meet the reliability requirements and splicing conditions.

In this Letter, we report a new technique to suppress temperature dependence in EDFA gain in C-band concatenating conventional EDF with high Al contents to a special EDF the glass host of which is Sb-doped silica, for the first time to the best knowledge of the authors.

Experiments and results: It was reported that an EDFA with Sb-doped multi-component silicate (MCS) glass host showed extension of gain bandwidth [4] as well as reduction of gain ripple in a hybrid configuration with Al-doped silica EDF [5]. Sb-doped MCS fibres prepared by crucible methods, however, are prone to be less reliable than high silica counterparts and require a special splicing technique.

Recently, a binary has been reported by the authors [6], with a high UV photosensitivity along with an enhanced temperature stability of fibre gratings. We have extended the same sol-gel-based fabrication technique [6] to dope Er3+ ions in the antimony oxide-silica glass, and prepared two fibre samples, Sb-EDF 1 and Sb-EDF 2. The compositions of glass hosts were estimated as around 3.5 mole% antimony oxide and 96.5 mole% SiO2 for Sb-EDF 1 and 6% antimony oxide, 1% Al2O3, and 93% SiO2 for Sb-EDF 2. The synthesised preform was drawn into fibre with a cladding diameter of 125 μm and the LP11 mode cutoff wavelength was located around 850 nm. Peak absorption at 1531 nm was measured to be 14.5 dB/m for Sb-EDF 1 and for Sb-EDF 2 the peak at 1531.5 nm was 85 dB/m. The fibres showed a background loss ~0.5 dB/m measured at 1200 nm, which was mainly attributed to OH loss. Splice loss to a conventional singlemode fibre, such as coming from SMF-28, was ~0.2 dB.

To measure temperature dependent gain of EDFs, a bidirectionally pumped two-staged EDFA was configured. Input optical signals were more than 19 channels, the outputs of which were multiplexed through an arrayed waveguide grating (AWG) and then inserted into a VOA to adjust the total input power level to ~2 dBm. The gain characteristics were measured from ~40 to +80°C with the gain medium inside a temperature-controlled chamber.

Firstly, the temperature dependent gain of a commercial Al-doped silica EDF, OFS-MP90, 10 m long, was measured as a reference. The gain spectra are shown in Fig. 1a, and their deviations with respect to the...
value at 20°C are presented in Fig. 1b. In the wavelength range from 1525 to 1565 nm with 20 input channels, it is found that the gain varied by a maximum of about ±1 dB from −40 to +80°C. As reported in [2], a large gain variation is observed at the wavelength range around 1525 nm.

Secondly, the temperature dependent gain of antimony-doped silica EDFs, Sb-EDF 1 and 2, was measured similarly with 19 input channels. In this case, however, the length of EDFs and the pump power were adjusted so that the gain levels at two peaks 1535.6 and 1552.4 nm would be equivalent. The fibre lengths were 3.5 m for Sb-EDF 1 and 30 cm for Sb-EDF 2. The measured gain variations according to temperature are shown in Fig. 2. For Sb-EDF 1, the gain variation was under ±0.75 dB from −40 to +80°C. Note that the gain deviation of Sb-EDF 1 in Fig. 2a shows the opposite sign in some wavelength ranges compared to that of OFS-MP980 in Fig. 1b. For 30 cm of Sb-EDF 2, shown in Fig. 2b, the gain deviation was within ±0.32 dB, which is a significant improvement over commercial EDF. Sb-EDF 2 also showed opposite signs of gain deviation in certain wavelength ranges. This fibre, however, showed only a few dB gain due to low efficiency and high Er concentration and, therefore, was used along with commercially available OFS-MP980 to improve gain and output power, which will be discussed below.

Based upon above observations, we propose that the overall temperature dependence of an EDFA could be inherently suppressed by concatenating Sb-EDFs with commercial EDF in certain wavelength ranges within the C-band where their temperature dependent gain deviations show opposite signs. Note that Sb-EDFs are mechanically compatible to conventional SMF as well as to commercial EDFs due to the high silica nature. The proposed configuration of EDFs could serve as an essential gain block for access networks significantly and reduce the burden of electrical temperature control.

To implement the idea, two kinds of hybrid configurations were experimented: (1) a segment of Sb-EDF 1 of 3.2 m inserted between two OFS-MP980 fibre segments, each 2 m long, and (2) 30 cm of Sb-EDF 2 inserted between 5 and 2 m of OFS-MP980. The measured gain deviations from the hybrid amplifiers are presented in Figs 3a and b, respectively. In Fig. 3a, wavelength ranges were found where temperature dependence was very low, especially from 1537 to 1547 nm, with the average gain variation < ±0.2 dB. From 1555 to 1565 nm, the gain variation was < ±0.16 dB. In Fig. 3b, most of the channels from 1525 to 1565 nm were stabilised within ±0.37 dB. In these configurations, the 980 nm pump was adjusted so that the average saturated gains were maintained around 15 dB, similar to the reference gain spectrum shown in Fig. 1.

Conclusion: A new technique to suppress temperature dependence in EDFA gain was demonstrated, concatenating Sb-doped silica EDFs between commercial EDF segments. Two types of Sb-doped silica EDF were fabricated that showed opposite signs in temperature dependent gain deviation compared to that of a commercial EDF. In hybrid configuration with OFS-MP980, Sb-EDF 1 gave a gain band more than 20 nm with a gain variation < ±0.2 dB and Sb-EDF 2 showed more than 30 nm bandwidth < ±0.37 dB. Even though the fibre composition, length, and pump power were not fully optimised yet, preliminary results show a strong potential to inherently suppress the temperature dependence in EDFA gain, to ultimately provide an "uncooled solution" to fibre amplifiers that could be readily applied in optical access networks.
Ytterbium-doped large-core fibre laser with 272 W output power

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A highly efficient cladding-pumped Yb-doped large-core fibre laser, generating up to 272 W of continuous-wave output power at 1.08 μm with a beam quality (M²) of 3.2, is reported. The slope efficiency was 83% with respect to the launched pump power. No saturation (roll-off) was observed in output power with increasing pump power.

Introduction: The continuous-wave (CW) output powers of fibre lasers operating with ytterbium (Yb)-doped fibres continue to grow and such lasers are now beginning to compete with conventional solid state lasers (e.g. Nd:YAG lasers) in many application areas. Fibre lasers benefit from a geometry that allows simple thermal management and a high beam quality. By applying the technique of cladding-pumping, fibre lasers with high-brightness, even diffraction-limited, output can be realised, even when low-brightness diode lasers are used as pump sources. Yb-doped fibre lasers offer a broad emission spectrum extending from ~1 to ~1.1 μm and can provide an excellent conversion efficiency of over 80% due to the low quantum defect when pumped with radiation around 915 or 975 nm. The low quantum defect and beneficial geometry make cladding-pumped Yb-doped fibre lasers (YDFLs) an ideal candidate for high-power sources operating around 1 μm. Recently, for example, 2 kW of output power was reported from highly multimoded devices that combined the output power from several fibre lasers [1].

The output powers achieved from close to diffraction-limited laser configurations are still somewhat lower. A 110 W cladding-pumped YDFL with an M² value of 1.1–1.7 and a conversion efficiency of 58% with respect to the incident pump power was reported in 1999 [2]. More recently, a 135 W YDFL with an M² value of 1.05 and a slope efficiency of 51% with respect to the total optical diode pump power was reported [3]. In both of these publications, fibres with relatively small cores of ~9 μm diameter were used. As a consequence of the long length of fibre used in these experiments (~60 m) and the small core, stimulated Raman scattering (SRS) limited the maximum achievable output power in [3]. Use of a larger core is preferable to realise further power scaling (assuming that good spatial mode quality can be maintained) because the effects of Raman scattering can be reduced via the corresponding reduction in the power density. Use of shorter fibre lengths as possible also helps to increase the SRS threshold. Maximising the pump absorption by fibre design, doping concentration (whilst maintaining good efficiency), and the choice of pump wavelength, is thus an important issue when developing high-power, high-brightness, fibre lasers.

Fig. 1. Yb-doped fibre laser arrangement with diode-stack pump source

HR: high reflectivity; HT: high transmission

Besides the recent results of YDFLs, high-power dual doped fibre lasers have started to be explored, in which the core was doped with Nd and Yb. The pump power was wavelength-multiplexed as 350 W at...