($N = mn$), $m + 1$ GFs and n GRs are required per circuit for $n - 1$ circuits (in this example, $N = 32$ and $n = 2$). In a conventional tunable filter using the full FSR range, m GFs and n GRs are required for all circuits. The increase in the number of optical gates is only one per circuit at most.

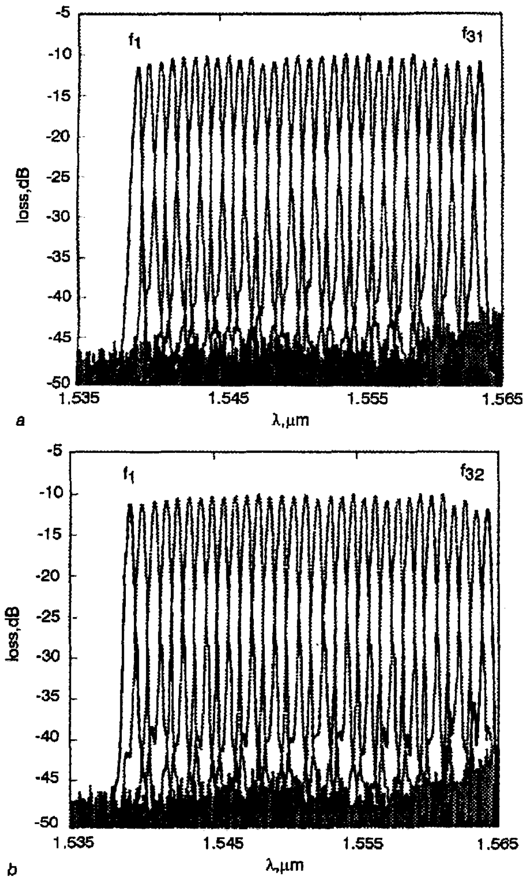

Fig. 2 *Measured transmission characteristics for 32 channel selection*

a Circuit 1
b Circuit 2

Experiment: We used a pair of silica-based fibre-pigtailed 32 × 32 wavelength routers. These were similar to the wavelength router reported in [5]. The wavelength channel spacing was 100GHz (0.8nm). The FSR and centre wavelength were 6400GHz and 1551.72nm. The optical gates were simulated by manually connecting and disconnecting the corresponding fibres with fibre connectors. The filter transmission characteristics were measured using the amplified spontanous emission noise of a fibre amplifier as the white noise source.

Fig. 2 shows the measured transmission characteristics for all 32 selected channels in each output port. The loss included the dividing loss of the divider and transmittance loss of the wavelength routers but did not include coupling losses. Because of the lack of b_{33} in WR1 and a_{34} in WR2 in this experiment setup, channel f_{32} cannot be selected in circuit 1. The maximum and minimum losses are −12.1 and −10.1dB, respectively. The loss variation is 2.0dB.

Summary: We have proposed a fast tunable filter with low loss and low loss imbalance by using only the centre port of wavelength routers with a reduced number of optical gates. Channel selection with two output ports was demonstrated for 100GHz-spaced 32 channel selection.

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Chirped-fibre-grating-based optical limiting amplifier for simultaneous dispersion compensation and limiting amplification in 10Gbit/s G.652 fibre link

S.L. Tzeng, H.C. Chang and Y.K. Chen

A chirped-fibre-grating-based erbium-doped optical limiting amplifier (CFG-OLA) is experimentally demonstrated. Both high constant output power of >15dBm with large dynamic range of >15dB and dispersion compensation capability can be achieved simultaneously in a 10Gbit/s standard (G.652) singlemode fibre link of 80km. A satisfactory power penalty can be obtained when the CFG-OLAs are used as power and in-line amplifiers.

Introduction: Chirped fibre gratings (CFGs) [1] are promising candidates for use as dispersion compensators for high bit rate (≥ 10Gbit/s) transmission over standard (non-dispersion shifted) fibres [2, 3], or G.652 fibres according to ITU-T recommendations, because they are compact, passive, low-loss, and can provide large differential group delay. Because the compensated signal is back-reflected, an optical circulator (OC) is commonly required to separate the input from the output of the device. For the CFG-compensated systems reported to date, the erbium-doped fibre amplifier (EDFA) used for compensating the span loss is always located between the preceding singlemode fibre (SMF) span and the OC. However, the insertion losses of the OC and CFG attenuate the compensated signal and thus result in a reduced power budget in the system link.

The optical limiting amplifier (OLA) [4], which provides a constant output power within a large input signal regime, has been demonstrated to facilitate easier network implementation. In this Letter, we investigate a CFG-based OLA (CFG-OLA) by placing a bidirectional EDFA between the OC and the CFG. Such an arrangement not only enables dispersion compensation to be realised, but also offers high constant output power. The output power, dynamic range and power penalty are investigated. Issues concerning performance improvements are also addressed.

Amplifier configurations and experiments: The configurations of conventional CFG-EDFA (configuration A) and proposed CFG-OLA (config. B), and their experimental setup are shown in Fig. 1. Each bidirectional EDFA (B-EDFA, because of no built-in optical isolators), employing a bidirectionally dual-pumping scheme, consists of two 1480nm pump lasers, two 1.48/1.55μm wavelength selective couplers (WSCs), and a piece of EDF. Each pump laser has an output power of 70mW, and an EDF (Lucent MP980) with an optimal length of 10m is used. The spectral characteristics of this apodised CFG are also shown at the bottom of Fig. 1. The 1552.53nm CFG, providing a dispersion of ~–1480ps/nm, has a reflectivity of 67% and a 3dB bandwidth of 0.51nm. The grating should thus be able to compensate for 87km of G.652 fibre. The total insertion loss of the CFG and OC is 5.6dB, which is mainly due to the low reflectivity of the CFG used.

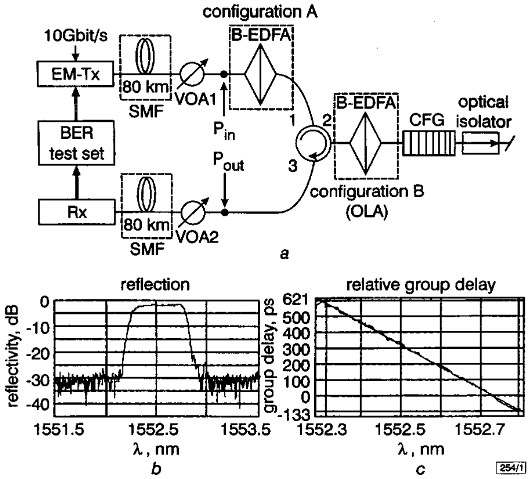

Fig. 1 *Experimental setup with conventional EDFA (configuration A) and proposed CFG-OLA (configuration B), and spectral reflection and group delay characteristics of used CFG*

a Experimental setup
b Spectral reflection characteristics
c Group delay characteristics

At the transmitter, CW light from a DFB laser at 1552.53nm is externally modulated at 10Gbit/s by an $LiNbO_3$ intensity modulator. An NRZ pseudorandom bit sequence with length of 2^{23}–1 is used as the modulating data. In the experiments, the CFG-OLA and CFG-EDFA modules were characterised separately in a system link. For a system with an amplifier input signal power, P_{in}, in the range –18 to –5dBm, an 80km SMF was located after port 3 of the OC; the 80km SMF was then moved before port 1 of the OC for P_{in} < –18dBm. The launched signal power into the 80 km link was controlled by the appropriate variable optical attenuator (VOA) so as to remove the effect of fibre nonlinearities. The amplified signal output power, P_{out}, was measured at port 3 of the OC. The receiver sensitivity of the *pin* receiver, measured by a bit error rate (BER) test set, at BER = 10^{-11} was –16.8dBm.

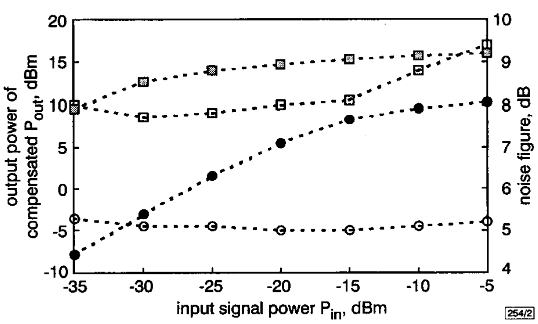

Fig. 2 *Compensated signal output power P_{out} and noise figure characteristics of proposed CFG-OLA and conventional CFG-EDFA*

● P_{out} (CFG-EDFA)
■ P_{out} (CFG-OLA)
○ NF (CFG-EDFA)
□ NF (CFG-OLA)

Results and discussions: Fig. 2 shows the signal output power P_{out} and the noise figure (NF) characteristics of the CFG-OLA and CFG-EDFA against P_{in}. Note that the CFG-OLA exhibits 'hard limiting' characteristics, and the dynamic range, defined as the 3dB output-power compression, is ≥ 25dB, i.e. from –30 to –5dBm. An output power ≥ +13dBm can be achieved within the dynamic range at the expense of a rather high NF of 7.6–9.5dB, which was attributed to the high signal-spontaneous (S-SP) beat noise, and the amplifier saturation effect at large input signal power. In contrast, a typical NF of ~5dB was obtained for the CFG-EDFA. However, for this 'soft limiting' CFG-EDFA, a low output power of ≤ +8dBm occurred within the 11dB dynamic range because the compensated signal was attenuated by the insertion loss of the CFG and OC.

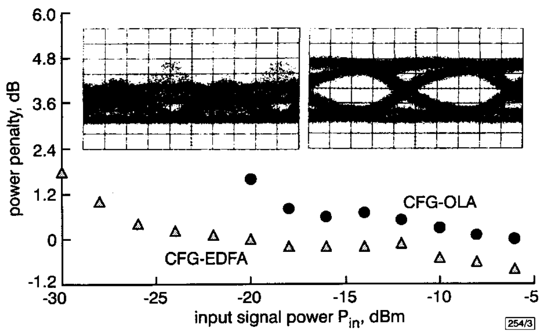

Fig. 3 *System power penalty of CFG-OLA and conventional CFG-EDFA against input signal power, P_{in}*

Inset: left and right eye patterns correspond to 80 km system link at received power of –16dBm without and with CFG, respectively, in OLA with P_{in} = –16dBm
● CFG-OLA
▲ CFG-EDFA

Fig. 3 shows the system power penalty of two amplifiers at BER = 10^{-11} against P_{in}. A negligible power penalty of 0dB is achieved when the CFG-OLA operated as a power amplifier with P_{in} = –5dBm. However, the power penalty increases to > 1dB when the CFG-OLA operated as an inline amplifier with P_{in} = –20dBm. This is mainly due to the poorer optical signal-to-noise ratio and the increased S-SP beat noise, caused by the amplified spontaneous emission being within the stopband of the CFG due to the insufficiently narrowband filtering which is detrimentally increased by the double-pass amplification, especially for small P_{in}. Thus, the dynamic range is reduced from 25 to 15dB, which stops the 1480nm pumped CFG-OLA from being a competent optical preamplifier. The right-hand eye pattern in the inset of Fig. 3 corresponding to the 80km system link, at a received power of –16dBm, with a CFG-OLA (where P_{in} = –16dBm) was quite open and clear compared with the left-hand eye diagram for the system without a CFG. Although P_{in} can be as small as –25dBm for the CFG-EDFA to keep power penalty to < 1dB, the low output power of +5dBm makes it unable to provide a sufficient power budget for the fibre span. The negative power penalty for the CFG-EDFA was due to the slightly positive chirp of the transmitter combined with the larger negative dispersive CFG. Therefore, the experimental results confirm the feasibility of the CFG-OLA.

To improve the system performance of the CFG-OLA, the following approaches can be used. First, the adoption of both 980nm pumping technology and a CFG with a narrower stopband width of 0.3nm may effectively improve the NF characteristics and the S-SP beat noise, and thus lower the power penalty. Second, the use of a CFG with a higher reflectivity of, for example, > 85%, instead of the present reflectivity of 67%, may result in a higher constant output power.

Conclusions: We have demonstrated a CFG-integrated OLA with a large dynamic range of > 15dB, a constant output power of > 15dBm, and a dispersion compensation capability in an 80km standard singlemode fibre link at 10Gbit/s. A tolerable power penalty of the CFG-OLA when it is used as a power and in-line amplifier has been achieved.

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Effect of macro-bending on dispersion of dispersion compensating fibres

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Using direct measurement the effect of macro-bending on the dispersion in dispersion compensating fibres was investigated. It was shown that even a relatively large bend radius of ~10cm can modify the fibre dispersion in the range 1500–1600nm.

Macro-bending with radii in the range from a few to tens of centimetres always occurs when fibres are used. Any effect of macro-bending on the fibre dispersion will have a major impact on the engineering aspects of fibre implementation such as packaging, installation and characterisation conditions etc. In conventional singlemode fibres such as dispersion shifted and standard telecommunication fibres, the macro-bending effect on dispersion is effectively negligible. The induced bending loss is the dominant effect, i.e. with a decrease in bending radius no significant change in dispersion takes place before the induced loss makes the fibre literally unusable. The situation can be dramatically different in dispersion compensating fibres (DCFs).

Silica-germanium dispersion compensating fibres currently achieve a dispersion of ~100ps/nm/km at 1550nm [1]. The fibres have a complex refractive index profile, high Δn, and a small core size to maximise the waveguide dispersion. The near field distribution of the electric field therefore plays the major role in determining the dispersion properties of the fibre. Fibre bending induces radial asymmetry in the field distribution affecting the fibre dispersion properties. In this Letter, we experimentally investigate the effect of macro-bending on dispersion compensating fibres.

For dispersion measurement, an interferometric technique [2] based on the application of a supercontinuum fibre laser source was used. The setup allows accurate and detailed data on dispersion to be obtained in the entire window of transparency of silica fibres. The interferometer incorporated two fused couplers providing significant simplicity in alignment in comparison with bulk optics configurations. The couplers had close to 3dB splitting ratio in the spectral range 1.1–1.7μm where measurements were undertaken, and were compensated for one against another in the interferometer to maximise the contrast of the interference pattern over the whole spectral range. The test fibre was typically 60cm long. The reference path was formed by two bulk collimators with one placed on a motorised precision translation stage which provided a variable delay. A supercontinuum self-Q-switched Yb fibre laser [3] was used as a 'white-light' source to feed the interferometer. The source provided a unique spectral brightness of > 0.2mW/nm in the spectral range 1.1–1.75μm. The laser was packaged in a compact, diode pumped module of 115 × 130 × 15mm making it simple and convenient to use. The high brightness and broad bandwidth of the source allowed the measurements to be undertaken in the spectral domain with a high spectral resolution using a conventional spectrum analyser. By monitoring the interferometric pattern in the spectral domain, the centre of the pattern corresponds to the wavelength for which the optical paths of the interferometer are equal. By scanning the reference path, the centre wavelength was measured as a function of the delay. The group delay against the wavelength of the test fibre results are obtained directly from this measurement, and the dispersion is then calculated as

$$D = \frac{1}{L \cdot c} \frac{\partial s}{\partial \lambda} \tag{1}$$

where D is the dispersion, L the length of the test fibre, c the speed of light in a vacuum, λ the wavelength, and s the delay length of the reference path of the interferometer. Fig. 1(i) shows the measured group velocity delay against wavelength for the case of unbent fibre. It can be seen that the technique allows the data to be obtained with high spectral resolution. For this curve, approximately 70 points were collected in the range 1200–1600nm with a step of 5–10nm. The dispersion curve in dispersion compensating fibres can be complicated, and detailed data over a wide spectral range are essential to obtain an accurate dispersion curve. Fig. 1(ii) shows the resulting dispersion profile. To obtain this curve, the interpolation method was used to fit to the experimental data. Two interpolation functions were used, a fifth-order Sellmeier function and a fifth-order polynomial function, depending on the shape of the curve. The fitted curve was differentiated and the quality of the fitting was tested by comparing it with direct point by point differentiation of the experimental points. For the type of curve shown in Fig. 1, polynomial interpolation was found to work better giving more accurate results at both ends of the measurement range.

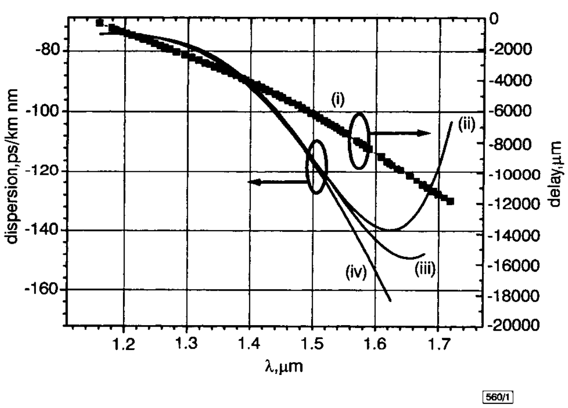

Fig. 1 *Delay time and dispersion for different bending diameters*
(i) delay
(ii) bend diameter ∞
(iii) bend diameter 20cm
(iv) bend diameter 6cm

To measure the effect of bending, the fibre was coiled around discs with different diameters. The results are summarised in Fig. 1 comparing the dispersion curves for three bending diameters: ∞, 20cm and 6cm. As would be expected the bending affects the longer wavelength part of the curve in the area of the highest dispersion. The field is less confined in this region, and the dispersion is extremely sensitive to the near field distribution [4, 5]. The bending of the waveguide changes its geometry modifying the field distribution in the fibre core. As a result the absolute value of the dispersion increases and the minimum shifts towards longer wavelengths. The shape of the curve as well as the dispersion slope changes around 1550nm even for relatively large bending radii.

Next the bend induced loss characteristics of this DCF were