have a minor effect on the payload, as shown in Fig. 3a. The received eye diagrams of label and payload after transmission, shown in Figs. 3c–d, indicate large eye openings. BER measurements verify error-free transmission performance of both the payload and the label. The BER curves in Fig. 4 indicate that the labelling penalty for the IM payload is only 0.5 dB, while the transmission penalty is ~0.7 dB. The IM payload induces ~3.7 dB penalty onto the received FSK label, while the transmission penalty is nearly 1 dB. In the above measurements, the penalties are measured at a BER of $10^{-9}$. The label receiving performance can be further improved through optimisation of the filter bandwidth. Fig. 5 shows the spectra of the FSK-labelled signals. The FSK tone spacing is equal to 12 GHz, while one tone is suppressed by 8 dB after demodulation in the FP filter.

![Eye-diagrams](image)

**Fig. 3** Eye-diagrams
a Original FSK signal
b FSK-labelled IM payload
c Demodulated label
d Decoded payload

![BER curves](image)

**Fig. 4** Measured BER performance of payload and label
a Payload
b Label

c) Further improved through optimisation of the filter bandwidth. Fig. 4 indicate that the labelling penalty for the IM payload is only 0.5 dB, while the transmission penalty is ~0.7 dB. The IM payload induces ~3.7 dB penalty onto the received FSK label, while the transmission penalty is nearly 1 dB. In the above measurements, the penalties are measured at a BER of $10^{-9}$. The label receiving performance can be further improved through optimisation of the filter bandwidth. Fig. 5 shows the spectra of the FSK-labelled signals. The FSK tone spacing is equal to 12 GHz, while one tone is suppressed by 8 dB after demodulation in the FP filter.

**Fig. 5** Optical spectra of FSK/IM signals before and after demodulation
Resolution bandwidth: 0.01 nm

**Conclusion:** We have demonstrated a Manchester-encoded FSK-labelled optical signal transmission link. A good modulation and transmission performance is achieved when using high-speed Manchester coding.

**Acknowledgment:** This work was partly supported by the IST-2000-28557 STOLAS project.

© IEE 2003
Electronics Letters Online No: 20030766
DOI: 10.1049/el:20030766
Jianfeng Zhang, Nan Chi, P.V Holm-Nielsen, C. Peucheret and P. Jeppesen (Research Center COM, Technical University of Denmark, 2800 Kgs. Lyngby, Denmark)
E-mail: jfz@com.dtu.dk

**References**

**E-band fibre Raman amplifier and implications of 1.4 μm water absorption**

D.A. Chestnut and J.R. Taylor

An E-band Raman amplifier in nonzero dispersion fibre is demonstrated. 1.4 μm water absorption does not hinder the amplifier itself but its characteristics due to water vapour in the external measurement instrument. The E-band could be used to extend the optical telecommunications bandwidth using nonzero dispersion fibre-based systems.

**Introduction:** Stimulated Raman scattering can be utilised in the form of fibre Raman amplifiers (FRAs) to provide broadband gain over any spectral region, provided a suitable fibre and pump are used. FRAs have primarily been of interest to optical telecommunications for
extending the usable bandwidth in both distributed and discrete amplifier formats, but there are also other applications outside telecommunications where compact, spectrally flexible, broadband amplifiers are required. Already rare-earth-doped fibre amplifier based pump sources have been used in compact configurations to generate visible [1] and ultraviolet light [2] and the use of FRAs in similar systems would be a natural extension of such work.

In the context of telecommunications, FRAs have been demonstrated across the low-loss window of silica both inside and outside of the erbium-doped fibre amplifier C-band (1530-1565 nm). Examples of spectral regions include the O-, S-, [4] L- and U-bands [5]. One spectral region that has traditionally been avoided in fibre-based systems is the E-band (1360-1460 nm) due to sharp water absorption peaks resulting from remaining hydroxyl impurities after the fibre manufacture process. However fibre drawing processes have advanced to significantly decrease this loss from several dB/km [6] to ~0.5 dB/km, which is only ~0.2 dB/km higher than the loss in the surrounding spectral regions. It appears likely that such improved, low-loss fibres, namely nonzero dispersion fibres (NZDFs), could be utilised to create efficient E-band FRAs.

In this Letter an E-band FRA using TrueWave NZDF is demonstrated. It is shown that spikes and dips exhibited across the FRA gain and noise figure (NF) spectra are a consequence of water vapour in external characterisation instruments and that water loss should not significantly affect the performance of the FRA itself.

**Experiment:** Fig. 1 shows the experimental configuration of the E-band FRA. Shown in the box is the FRA itself based on a 10 km TrueWave NZDF with a zero dispersion wavelength of 1447 nm. The manufacturer-provided fibre loss with low resolution is shown in the inset of Fig. 2. The FRA pump comprised a continuous-wave (CW) 1310 nm fibre Raman laser (FRL) that provided up to 1.9 W into the NZDF. The FRL was counterpropagated against a signal using optical circulators that were optimised for use around 1.3 μm. For characterisation of the FRA, a CW external cavity tunable semiconductor probe laser (TL) that operated over 1360-1440 nm was employed with an optical spectrum analyser (OSA). A small signal power of ~21 dBm in the NZDF was used. In/out gain and NF measurements were made in the OSA in 0.5 nm increments by comparing the signal powers at the FRA input and output, as shown in Fig. 1.

When using the TL near the water peaks, lasing instabilities and mode hopping were observed due to water vapour in the optical cavity. Consequently the laser was reconfigured with a valve accessing the cavity so that air-free nitrogen (AFN) could be used to purge the TL of water vapour. After purging for several hours the lasing stability near the water peaks improved.

**Results:** Fig. 2 shows the In/out gain and NF measurements for FRL powers of 1.9, 1.2 and 0.7 W in the NZDF. A maximum gain of 39 dB was observed at a peak wavelength of 1398 nm for 1.9 W FRL power. Gains in excess of 10 dB were observed over a 56 nm bandwidth in this case. The NFs were typically ~8 dB except for FRL powers greater than 1.5 W where NFs as high as 12.5 dB were observed around 1400 nm. It was found that under these higher FRL powers, the gain was large enough for the Raman amplified spontaneous emission (ASE) to lase (Fig. 2 inset) and cause an increased NF. With optimisation of the NZDF length decreased NF values are expected.

Across the gain and NF spectra spikes and dips were observed due to water absorption. To determine the location of this absorption the TL output was divided in a broadband ~3 dB fibre coupler and simultaneous power measurements were made on the OSA and on a semiconductor optical power meter (OPM). An example of the results around a TL wavelength of 1395 nm is shown in Fig. 3. The TL was set to automatic power control, which means that the output power was continuously monitored through an internal tap coupler and an automatic feedback loop varied the drive current appropriately to maintain a constant output power. Any drops in power due to water absorption in the TL cavity were recovered automatically. In addition the TL was purged by AFN to avoid lasing instabilities. Hence, as would be expected a fairly constant OPM reading was observed as the TL was tuned. However, simultaneously a large drop in power by as much as 15 dB was observed on the OSA. Such a loss would not be expected in the FRA, as only an increased loss of ~2 dB in the 10 km NZDF is inferred by the manufacturer specifications. It is concluded that absorption by water vapour in the OSA, which has a much larger air cavity than the FRA, is the main source of the spikes and dips in the FRA gain and NF spectra. Another source of the observed spikes, in particular, is the spectral repeatability of the TL over the ~0.1 nm bandwidths of the sharp absorption lines. If the exact wavelength is not replicated in the FRA In and Out power measurements, then the absorption loss could in some cases appear incorrectly as gain.

**Large-signal In/out gain measurements were made on the FRA for pump powers of 1.9, 1.2 and 0.7 W in the NZDF. It was found that the gains for each pump power were fairly constant up to an output signal power of ~10-20 mW where spectral distortions in the signal were observed. These distortions consisted of the transfer of energy to longer wavelengths with an initial peak at around a 0.09 nm separation from the signal wavelength. Considering the narrow linewidth of the TL, the spectral signature of the distortions and the fairly high signal powers, it is concluded that stimulated Brillouin scattering is responsible for these distortions.

**Conclusions:** An E-band FRA in NZDF has been demonstrated and it has been shown that 1.4 μm water absorption in the FRA itself does not constitute a significant problem. Instead water vapour in the external FRA characterisation instruments, specifically the OSA and the probe TL, leads to characterisation problems such as spikes and dips in the FRA gain and NF spectra. As in current telecommunications systems small air-cavity diode lasers constitute the signals (and water vapour in the similarly sized OPM did not cause measurement problems), E-band FRAs should be able to operate efficiently and extend the telecommunications bandwidth. For more accurate FRA characterisation, however, the TL and OSA will likely require purging or vacuum sealing.
Group delay ripple (GDR) is one of the most significant impediments in the application of chirped fibre Bragg gratings (CFBG) for dispersion compensation. GDR is defined as the deviation from the desired linear group delay against wavelength and gives rise to substantial OSNR penalty [1, 2]. It originates from both random and systematic errors introduced during the fibre grating fabrication process. For a tunable DC FBG, the tuning mechanism can also introduce small variations in GDR. Several papers suggested different modifications of the fibre grating fabrication process in order to reduce GDR [3-6]. It is known that the high-frequency GDR components (e.g. for 43 Gbit/s, having a period <0.1 nm in wavelength) do not significantly contribute to the OSNR penalty [2, 7] and experience a fundamental high-frequency cutoff [8]. Recently, a method for low-frequency GDR correction by successive UV exposures was suggested [9]. This method enables trimming of both systematic and random components of GDR and is an effective tool for fabrication of high-performance dispersion compensation devices. In this Letter we report the fabrication of a low GDR tunable dispersion compensator (TDC) using the technique developed in [9].

Our technique is based on iterative correction of the GDR. To correct slowly varying GDR we used an approximate 'adiabatic' solution of the inverse problem relating GDR against wavelength to the deviation from the desired linear group delay, discussed further below, we determine the required value of the correction index and demonstrate a TDC that was fabricated using our new technique. The low-frequency GDR of the grating used in the TDC is corrected from ±10 to ±2 ps. The OSNR penalty measured for 43 Gbit/s CSRZ signal transmission is <0.5 dB for the entire tuning range of 270 to 750 ps/nm, and carrier frequencies in the detuning range of ±10 GHz. The value of the measured OSNR penalty is in good agreement with the one obtained by numerical simulation, which indicated reduction of OSNR penalty after GDR correction from 4 dB to <1 dB.

Our method of GDR correction is shown in Fig. 1. First, the grating is inscribed using the conventional phase mask UV grating writing technique (Fig. 1a). Immediately after the CFBG is written its GDR is characterized (Fig. 1b). Then, by an approximate adiabatic treatment of the group delay, discussed further below, we determine the required index profile to reduce the measured GDR (Fig. 1c). Lastly, this index variation is introduced by direct ‘DC’ UV exposure (Fig. 1d). We continue the iterative steps (b → c → d → b) of the UV trimming until the desired reduction of the GDR is achieved.

We assume that the GDR is relatively small (usually it is ~10 ps for dispersion ~1000 ps/nm and reflection bandwidth ~1 nm) and slowly varying (we are correcting the low-frequency part of the GDR). Then, in the simplest adiabatic approximation, the DC index variation, δnc(ω) which compensates the GDR, δG(ω), is defined by

$$\delta n_c(\omega) = \text{const} \times \frac{C_G}{\Delta \omega} \times \frac{1}{51(2\pi G_C \omega)}$$

*Fig. 1 Scheme of fibre grating correction*

a) Fibre grating writing  b) Characterization  c) Determination of correction index  d) Correction