Dispersion compensating chirped fibre gratings

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Summary

The dispersion characteristics of linearly chirped fibre gratings have been studied in detail and design criteria established. It is shown that in order to compensate the linear dispersion of 100km of standard fibre. over a certain FWHM bandwidth, the required fibre-grating length is 17.7cm/nm. Dispersion compensation measurements for both a 200km. 2.5Gbit/s direct-modulated transmitter and a 216km. 10Gbit/s externally-modulated transmitter experiment confirm these predictions.

Introduction

Chirped fibre gratings[1-5] are of particular interest for compensating the dispersion (~17ps/nm.km @ 1.55μm) of installed step-index (SI) fibre links since they are compact, low-loss, polarisation-insensitive and offer high negative-dispersion. In previous work a chirped fibre grating has been employed to effectively compensate for the dispersion of 160km of standard fibre in a 10Gbit/s externally modulated transmitter experiment[4]. Whilst more recently in a similar experiment, 270km of fibre was compensated. however in this case, with an ~2dB penalty[5].

In this paper we present a theoretical and experimental investigation of the bandwidth-dispersion trade-off for fixed length tunable linearly-chirped fibre gratings and give design criteria for such gratings. In addition we present experimental results on a 200km. 2.5Gbit/s direct-modulated and a 216km, 10Gbit/s externally- modulated transmission system operating around 1.55μm over SI fibre.

Dispersion Characteristics of Linearly-Chirped Grating

The reflection characteristics of the fibre gratings have been calculated by using the general coupled-mode theory applicable to non-uniform, aperiodic structures[5,7]. The refractive index variation is considered to be

$$n(z)=n_0\{1+\sigma(z)+2h_0(z)[\cos(K_0 z+\phi(z))]\},$$

where n_0 is the fibre refractive index, $h_0(z)$ describes the amplitude of the induced refractive-index change (apodisation profile), $\sigma(z)$ is the accompanied background refractive-index change, $K_0=2\pi/\Lambda_0$ is the reference Bragg wavevector (Λ_0 is the reference Bragg period) and $\phi(z)$ is the chirp function. In the case of unapodised, linearly-chirped gratings, h_0 is constant and $\phi(z)= K_0 C z^2$, where C (in m^{-1}) is the chirp parameter. The variation of the local Bragg wavelength across the grating length (L_{GP}) is given by $\Delta\lambda_B = -2\lambda_0 C L_{GP}$, where λ_0 ($=2n_0\Lambda_0$) is the reference Bragg wavelength. The grating parameters used in the simulations were n_0= 1.45, λ_0= 1552nm and h_0= 10^{-5}, unless otherwise stated.

Figure 1a shows a typical reflection response of a linearly chirped grating as a function of the wavelength detuning from the central Bragg wavelength λ_0. The grating parameters are L_{GP}= 2cm, h_0= 3×10^{-5} and C= -0.008m^{-1}. Figure 1(b) shows that the dispersion of a linearly-chirped grating. The mean dispersion D_m, i.e. the dispersion experienced on average by the transmitted data or short pulse filling the FWHM reflection bandwidth of the grating, is given by the slope of best-fitted straight line (dashed line). The time-delay difference across the full-width, half-maximum (FWHM) reflection bandwidth is ~185ps, which corresponds to the maximum time delay due to double-passage through the 2cm fibre grating. The FWHM bandwidth is ~0.46nm and the resulting mean dispersion is ~ 400ps/nm.

Figure 2(a) shows the variation of the mean linear dispersion as a function of the FWHM bandwidth, for grating lengths of 2cm-10cm. The bandwidth is increased by increasing the chirp parameter. It is shown that decreasing the bandwidth of a chirped grating results in a rapid increase of the provided dispersion. The inset of Fig. 2(a) shows dispersion-vs-FWHM bandwidth results of a slightly-apodised, linearly-chirped, 4cm-long fibre grating. The solid line is the calculated response while the solid dots are experimental data obtained by a new accurate interferometric technique[8]. A very good agreement between experiment and theory is observed. Figure 2(b), on the other hand, shows the mean dispersion obtained over bandwidth 0.1nm-0.5nm, as a function of the grating length. It is shown that for each bandwidth, the dispersion increases linearly with the grating length.

200km 2.5Gbit/s direct modulated transmitter system

In this section we describe the incorporation of a chirped fibre grating into a commercial 2.5Gbits^{-1} directly-modulated system operating at 1536nm. As a consequence of the direct modulation the transmitter was chirped and exhibited a 3dB optical bandwidth of 0.1nm and a 20dB bandwidth of 0.3nm, ie equivalent to a 10Gbit/s modulation signal. An ~20mm grating with linear chirp, to give a 0.3nm 3dB bandwidth, is shown to negate the dispersion of ~50km of standard fibre. This allowed transmission through 200km of standard fibre with a 3dB penalty, which compares with a ~8.5dB penalty without the compensation.

The experimental set up is shown in Figure 3. The basic link consisted of a commercial multiplexer and transmitter, Phillips SDH 2.5Gbits^{-1} system. The multiplexer combines 16 channels of data at 140Mbits^{-1} up to a line rate of 2.5Gbits^{-1}. In the absence of data on any channel, the multiplexer generates random data. Random data was input to several of the channels whilst, on the test channel, data at 140Mbits^{-1} with a 2^{23}-1 pattern length was employed. The transmitter consisted of a directly-modulated DFB laser with wavelength centred at 1536nm whose chirped output had a 3dB bandwidth of 0.108nm and 10dB bandwidth of 0.24nm (Figure 4a). As a consequence of this chirp a penalty was observed for transmission distances in standard fibre in excess of a few tens of km. The transmitter was followed by a single-stage, 980nm-pumped erbium-doped power-amplifier giving an output power of +12dBm which was transmitted through standard fibre having lengths of 100, 143 and 200km. In the latter case, a dual-stage 980nm-pumped line amplifier giving an output power of +13dBm was incorporated. The output of the link was coupled via a variable attenuator to a commercial, Phillips, receiver and demultiplexer.

Dispersion-compensation of the link was provided by incorporating a chirped fibre grating between the transmitter and power amplifier. Since the grating operates in reflection, an optical circulator was included to convert it to a transmission device. The fibre grating was written with a frequency-doubled excimer laser in a germania-boron co-doped fibre (0.1 NA, 1 µm λ_{cutoff}). The grating was ~20mm in length with an approximately Gaussian strength profile and ~70% peak reflectivity. In its as-written state it had some residual chirp and a measured bandwidth of ~0.2nm. The grating was further chirped to a 3dB bandwidth of ~0.3nm as shown in Figure 4b by applying the temperature profile indicated in Figure 3. The centre wavelength was also tuned to match the laser wavelength of 1536nm. Once chirped, the grating reflectivity reduced and thus the circulator-grating combination exhibited an insertion loss of 3.5dB, but owing to its location this had a negligible effect on the link power-budget. Subsequent to these measurements the grating was found to exhibit approximately 50ps of polarisation mode dispersion due to birefringence in the grating fibre. However, owing to the non-transform-limited data (chirped source) an improvement in system performance was nevertheless obtained.

Bit-error-rate (BER) curves for the system are shown in Figure 5. Data are given for back-to-back and direct transmission through 100, 143 and 200km of standard fibre. Dispersion-equalised curves, with the chirped grating included, are given for back-to-back and transmission through 100 and 200km. In the case of direct transmission, a back-to-back sensitivity of -32.7dBm at a 10^{-9} BER is observed. At this error rate a penalty of 1.3dB was found at 100km, increasing to 3.2 and 8.5dB at 143 and 200km, respectively. The increase in penalty with distance is shown more clearly in Figure 6. With the grating incorporated, the back-to-back sensitivity is actually improved by 1.2dB, since the grating compresses the chirped-source pulses. The grating virtually eradicates the penalty at 100km (0.5dB) and significantly reduces the penalty at 200km to only 3dB. No floor in the error-rate curves was observed when using the grating. The increase in penalty with distance in this case can be compared with the direct result in Figure 6, where it can be seen that the grating dispersion is equivalent (but opposite in sign) to around 50km of standard fibre in agreement with the predictions of figure 2a.

100-220km 10Gbit/s externally modulated transmitter system

In this section we present a detailed investigation of the bandwidth-dispersion trade-off for a fixed (40mm) length tunable linearly-chirped fibre grating. In addition we demonstrate that using such a grating we can precisely compensate the dispersion in a 10Gbit/s transmission experiment for SI fibre lengths anywhere in the range 103-216km. For the longest span and, thus, narrowest bandwidth compensator its centre wavelength is found to be critical (±5pm) but well within the tolerance of possible active stabilisation.

The basic link is shown schematically in Figure 7 and was established such that compensation of linear dispersion for total span lengths up to 216km could be investigated. A 10Gbit/s externally modulated transmitter was employed. This exhibited negative chirp (α=1) to maximise transmission distance over step index fibre. This was followed by power-, line- and pre-amplifiers as well as a receiver. Attenuators were included in each section such that, when adding fibre or the dispersion compensator, power levels in the link were maintained constant to eliminate penalty variations due to amplifier noise variations. Receiver sensitivity was measured by varying the input to the commercial preamplifier with integral narrow band ($\Delta\nu$=50GHz) tracking ASE filter. At all times power levels in the link were such that operation in the linear regime was insured.

Dispersion compensation of the link was provided by incorporating a chirped fibre grating between the transmitter and power amplifier. Since the grating operates in reflection, an optical circulator was included to convert it to a transmissive device. The linear fibre grating was written with a frequency-doubled excimer laser and scanning interferometer in hydrogenated standard telecommunications fibre. The grating was approximately 40mm in length with flat top profile and slight apodising at the edges. The measured reflectivity was ~30%. The grating was mounted such that its centre wavelength could be mechanically tuned to match that of the transmitter whilst a linear chirp could be applied via a linear temperature gradient as indicated in Figure 7.

Figure 8(a,b) show typical reflection spectra and time delay characteristics measured using an interferometric set up[8] for a temperature differential of 15°C (15°C/45mm). A 3dB reflection bandwidth of 0.186nm is observed, however modulation in the spectra is present due to the near flat-top profile of the grating. Nevertheless, a near linear time delay against wavelength characteristic is observed across the reflection band, in this case, with a slope of -1401ps/nm. No polarisation sensitivity to this slope was observed. Figure 2a shows the measured bandwidth-dispersion characteristic for the grating. As anticipated, the bandwidth- dispersion product is near constant and given by the grating length. Once chirped, the grating reflectivity reduced and thus, for a typical bandwidth of 0.287nm the circulator-grating combination exhibited an insertion loss of ~8.5dB, but owing to its location this had negligible effect on the link power budget. The polarisation dependent loss of the grating-circulator combination was measured to be ~0.1dB.

Figure 9 plots the receiver penalty, compared to the back-to-back sensitivity of -27dBm and measured for a 2^{31}-1 data pattern and a 10^{-11} BER, for varying span lengths . Results are compared with and without the grating. Without the grating the receiver sensitivity is observed to improve (-ve penalty) for short span lengths and exhibit a minimum around 50km due to the negative-chirped transmitter. For increasing span lengths, the penalty increased sharply with 0 and 3.5 dB penalties being observed for 80km and 102.6km spans, respectively. In the case of the dispersion compensated link, by variation of the grating dispersion and hence bandwidth as indicated, a large span variation, 102.6-185.3km, where a receiver improvement of 4.5-5dB is obtained. Optimisation of the grating dispersion was investigated in each case as shown in figure 10 where the BER penalty as a function of temperature differential is plotted. From this figure and Figure 2a we infer that for a <X10 BER penalty the dispersion must be compensated to within ~±150ps/nm.

For the increased span of 215.8km a reduction in the dispersion compensation is observed. In the case of the 185.3 and 215.8km spans the grating 3dB-bandwidth of 0.144nm corresponded to the transmitter 11.5dB-bandwidth and thus setting of the grating centre wavelength was critical (±0.005nm). This wavelength sensitivity was reduced (±0.01nm) by increasing the grating bandwidth which decreases the dispersion and thus incurs a slight penalty. In this case the 0.166nm 3dB grating bandwidth corresponded to the 14dB transmitter bandwidth. These wavelength tolerances, although tight, are not unreasonable as long as wavelength tracking of the grating/ transmitter is provided. If developed such a filter could be employed in the pre-amplifier to provide noise filtering in addition to dispersion compensation. In this case the flat-top spectral response of a chirped filter may be advantageous compared to the response of Fabry-Perot type filters.

Discussion

A 2cm, 0.3nm FWHM linearly chirped grating has been employed in a 2.5Gbit/s direct-modulated transmitter system to compensate the dispersion of ~50km of SI fibre whilst a similar 4cm, 0.144nm FWHM grating has been employed in a 10Gbit/s exernally-modulated transmitter system to compensate the dispersion of ~150km of SI fibre. In both cases the use of gratings facilitated transmission distances in excess of 200km. Figure 11 plots the grating length required to achieve a mean dispersion of 1700ps/nm (equivalent to 100km SI fibre) and 3400ps/nm, respectively, as a function of the FWHM grating bandwidth. It is shown that for a target mean dispersion of 1700ps/nm (3400ps/nm), the grating-length requirements increase linearly with the FWHM bandwidth at a rate of ~17.7cm/nm (~35.45cm/nm). The results suggest that a 4cm-long grating is the shortest required grating to obtain a linear dispersion of 3400ps/nm over 0.1nm bandwidth. This is the dispersion required to compensate the transmission of 10Gbit/s data over ~200km of SI fibre. This is in very good agreement with the experimental results where 10Gbit/s optical data (0.144nm bandwidth) were successfully dispersion-compensated over ~150km of SI fibre. In some applications, however, a certain dispersion compensation should be achieved over a much wider bandwidth. This is likely to be encountered either in the case of WDM operation where several optical channels are required to be dispersion compensated simultaneously or the case of single-channel operation where the laser central wavelength is not precisely specified. To achieve a dispersion of 1700ps/nm over a 5nm bandwidth, our calculations show that the length of the required grating is 88.5cm. Such long gratings are beyond the capabilities of the present grating technology but not unrealsitic for the future.

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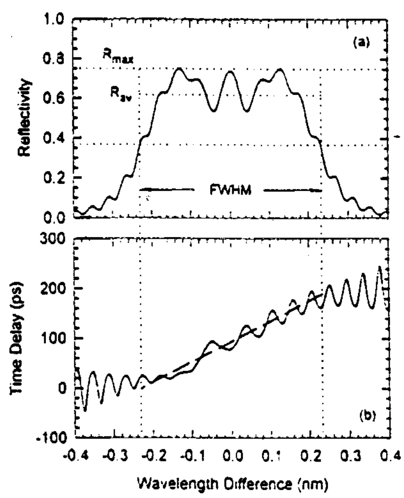

Figure 1:(a) Power reflectivity, and (b) equivalent time delay as a function of the wavelength detuning from the central Bragg wavelength (λ0=1552nm). The rest of the grating parameters are LGR= 2cm, h0= 3x10-5 and C= -0.008m-1.

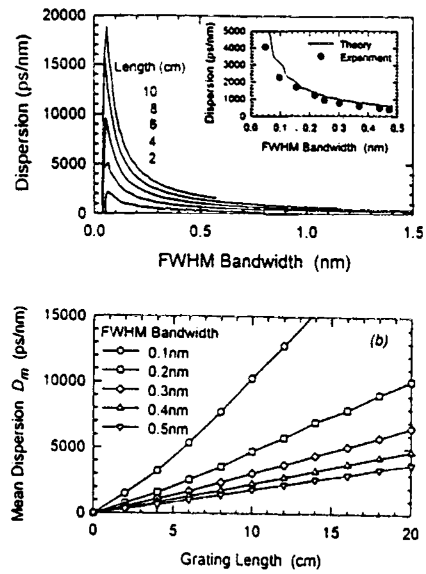

Figure 2: Mean dispersion as a function of (a) the FWHM reflection bandwidth and (b) the grating length. The inset in (a) shows theoretical and experimental results of a 4cm-long, slightly apodised, linearly-chirped grating.

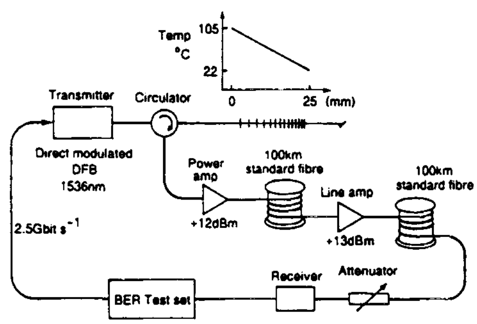

Figure 3: Experimental setup for the 2.5Gbit/s direct-modulated transmitter dispersion compensation experiment.

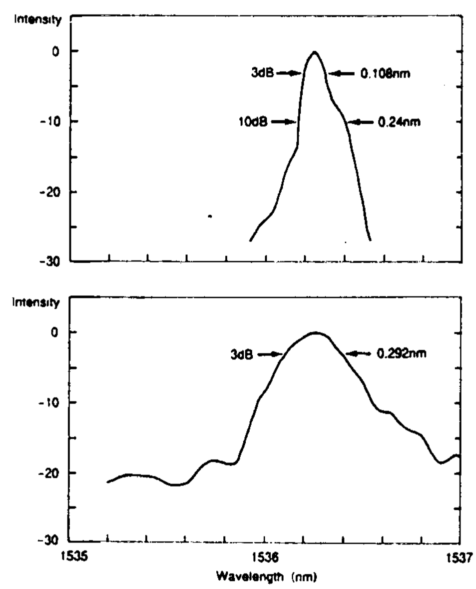

Figure 4: Spectra of (a) the DFB transmitter and (b) the chirped grating reflectivity.

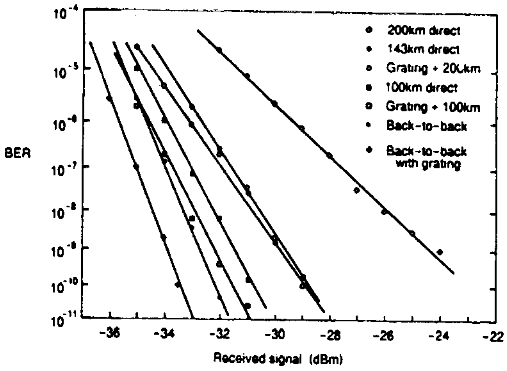

Figure 5: BER curves for the system.

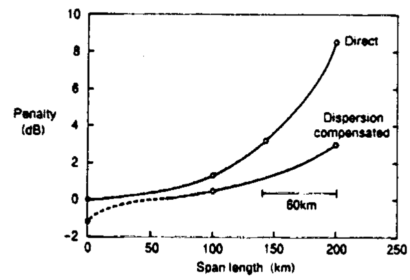

Figure 6: Transmission penalty at 10^{-9} BER as a function of span length with and without dispersion compensation.

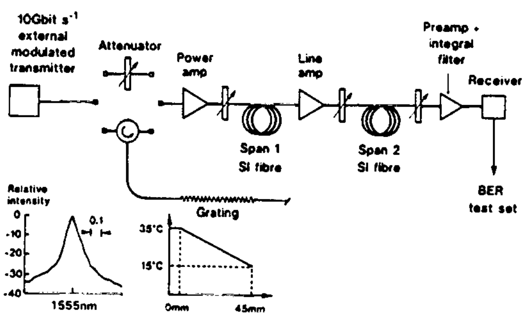

Figure 7: Experimental setup for the 10Gbit/s externally-modulated transmitter dispersion compensation experiment.

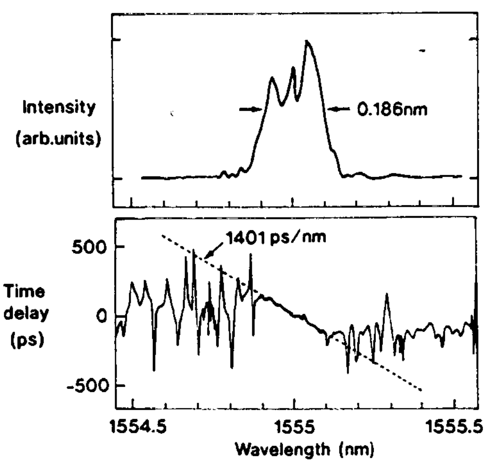

Figure 8(a,b): Typical reflection spectra and time delay characteristics measured using an interferometric test rig[8], in this case for a temperature differential of 15°C/45mm.

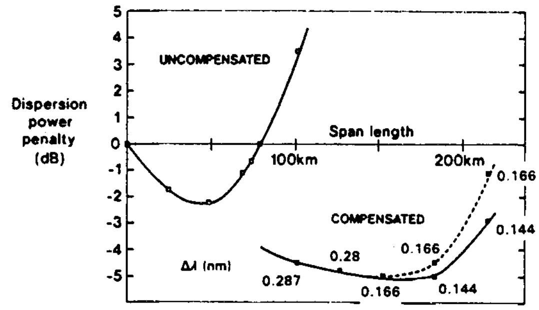

Figure 9: Receiver penalty compared to the back-to-back sensitivity of -27dBm at a 10^{-11} BER for varying span lengths.

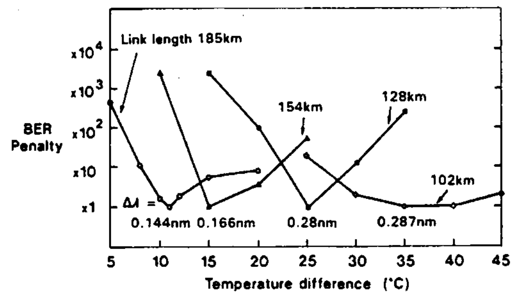

Figure 10: BER penalty as a function of temperature differential for span lengths in the range 102.6-185.3km. Results indicate the degree of dispersion tuning.

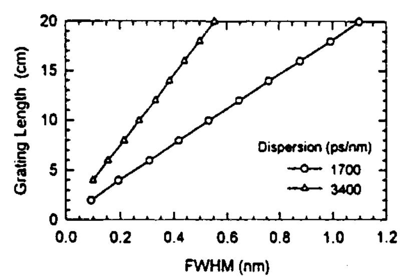

Figure 11: Grating length required to achieve mean linear dispersion of 1700ps/nm and 3400ps/nm as a function of the FWHM reflection bandwidth.