DESIGN OF APODISED LINEARLY-CHIRPED FIBRE GRATINGS FOR OPTICAL COMMUNICATIONS

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The dispersion characteristics of apodised linearly-chirped fibre gratings have been studied systematically. It is shown that the *hyperbolic tangent profile* results in an overall superior performance, as it provides highly linearised time-delay characteristics with minimum reduction in the linear dispersion. To compensate for the linear dispersion of 100km of standard telecom fibre over certain bandwidth (in nm), the required grating length is 19.24cm/nm.

Introduction

Chirped fibre gratings can be effectively used for dispersion compensation in high-bit-rate, long-haul fibre communication links [1-2], short pulse restoration [3-4], as well as, for the implementation of high quality fibre laser cavities of various geometries [5]. In this paper, we investigate thoroughly the reflection and dispersion characteristics of apodised linearly chirped gratings for dispersion compensation in high-bit rate optical transmission. The mean linear dispersion, as well as, the variations of the dispersion across the FWHM bandwidth for different apodisation profiles are calculated and compared with each other. The effect of the apodisation on the performance of linear transmission fibre links is quantified by calculating the resulting eye-opening penalty. It is shown that the *hyperbolic tangent profile* (tanh) results in overall superior performance, as it provides highly linearised time-delay characteristics with minimum reduction in linear dispersion. This results in compensated fibre links of a maximum length and minimum transmission penalty. It is shown that in order to compensate for the linear dispersion of 1 00km of standard telecom fibre (D = 1 7ps/nm/km) over certain bandwidth (in nm), the required grating length is 19 .24cm/nm when the tanh apodisation profile is used. The required length is 17 .54cm/nm in the unapodised case and increases to 22.38cm/nm when a sine apodisation profile is utilised.

Characterisation of Apodised Linearly-Chirped Gratings.

The reflection characteristics of the fibre gratings have been calculated by using the general coupled-mode theory applicable to non-uniform, aperiodic structures [6-7]. The refractive index variation is considered to be $n(z)=n_0\{1+2h(z)[\cos(K_0z+\phi(z))]\}$, where n_0 is the fibre refractive index, $h(z)=h_0 f(z)$ describes the amplitude variation of the induced refractive-index change ($f(z)$ is the apodisation profile), $K_0=2\pi/\Lambda_0$ is the reference Bragg wavevector (Λ_0 is the reference Bragg period) and $\phi(z)$ is the chirp function.

The apodisation profiles considered in this study were Blackman, raised sine, sinc, sine and hyperbolic tangent. The hyperbolic tangent profile is defined as $f(z)=\tanh(2az/L)$, $0\leq z\leq L/2$, and $f(z)=\tanh[2a(L-z)/L]$, $L/2\leq z\leq L$, (a=4). In the case of unapodised linearly-chirped gratings $f(z)=1$ and $\phi(z)=K_0Cz^2$, where C (in m^{-1}) is the chirp parameter. The variation of the local Bragg wavelength across the grating length (L) is given by $\Delta\lambda_B = 2\lambda_0 CL$, where λ_0 ($=2n_0\Lambda_0$) is the centre Bragg wavelength. The grating parameters used in the simulations were n_0= 1.45 and λ_0= 1550nm.

The two parameters of interest, which the apodisation profile comparison is based upon, are the mean linear dispersion D_m (in ps/nm) and the average time-delay ripples $\Delta\tau_m$ (in ps) across the FWHM grating bandwidth. For each grating, both parameters are obtained from the resulting time-delay versus wavelength characteristics. The mean dispersion D_m is given by the slope of the best-fitted straight line while the average time-delay ripple $\Delta\tau_m$ is given by the mean value of the absolute differences of the actual time delays from the best-fitted straight line. D_m is the dispersion experienced on average by the transmitted data or short pulse filling the FWHM reflection bandwidth of the grating. $\Delta\tau_m$, on the other hand, is a measure of higher-order dispersion that results in BER degradation or pulse pedestal and breakup (for a perfect linearised grating $\Delta\tau_m$=0).

The various grating dispersion compensators were further characterised by calculating the maximum length of the dispersion-compensated fibre link and resulting eye-opening penalty [8]. 10Gbit/s NRZ data

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streams constisting of 2^7-1 bits were considered. The fibre linear dispersion was 17ps/(nm km). To focus on the grating related effects only, transmission nonlinearities were not included in the study.

Numerical Results

Figures 1(a) and (b) show the variation of the mean linear dispersion D_m and average time-delay ripple, respectively, as a function of the FWHM grating bandwidth for different apodisation profiles. The unapodised case is also shown for comparison. The FWHM reflection bandwidth is increased by varying the chirp parameter and the refractive index modulation depth (h_0) adjusted to obtain maximum reflectivity R = 0.999. The total grating length is 10cm. It is shown that, for the same bandwidth, apodisation profiles with increasing degree of truncation (tanh → sin → sinc → sin^2) result in progressively reduced linear dispersion, as expected. This will affect the maximum fibre-link length that can be compensated. On the other hand, all apodisation profiles result in quite similar $\Delta\tau_m$ variations (although significantly reduced as compared with the unapodised case). This is due to the fact tighter apodisation profiles require larger index modulation to achieve the same reflectivity, which tends to increase the average time-delay ripples. In fact, for bandwidth >~0.4nm, the tightest profiles result in slightly larger $\Delta\tau_m$. It is therefore anticipated that, for given bandwidth and reflectivity, the different apodisation profiles will result in similar transmission penalties.

Figure 2 shows the eye-opening (EO) penalty as a function of the fibre-link length for the different apodisation profiles. The unapodised case is also shown for comparison. The FWHM reflection bandwidth is 0.2nm and the rest of the parameters are similar to the ones in Figure 1. It is first shown that all apodisation profiles result in a ~4dB reduction in the EO-penalty as compared with the unapodised case. In addition, the tanh profile gives maximum compensated fibre-link length (~315km), very close to the unapodised case (335km), and results in the best overall performance. Tighter apodisation profiles truncate the grating unnecessarily and reduce substantially the compensated fibre length (sine profile results in ~30% compensated-length reduction compared with tanh).

Figures 3(a) and (b) show the variation of the mean linear dispersion D_m and average time-delay ripple, respectively, as a function of the FWHM grating bandwidth for different grating lengths. The apodisation profile is tanh(a=4) and the maximum reflectivity R = 0.999. It is shown that, for a given reflectivity and bandwidth, the mean linear dispersion increases proportionally with the grating length. The average time-delay ripple, however, remains almost unaffected despite the fact that the required amount of chirp is different for the various grating lengths. Therefore, for a given reflection bandwidth and data bit-rate, using longer gratings will result in an increased compensated link length without a substantial transmission penalty. This is clearly demonstrated in Figure 4 where the EO-penalty is plotted as function the fibre-link length for different grating lengths. The grating bandwidth is 0.2nm and the rest of the parameters are similar to Figure 3.

Figures 5(a) and (b) show the variation of the mean linear dispersion D_m and average time-delay ripple, respectively, as a function of the FWHM grating bandwidth for different grating reflectivities. The apodisation profile is tanh(a=4) and the grating length L = 10cm. It is shown that, for certain bandwidth, e.g. 0.2nm, increasing the grating reflectivity from 90% to 99.9%, increases D_m from ~4000ps/nm to ~5000ps/nm, and $\Delta\tau_m$ from ~10ps to ~30ps. The large increase in D_m (~25%) is primarily due to the fact that ultra-high reflectivity gratings require strong refractive index modulation which tends to increase the reflection bandwidth. Therefore, to achieve the same bandwidth, ultra-strong gratings require a smaller chirp parameter which results in higher mean linear dispersion. However, in this case, the resulting dispersion is quite nonlinear within the FWHM bandwidth and can be locally much larger than D_m. This means that ultra-strong chirped gratings can compensate fibre links with total dispersion larger than D_m although the useful bandwidth is somewhat reduced due the nonlinearities in the dispersion characteristics. For reflectivities lower than ~80%, the dispersion characteristics become progressivelly linear and the variation in D_m and $\Delta\tau_m$ become insignificant. Figure 6 shows the EO-penalty as a function of the link length for various grating reflectivities. The FWHM reflection bandwidth is 0.2nm and the other parameters are similar to Figure 5. It is shown that increasing the grating reflectivity form 90% to 99.9% results in a 40% increase of the maximum compensated link length with only 0.15dB increase of the EO-penalty. Reducing the reflectivity below 80% has no effect on the compensated link length or the EO-penalty.

Finally, Figure 7 shows the grating length required to achieve mean linear dispersion D_m = 1700ps/nm as a function of the FWHM reflection bandwidth for tanh(a=4) and sine apodisation profiles.

The unapodised case is also included for comparison. The grating reflectivity is 99.9%. It is shown, in all cases, that required grating length increases quasi-linearly with the FWHM bandwidth. The required grating length is 19.24cm/nm and 22.38cm/nm when the tanh(a=4) and sine apodisation profiles are used, respectively. In the unapodised case, the slope is 17.54cm/nm.

Conclusions

The reflection and dispersion characteristics of apodised, linearly-chirped fibre gratings have been studied systematically. It is shown that the *hyperbolic tangent profile* (tanh) results in overall superior performance, as it provides highly linearised time-delay characteristics with minimum reduction in linear dispersion (as compared with the unapodised case). This results in compensated fibre links of a maximum length and minimum transmission penalty. It is shown that in order to compensate for the linear dispersion of 100km of standard telecom fibre (D = 17ps/nm/km) over certain bandwidth (in nm), the required grating length is 19.24cm/nm when the tanh apodisation profile is used. The required length is 17.54cm/nm in the unapodised case and increases to 22.38cm/nm when a sine apodisation profile is utilised. 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 in the case of single-channel operation where the laser central wavelength is drifting considerably. To achieve a dispersion of 1700ps/nm over a 5nm bandwidth using tanh apodisation profile, the length of the required grating is 96.2cm. Such long gratings are beyond the capabilities of the present fibre grating technology.

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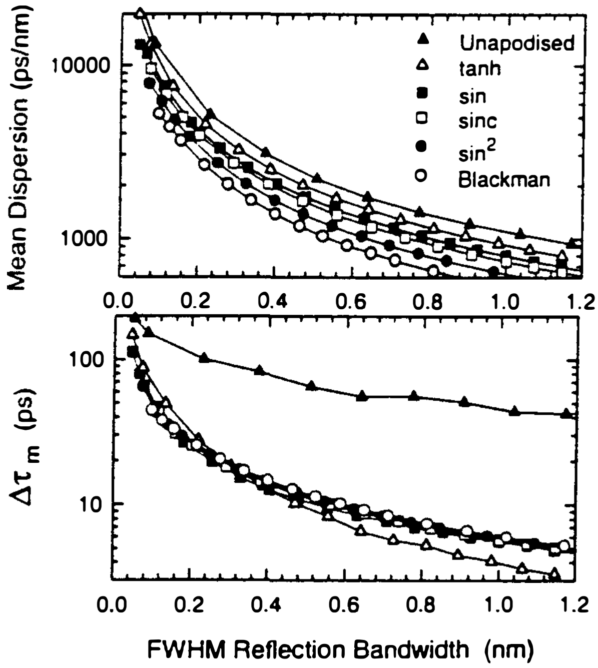

Figure 1: (*a*) mean linear dispersion D_m, and (*b*) average time-delay ripple as a function of the FWHM grating bandwidth for different apodisation profiles. The grating length is 10cm and the reflectivity R = 0.999.

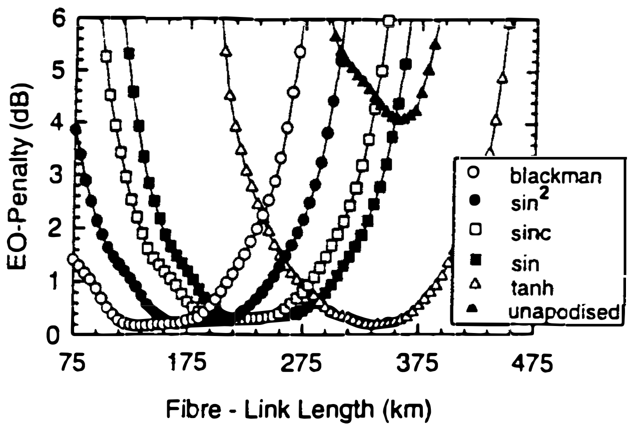

Figure 2: EO-penalty as a function of the fibre-link length for the different apodisation profiles. The FWHM reflection bandwidth is 0.2nm and the rest of the parameters are similar to Figure 1.

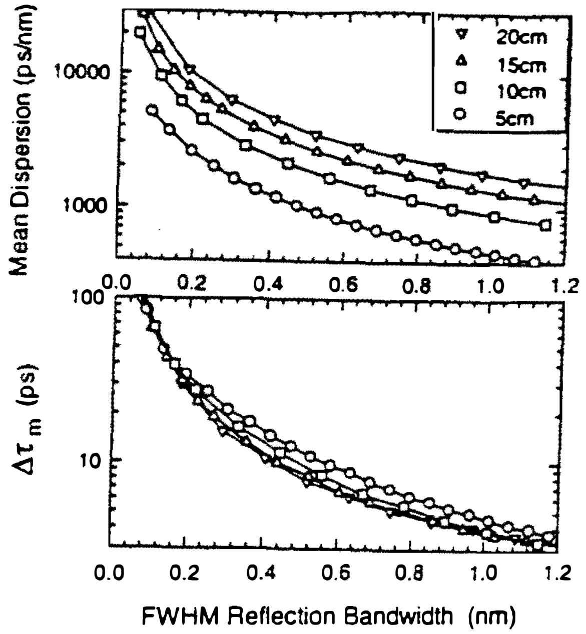

Figure 3: (*a*) mean linear dispersion D_m and (*b*) average time-delay ripple as a function of the FWHM grating bandwidth for different grating lengths. The apodisation profile is tanh(a=4) and the maximum reflectivity R = 0.999.

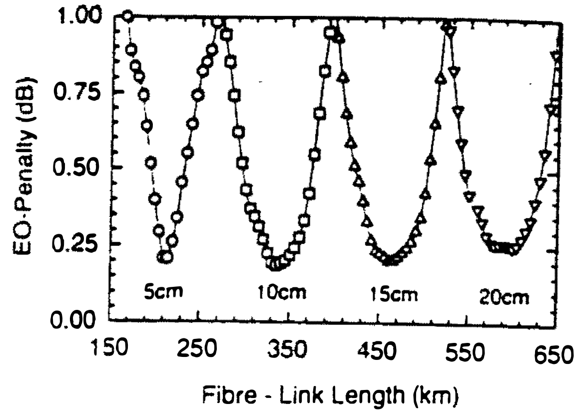

Figure 4: EO-penalty as a function of the fibre-link length for different grating lengths. The grating bandwidth is 0.2nm and the rest of the parameters are similar to Figure 3.

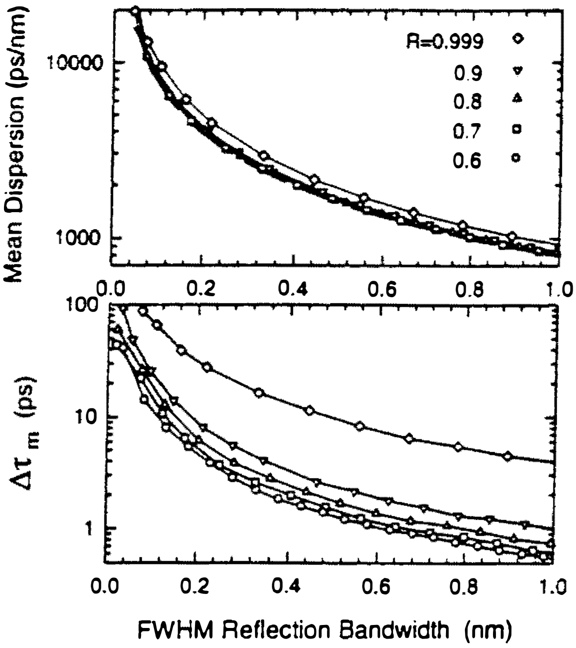

Figure 5: (*a*) mean linear dispersion D_m and (*b*) average time-delay ripple as a function of the FWHM bandwidth for different grating reflectivities. The apodisation profile is tanh(a=4) and the grating length L = 10cm.

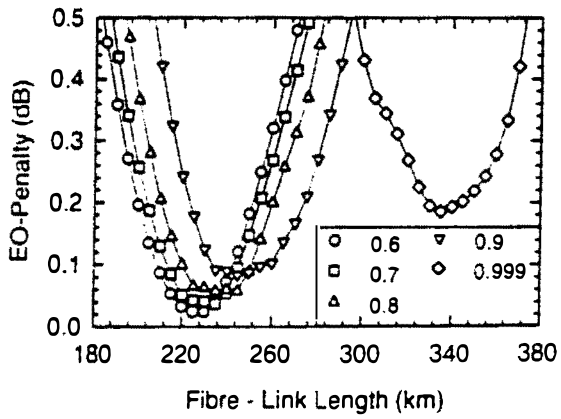

Figure 6: EO-penalty as a function of the link length for various grating reflectivities. The FWHM reflection bandwidth is 0.2nm and the other parameters are similar to Figure 5.

Figure 7: Grating length required to achieve mean linear dispersion D_m = 1700ps/nm as a function of the FWHM reflection bandwidth for tanh(a=4) and sine apodisation profiles. The unapodised case is also included for comparison.