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DESIGN OF LINEARLY-CHIRPED FIBRE GRATINGS FOR OPTICAL COMMUNICATIONS

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ABSTRACT

The dispersion characteristics of linearly chirped fibre gratings have been studied systematically. It is shown that in order to compensate the linear dispersion along 100km of STF, over a certain FWHM bandwidth, the required fibre-grating length is 17.7cm/nm. Compensation of the linear dispersion of 100km over a FWHM bandwidth of 5nm, require a fibre grating of 88.5cm. On the other hand, perfect recompression of 10ps optical pulses over a distance of 100km require a fibre grating of about 22cm.

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Introduction

Fibre gratings are proving to be one of the most important recent developments in the field of optical technology. They basically constitute generalised Bragg reflectors whose reflection and dispersion characteristics can be accurately adjusted by proper design. They 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 linearly chirped gratings for use in dispersion-management applications, such as, dispersion compensation in data-transmission links and short-pulse manipulation. The mean linear dispersion, as well as, the variation of the dispersion across the FWHM bandwidth under the same chirping conditions are calculated and compared with experimental results showing a very good agreement. It is shown that in order to fully compensate for the linear dispersion of 100km (200km) of standard telecom fibre (STF) over certain bandwidth (in nm), the required grating length is **17.7cm/nm (35.5cm/nm)**. The results have also been used to calculate the grating-length requirements for perfect recompression of propagating short sech^2 optical pulses.

Dispersion Characteristics of 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 $n(z)=n_0\{1+\sigma(z)+2h_0(z)[cos(K_0z+\phi(z))]\}$, 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 $\phi(z)= K_0Cz^2$, where C (in m^{-1}) is the chirp parameter. The variation of the local Bragg wavelength across the grating length (L_{GR}) is given by $\Delta\lambda_B = 2\lambda_0 C L_{GR}$, where λ_0 $(=2n_0\Lambda_0)$ is the reference Bragg wavelength. The grating parameters used in the simulations were $n_0= 1.45$, $\lambda_0= 1552$nm and $h_0= 10^{-5}$, unless otherwise stated.

Figure 1 shows a typical reflection response of a linearly chirped grating as a function of the wavelength detuning from the central Bragg wavelength λ_0 and is mainly used to define the various parameters calculated in the present analysis. The grating parameters are $L_{GR}=$ 2cm, $h_0= 3\times10^{-5}$ and $C= -0.008$m^{-1}. Figure 1(b) shows that the dispersion of a linearly-chirped grating increases non-linearly across the FWHM bandwidth. The mean dispersion D_m (in ps/nm) across the FWHM bandwidth is given by the slope of best-fitted straight line (dashed line) while the mean time-delay variation $\Delta\tau_m$ (in ps) is given by the mean value of the difference of the actual time delay 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 pedestals and break-ups. 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 mean dispersion D_m provided by the chirped grating, as a function of the chirp parameter C, for grating lengths of 2cm-10cm. For each grating length, D_m exhibits a 1/x dependence on C. This is due to the fact that, although, the total time delay across the FWHM bandwidth is independent of C (and given approximately by the double-passage time delay), the FWHM bandwidth increases linearly with C (see Fig. 3(b)). It is also shown that for small chirp parameters, longer gratings exhibit much larger dispersion while for large chirp parameters ($C >$ ~0.002 - not shown here) the dispersion becomes length independent. However, even in this regime longer gratings exhibit much wider FWHM bandwidth (c.f. Fig. 3(b)). Figure

2(b) shows the mean time-delay variation $\Delta\tau_m$ as a function of the parameter C. It is shown that the high linear dispersion provided by the longer unapodised, linearly-chirped gratings for small chirp parameters is accompanied by an increased mean time-delay variation. Increasing the chirp parameter reduces the mean-time-delay undulations and results in a quasi-linear increase of the time delay with the wavelength detuning, independently of the grating length. $\Delta\tau_m$ can be reduced considerably by properly apodising the grating strength. Apodisation, however, does not affect the obtained mean dispersion and does not alter significantly the presented results.

Figure 3(a) shows the maximum-reflectivity variation (R_{max}) as a function of the chirp parameter C, for grating lengths of 2cm-10cm. It is shown that although, when unchirped ($C = 0.0$), the longer gratings exhibit, as expected, higher reflectivities, the chirped gratings give almost indistinguishable reflectivities for $C > \sim 0.005$. The decrease in reflectivity with C is due to the gradual dephasing owing to the change of period along the grating. On the other hand, the resulting FWHM bandwidth (Fig. 3(b)) increases linearly with the chirp parameter at a rate proportional to the grating length, as expected.

Figure 4(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 (see Fig. 2(b)). It is shown that decreasing the bandwidth of a chirped grating results in a rapid increase of the provided dispersion. For FWHM bandwidth larger than ~1nm, the dispersion provided by linearly-chirped gratings tends to zero, irrespectively of the grating length. The inset of Fig. 4(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 4(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.

Figure 5 plots the grating length required to achieve a mean dispersion of 1700ps/nm 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 STF. This is in very good agreement with recent experimental results [2] where 10Gbit/s optical data (0.144nm bandwidth) were successfully dispersion-compensated over ~150km of STF. 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 drifting considerably. *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 grating are beyond the capabilities of the present grating technology. However, rapid advances in the phase-mask technology promise the fabrication of meter-long fibre gratings in the near future.

In addition we have investigated the limitations of short pulse propagation over STF and grating compensation. Short, 16ps sech^2 pulses of 0.156nm FWHM bandwidth are first broadened by reflection on the chirped grating and then allowed to propagate and recompress along negative-dispersion STF (~-17ps/(nm.km). Figure 6 shows the optimum STF propagation length and the corresponding output pulse temporal width as a function of the pulse/grating FWHM bandwidth ratio. The grating length is 4cm. Decreasing the grating FWHM bandwidth (by reducing the linear chirp) results in progressively longer optimum propagation distances. This is due to the fact that the reduction of the grating bandwidth is accompanied by an increase of the mean linear dispersion (see Fig. 3(b)). However, the corresponding minimum recompressed-pulse temporal width increases as the grating bandwidth decreases, owing to the severe impact of the increasing pulse filtering, as well as, the accompanying increase in the mean time-delay variation (discussed in Fig. 3(b)). From Figure 6, it is deduced that in order to achieve almost-perfect recompression of propagated short sech^2 pulses, the FWHM grating bandwidth is required to be over five times greater than the pulse bandwidth. From Figure 5, it then deduced that *perfect recompression of 10ps optical pulses (0.25nm FWHM bandwidth), after being propagated a distance of 100km, would require a 22.125cm-long fibre grating.*

Conclusions

The reflection and dispersion characteristics of unapodised, linearly-chirped fibre gratings have been studied systematically. It is shown that in order to compensate the linear dispersion along 100km and 200km of STF over a certain FWHM bandwidth, the required fibre-grating length is **17.7cm/nm** and **35.5cm/nm**, respectively. This means that compensation of the linear dispersion of 100km over a FWHM bandwidth of 5nm, require a fibre grating of 88.5cm. On the other hand, perfect recompression of 10ps optical pulses, after

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propagating a distance of 100km, would require a fibre grating of about 22cm. The effect of different apodisation profiles and coupling strengths on the grating reflection and dispersion characteristics have also been studied and the results will be discussed in the presentation.

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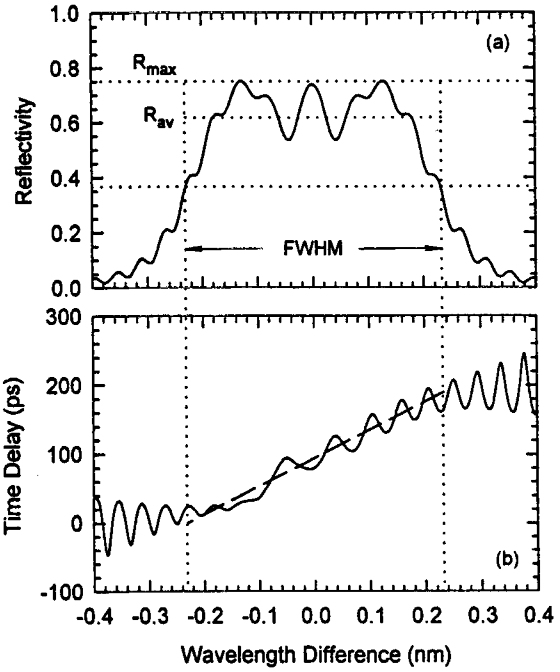

FIGURE 1: **(*a*) Power reflectivity, and (*b*) equivalent time delay as a function of the wavelength detuning from the central Bragg wavelength (λ_0=1552nm). The rest of the grating parameters are L_{GR}= 2cm, h_0= 3x10^{-5} and C= -0.008m^{-1}.**

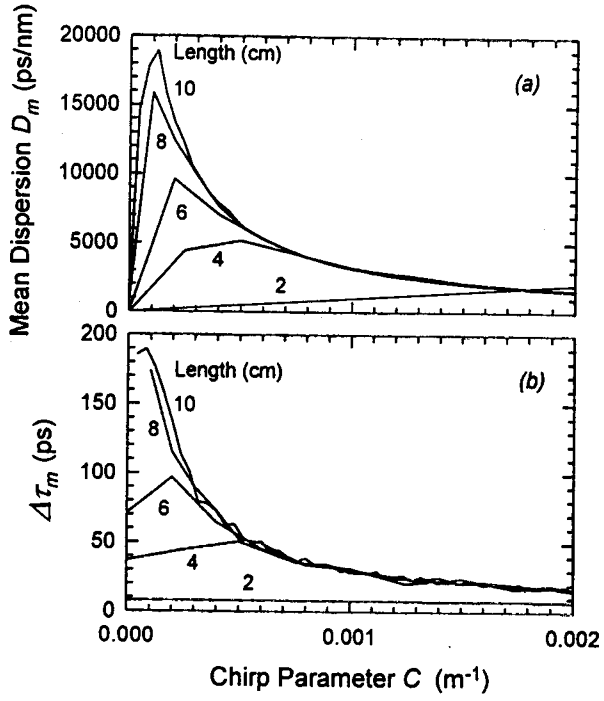

FIGURE 2: (a) Mean dispersion and (b) Mean time-delay variation as a function of the chirp parameter *C*, for grating lengths 2cm to 10cm.

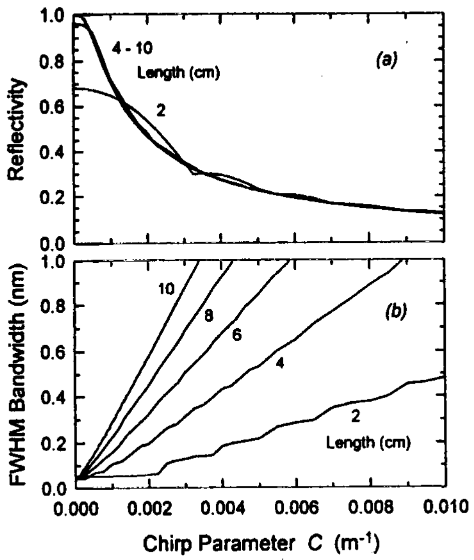

FIGURE 3: (*a*) Maximum reflectivity (R_{max}), and (*b*) FWHM reflection bandwidth as a function of the chirp parameter *C*, for grating lengths 2cm to 10cm.

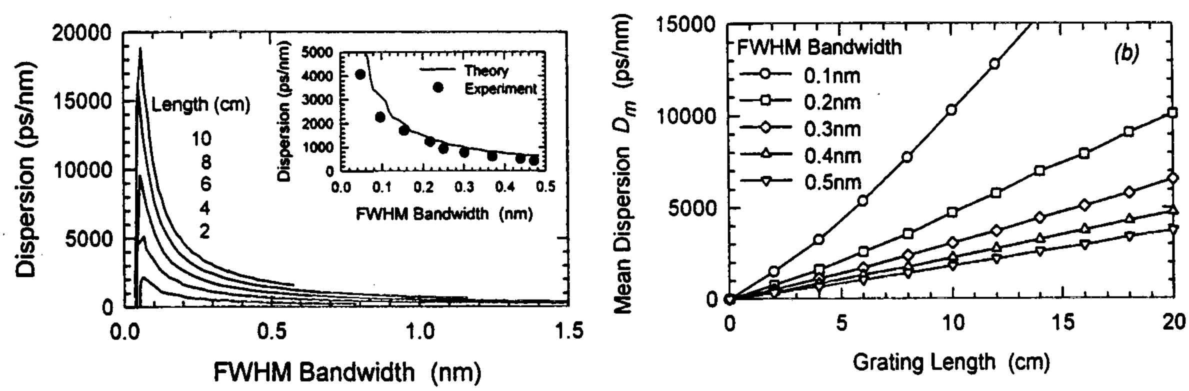

FIGURE 4: Mean dispersion as a function of *(a)* the FWHM reflection bandwidth and *(b)* the grating length. The inset in (a) shows theoretical and experimental results of a 4cm-long, slightly apodised, linearly-chirped grating.

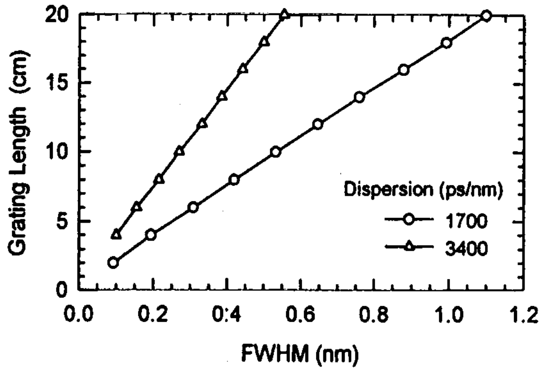

FIGURE 5: Grating length required to achieve mean linear dispersion of 1700ps/nm and 3400ps/nm as a function of the FWHM reflection bandwidth.

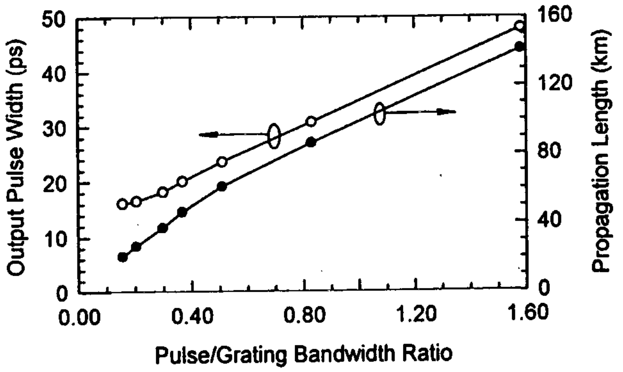

FIGURE 6: Output-pulse temporal width and optimum propagation distance as a function of the pulse/grating bandwidth ratio. The grating length is 4cm.