Optimization of the apodization strength for linearly chirped Bragg grating dispersion compensators in optical fiber communications links

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Abstract: - The optimization of apodized linearly chirped fiber Bragg gratings in the field of chromatic dispersion compensation is discussed in terms of group delay response and pulse recompression. To develop this study two prototype scenarios are considered to show the different behavior of the compensating devices in function of the link length. Simulation results for 20 ps gaussian pulses transmitted and recompressed with different grating designs over the both links are presented. The maximum deviation error and the regression slope parameters are introduced to compare the quality of the group delay response to establish an optimum design of the apodization strength.

Key-Words: - Bragg gratings, dispersion compensation, pulse recompression, apodization , chirp, group delay ripple, compression ratio.

1 Introduction

Degradation of transmitted signals due to chromatic dispersion is one of the major limiting factors in long haul optical communication links, since transmission rates are constantly increasing and the loss of optical fiber becomes lower. Several techniques have been proposed to achieve dispersion compensation and pulse recompression as prechirped pulse transmission or dispersion shifted fibers. However, the first one does not cancel the dispersion completely, and the second one requires modifying existing fiber links. In recent years, there has been increasing interest in dispersion compensating fiber Bragg gratings because they are entirely passive and their size, cost and fiber compatibility make them very attractive devices[1]. Given that the group delay response plays a decisive role in the dispersion compensation behavior [2], a detailed study of the design parameters that influence this delay function would be helpful to achieve optimum results.

In this paper we present a study about the effect of the apodization strength in function of the total amount of dispersion to be compensated, this is, the fiber link length. Two general prototypes has been considered, and we have computed the simulated results for gaussian pulses transmitted and recompressed with the different ALCFBG's designs.

In Section II we develop the dispersion compensation design and in Section III we present and discuss the computed results for the different apodization strength profiles in the two scenarios. Finally, In Section IV the main conclusions are presented.

2 Dispersion compensation design

For a determined optical link, with an specified length L_f and dispersion parameter D_f , we can design a Bragg grating that can achieve the opposite dispersion level in order to cancel this undesirable effect. Some of the parameters as the linear chirp will be determined by the time delay slope required, but others as apodization function and modulation depth open a wide variety of possibilities to improve the response of the device. The minimum length required to compensate the dispersion introduced by the fiber link is [3]:

$$L_0 = \frac{c \Delta l D_f L_f}{2n} \qquad (1)$$

Where c is vacuum speed, n is the refractive index of the fiber, and $\Delta\lambda$ is the bandwidth to compensate for chromatic dispersion. In fact, L_0 is the required length for a uniform grating. Nevertheless, we can apodize the Bragg grating, but in that case we should use a greater length to compensate the reduction of the coupling strength caused by the apodization profile at the grating ends [4]. In order to establish an optimum profile to acquire the best dispersion compensation, several parameters have been reported in previous works, as the performance versus the apodization factor or the grating length. [5]. However, the problem about the grating length required to compensate the chromatic dispersion can be directly solved increasing the minimum length required L_0 proportionally to the apodization factor $0<a_{eff}<1$[3]:

$$a_{eff} = \frac{L_{eff}}{L} = \frac{\int_0^L z f(z) dz}{\int_0^L z dz} \qquad (2)$$

The smaller the factor, the tighter the apodization profile. This way the equivalent length of the apodized grating is $L_{eq}=L_0/a_{eff}$ which increases for 'tight' apodization functions $f(z)$, and tends to the minimum length L_0 for profiles more similar to non-apodized or square profiles. From the point of view of the kind of the apodization function several proposals have been made. In [5] it has been concluded that "broad flat center and smoothly decaying wings" give better grating performance. On the other hand, in [3] is showed that optimum apodization profiles have not only a flat center region but also edges with continuously decaying slopes. However the optimum performance will strongly depend on the length of the link, this is, the total amount of dispersion to be compensated. This way, we are not going to compare different apodization functions as *sinc*, *hyperbolic tangent*, *Blackman*, etc., since their characteristics have been studied in the literature. In fact, we have chosen a *raised cosine* profile as expressed in (3) because it is in good

$$f(z) = \left(\cos\left(\frac{p}{L_{eq}} z \right) \right)^a \qquad (3)$$

agreement with the previous statements, continuously decaying edges, and we have studied the influence of the strength of this profile in function of the total amount of dispersion to be compensated. Each time we change the tightness of the profile the chirp factor will be computed depending of the equivalent length accordingly to [6]

$$F = \frac{4pn^2 L_{eq}^2}{l_B^2 c D_f L_f} \qquad (4)$$

3 Pulse recompression

We are going to analyze two scenarios, a short link of 30 km, and a longer link of 100 km of standard singlemode fiber with a second-order dispersion parameter of 17 ps/nm·km. The pulses under consideration will be gaussian pulses, defined as:

$$A(0,t) = A_0 \exp\left[-\frac{1+iC}{2} \left(\frac{t}{T_0} \right)^2 \right] \qquad (5)$$

Where T_0 is the half-width at $1/e$ intensity point, fixed to 20 ps, and the peak amplitude has been set to $A_0=1$. It is also possible to analyze prechirped pulses, with a determined value for the chirp parameter C, although for the present work we have limited our study to non-prechirped pulses.

We consider the case where the carrier wavelength is far away from the zero-dispersion wavelength so that the third-order dispersion is negligible, this way the amplitude of the transmitted pulse can be expressed as [7]:

$$A(z,t) = \left(\frac{A_0 T_0}{\left[T_0^2 - ib_2 z(1+iC) \right]^{1/2}} \right) \times \exp\left(-\frac{(1+iC)t^2}{2\left[T_0^2 - ib_2 z(1+iC) \right]} \right) \qquad (6)$$

To show the results for the transmitted pulse the time axis in Fig.2 and Fig.4 is displayed assuming a reference frame moving with the pulse $t' = t - \beta_1 z$ where $\beta_1 = 1/v_g$. In order to compensate the transmitted pulse for the chromatic dispersion of the fiber link, we can consider one of the classical setups where the broadened pulse is recompressed and back reflected from a chirped Bragg grating and extracted with an optical circulator. We have considered for the Bragg grating $ê_0 L_{eff}$ product a value of 7.08, which is inside the range of maximum restoration, to guarantee a good peak power result. The recompressed pulse is computed in the frequency domain as the product of the Fourier transform of the transmitted pulse amplitude and the reflection coefficient of the Bragg grating, obtained through Coupled Mode Theory and computed with a transfer matrix method [8]. Finally, the inverse Fourier transform is calculated to show the profile of the recompressed pulse in the time domain.

3.1 Short links

We start our study with a 30 km standard non-shifted fiber with a total amount of 510 ps/nm chromatic dispersion as a prototype of relatively short link. To study the effect of the apodization strength in pulse recompression we have compared the non-apodized design with the performance of three different raised-cosine profiles of increasing strength shown in Fig.1 The computed numerical results are summarized in Table 1. Obviously, the uniform grating achieves the shorter length, even reaching the same compression ratio of the apodized ones, $C_ô=0.95$. But given the high group delay ripple (mean ripple=13.84 ps in the 3 dB band) the recompressed pulse will suffer of a noticeable sidelobe level, as can be observed in Fig.2(b).

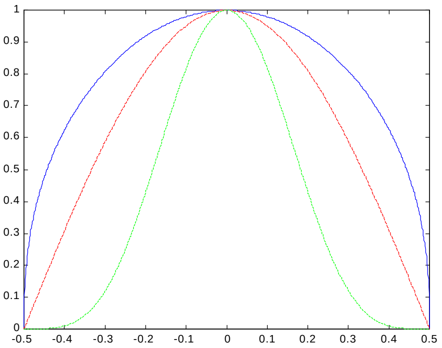

Fig 1. Raised cosine apodization profiles of increasing strength *a*=0.4 (solid, a_{eff}=0.7), *a*=1(dotted, a_{eff}=0.6), *a*=4 (dashed, a_{eff}=0.37)

In Fig.2(a) is showed the group delay response as well as the first degree polynomial that best fits the response in a least-squares sense. In order to justify the not so bad results obtained for a non-apodized grating it is important to note that although the mean dispersion of this device is 286.48 ps/nm far away from the ideal 510 ps/nm of the link, the slope of the linear regression is 518 ps/nm.

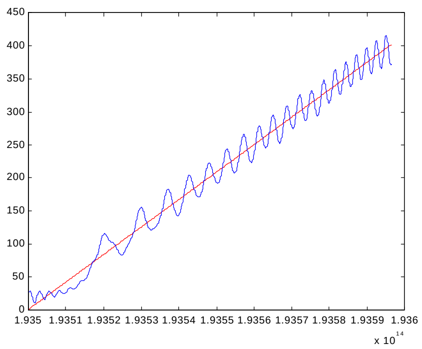

Fig2.(a) Group delay response (rippled) and linear regression for a 50 km, D_f=17 ps/nm/km link, non-apodized grating

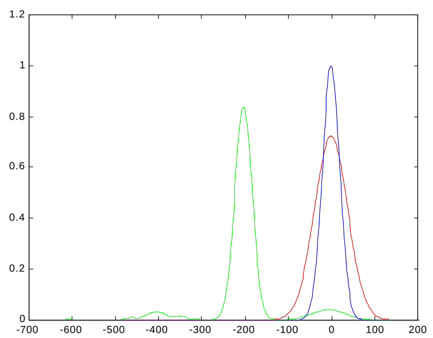

Fig.2(b) Initial, transmitted and recompressed pulse for a 50 km, D_f=17 ps/nm/km link, non-apodized grating.

In other words, the quite high ripple oscillates around a linear response very close to the ideal slope.

When we apodize the grating with a *raised cosine* profile with parameter *a*=0.4, it is obtained that the compression ratio has increased to $C_ô$=1, the mean dispersion acquired is 439 ps/nm and the regression slope is 517 ps/nm, not really far from the uniform case, but now the mean ripple is only 2.47 ps, as can be seen in Fig.3. Besides, the grating length is only one centimeter longer than the uniform case. Following the study for 'tighter' apodization profiles, some important conclusions can be extracted. First of all, we can not affirm that the stronger the apodization, the better pulse recompression. As we can observe in Table 1, when the apodization factor is increased, the regression slope D_r effectively is more closer to the ideal 510 ps/nm, but the mean error is not constantly decreasing, and the Compression ratio does not improve. However, as expected, the grating length increases, which is a very important constraint for the mask process or exposure times. This behavior can be explained since for small apodization factors the ripple is high but with a linear slope, very close to the ideal one.

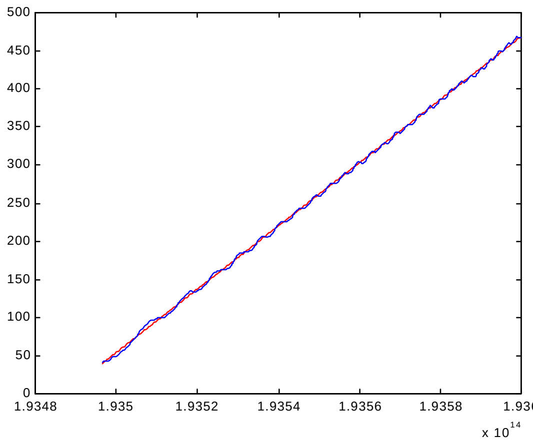

Fig.3.Group delay response (rippled) and linear regression for a 50 km, D_f=17 ps/nm/km link, raised cosine-apodized grating (*a*=0.4)

	Uniform	r.c(*a*=0.4)	r.c(*a*=1)	r.c(*a*=4)
L_{eq}	4.22 cm	5.3 cm	6.64 cm	11.27 cm
R_{max}	0.8	0.71	0.70	0.69
D_r	518	517	514.7	514
$å_m$	13.84	2.47	0.68	0.83
$C_ô$	0.95	1	0.95	1

Table 1. Equivalent length, maximum Reflectivity, regression slope, mean error rate and compression ratio for uniform, and raised cosine apodizations (*a* parameter values: 0.4,1,4)

However, for higher apodization factors the group delay is smoother, but not so linear, leading to not so good compression ratios, as happened for the raised cosine with *a*=1. If we extreme the conditions reaching to a very ‘tight’ profile (a=4), we will obtain again good results, with a regression slope of 514 ps/nm. The prize paid in terms of grating length, however, can be very expensive. The improvement of the behavior from the *a*=0.4 raised cosine apodization to the a=4 profile, does not justify a double length of the Bragg grating, at least for relatively short links, specially since the compression ratio with the first one is as good as the second one.

3.2 Long links

The results of dispersion compensation for longer links can give an extra amount of information to design the optimum grating device. For 100 km of standard singlemode optical fiber, with the same second-order dispersion parameter 17 ps/nm/km, this is, a total dispersion of 1700 ps/nm, we have compared the same four cases of the previous section. Now, following the Bragg grating design steps showed in (1), (2) we have a chirped Bragg grating with ê$_0$$L_{eff}$= 11.81.

	Uniform	r.c(*a*=0.4	r.c(*a*=1)	r.c(*a*=4)
L_{eq}	7 cm	8.83 cm	11.06 cm	18.78 cm
R_{max}	0.99	0.98	0.97	0.95
D_r	1722	1755	1745	1741.5
å$_m$	44.57	8.91	5.68	6.68
å$_d$	88.3	35.07	13.85	14.47
C$_ô$	0.8	0.8	0.8	0.8

Table 2. Equivalent length, maximum Reflectivity, regression slope, mean error rate, maximum deviation error, and compression ratio for uniform, and raised cosine apodizations (*a* parameter values: 0.4,1,4)

In this case, we can observe from Table 2. that the compression ratio does not improve with the apodization strength, but there are other parameters that predict a higher amount of sidelobe level in the time domain recompressed pulse, as the mean error rate, or the deviation of the regression slope from the ideal case of 1700 ps/nm. The uniform profile can be directly discarded given the 44.57 ps of mean error rate, what will degrade the recompressed pulse as can be seen in Fig.4. To choose between lower or higher apodization factors now we have to compare the mean error, and the regression slope. This time, the stronger the apodization, the better results, given that the total amount of dispersion to compensate is higher.

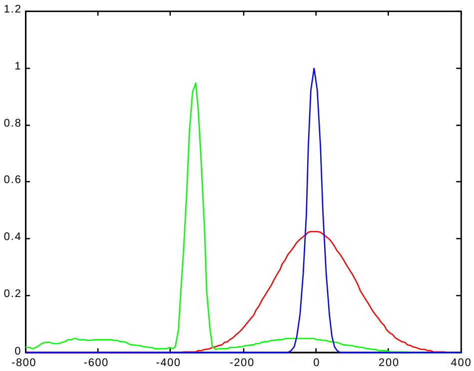

Fig 4. Initial, transmitted and recompressed pulses for a 100 km, D_f=17 ps/nm/km link, non-apodized grating.

But we have introduced another parameter to establish a better comparison, the maximum deviation error, computed as the maximum deviation from the delay response to the regression slope in the 3 dB bandwidth. This shows us that the *a*=4 profile has more deviation error (å$_d$=14.47) than the *a*=1 (å$_d$=13.85), although the rest of parameters are better. It can be seen in Fig.5(b) and Fig.5(c) how the delay response losses linearity in the second case. Consequently, it is not worth to increase arbitrarily the apodization strength, and consequently the grating length, in order to provide a better performance, because with middle apodization factors (about 0.6) both the compression ratio and the sidelobe level give good enough results for signal regeneration [Ou]. The graphic representation of the group delay for the three previous apodization profiles are presented in Fig.5 where it can be observed how the delay is smoother for stronger apodization profiles but begins to loss linearity.

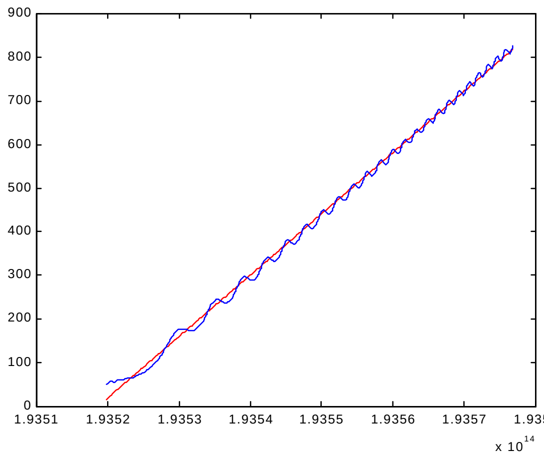

Fig.5(a) Group delay response (rippled) and linear regression for a 100 km, D_f=17 ps/nm/km link, raised cosine-apodized grating (*a*=0.4)

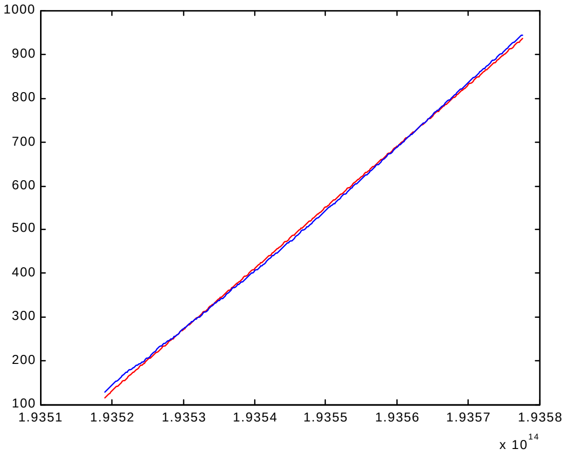

Fig.5(b) Group delay response (rippled) and linear regression for a 50 km, D_f=17 ps/nm/km link, raised cosine-apodized grating (*a*=1)

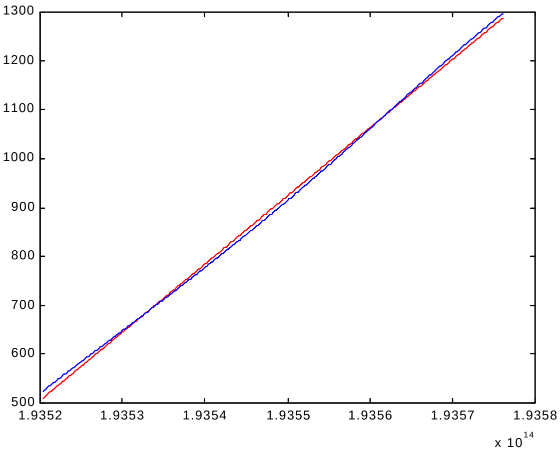

Fig 5(c) Group delay response (rippled) and linear regression for a 50 km, D_f=17 ps/nm/km link, raised cosine-apodized grating (*a*=4)

4 Summary

We have presented a review of the state-of-the art criteria for the design of optimum apodized linearly chirped fiber Bragg gratings for dispersion compensation and extended the study to short distance and long distance scenarios. We have introduced new parameters as maximum deviation error and regression slope to study the behavior of the time delay response that can give extra information to select the proper design in function of different requirements. The analysis of two prototype of standard fiber links suggests that there is not a general optimum apodization factor for chromatic dispersion compensation, but we can observe that for "short" links it will be enough with profiles like *raised cosine* with *a*=0.4 (a_{eff}=0.79) while for "long" links it is better to use stronger functions like the *a*=1 function (a_{eff}=0.6). In any case, really strong functions with low apodization parameters (a_{eff}<0.4) are not justified in terms of compression ratio or sidelobe level, taking into account the increasing difficulty of the mask process.

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