Optimized Fiber For Terabit Transmission

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Abstract

Optical fiber with a chromatic dispersion value of 8 ps/nm/km at 1550nm is a good compromise for transmission systems working at Terabit/s rate. Such a value is sufficiently high to avoid Non Zero Dispersion Shifted Fibers (NZDSF) limitations and sufficiently low to avoid Single Mode Fibers (SMF) ones. Moreover, it allows an interesting trade-off between the chromatic dispersion slope and the effective area. Fiber with optimized propagation characteristics has been realized. This fiber, called TeraLight™, has been used in a 1.5 Tb/s system (150 Channel at 10Gb/s in both C and L band with a 50GHz channel interspacing) and in a 1.28 Tb/s system (32 Channel at 40Gb/s). It is adapted for a use in the S wavelength band.

Keywords

Optical Fiber; Guided Propagation; Chromatic Dispersion; Fiber Design.

1. Introduction

Terabit transmission systems through optical fiber are about to become a reality. With an intensive occupancy rate of the C+L bands, between around 1530 and 1610 nm, transmission capacities as high as 3Tb/s have been obtained [1]. Even higher capacities could be reached with the use of enhanced C and L bands and with the opening of a short wavelength band, S, typically between 1450 and 1500 nm.

The choice of the most suitable transmission fiber to meet high capacity and upgradability requirements of Dense Wavelength Division Multiplexed (DWDM) transmissions is one of the main issues in optical transmission systems. Dispersion Shifted Fibre (DSF) exhibits a too low dispersion that enhances the impact of cross-nonlinearities and mainly Four Wave Mixing (FWM). Standard Single Mode Fibre (SMF), with its large 17 ps/nm/km dispersion value in the 1550 nm window, is more suitable for DWDM transmissions as the large dispersion reduces drastically the impact of cross-nonlinearities [2]. Nevertheless, at 10 Gbit/s per channel and above, over terrestrial transmission distances (typically 500 km), such a fiber requires dispersion compensation. Dispersion Compensating Fiber (DCF) can be used for this purpose but it impacts both on the system cost and, due to its large attenuation, on the Signal-to-Noise Ratio (SNR) at the end of the transmission. There must be a trade-off in terms of chromatic dispersion between DSF and SMF, which will minimize the required amount of dispersion compensation while still providing an efficient cross-nonlinearities reduction. First generation Non Zero Dispersion Shifted Fibers (NZDSF) were expected to meet the requirements, but their local dispersion is still too low and cross non-linear effects are still damaging at the channel spacing considered today [3-4]. A solution to decrease these cross-nonlinear impairments is to increase the effective area of the NZDSF. In fact, such a Large Effective Area NZDSF (LEA-NZDSF) has already shown good transmission performance [5], but this has been done at the expense of a high chromatic dispersion slope.

A new transmission fiber, optimized for present and future needs, seems to be an important challenge. For such an optimization, careful analysis of system requirements as well as a good knowledge of fiber design capabilities is needed. In this paper, we first present a detailed analysis of system requirements for transmission fiber in the case of DWDM high-bit-rate transmission. We then present extensive design results to find best-suited index profiles when system consideration is taken into account.

2. System Requirements

The aim of this part is to focus on the value of the local dispersion of the transmission fiber to find out its optimal value. This is done by numerically varying the dispersion and optimizing in each case the dispersion management. Dispersion management must indeed be carried out carefully considering its critical importance on transmission performance [6].

2.1 Simulation parameters

The simulated transmission link is reported on Fig. 1. At the transmitter side, thirty-two randomly decorrelated channels, 100 GHz spaced, modulated at 10 Gbit/s with a Non-Return to Zero (NRZ) modulation format, are generated with wavelength ranging from 1535.04 nm to 1559.78 nm that fall within the ITU-T recommended grid.

The transmission line consists of five 100 km-long spans of transmission fiber, whose chromatic dispersion is to be optimized, and of 6 dual-stage optical amplifiers. Such an architecture allows to insert dispersion compensation between the two stages with reduced impact on the Noise Figure (NF) of the total amplifier. In our simulations, the power per channel at the output of the amplifiers is set to 5 dBm. Their noise is taken into account by an accurate model that calculates the impact of the internal loss due to the dispersion compensation on the total NF. As an example, when internal loss is set to 0 dB, the NF of the amplifier is 5 dB, and when the loss is 11 dB (which corresponds to the DCF needed to compensate exactly for 100 km of SMF), the NF is 6.5 dB. At the end of the transmission, the receiver power sensitivity is evaluated for a Bit Error Rate (BER) of 10^{-10} and compared to the sensitivity without transmission to obtain the transmission penalty. Characteristics of DCF correspond to commercially available data : dispersion at 1550 nm is -80 ps/nm/km, dispersion slope is -0.12 ps/nm²/km, and attenuation is 0.6dB/km. Concerning the transmission fiber, its zero dispersion wavelength is varied from 1300 nm to 1550 nm, by 50 nm steps, which corresponds to dispersion values at 1550 nm ranging from 0 to 17.5 ps/nm/km by 3.5 ps/nm/km steps. In each case, the dispersion management of the link is optimized by considering in line 90% span dispersion compensation according to [7] and optimizing the amount of pre and post-compensation by 200 ps/nm steps. Then, to only focus on the impact of the dispersion of the transmission fiber, the dispersion slope is set to 0.07 ps/nm²/km and the effective area to a constant 50 µm², whatever the dispersion. To finish, note that the span budget is a large 28 dB to comply with field requirements.

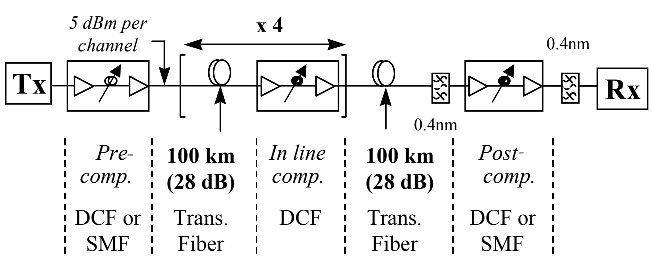

Figure 1. Simulated transmission Setup.

2.2 Results and discussion

Dispersion management is optimized for each chromatic dispersion of the fiber by selecting a value of pre-compensation between -100% and 100% of the cumulated dispersion of one fiber span, and sweeping the value of the post-compensation from -2000 ps/nm to 2000 ps/nm by 200 ps/nm steps. In each case the sensitivity penalties for a 10^{-10} BER are calculated for the 32 channels, as well as the mean penalty and the difference between the best and the worst channel sensitivities. We choose as the best map the one that leads to both the lowest mean penalty and the lowest difference between the best and the worst channel sensitivities. The results are reported on Fig. 2 for a dispersion of 17.5 (2a), 7 (2b) and 3.5 ps/nm/km (2c). The optimal dispersion map is reported in each case, plotting the cumulated dispersion for channel 1 (dashed) and channel 32 (full) as a function of the distance. The corresponding sensitivity penalties for a BER of 10^{-10} are plotted for each of the 32 channels. Note that when dispersion is zero, error floors are obtained due to the FWM. The mean penalty and the difference between the best and the worst channel sensitivities decrease as dispersion increases, as expected [2], because of the lower impact of cross nonlinear effects.

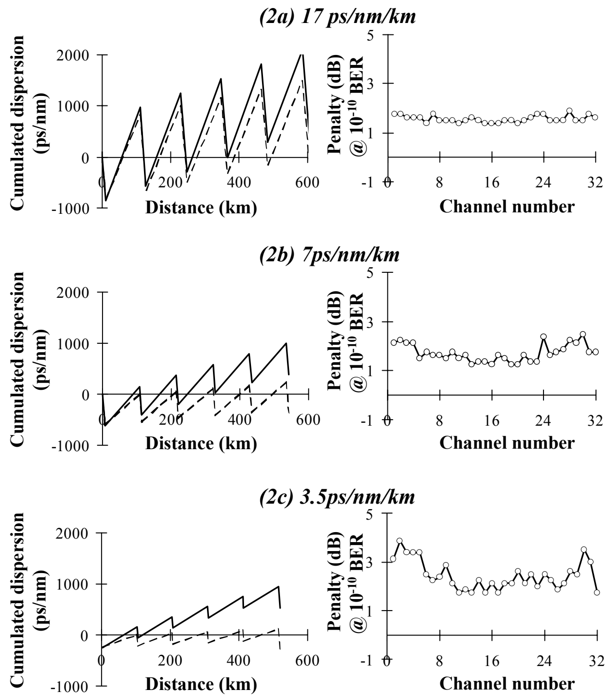

Figure 2. Best maps obtained after dispersion management optimisation and corresponding channel penalties for a 10^{-10} BER, for various values of fibre dispersion at 1550 nm.

To see more clearly the evolution of the penalty as a function of the chromatic dispersion of the fiber, we have plotted on Fig. 3 the best, the worst and the mean penalties for the 32 channels as a function of the fiber dispersion. Once again, the benefic impact of high local dispersion to suppress cross-nonlinear effects can be observed on Fig. 3. If we only consider the mean penalty, we can see on Fig. 3 that a minimum is reached for 14 ps/nm/km and that above this value it increases again because of the SNR degradation due to compensation modules. Nevertheless, a chromatic dispersion of 7 ps/nm/km looks like a threshold value: while worst sensitivity penalties remain below 2.5 dB for dispersion values above 7 ps/nm/km they dramatically increase for dispersion values below 7 ps/nm/km. Consequently, 7 ps/nm/km is the lowest value to guarantee an efficient suppression of cross-nonlinearities. This value of dispersion is an interesting choice for various reasons. First, the amount of needed DCF is more than twice as low as for SMF, which reduces both the compensation loss and cost. Second, other optical elements such as optical add-and-drop multiplexers can then be inserted inside the dual-stage amplifiers of the link while keeping the inter-stage loss to an acceptable level. Third, the reduced length of DCF also leads to reduced polarization mode dispersion in the link, which is of crucial importance at high bit-rate.

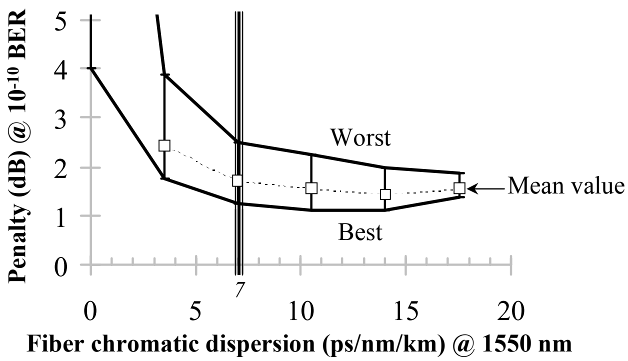

Figure 3. Results obtained as a function of fibre chromatic dispersion. The effective area is a constant 50 μm^2.

In summary, we demonstrate here that there is a good trade-off around 7-8 ps/nm/km for the chromatic dispersion of the transmission fiber. Such a dispersion guarantees an efficient suppression of cross-nonlinearities in DWDM systems while strongly reducing the DCF length needed in the compensation architecture of the link.

3. Fiber Design

Which fiber propagation characteristics would be obtained for a 8 ps/nm/km chromatic dispersion requirements in the 1550 nm window? We will here study fiber refractive index designs with such a chromatic dispersion value and compare this new family to the preceding ones.

3.1 Key propagation characteristics

Chromatic dispersion is not the only parameter to be considered when designing fiber refractive-index profile. First, the flattest variation of the chromatic dispersion is required. Chromatic dispersion slope at 1.55µm, C', which is the derivative of chromatic dispersion with wavelength needs to be minimized for a more efficient dispersion management over the amplifying bands. The second propagation characteristic (at 1.55µm) to take into account is the Effective Area, A_{eff}. Effective area is a key parameter in describing optical non-linearities and a large effective area is an efficient way to reduce non-linear effects [8]. Fiber refractive-index needs also to ensure good behavior of the fiber in cable. We consider three following parameters at 1.55 µm : bending and microbending losses which need to be minimized and cutoff wavelength which needs to ensure a single mode behavior of the fiber in the operating channels wavelength. Last but not least, fiber loss needs to be equivalent to preceding generations, that is around 0.2 dB/km in the 1550 nm window.

To compute all these parameters, we use a program that solves the scalar wave equation for arbitrary index profiles and wavelength, using Sellmeier formula for λ-dependence of silica, germanium- and fluorine-doped silica refractive index [9,10]. Once the propagation constant (or effective index) and fundamental mode field distribution is known, we can compute : mode field diameters Petermann 1 and 2 and effective area A_{eff}; chromatic dispersion C and chromatic dispersion slope C'. We can also compute bending loss for any radius using the radiation model of ref. [11] and a microbending sensitivity parameter Sµc that we defined according to ref. [12]. At last, we also look at the tolerance of propagation characteristics to small fiber-parameter deviations. Small changes in propagation characteristics with changes in core radius and core-cladding refractive index will insure a good control and a good reproducibility of chromatic dispersion during the manufacture process.

3.2 Results and discussion

Optimizing both key parameters, dispersion slope C' and effective area A_{eff} together with low loss, and good cabling behavior is difficult to achieve, as high effective areas are usually associated with high dispersion slope [13].

As a reference, we first studied simple step-index design. As expected, step design is interesting for high chromatic dispersion values and results in too small effective area when chromatic dispersion is below 10 ps/nm/km. We then focused on the well known trapezoid+ring profile shape (Figure 4), which presents more manageable trade-off between effective area and slope values and which presents the technical advantage of a well-controlled process with loss level equivalent to that of SMF.

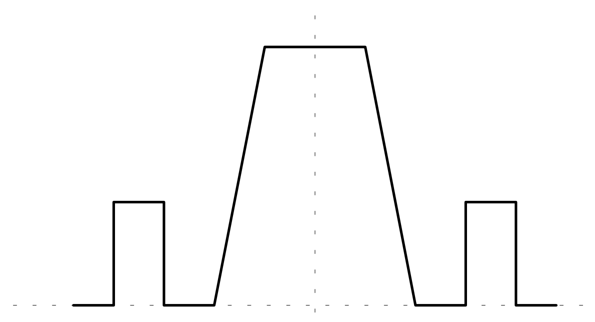

Figure 4. Representation of the trapezoid+ring refractive index profile shape.

This type of profile has 6 adjustable parameters : height of central trapezoid and ring, width and position of ring, trapezoid shape and radius. All these parameters are scanned to find the family of index profiles leading to set chromatic dispersion values C_0, that is 0 to 16 ps/nm/km by 4 ps/nm/km step.

In a given family, we first study the influence of bending loss and cutoff wavelength. These two parameters have a dramatic influence on possible effective area and dispersion slope values. This is illustrated on Fig. 5 for chromatic dispersion C_0 set to 8ps/nm/km. Each curve of Fig. 5 represents the smallest available dispersion slope as a function of effective area but for several given bending loss values. Those curves allow us to follow exactly how the slope changes as effective area and bending loss values are increasing. It is clear that the higher the bending loss level, the smaller the dispersion slopes are. But too large bending loss will lead to poor cablability. The impact of cutoff wavelength is quite similar to that of bending loss, that is the higher the cutoff wavelength, the smaller the slope. But cutoff value is also limited to ensure single mode behavior in cable. So optimum bending loss and cutoff wavelength values have to be carefully chosen to allow the best trade-off between effective area and slope, together with a good behavior in cable.

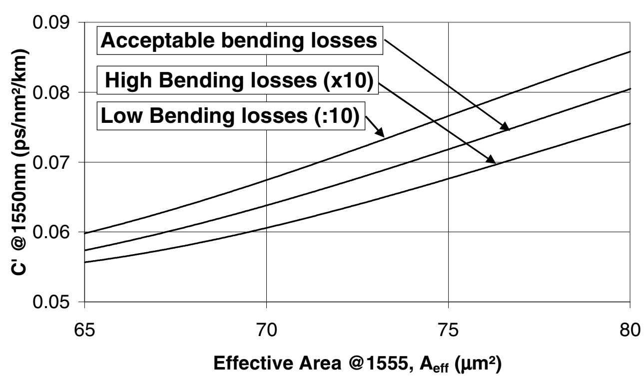

Figure 5. Chromatic dispersion slope as a function of effective area obtained for a chromatic dispersion, C, of 8 ps/nm/km and constant λ_c.

Once optimum bending loss and cut-off wavelength values are chosen to ensure a good behavior in cable, we now study the impact of chromatic dispersion value on the trade-off between effective area and slope. This is illustrated by the curves of Figure 6, which shows how dispersion slope is limited by effective area for different chromatic dispersion values.

The curves of Fig. 6 show several key features. It first appears that increasing the chromatic dispersion values allows a better trade-off between effective area and slope. For example, changing chromatic dispersion from 4 to 8 ps/nm/km allows an effective area increase of about 7 µm², when the slope C' is around 0.06 ps/nm²/km. The chromatic dispersion slope also decreases from 0.07 to 0.058ps/nm²/km, when effective area A_{eff} is around 65 µm².

The improvement of the trade-off between effective area and slope is noteworthy in the large effective area domain. Indeed, as shown in Fig. 6, the variation of C' with A_{eff} decreases when the chromatic dispersion increases. For an effective area of 80 µm², changing chromatic dispersion from 4 to 8 ps/nm/km allows a chromatic dispersion slope decrease of 0.022 ps/nm²/km, from 0.102 to 0.080 ps/nm²/km. Chromatic dispersion values over 8 ps/nm/km conduct to more interesting trade-off between effective area and slope, but we remind that in this case system design is no longer optimized due to DCF in the compensation architecture of the link.

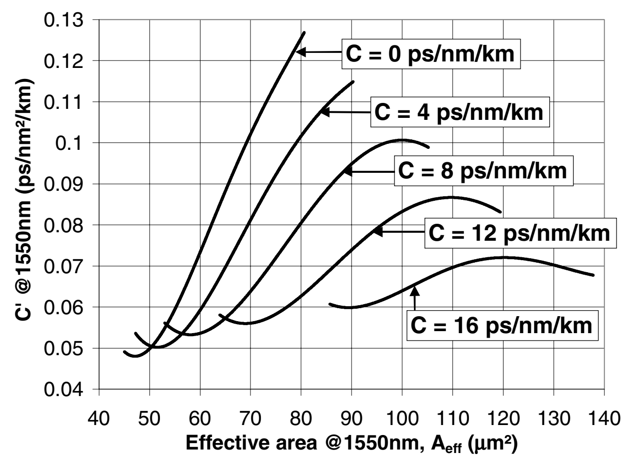

Figure 6. Chromatic dispersion slope as a function of effective area for a set of chromatic dispersion Targets (0, 4, 8, 12 and 16 ps/nm/km), constant λ_c and bending loss @1550 nm (ensuring production of fibers with a good behavior in cable).

We now focus on solutions with an effective area of about 70 µm², which is a good trade-off to reduce fiber nonlinearities while maintaining a reasonable chromatic dispersion slope. Figure 7 shows the chromatic dispersion slope as a function of the chromatic dispersion for an effective area of 65 µm². It illustrates the huge impact of chromatic dispersion. Indeed, attractive chromatic dispersion slopes lower than 0.06 ps/nm²/km are obtained for chromatic dispersion values over 7 ps/nm/km.

A chromatic dispersion value of 8 ps/nm/km is then a good compromise from a fiber design point of view.

4. Experimental Validation

A novel type of fiber, with local dispersion around 7-8 ps/nm/km and effective area around 65µm², was designed after these numerical results. Fiber results are in very good agreement with our numerical predictions. Microbending loss is comparable to that of standard fibers and cable trials have shown a very good behavior.

The efficient suppression of cross-nonlinear effects was confirmed in a record transmission experiment of 150 channels at 10 Gbit/s over 400 km [14]. BER as low as 10^{-15} have been achieved with channel spacing as low as 50 GHz. A transmission of 32 channels at 40 Gbit/s over 300 km has also been demonstrated [15].

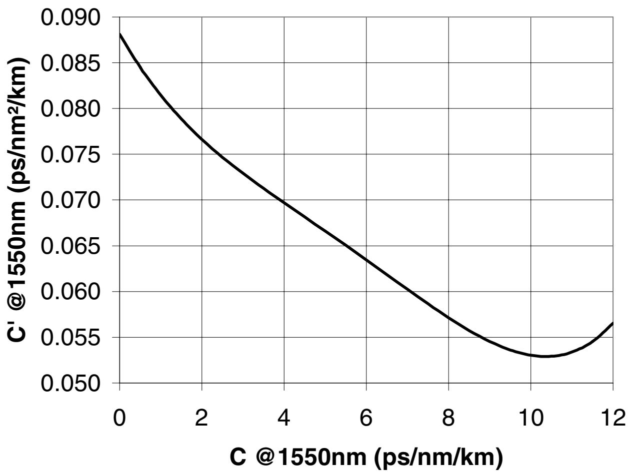

Figure 7. Chromatic dispersion slope as a function of chromatic dispersion for an effective area of 65 µm², constant λ_c and bending loss @1550 nm (ensuring production of fibers with a good behavior in cable).

5. Conclusions

To conclude, a chromatic dispersion value of 8 ps/nm/km is a good compromise: it is sufficiently high to avoid NZDSF limitations, sufficiently low to avoid SMF ones, and it allows an interesting trade-off between effective area and slope. Such propagation characteristics have been experimentally validated and conducted to a new fiber, called TeraLight™, with the expected propagation characteristics and cabling behavior. This fiber has been used in a 1.5 Tb/s system (150 Channel at 10 Gb/s in both C and L band with a 50 GHz channel interspacing) and in a 1.28 Tb/s system (32 Channel at 40Gb/s). It is adapted for a use in the S wavelength band.

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Biographies

Louis-Anne de Montmorillon received an engineering degree in Optics from the Ecole Supérieure d'Optique in Orsay, France in 1993. He received his Ph. D. degree in Physics from the university of Paris-Sud (France) in 1997 for a work pursued at the Institut Supérieur d'Optique Appliquée, devoted to photorefractive ultrasonic detection. He then joined Alcatel in the Fiber optic R&D unit, Conflans Sainte-Honorine (France).

Alain Bertaina was born in 1973. In 1995, he received an engineering degree in Optics from the Ecole Supérieure d'Optique in Orsay (France). He joined Alcatel in 1997 in the Corporate Research Centre, Marcoussis (France) and received his PhD in Photonics and Optics from the University of Paris XI in 2000 for a work devoted to the impact of the fibre characteristics on the performance of high bit rate transmission systems.

Pierre Sillard received the Engineering Diploma from the Ecole Nationale Supérieure des Télécommunications in Paris, France, in 1994, and the Ph. D. degree from the University of Paris VI in 1998. His thesis work was pursued at the Laboratoire Central de Recherches of Thomson-CSF on the subject of laser resonators with self-pumped phase conjugate mirrors. He then joined Alcatel in the Fiber optic R&D unit, Conflans Sainte-Honorine (France).

Ludovic Fleury received a Physics diploma in 1992 and a Ph. D. degree in optical spectroscopy in 1995 from University of Bordeaux (France) for a work devoted to single molecule spectroscopy in condensed matter. He worked as post-doctorate at Institute of Technology of Chemnitz, Germany, and ETH University of Zürich, Switzerland, from 1995 to 1998. He then joined Alcatel in the Fiber optic R&D unit, Conflans Sainte-Honorine (France).

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Sébastien Bigo was born in Cagnes-sur-Mer, France, in 1970. In 1992, he graduated from the Ecole Supérieure d'Optique, University of Paris XI. In 1996, he received a ph.D. degree in physics for a work devoted to all-optical processing and soliton transmission. He joined Alcatel in 1993 in the Photonics Networks Unit of the Corporate Research Center, Marcoussis (France), while being a student at the University of Besançon, France. Since 1997, he has worked on high-capacity WDM terrestrial systems. He is now deputy leader of the terrestrial transmission group. He has authored and co-authored more than 50 papers and 20 patents.

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