Optimal packaging of dispersion-compensating fibers for matched nonlinear compensation and reduced optical noise

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A method of packaging dispersion-compensating fibers (DCFs) is discussed that achieves optimal nonlinearity compensation and a good signal-to-noise ratio simultaneously. An optimally packaged dispersion-compensating module (DCM) may consist of portions of DCFs with higher and lower loss coefficients. Such optimized DCMs may be paired with transmission fibers to form scaled translation-symmetric lines that could effectively compensate for signal distortions due to dispersion and nonlinearity, with or without optical phase conjugation. © 2005 Optical Society of America

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Dispersion-compensating fibers (DCFs) have become essential components in high-speed long-distance fiber-optic transmissions.[1] Often they are packaged into compact dispersion-compensating modules (DCMs) and integrated with fiber-optic amplifiers at the repeater sites. The loss of signal power in DCFs requires extra gain from optical amplifiers, and amplifiers introduce noise. Because of their small modal area, DCFs could be significant contributors of nonlinearity if the power of the signals that are carried is not limited to a low level. In the past, DCF manufacturers have strived to reduce the loss of DCFs and to lower their nonlinearity by enlarging the modal area.[2] However, reduced DCF nonlinearity does not necessarily translate into improved overall transmission performance. Recently, it has been demonstrated that one may take advantage of the nonlinear response of DCFs to compensate for the nonlinearity of transmission fibers (TFs).[3–5] Simply minimizing the loss in such nonlinearity-compensating DCFs is not necessarily consistent with the best system performance either. This Letter proposes and tests a method of packaging DCFs to achieve optimal nonlinearity compensation and a good signal-to-noise ratio (SNR) simultaneously. Simply stated, an optimally packaged DCM may consist of two (or more) portions of DCFs with higher and lower loss coefficients. In the first portion that experiences high signal power, the loss coefficient may be intentionally increased in proportion to the DCF dispersion with respect to a TF. In another portion where the signal power is low and nonlinearity is negligible, the loss coefficient may be minimized to output stronger signals while compensating for the remaining dispersion due to the TF.

Effective nonlinearity compensation between DCFs and TFs, with or without optical phase conjugation (OPC), relies on careful arrangements of different types of fiber in a transmission line to form so-called scaled translation symmetry.[3,4] Analytical theory and numerical simulations verifying nonlinearity compensation using translation symmetry have been established previously.[3,4] Basically, for two fibers to be matched for translation symmetry in the scaled sense about an optical phase conjugator, their parameters need to obey the following scaling rules[3]:

$$(\alpha', \beta_2', \beta_3', \gamma' P_0') = R(\alpha, -\beta_2, \beta_3, \gamma P_0), \tag{1}$$

where α, β_2, β_3, and γ are the loss, second-order dispersion, third-order dispersion, and Kerr nonlinear coefficient, respectively, for one fiber; the primed parameters are the corresponding parameters of the other fiber; P_0 and P_0' are the signal powers input to the two fibers, respectively; and $R>0$ is a scaling factor. Such scaled translation symmetry permits nonlinearity compensation between the two matched fibers up to the first-order nonlinear perturbation.[3] The seemingly limited compensation capability based on perturbation is in fact quite relevant and powerful in practice, because the nonlinear response of each fiber segment is indeed perturbative in long-distance transmission lines, and matched fiber pairs may be arranged in a mirror-symmetric order to effectively undo the nonlinear distortions that may have accumulated far beyond the regime of perturbations.[3] In the absence of OPC, a DCF and a TF may still be arranged in translation symmetry in the scaled sense according to the following rules[4]:

$$(\alpha', \beta_2', \beta_3', \gamma' P_0') = R(\alpha, -\beta_2, -\beta_3, \gamma P_0), \tag{2}$$

where again $(\alpha, \beta_2, \beta_3, \gamma)$ and $(\alpha', \beta_2', \beta_3', \gamma')$ are parameters of the two types of fiber. In both scaling rules (1) and (2), the requirements for the third-order dispersion may be relaxed, then the two fibers are not in strict translation symmetry across a band of wavelength channels; rather, the symmetry and nonlinearity compensation between them become approximate. Nevertheless, such approximation is often good when the value of $|\beta_2/\beta_3|$ is high, so the percentage

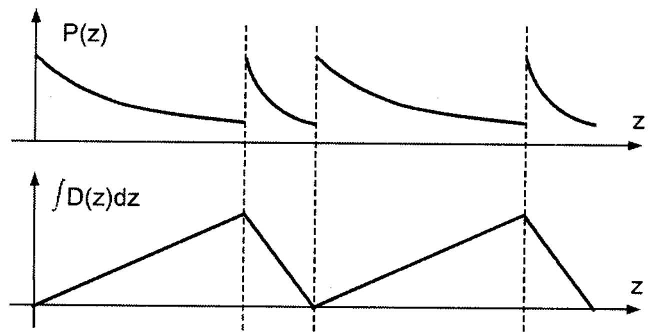

Fig. 1. Power map and M-type dispersion map over the transmission distance of two traditional fiber spans.

change of β_2 is only small across the band, which is exactly the case for standard single-mode fibers (SMFs) in the 1550 nm band.

The great advantage of nonlinearity compensation using scaled translation symmetry is that a pair of matched fiber segments are required to have the same sign for the loss or gain coefficients and opposite dispersion. Such conditions are naturally satisfied in conventional fiber transmission systems, where a TF, for example, a SMF, may be paired with a DCF as matched counterparts. However, traditional transmission lines are usually set up with the same configuration for all spans, that is, with a TF followed by a DCF. Consequently, the accumulated dispersion in all spans is single sided, that is, stays always positive or always negative. Such dispersion may be called an M-type dispersion map, as shown in Fig. 1, where no two spans could form a scaled translation symmetry. Our proposal is to simply exchange the ordering of the TF and DCF for some spans, which may be paired with traditional spans to form an N-type dispersion map, where the accumulated dispersion may go both positive and negative and trace an N-like curve, as shown in Fig. 2. A scaled translation symmetry is formed between two matched fiber spans as in Fig. 2, in the sense that the TF of the first span is scaled translation-symmetric to the DCF of the second span, and the DCF of the first span is scaled translation-symmetric to the TF of the second span. Such translation symmetry between two matched spans could cancel some of their intrachannel nonlinearities or compensate for all nonlinearities up to the first-order perturbation if an optical phase conjugator is installed in the middle. Furthermore, many pairs of matched spans may be arranged into a mirror-symmetric order about the point of OPC to form a long-distance transmission line, whose second part could undo the nonlinear distortions due to the first part that may have accumulated far beyond the regime of perturbations.[3]

In traditional transmission lines, each fiber span has a TF and a DCM at the end, which consists of a conventional DCF with a multistage erbium-doped fiber amplifier (EDFA). Many such conventional fiber spans are cascaded to form a line with an M-type dispersion map, as shown at the top of Fig. 3, where a conventional DCM is denoted by CDCM_M. If the order of TF and DCF is switched for every other span, then an N-type dispersion map is formed, and two adjacent DCFs may be packaged into one DCM, denoted by CDCM_N, as shown in the middle of Fig. 3. As a result of the N-type dispersion map, intrachannel nonlinearities may be suppressed to some extent, and all fiber nonlinearities may be partially compensated for in the presence of OPC in the middle of the transmission line. However, compensation of nonlinearity is not optimal, as scaling rules (1) and (2) are not satisfied by conventional DCFs paired with TFs. Indeed, DCF manufacturers have succeeded in reducing the loss of DCFs, as lowering DCF loss was thought to monotonically improve the performance of transmission systems.[2] The dispersion-to-loss ratio (DLR) of state-of-the-art DCFs is often much larger than that of TFs. From the standpoint of matched nonlinearity compensation, it would be advantageous to (intentionally) raise the loss of DCFs such that the DLRs of DCFs and TFs are matched to satisfy the scaling rules, at least for portions of fibers

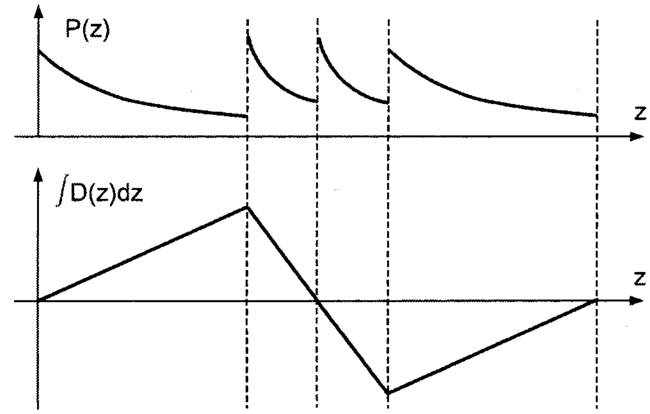

Fig. 2. Power map and N-type dispersion map over the transmission distance of two matched fiber spans for scaled translation symmetry.

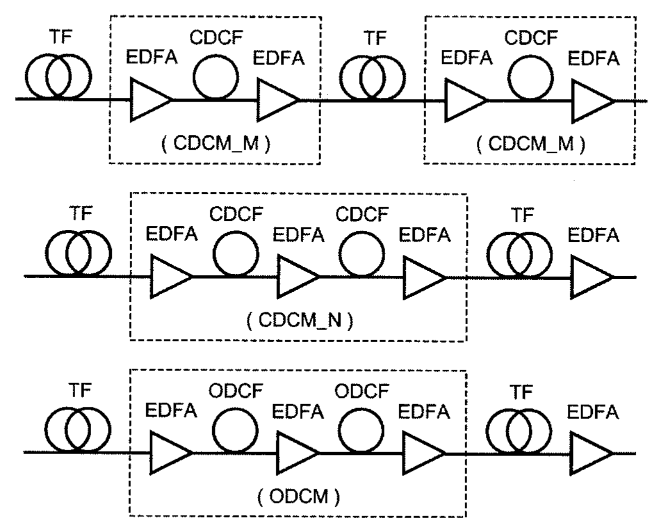

Fig. 3. Three configurations of transmission lines with different dispersion maps and DCMs. Top, M-type dispersion map using conventional DCMs; middle, N-type dispersion map using conventional DCMs; bottom, N-type dispersion map using optimized DCMs. CDCF, conventional DCF; ODCF, optimized DCF; CDCM_M, conventional DCM in an M-type dispersion map; CDCM_N, conventional DCM in an N-type dispersion map; ODCM, optimized DCM.

carrying high-power signals. On the other hand, in regions of DCFs experiencing low signal power, the nonlinearity is weak and negligible, and then the scaling rules may be disregarded and the loss of DCFs may be minimized to enhance the optical SNR at the end of dispersion compensation. Therefore, an optimized DCM (ODCM) may consist of sections of DCFs with higher and lower loss coefficients, as well as multiple EDFA stages to repeat the signal power and regulate the signal power in the lossier portions of DCFs, according to a set of scaling rules with respect to the TFs. Higher DCF loss may be induced by intrinsic material attenuation during fiber manufacturing or by bending loss during fiber packaging.[3]

To give an example of ODCM and test its performance in nonlinearity compensation, we simulated (using VPItransmissionMaker) and compared three transmission systems, all of which have 12 recirculating loops and an optical phase conjugator in the middle. For the first system, each loop consists of two identical spans of 100 km SMF followed by a CDCM_M, as shown at the top of Fig. 3. For the second system, each loop has a 100 km SMF followed by a CDCM_N, then a 100 km SMF followed by a 20 dB EDFA. For the third and optimized system, each span consists of a 100 km SMF followed by an ODCM, then a 100 km SMF followed by a 20 dB EDFA. Each CDCM_M has a 15 dB EDFA, a 20 km conventional DCF, then a 15 dB EDFA. Each CDCM_N has a 15 dB EDFA, a 20 km conventional DCF, then another 15 dB EDFA, a 20 km conventional DCF, and finally a 10 dB EDFA. By contrast, each ODCM consists of a 21 dB EDFA, a 10 km optimized DCF, a 10 km conventional DCF, a 15 dB EDFA, then a 10 km optimized DCF, a 10 km conventional DCF, and a 14 dB EDFA. Note the adjustment of signal power in the optimized DCFs to fulfill the scaling rules. The SMF has loss $\alpha = 0.2$ dB/km, dispersion $D = 16$ ps/nm/km, dispersion slope $S = 0.055$ (ps/nm^2)/km, and effective modal area $A_{\text{eff}} = 80\ \mu\text{m}^2$. The conventional DCF has $(\alpha', D', S', A_{\text{eff}}') = (0.5, -80, -0.275, 20)$ in the same units. The optimized DCF differs from the conventional one only by loss coefficient $\alpha'' = 1.0$ dB/km. The same silica nonlinear index $n_2 = 2.6 \times 10^{-20}$ m^2/W is taken for all fibers. All EDFAs have the same noise figure of 4 dB. The center frequency is 193.1 THz. The inputs are four 40 Gbits/s channels, spaced by 200 GHz, copolarized and return-to-zero modulated with 33% duty and a pulse peak power of 15 mW. Eye diagrams of optical signals at the end of transmissions are shown in Fig. 4, where the top diagram displays severe nonlinear distortions for the conventional line with the M-type dispersion map, while the middle diagram shows improved but still seriously impaired signals of the line with the N-type dispersion map using conventional DCMs. The bottom diagram demonstrates a significant improvement of signal quality by using optimized DCMs and scaled translation symmetry, where the signal distortions are due mainly to EDFA noise and possibly to some uncompensated nonlinearity.

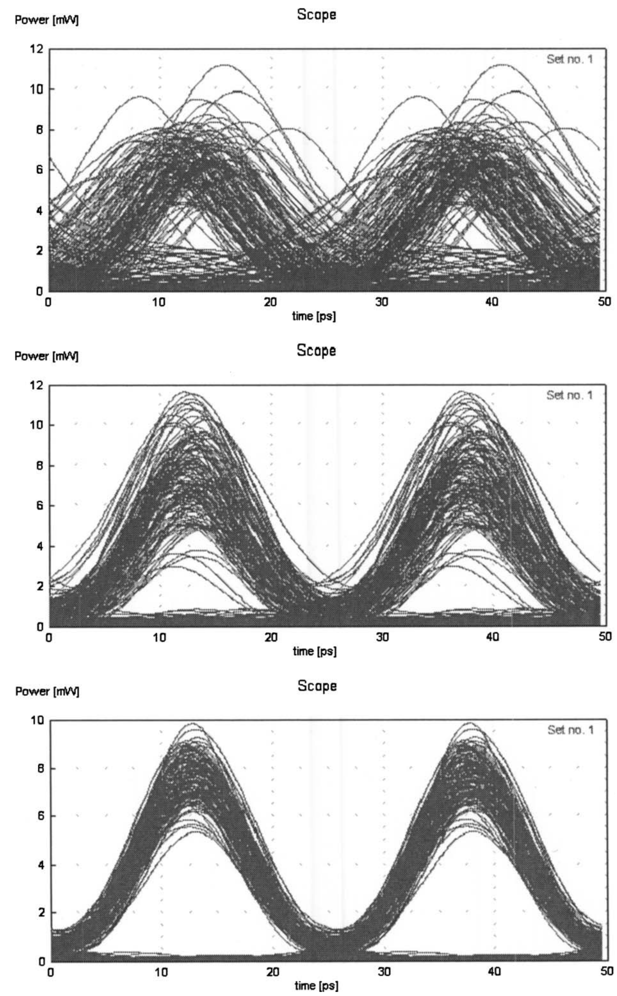

Fig. 4. Optical eye diagrams at the end of transmissions. Top, conventional line with the M-type dispersion map; middle, line with conventional DCMs in the N-type dispersion map; bottom, system using optimized DCMs and scaled translation symmetry.

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