

Long-distance transmission of bandwidth-managed solitons in fibres with alternating dispersion

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It is shown that bandwidth management in dispersion-alternating fibres allows noise accumulation in spaces to be suppressed and signal pulses, bandwidth-managed solitons (BMS), to be stably propagated over ultra-long distances. Both the amplitude and timing jitter of the signal pulses are greatly reduced by using BMS while the transmission distance is dramatically increased.

Significant progress has been made recently in the use of high bit rate dispersion-managed soliton (DMS) transmission for industrial applications [1, 2]. One of the major disadvantages of DMS systems is the accumulation of amplified spontaneous emission (ASE) noise and the noise induced by four-wave mixing. To discriminate the noise and stabilise the signal using passive devices, the nonlinear features must be exploited. In principle, the Kerr nonlinearity in the fibre, if used properly, is sufficient for this purpose. For instance, the sliding filtering technique [3] enables suppression of the noise in the spaces and transmission of the soliton signals the central frequency of which slides with distance. However, for applications such as all-optical networking, it is desirable to use fixed central frequency signals. In this Letter a mechanism is proposed that allows us to discriminate the noise and support stable signal pulse propagation in dispersion-managed fibres without changing the central frequency of the signals. The mechanism, referred to hereafter as the bandwidth-managed soliton (BMS) mechanism, is based on the following physical principle. The bandwidth in DMS transmission oscillates with distance. For a two-step dispersion map, the bandwidth is maximum at the chirp free point of the anomalous dispersion span and minimum at the chirp free point of the normal dispersion span. The key concept of BMS transmission is to insert into the DMS system a bell-shaped filter (BF) at the point where the bandwidth is near its minimum and a V-shaped filter (VF) at the point where the bandwidth is near its maximum, such that the top of the BF and the bottom of the VF are set at the central frequency of the pulse. In this case, owing to bandwidth guiding, DMS transmission experiences less loss than the noise, the bandwidth of which remains constant. Hence, it is possible to discriminate the noise. To show this, we assume for simplicity that, first, BMS transmission has a Gaussian shape with a quadratic chirp, and secondly, that the BF and VF have Gaussian shapes near their maximum and minimum, respectively. The energy transmission coefficient through the BF with the response function $f_1(\nu) = \exp[-2 \ln(2)\nu^2/\Delta^2]$ is $T_1 = 1/\sqrt{1+B_1^2/\Delta^2}$, and the energy transmission coefficient through the VF with the response function $f_2(\nu) = C \exp[2 \ln(2)\nu^2/v^2]$ is $T_2 = C^2/\sqrt{1-B_2^2/v^2}$, where B_1 and B_2 are the FWHM bandwidths of the pulse at the input of the BF and VF, respectively, Δ is the FWHM bandwidth of the BF, ν is the full width at double minimum bandwidth of the VF, v is the light frequency, and $B_2 < v$. If G is the net gain per map period taking into account the total losses except the losses in the BF and VF, the energy balance for the soliton requires that $T_1 T_2 G = 1$. By contrast, for the central frequency noise component the transmission coefficient through the BF is 1 and through the VF is C^2 . Hence, the total transmission coefficient of the central frequency noise component per one map period is $T_0 = C^2 G$. As $G = 1/T_1 T_2$, we obtain

$$T_0 = \sqrt{(1 + B_1^2/\Delta^2)(1 - B_2^2/v^2)} \quad (1)$$

In the system with $\Delta \leq \nu$, all frequency components of the noise will attenuate if $T_0 < 1$. Thus we obtain from eqn. 1 the following criterion for discriminating the noise

$$R = \frac{\nu^2}{B_2^2} - \frac{\Delta^2}{B_1^2} < 1 \quad (2)$$

When the propagation is linear, $B_2^2 = B_1^2 + \Delta^2$ and hence always $R = (\nu^2 - \Delta^2)/B_1^2 + \nu^2/\Delta^2 \geq 1$ as $\Delta \leq \nu$ and, consequently, $T_0 \geq 1$. This means that in the linear case there is always a net gain for the central frequency noise component. However, in nonlinear propagation, the DMS bandwidth expands in the anomalous span, so that it becomes $B_2^2 < B_1^2 + \Delta^2$. If B_2 becomes larger than the

threshold bandwidth B_{th} such that $B_2^2 < B_{th}^2 = (B_1^2 + \Delta^2)\Delta^2/\nu^2$ then $R < 1$ and $T_0 < 1$. Hence the noise is discriminated while the signal can propagate in a lossless manner.

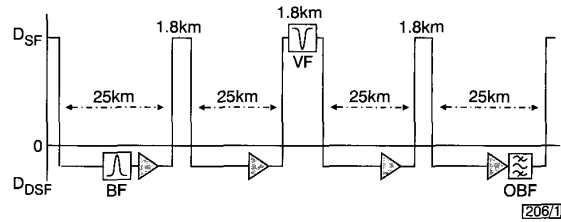


Fig. 1 Schematic diagram of dispersion map

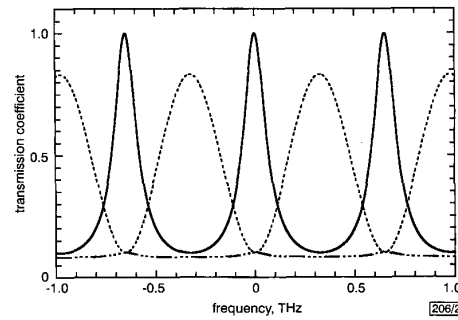


Fig. 2 Response functions $f_{1,2}(\nu) = |F_{1,2}(\nu)|^2$ for BF and VF, respectively, and their product $f_1(\nu)f_2(\nu)$ against frequency ν

— BF
 VF
 - - - product $f_1(\nu)f_2(\nu)$

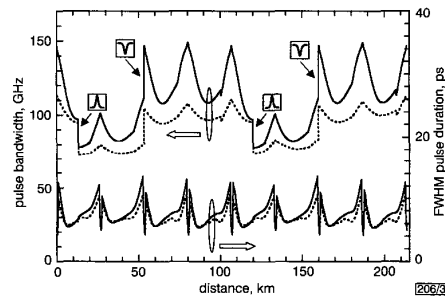


Fig. 3 Dependence of pulse bandwidth and pulse duration inside map over two map periods for 410 fJ and 171 fJ pulse energies, respectively, taken at zero distance

— 410 fJ
 171 fJ

We demonstrate BMS transmission numerically in the dispersion map shown in Fig. 1. The dispersion map consists of four spans of dispersion-shifted (DSF) fibre each 25 km in length and four spans of standard fibre (SF) each 1.8 km in length with dispersion coefficients of -1.2 ps/nm-km and 16.7 ps/nm-km, respectively. The path average dispersion is 0.02 ps/nm-km, the dispersion slope in both SF and DSF is 0.07 ps²/nm-km, and the Kerr coefficient is $n_2 = 2.6 \times 10^{-16}$ cm²/W. The amplifiers are located 19.6 km from the beginning of the normal dispersion span with an amplifier spacing of 26.8 km. This location was chosen to reduce the stretching factor associated with DMS transmission in the loop experiment [4]. An optical bandpass filter (OBF) with a bandwidth of 2.8 nm and Gaussian shape was used to flatten the gain of the amplifiers at the central frequency. A Fabry Perot filter with reflection coefficient $r = 0.52$, free spectral range $S = 0.65$ THz and transfer function $F_1(\nu) = (1-r)/[1-r \exp(i2\pi\nu/S)]$ was used as the BF. The sinusoidal response filter (of an AmpFlat filter type of Santec Corp.) with transfer function $F_2(\nu) = a + b \exp(i2\pi\nu/S)$ with $a = 0.6152$ and $b = 0.2968$ was used as the VF. The response functions of the BF and VF are shown in Fig. 2. The BF is located at the midpoint of the normal dispersion span while the VF is located at the midpoint of the anomalous dispersion span. An additional amplifier with a gain of 10.5 dB was

placed in front of the VF to compensate for the loss caused by the VF. The spontaneous emission factor for all amplifiers was set to 1.3. In the model, we took into account the saturation effect in the EDFAs by setting the saturation power to 10mW and the relaxation time to 1ms [5]. In this case, periodically stationary BMS propagation proves to be remarkably stable over > 200000km. As shown in Fig. 3, inside the map BMS transmission is bandwidth-guided. In Fig. 3 $B_1 = 96.9\text{GHz}$, $B_2 = 111.9\text{GHz}$ for a pulse energy of 410fJ and $B_1 = 94.7\text{GHz}$, $B_2 = 80.8\text{GHz}$ for a pulse energy of 171fJ. The filter bandwidths estimated from Fig. 2 are $\Delta = 142.9\text{GHz}$ and $\nu = 166.7\text{GHz}$, hence $B_{th} = 93.5\text{GHz}$ for the higher pulse energy and $B_{th} = 92.1\text{GHz}$ for the lower pulse energy.

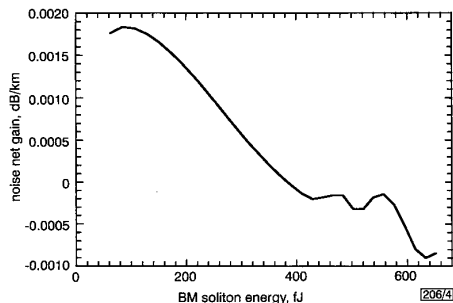


Fig. 4 Dependence of net gain coefficient for central noise component on energy of BMS

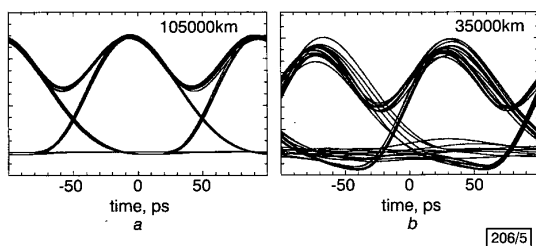


Fig. 5 Eye diagrams of 64 pseudorandom bit stream transmission with equal number of marks and spaces in system with and without bandwidth management

a With bandwidth management (BMS) over 105000km
b Without bandwidth management (DMS)
8GHz bandwidth fifth-order Bessel filter is used

Thus, $B_2 > B_{th}$, which means that the criterion in eqn. 2 holds and the noise is discriminated for a pulse energy of 410fJ. Conversely, $B_2 < B_{th}$, $R > 1$ and the noise has a net gain for a pulse energy of 171fJ. In Fig. 4, we calculate the dependence of the net noise gain on the energy of BMS transmission. Note that when the BMS energy is larger than the threshold energy (~380fJ) the noise net gain becomes negative, thus leading to suppression of the noise intensity in the spaces. In Fig. 5, we compare the eye diagrams for the transmission of a 64 pseudorandom bit stream with and without bandwidth management. In the latter case, the parameters of all four amplifiers are the same but the BF and VF filters as well as the 10.5dB compensating amplifier are removed. The remarkable improvement in the eye in Fig. 5a compared to Fig. 5b is due to three factors. First, the noise in the spaces is almost completely eliminated and does not grow with distance. Note that this suppression occurs despite ~10.5dB extra loss in the case of Fig. 5a. Secondly, the amplitude and timing jitter is dramatically reduced due to the strong confinement of the pulse central frequency and bandwidth. Thirdly, the transmission distance is tripled. Future work will focus on analysing the dynamics of BMS transmission depending on the BF and VF parameters as well as the dispersion-managed fibre parameters.

Acknowledgment: This work was supported by an AFOSR grant. The author appreciates the encouragement of G.M. Carter and C.M. Menyuk.

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Calculation of 3D trajectories of moving objects from unsynchronised stereo video signals

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A method for the 3D reconstruction of moving objects from unsynchronised stereo video signals is presented. Using a video mosaicing technique for each video signal, all frames are registered in a reference frame and the trajectories of moving objects obtained as a static structure in a scene, so that correspondence can be determined from an epipolar geometry.

Introduction: In traditional 3D calculation methods, the fact that the stereo sequences are synchronised is typically an essential assumption [1]. However, we have found that 3D information can be extracted without synchronisation when each sequence of stereo video signals is captured by a stationary camera (i.e. without translation). In this case, the trajectories of moving objects can be obtained with respect to a reference frame by using inter-image homographies for image mosaicing. These trajectories can be regarded as a static structure in a scene so that corresponding points can be determined from an epipolar geometry. Obviously, time stamping or synchronisation is not necessary for studying dynamic motion in stereo signals. From the matching results of the trajectories, the projective structure of the moving objects is calculated. Finally, we reconstruct their metric structure, using at least five known points in the background.

Reconstruction method: First, we construct the trajectories of a moving object in a pair of stereo video signals. Assuming that each video image is captured by a stationary camera, video mosaicing techniques calculate the inter-image homographies between a reference frame and other frames in each video signal [2]. Meanwhile, we track the positions of the feature points of a moving object. The tracked positions of each video signal are transferred to its corresponding reference frame and then interpolated using a linear function or splines. As a result, we can obtain a pair of trajectories s_l and s_r in the pair of reference frames I_l and I_r . These trajectories can be regarded as a static structure in a scene so that corresponding points can be determined from an epipolar geometry.

Secondly, we estimate the fundamental matrix **F** between the two reference frames, I_l and I_r , which will be used for the trajectory matching in the following step. Given a minimum of five corresponding points/lines in general positions between the two