Long-haul Fiber-optic Transmission Utilizing DMS Modulation Format

B. Stojanović[1], D. Milović[2], M. Stefanović[3] and N. Spasojević[4]

***Abstract* – This paper investigates the stable soliton propagation over the long-haul fiber-optic system. Soliton system design provides transmission of undistorted pulses over a long distances through the SSMF. The similar effect on pulse dynamics is accomplished if a periodic dispersion compensation is applied on fiber-optic transmission. It has been shown that the so-called dispersion-managed soliton (DMS) can propagate over long-haul distances.**

***Keywords* – Long-haul transmission, soliton, DMS map.**

I. Introduction

Long distance fiber-optic telecommunication systems carry digital information over terrestrial distances ranging from 3,000 km to 5,000 km and transoceanic distances ranging from 5,500 km to 12,000 km. During the last 10 years these systems have evolved significantly.

Wavelength Division Multiplexing (WDM) [1], is a technology that allows multiple information streams to be transmitted simultaneously over a single fiber at data rates as high as the fiber plant will allow. WDM technology utilizes a composite optical signal carrying multiple information streams, each transmitted on a distinct optical wavelength. By allowing multiple WDM channels to coexist on a single fiber, one can tap into the huge fiber bandwidth with multiple, simultaneous, extremely high frequency signals of terahertz (THz) range.

The performance of high-speed fiber-optic communication systems is generally limited by GVD effect that broadens the pulse and disperses its energy. Solitons are useful to improve the performance of such dispersion limited communication systems since they can maintain their width over long distances by balancing the effect of GVD through the nonlinear phenomenon of SPM. In the soliton system design, many unavoidable limiting factors are to be considered and understood like the effect of fiber loss, mutual interactions between two neighboring pulses and the Gordon-Haus effect.

[1]Bratislav D. Stojanović is with the Faculty of Electronic Engineering, Beogradska 14, 18000 Niš, Serbia and Montenegro, E-mail: batas@ni.ac.yu

[2]Daniela M. Milović is with the Faculty of Electronic Engineering, Beogradska 14, 18000 Niš, Serbia and Montenegro, E-mail: dacha@elfak.ni.ac.yu

[3]Mihajlo Č. Stefanović is with the Faculty of Electronic Engineering, Beogradska 14, 18000 Niš, Serbia and Montenegro, E-mail: misha@elfak.ni.ac.yu

[4]Nebojša D. Spasojević is with the NIS Jugopetrol, Milentija Popovića 1, 11000 Belgrade, Serbia and Montenegro, E-mail: nebojsa.spasojevic@jugopetrol.co.yu

Dispersion-managed soliton wavelength-division multiplexed (WDM) transmission with 20 Gbit/s per channel is a promising way to realize long-haul systems with an aggregate transmission capacity greater than 100 Gbit/s. Optimizing the performance of such dispersion-managed system is of crucial importance, and requires lunching properly shaped and chirped pulses into the fiber to minimize the shedding of energy into a dispersive pedestal [2].

II. Soliton propagation

It is well known that the pulse propagation in an nonlinear dispersive medium [3], as the optical fiber is, can be described with the Generalized Nonlinear Schrödinger's partial differential Equation (GNLS),

$$\frac{\partial A}{\partial z}+\frac{1}{v_g}\frac{\partial A}{\partial t}+\frac{i}{2}\beta_2\frac{\partial^2 A}{\partial t^2}+\frac{\alpha}{2}A=i\gamma|A|^2A \tag{1}$$

where β_2 is dispersion coefficient, v_g is group velocity, γ is nonlinearity coefficient defined as

$$\gamma=\frac{n_2\omega}{cA_{\mathtt{eff}}} \tag{2}$$

and A_{eff} represents the effective core area (typically 10-20 μm^2 in visible region), c is speed of light, ω is the pulse central frequency and n_2=3,2×10^{-16}cm^2/W for silica fiber.

Ignoring fiber loss (α = 0), and introducing normalized units, the GNLS in Eq. (1) can be written as

$$j\frac{\partial}{\partial\xi}u=\frac{1}{2}\operatorname{sgn}(\beta_2)\frac{\partial^2}{\partial\tau^2}u-\frac{L_D}{L_{NL}}|u|^2u \tag{3}$$

where u is the normalized field amplitude given by

$$u=A/\sqrt{P_0}\ ,$$

with P_0 peak power at fiber input,
ξ is the normalized transmission distance given by

$$\xi=z/L_D\,,$$

L_D is the dispersion length, L_{NL} and is nonlinear length, τ is the normalized, retarded time given by

$$\tau=T/T_0=(t-z/v_d)/\sqrt{L_D|\beta_2|}$$

Using the inverse scattering method [4], Eq. (3) can be solved analytically for a launched pulse shape, which satisfies the equation at any distance point.

Among others, so-called soliton [4,5] solutions exist in the anomalous dispersion regime ($\beta_2 < 0$), which satisfy the criterion

$$N = \sqrt{\frac{L_D}{L_{NL}}} = 1,2,.. \tag{4}$$

Of special interest is the fundamental soliton solution, as its pulse shape is not altered during propagation. It is given for the case $L_D = L_{NL}$ as

$$u(\xi,\tau) = \mathrm{sech}(\tau)\mathrm{e}^{j\xi/2} \tag{5}$$

Only the phase of the fundamental soliton is undergoing a circular change with period. Other, higher order soliton solutions of interest for fiber-optic communications are those of the same initial pulse shape as the fundamental one

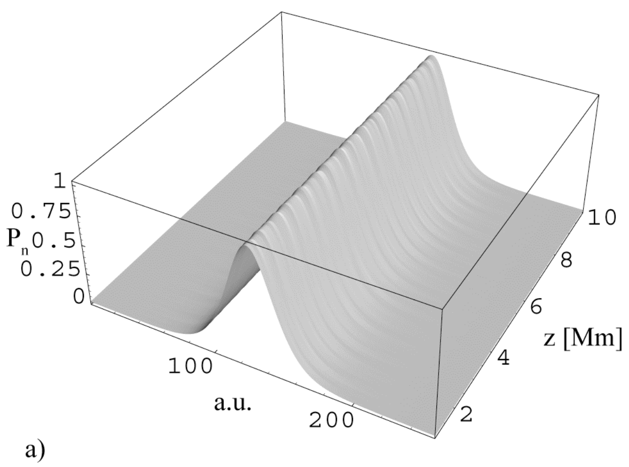
$$u(0,\tau) = N\,\mathrm{sech}(\tau) \tag{6}$$

At the fiber input, the peak power and width of the soliton are related by (4). Using definitions for dispersion and nonlinear lengths, $L_D = T_0^2/|\beta_2|$ and $L_{NL} = 1/(\gamma|A|^2)$, one gets [4]

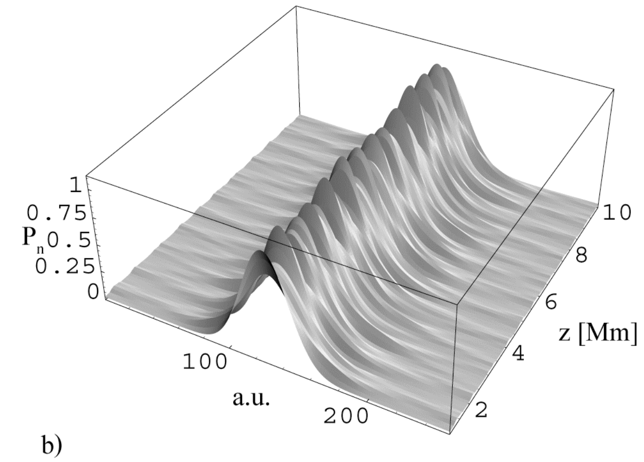
$$P_0 = N^2 \frac{|\beta_2|}{\gamma T_0^2} \approx N^2 3{,}107 \frac{|\beta_2|}{\gamma T_{FWHM}^2} \qquad N = 1,2,... \tag{7}$$

where T_0 is the pulse duration (half-width 1/e-intensity) and T_{FWHM} is the FWHM (full-width at half maximum) pulse duration.

Figure 1 shows the pulse shape evolution of the fundamental soliton in comparison with a Gaussian pulse. For both pulses, the peak power is 8.141 mW and the FWHM duration is 20 ps. It can be seen how the fundamental soliton retains its shape, while the Gaussian pulse shape is changing rapidly as it tries to balance linear (pulse-spreading) and nonlinear (pulse-compressing) forces.



a)



b)

Fig. 1 Evolution of sech (a) and Gaussian (b) shaped pulses of equal FWHM duration, (no fiber attenuation).

The similar effect on pulse dynamics is accomplished if a periodic dispersion compensation is applied in the pulse propagation. It has been shown that the so-called dispersion-managed soliton (DMS) can be propagated over long-haul distances. Inside each dispersion map, the characteristics of DMS evolution is governed by local dispersion values. Thus, the DMS changes its width and peak power inside each dispersion map (it "breathes" with local dispersion) [2,6].

III. DMS MODULATION FORMAT

The study of propagation in optical fibers with non-uniform dispersion has recently become a key topic in long-haul optical transmission. Dispersion management is the term for a technique in which the transmission path is constructed from section of two or more fibers or other elements with different dispersion. We can represent this with a dispersion map below

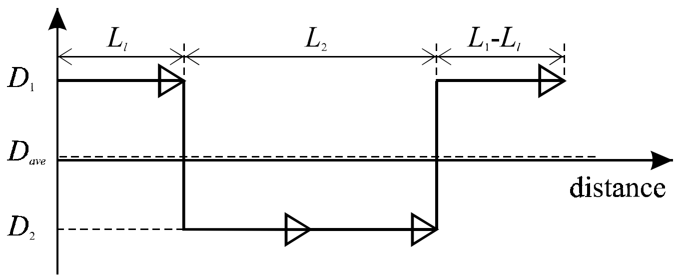


Fig. 2 Dispersion map

If the map contains both anomalous ($\beta_2 < 0$) and normal ($\beta_2 > 0$) dispersion sections (in the map, D_1 is anomalous and D_2 is normal dispersion), then, although at any point in the system the dispersion is substantial, the path-average dispersion (D_{ave}) over the whole system can be close to zero. This procedure strongly modifies the nonlinear transmission properties of the system compared to one constructed with uniform low-dispersion fiber. In addition, it produces a high local dispersion at any given point, and yet a low path-average dispersion. By adopting a suitable dispersion management scheme for soliton transmission, it is possible to substantially increase the soliton energy compared to the equivalent uniform fiber with equal path-average dispersion.

Design of initial pulse power and width is critical for successful propagation of DMS. One important parameter determining the DMS behavior is the dispersion map strength S_D, given as

$$S_D = \frac{\lambda^2}{2\pi c}\frac{(D_1 - D_{ave})L_1 - (D_2 - D_{ave})L_2}{T_0^2} \qquad (8)$$

where D_1, D_2 are the dispersion coefficients, and L_1, L_2 are the lengths of the anomalous and normal dispersion spans, respectively, and

$$D_{ave} = \frac{D_1 L_1 + D_2 L_2}{L_1 + L_2} \qquad (9)$$

is the average dispersion of the dispersion map.

Utilizing the advantages of DMS propagation in the anomalous dispersion regime on the one hand, and avoiding interactions with neighboring pulses on the other hand, the dispersion map strength should be in the range of $4 \leq S_D \leq 10$.

Dispersion-managed solitons are not sech-shaped anymore; they tend to be more Gaussian-shaped. In general, it is difficult to determine the proper pulse shape, width and power for a DMS, as these parameters depend strongly on the applied dispersion map and amplifier positioning. There are three main rules for launching the proper DMS into a system, and thus avoiding energy shedding throughout the propagation. Firstly, the path-average dispersion mast be anomalous (as it is in Fig. 2), so that there is a net dispersion of the right sign to balance the nonlinearity of fiber. Secondly, the period of the dispersion compensation cycle must be short compared to nonlinear length (L_{NL}) of the system. Finally, dispersion maps in which one of the fibers is much closer to zero dispersion than the other should be avoided, or energy is rapidly coupled out of the pulse into dispersive waves. This effectively implies the need of fibers with opposite sign dispersion. It should be taken into consideration, that, the energy of the launched pulse should match the energy of the true DMS solution for the particular dispersion map.

A typical single channel DMS system with a bit rate of 10 Gbit/s is considered here. The initially Gaussian pulses are launched. The dispersion map consists of a span of anomalous DSF with dispersion D_1 (2,80 ps/nm·km) and length L_1 (100 km) and a span of normal DSF with dispersion D_2 (-2,40 ps/nm·km) and length L_2 (100 km). Pulses are launched in each channel at L_l, ($L_l = L_1/2 = 50$ km) here, from the middle of the anomalous dispersion span. Figure 2 illustrates graphically the meaning of parameters of dispersion map.

Figure 3 shows typical DMS pulse evolution over a symmetric dispersion map, e.g., anomalous and normal dispersion fiber spans are of equal lengths ($L_1 = L_2 = 100$km). Here the DMS is found to be approximately of Gaussian shape with 20 ps FWHM duration and 1.63 mW peak power at the middle of the anomalous dispersion fiber, where it is launched. Note that no chirp is added.

At each optical amplifier, spontaneous emission adds photons of white noise to the signal. This results in a small random change of the central frequency of each pulse. Due to velocity dispersion, these frequency changes are translated into velocity shifts, and hence, cause timing jitter. In a uniform dispersion system, reducing Gordon-Haus timing jitter can only be done by lowering the signal power, which is clearly detrimental to the received SNR. Dispersion management provides an escape from this problem by providing an extra degree of freedom in design. As the strength of the dispersion map (S_D) is increased, soliton energy is enhanced without any increase in either the optical bandwidth or the path-average dispersion. The increased number of photons in the soliton renders the addition of any given number of noise photons less significant, and so produces a smaller frequency shift (timing jitter). In addition, the increase of power for DMS systems compared to classical soliton systems using pulses of comparable duration results in an increased optical signal-to-noise ratio (OSNR) without the need to increase the average dispersion. This is advantageously as it allows higher robustness against ASE-noise induced timing jitter and amplitude fluctuations.

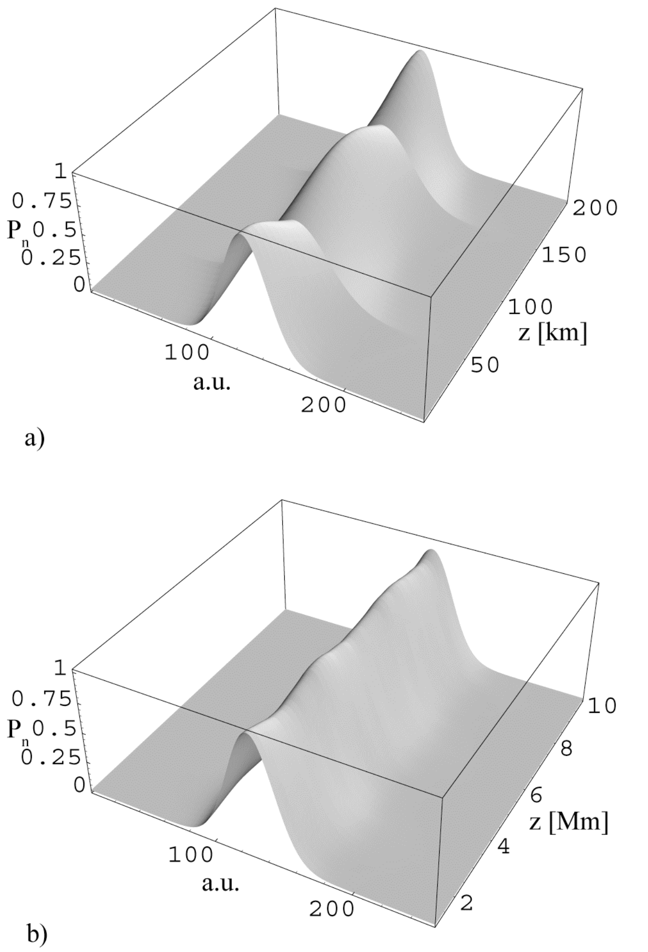


Fig. 3 Evolution of dispersion-managed soliton. (a) over one dispersion map of 200 km, (b) over 10,000 km with snap shots after each dispersion map (200 km), (no fiber attenuation).

The graph 3.a shows pulse dynamics inside the map, where pulse 'breathing' is recognizable. The DMS pulse width is smallest in the middle of the spans, and widest at the edges between anomalous and normal dispersion fiber spans, where chirp is broadening the spectrum as well. The graph 3.b shows stable evolution over 10,000 km, where snap shots are taken after each dispersion map. Slight modifications of pulse peak power and width are recognizable over the distance, which results from the fact that the launched Gaussian pulse is not the true solution of the propagation equation.

IV. Conclusion

The advantage of DMS system compared to classical soliton systems is the possibility to utilize larger local dispersion values, which results in increased robustness against disturbing fiber nonlinear effects (such as FWM, XPM) and timing jitter due to ASE-noise. It allowed the usage for high-capacity long-haul system applications.

Another highly novel feature of these solitary waves is that their pulse shapes are not the hyperbolic secants of regular optical fiber solitons. The pulse profile changes with different dispersion maps chosen, that is, with different couple of values D_1 and D_2. As the dispersion variation is increased there is a transition from the uniform fiber hyperbolic secant solitons to the Gaussian form, and to super Gaussian form.

And finally, as previously mentioned, dispersion managed systems also reduce the timing jitter compared to uniform dispersion systems.

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