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A PRINCIPAL INVESTIGATION OF THE GROUP VELOCITY DISPERSION (GVD) PROFILE FOR OPTIMUM DISPERSION COMPENSATION IN OPTICAL FIBERS: A THEORETICAL STUDY

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Abstract—In this paper, an analytical method for management of optimum group velocity dispersion (GVD) for compensation of chromatic dispersion in optical fibers is proposed. The proposed method mathematically is based on the Volterra series as alternative method for solution of the nonlinear Schrödinger equation (NLS). Based on analytical solution of the nonlinear equation in pulse propagation, we propose a differential equation including optimum GVD for complete dispersion compensation for given dispersion coefficient and fiber length. The obtained integro-differential equation is solved for special cases and it is shown that the obtained results are so better than traditional dispersion compensation cases. Also, the proposed technique can be applied to fiber design to introduce an especial GVD profile for dispersion less transmission.

1. INTRODUCTION

Optical fiber is physical medium for realization of optical communication algorithms which is one of acceptable and interesting methods recently for data communications. There are two main problems in this physical medium that are dispersion and power loss. Selection of suitable carrier wavelength such as 1.55 um corresponding to minimum loss of common optical fibers really can be removed the loss problem of this physical medium for light propagation. Also, Erbium doped fiber amplifiers (EDFA) which are completely compatible with fibers can be used to compensate optical loss through propagation. The second and important problem is dispersion effect. Complete solution for this problem doesn't exist. There are huge proposals for dispersion compensation which in the following we review some of them briefly and discuss advantages and disadvantages.

Pre-chirping is one of common methods for dispersion compensation [1, 2]. Minus chirping in the case of positive GVD introduces pulse compression and can be used as dispersion compensator which is try to broad optical pulse. Digital modulation such as frequency shifted keying (FSK) is another method for dispersion compensation [3–5]. Nonlinear pre-chirping is another method for dispersion compensation [6, 7]. In this method semiconductor optical amplifier is used in the saturation region. Also, some post dispersion compensation methods were used. One of common method in this category is dispersion compensating fibers [8–11]. In this method fiber with negative dispersion in given wavelength which basic fibers have positive values is used to compensate pulse broadening.

Optical fibers with given phase dependency on frequency is another method for dispersion compensation of optical fibers [1, 12, 15]. Fiber Bragg Grating is another method for dispersion compensating in optical fibers [16–18]. Using the parameters used in Bragg grating frequency response of this structure can be managed and dispersion compensation can be done. Optical phase conjugation can be used for dispersion compensation also [19]. Finally a more common method named dispersion management technique is used for dispersion compensation [1, 20]. In this method periodic function for GVD is used to overcome to overall dispersion induced through propagation. Since light propagation through optical fibers using some acceptable approximations governed by Nonlinear Schrödinger equation (NLS). This equation is nonlinear and analytical solution is hard to obtain. Analytical solutions are so excellent to show nature of phenomenon in propagation. For handling of NLS equation in the past the Volterra series was used [21–27]. Since two or three terms of this series completely describe light propagation and show some of important phenomenon in fibers, we concentrate on this method for analytical solution.

As it discussed in the presented methods for dispersion compensation in optical fibers the question "what is optimum dispersion group velocity dispersion?" doesn't addresses truly. At least we don't find anything about what is differential equation addressing optimum group velocity dispersion?

For presentation a suitable and mathematical framework in this paper we concentrate on this subject. On the other hand we like, develop a novel mathematical method managing complete dispersion compensation and optimum group velocity dispersion in optical fibers. For this purpose analytical solution of NLS equation in frequency domain is considered. For this task the Volterra series is used. After determination of the Volterra Kernels we apply similarity principle of the output and input signal pulses. The result is an integro-differential equation managing optimum GVD profile. Finally solution of the obtained equation can be considered as optimum profile for dispersion compensation. Then for evaluating of obtained result the optimum GVD profile is applied to the fiber and using split step Fourier method light propagation is studied. Our simulated results show that dispersion compensation in the case of GVD profile obtained from the proposed method is so better than other cases presented in the literature. We compared our proposal with some of previous presented cases.

Organization of the paper is as follows.

Mathematical background is presented in Section 2. Simulated results and discussion is considered in Section 3. Finally the paper ends with a short conclusion.

2. MATHEMATICAL BACKGROUND

In this section mathematical basis for developing a differential equation for optimum GVD in optical fibers is presented. For this purpose, we start from the nonlinear Schrödinger equation in frequency domain with assuming $\beta_1 = \beta_3 = 0$ [15, 16]. Then using the Volterra series the solution of NLS equation is expressed in terms of the Volterra Kernels [17–21]. After substituting these functions into the NLS equation we obtain the first order differential equation, which is important and can be solved at least numerically. In this work, we only consider two kernels (First and Third orders). Using traditional techniques for solution of first order differential equations and similarity between initial and final wave shapes $(A(\omega, z) = k(z)A(\omega))$, we obtain an integro-differential equation where optimum GVD is main variable which should be determined. For doing this algorithm the following mathematical formalism are used.

$$\frac{\partial A(\omega,z)}{\partial z} = G_1(\omega)A(\omega,z) + \int\limits_{-\infty}^{+\infty}\int\limits_{-\infty}^{+\infty} G_3(\omega_1,\omega_2,\omega-\omega_1+\omega_2)A(\omega_1,z)A^*(\omega_2,z)A(\omega-\omega_1+\omega_2,z)d\omega_1 d\omega_2, \quad (1)$$

where

$$A(\omega,z), \quad G_1(\omega) = -\frac{\alpha_0}{2} + j\frac{\beta_2}{2}\omega^2$$

and

$$G_3(\omega_1,\omega_2,\omega-\omega_1+\omega_2) = j\left(1+\frac{\omega}{\omega_0}\right)[a_0 + Q_R S_R(\omega_1-\omega_2)]$$

are slowly varying complex envelope of the optical field, the linear dispersion kernel and the fiber nonlinear kernel respectively [3–6].

It should mention that Eq. (1) can be used in propagation of solitons through optical fibers which has been a major area of research given its potential applicability in all optical communication systems and named Gabitov-Turitsyn equation (GTE) [28–31]. The GTE extensively studied in the past and has ultra high important in high-speed communications.

Now based on Eq. (1), we let the second order dispersion (GVD) depends on distance.

Based on the Volterra series [8] that is used for analysis of nonlinear systems the following solution for Eq. (1) can be considered [3–6].

$$A(\omega,z) = H_1(\omega,z)A(\omega) + \int\limits_{-\infty}^{+\infty}\int\limits_{-\infty}^{+\infty} H_3(\omega_1,\omega_2,\omega-\omega_1+\omega_2,z)A(\omega_1)A^*(\omega_2)A(\omega-\omega_1+\omega_2)d\omega_1 d\omega_2, \quad (2)$$

where H_1 and H_3 are the linear and third order nonlinear transfer functions (Volterra kernels) respectively. After substituting the proposed solution into Eq. (1), the following differential equations for H_1 and H_3 are obtained.

$$\frac{dH_1(\omega,z)}{dz} - \left[-\frac{\alpha_0}{2} + j\frac{\omega^2}{2}\beta_2(z)\right]H_1(\omega,z) = 0 \quad (3)$$

$$\frac{dH_3}{dz}(\omega_1, \omega_2, \omega - \omega_1 + \omega_2, z) - \left[-\frac{\alpha_0}{2} + j\frac{\omega^2}{2}\beta_2(z)\right]$$
$$\times H_3(\omega_1, \omega_2, \omega - \omega_1 + \omega_2, z) = G_3(\omega_1, \omega_2, \omega - \omega_1 + \omega_2)$$
$$\times \exp\left[-\frac{3\alpha_0}{2}z + \frac{j}{2}\left(\omega_1^2 - \omega_2^2 + (\omega - \omega_1 + \omega_2)^2 \int \beta_2(z)dz\right]\right) \quad (4)$$

With considering techniques used in first order linear differential equations such as applying the suitable integrating factor given in the following the Volterra kernels can be obtained.

$$\lambda = \exp\left[\int -\left(-\frac{\alpha_0}{2} + j\frac{\omega^2}{2}\beta_2(z)\right) dz\right] = \exp\left[\frac{\alpha_0}{2}z - j\frac{\omega^2}{2}\int \beta_2(z)dz\right], \quad (5)$$

Considering Eq. (5) and boundary condition $H_1(\omega, 0) = 1$ the following solution is extracted.

$$H_1(\omega, z) = \exp\left[-\frac{\alpha_0}{2}z + j\frac{\omega^2}{2}\int \beta_2(z)dz\right] \quad (6)$$

It should be mentioned that from the mentioned boundary condition the following result is obtained.

$$\int \beta_2(z)dz\Big|_{z=0} = 0$$

Also, the following solution is given for the third order nonlinear transfer function.

$$H_3(\omega_1, \omega_2, \omega - \omega_1 + \omega_2, z) = \exp\left[-\frac{\alpha_0}{2}z + j\frac{\omega^2}{2}\int \beta_2(z)dz\right]$$
$$\times \left[G_3(\omega_1, \omega_2, \omega - \omega_1 + \omega_2)\right.$$
$$\left.\int \exp\left[-\alpha_0 z + j\left(\omega_1^2 - \omega(\omega_1 - \omega_2) - \omega_1\omega_2\right)\int \beta_2(z)dz\right] dz + c\right]$$

where $C = 0$ is direct conclusion of the following boundary condition.

$$H_3(\omega_1, \omega_2, \omega - \omega_1 - \omega_2, 0) = 0$$

In the following, optimum GVD for undistorted pulse propagation inside optical fiber based on the developed mathematical relation is proposed. For this purpose, we assume that the field spectrum after propagation to desired distance z should be proportional to the case at $z = 0$. On the other hand we have

$$A(\omega, z) = k(z)A(\omega). \quad (7)$$

It should be mentioned that $k(z)$ is attenuation coefficient in the propagation process. Traditionally it is exponential decay with absorption coefficient at carrier wavelength. Now, with substituting Eq. (7) into Eq. (2), we have

$$k(z)A(\omega) = H_1(\omega, z)A(\omega) + \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} H_3(\omega_1, \omega_2, \omega-\omega_1+\omega_2, z)A(\omega_1)A^*(\omega_2)A(\omega-\omega_1+\omega_2)d\omega_1 d\omega_2,$$

Now with some mathematical simplification and ignoring from the Raman effect (Eq. (8)) [8], the following integro-differential equation managing the GVD is obtained (Eq. (9)).

$$G_3(\omega_1, \omega_2, \omega-\omega_1+\omega_2) = G_3(\omega) = \left[1 + \frac{\omega}{\omega_0}\right] a_0, \tag{8}$$

where a_0 is the Kerr coefficient.

$$\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\left[G_3(\omega)\exp\left[j\left(\omega_1^2-\omega(\omega_1-\omega_2)-\omega_1\omega_2\right)\int \beta_2(z)dz\right]\right] \times A(\omega_1)A^*(\omega_2)A(\omega-\omega_1+\omega_2)d\omega_1 d\omega_2 = \exp(\alpha_0 z)\frac{d}{dz}\left[\frac{k(z)}{H_1(\omega, z)}\right]A(\omega) \tag{9}$$

Eq. (9) is main result of this section and using the input field spectrum, fiber and attenuation parameters, the optimum GVD can be determined. In the following we consider an example.

Example: As an example, we consider the following Gaussian profile for input pulse.

$$A(\omega) = A_0 e^{\left[\frac{(\omega-\omega_0)^2}{2\sigma^2}\right]} \tag{10}$$

So, for calculation of the appeared terms in Eq. (9), we have

$$A(\omega_1)A^*(\omega_2)A(\omega-\omega_1+\omega_2) = A_0^3 e^{\left(\frac{3\omega_0^2-2\omega\omega_0+\omega^2}{2\sigma^2}\right)} e^{\left(-\frac{\omega_1^2+\omega_2^2-\omega(\omega_1-\omega_2)-\omega_1\omega_2-2\omega_0\omega_2}{\sigma^2}\right)}. \tag{11}$$

Now, with substituting of Eqs. (10), (11) into Eq. (9), we obtain the following final equation.

$$e^{(\alpha_0 z)} A_0 e^{\left[\frac{(\omega-\omega_0)^2}{2\sigma^2}\right]} \frac{d}{dz}\left[\frac{k(z)}{H_1(\omega, z)}\right] = A_0^3 G_3(\omega) e^{\left(\frac{3\omega_0^2-2\omega\omega_0+\omega^2}{2\sigma^2}\right)}$$

$$\times\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} e^{\left[-\frac{\omega_1^2+\omega_2^2-\omega(\omega_1-\omega_2)-\omega_1\omega_2-2\omega_0\omega_2}{\sigma^2}\right]}\times e^{\left[j(\omega_1^2-\omega(\omega_1-\omega_2)-\omega_1\omega_2)\int\beta_2(z)dz\right]}d\omega_1 d\omega_2 \tag{12}$$

Finally, using some mathematical manipulation, we obtain the following result.

$$e^{(\alpha_0 z)}e^{\left[\frac{\omega_0^2}{2\sigma^2}\right]}\frac{d}{dz}\left[\frac{k(z)}{H_1(\omega,z)}\right]=A_0^2G_3(\omega)$$
$$\times\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} e^{\left[-\frac{\omega_1^2+\omega_2^2-\omega(\omega_1-\omega_2)-\omega_1\omega_2-2\omega_0\omega_2-j\sigma^2(\omega_1^2-\omega(\omega_1-\omega_2)-\omega_1\omega_2)\int\beta_2(z)dz}{\sigma^2}\right]}d\omega_1 d\omega_2 \tag{13}$$

For solving Eq. (13) the following relation is used.

$$\int_{-\infty}^{+\infty}\exp\left[-\frac{ax^2+bx}{c}\right]dx=\sqrt{\frac{\pi c}{a}}\exp\left(\frac{b^2}{4ac}\right),\quad\left(\frac{a}{c}>0\right) \tag{14}$$

After sufficient mathematical manipulation the following final form of the proposed integro-differential equation is obtained.

$$\frac{2\pi\sigma^2A_0^2G_3(\omega)}{\sqrt{\sigma^4\left(\int\beta_2(z)dz\right)^2-j6\sigma^2\int\beta_2(z)dz+3}}$$
$$\times e^{\left[-\frac{ja_1\left(\int\beta_2(z)dz\right)^3+b_1\left(\int\beta_2(z)dz\right)^2+jc_1\int\beta_2(z)dz+d_1}{ja_2\left(\int\beta_2(z)dz\right)^3+b_2\left(\int\beta_2(z)dz\right)^2+jc_2\int\beta_2(z)dz+d_2}\right]}$$
$$=\left\{\frac{dk(z)}{dz}+k(z)\left[\frac{\alpha_0}{2}-j\frac{\omega^2}{2}\beta_2(z)\right]\right\}\times e^{\left[\frac{\omega_0^2}{\sigma^2}+\frac{3}{2}\alpha_0 z-j\frac{\omega^2}{2}\int\beta_2(z)dz\right]}, \tag{15}$$

where $a_1=(80\omega^2-32\omega\omega_0)\sigma^6$, $a_2=16\sigma^8$, $b_1=(-112\omega^2-64\omega_0^2+224\omega\omega_0)\sigma^4$, $b_2=80\sigma^6$, $c_1=[-48\omega^2-128\omega_0^2+224\omega\omega_0)\sigma^2$, $c_2=144\sigma^4$, $d_1=16\omega^2+64\omega_0^2-32\omega\omega_0$ and $d_2=-48\sigma^2$.

With considering $B(z)\overset{\Delta}{=}\int\beta_2(z)dz$, we have

$$\frac{2\pi\sigma^2A_0^2G_3(\omega)}{\sqrt{\sigma^4B^2(z)-j6\sigma^2B(z)+3}}\times e^{\left[-\frac{ja_1B^3(z)+b_1B^2(z)+jc_1B(z)+d_1}{ja_2B^3(z)+b_2B^2(z)+jc_2B(z)+d_2}\right]}$$
$$=\left[\frac{dk(z)}{dz}+k(z)\left(\frac{\alpha_0}{2}-j\frac{\omega^2}{2}\frac{dB(z)}{dz}\right)\right]\times e^{\left[\frac{\omega_0^2}{\sigma^2}+\frac{3}{2}\alpha_0 z-j\frac{\omega^2}{2}B(z)\right]} \tag{16}$$

As an especial case, if we assume that $k(z) = \exp\left(-\frac{\alpha_0}{2}z\right)$, the final differential equation is obtained as follows.

$$\frac{dB(z)}{dz} = -\frac{2}{\omega^2}\mathrm{Im}\left\{\frac{2\pi\sigma^2 A_0^2 G_3(\omega)}{\sqrt{\sigma^4 B^2(z) - j6\sigma^2 B(z) + 3}} \times e^{\left[-\frac{ja_1 B^3(z)j + b_1 B^2(z) + jc_1 B(z)j + d_1}{ja_2 B^3(z)j + b_2 B^2(z) + jc_2 B(z)j + d_2} - \frac{\omega_0^2}{\sigma^2} - \alpha_0 z + j\frac{\omega^2}{2}B(z)\right]}\right\} \tag{17}$$

It should be mentioned that Eq. (17) must satisfy the following condition.

$$B(0) = 0$$

3. SIMULATION RESULTS AND DISCUSSION

The proposed differential equation in previous section is stiff type and analytical solution is so hard and also numerical evaluation needs carefully investigations. For extraction of the GVD parameter versus distance, we solve numerically Eq. (17) with the following parameters as an example.

$$\frac{\omega_0}{2\pi} = 193.54\,\mathrm{THz}, \quad \frac{\omega}{2\pi} = 195\,\mathrm{THz}, \quad \sigma = 10^{12}, \quad A_0^2 = 2\,\mathrm{mW}$$
$$a_0 = 0.00117049\frac{1}{\mathrm{W-Km}}, \quad \alpha_0 = 0.2\,\mathrm{dB/km}, \quad L = 100\,\mathrm{Km}$$

Now, using numerical investigation of Eq. (17), desired profile of GVD is obtained and the simulated result is illustrated in the following figures. We find out that damped triangular profile of GVD is one of acceptable solutions of developed differential equation in previous section for optimum group velocity dispersion (Eq. (17)).

Now in the following based on obtained GVD in Fig. 1, different optical pulse propagation through this medium is investigated. Fig. 2 shows super Gaussian incident pulse through optical fibers compensated with uniform triangular GVD profile (Output Pulse 1) and damped triangular GVD profile (Output Pulse 2). Also, for illustration of the difference between these two methods of compensation, Fig. 3 shows precisely top of these pulses in detail. It is shown that dispersion compensating using GVD profile of our proposed equation is so better than uniform triangular GVD profile.

Similar simulation corresponds to the Gaussian and Sech distributions are illustrated in Figs. 4 and 5.

Also, in other set of simulations (Figs. 6–9) we compare different distribution field propagation through fibers compensated

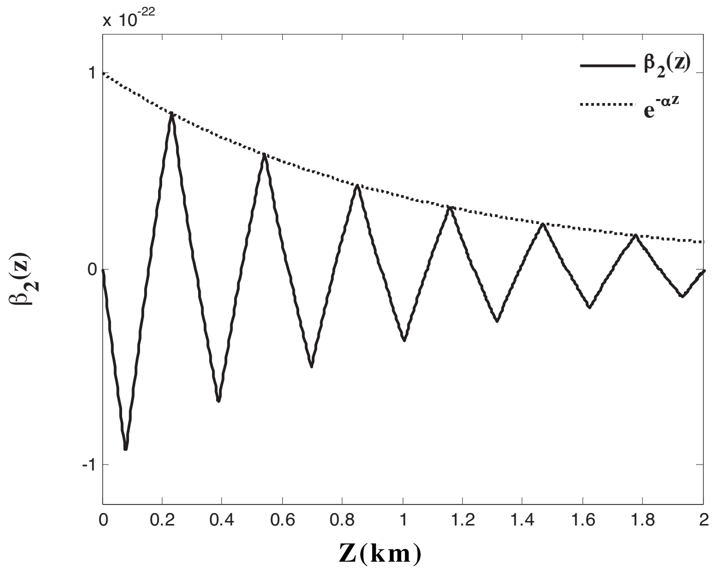

Figure 1. Optimum GVD vs. distance for complete dispersion less transmission.

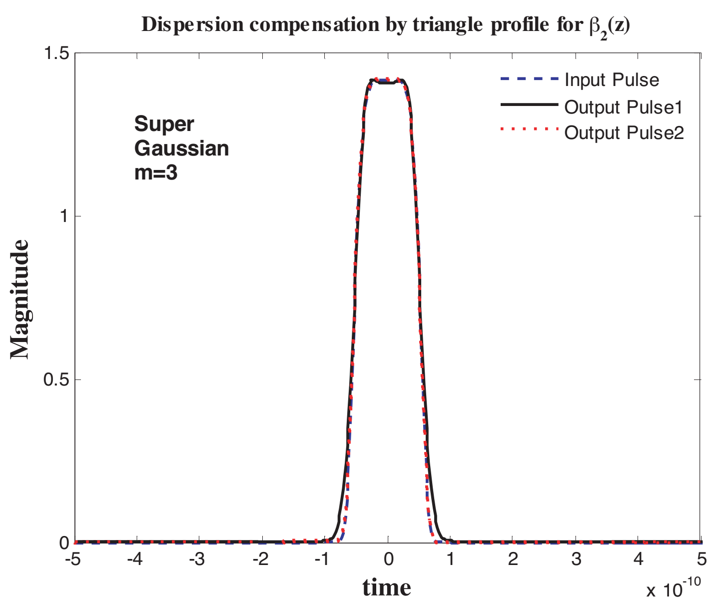

Figure 2. Simulated result for super Gaussian input pulse.

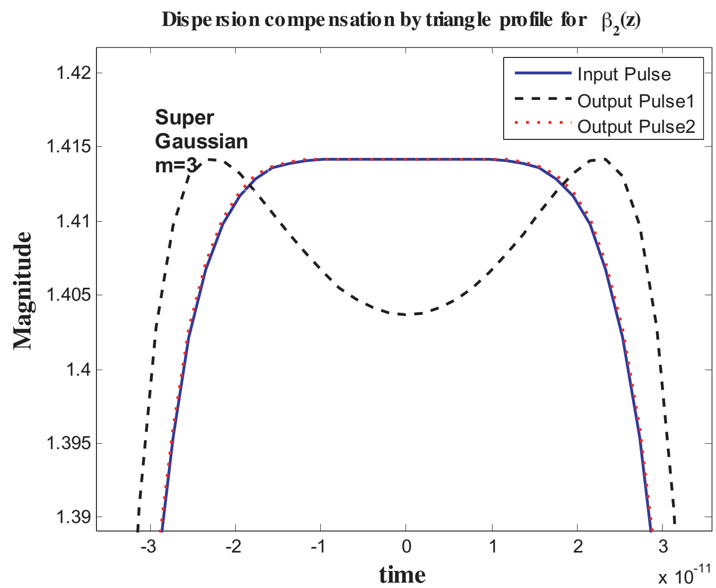

Figure 3. Simulated result for Super Gaussian input pulse.

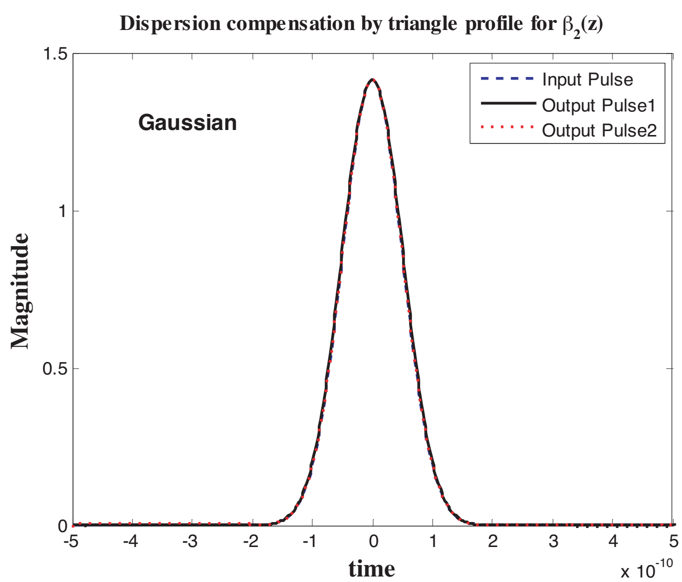

Figure 4. Simulated result for Gaussian input pulse.

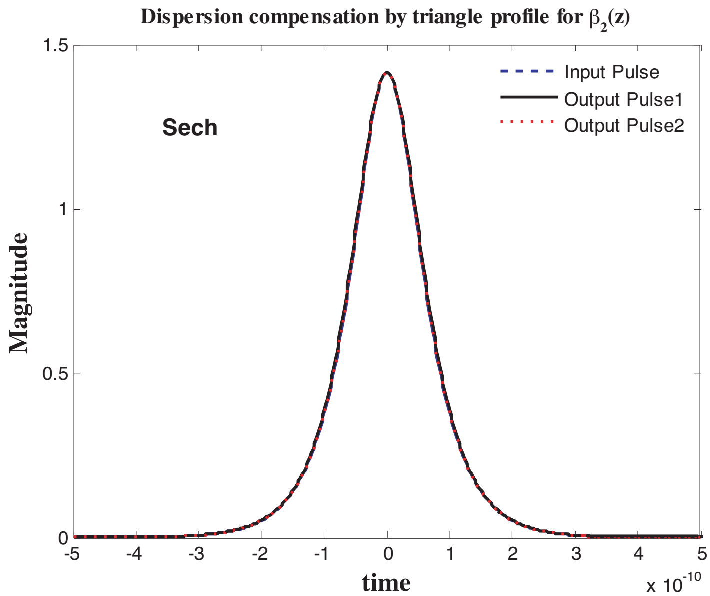

Figure 5. Simulated result for Sech input pulse.

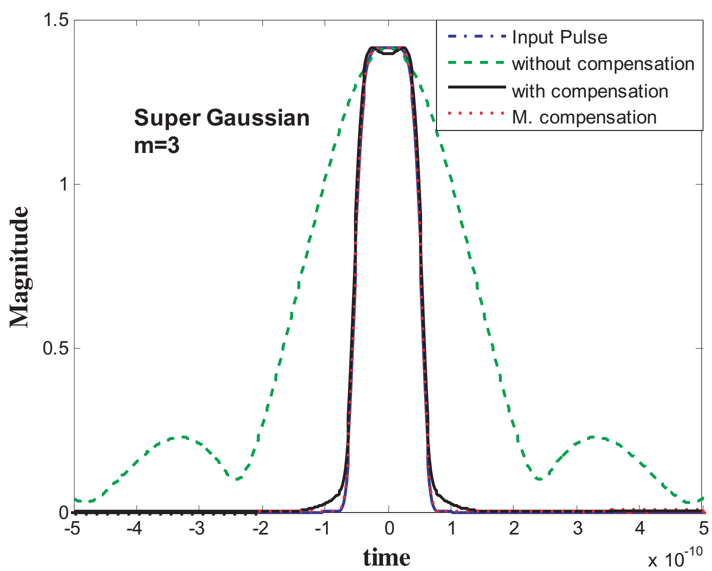

Figure 6. Simulated result for Super Gaussian input pulse.

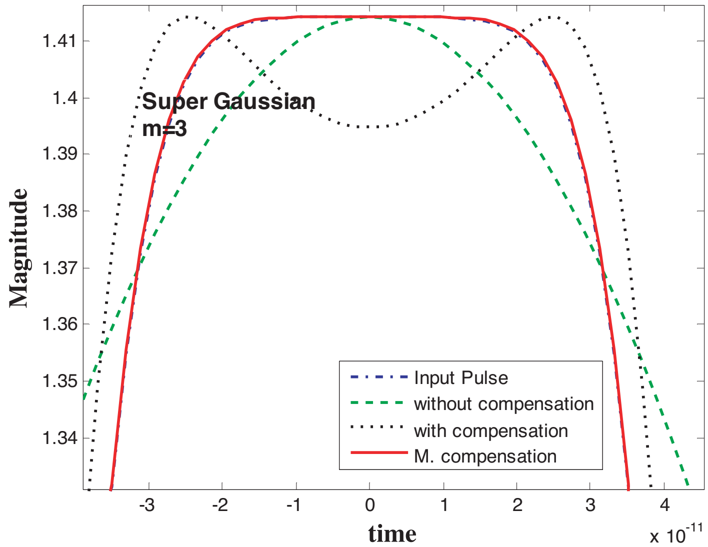

Figure 7. Simulated result for Super Gaussian input pulse.

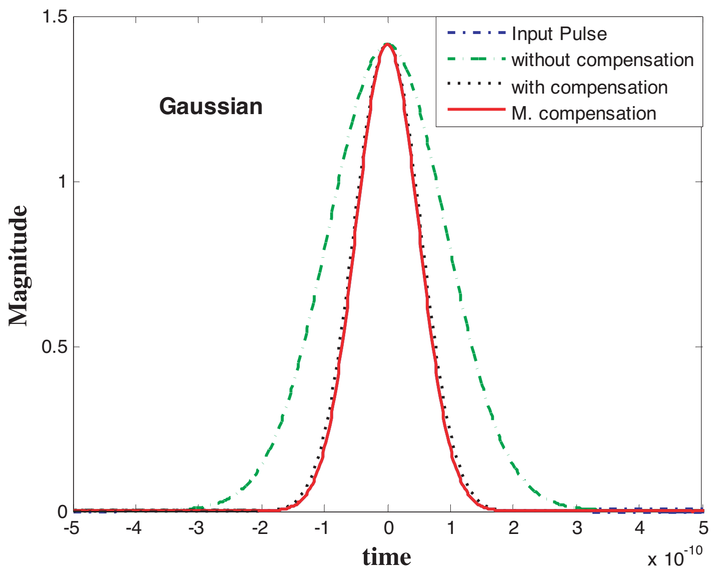

Figure 8. Simulated result for Gaussian input pulse.

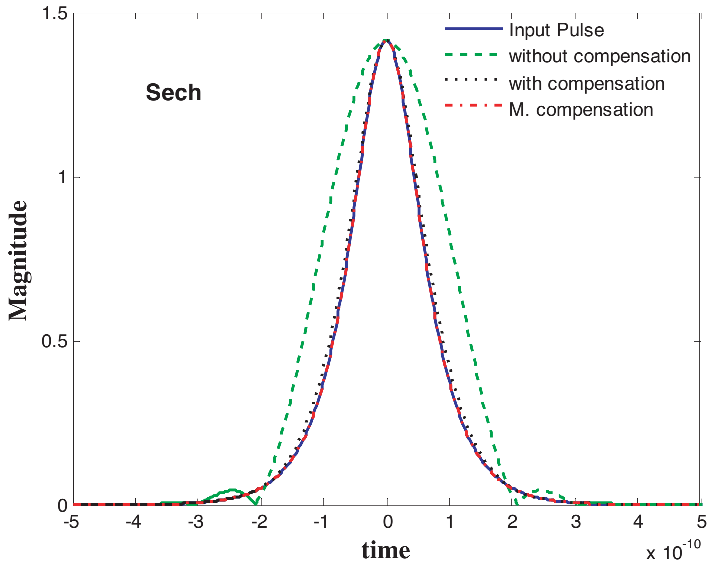

Figure 9. Simulated result for Super Gaussian input pulse.

with rectangular (label: with compensation) and damped triangular (label: M. compensation) GVD profiles. Also, it is observed that GVD profile obtained from the proposed differential equation is successful than other profiles.

In this section some simulated results based on obtained differential equations and numerical analysis of pulse propagation through optical fibers were presented and compared together. It was shown that the proposed optimum differential equation for GVD is so powerful method for compensation.

4. CONCLUSION

In this paper we have derived an integro-differential equation managing optimum group velocity dispersion. We have simulated the proposed GVD profile and compared with traditional GVD profiles for dispersion compensation. We have observed that the GVD profile obtained from the proposed differential equation is operated so better than traditional cases. We think that the proposed method for dispersion compensation will open a new insight in the field of dispersion compensation.

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