Journal of Nature, Life
and Applied Sciences
Volume (6), Issue (2): 30 Jun 2022
P: 110 - 119

AJSRP
ISSN: 2522-3356

مجلة العلوم الطبيعية
والحياتية والتطبيقية
المجلد (6)، العدد (2): 30 يونيو 2022م
ص: 110 - 119

Theoretical Analysis of The Super-Gaussian Pulse Propagation in Solid-Core Photonic Crystal Fiber

Mohammed Salim Jasim Al-Taie

Misan Governorate Education Directorate || Ministry of Education || Iraq

Abstract Fiber optics have been greatly enhanced by photonic crystal fibers based on microstructure air-glass designs. On the one hand, such fibers enable highly tight light confine in a small mode shape region, resulting in significantly improved alternative options between light and dielectric medium. Photonic crystal fibers, on the other hand, allow light to be guided via air cores instead of glass. As a result, the latter form of fiber decreases of optical nonlinearities in ways that classic fiber designs cannot. The chirp effect and dispersion of photonic crystal fibers with super-Gaussian pulses during various pulses durations are examined in this paper. In both normal and anomalous dispersion patterns. As done the chirp effect and fiber dispersive nonlinear effects are investigated. For this study, the mathematical model of the solution of nonlinear equation is split-step Fourier method. The peak power reduces for broad pulses. When the magnitude of the super-Gaussian pulse increasing proportion, the pulse constriction is also noticeable, Furthermore, these results disclose important facts, such as the fact that an anomalous dispersion system is superior to a regular dispersion system for pulse. These findings are incredibly useful in learning more about photonic crystal fiber and improving data speeds in modern optical communication systems.

Keywords: Photonic Crystal Fiber, Super-Gaussian Pulse, Nonlinear Effects, Dispersion, Chirp, Split-Step Fourier.

التحليل النظري لانتشار نبضة سوبر- كاوسية في ليف بلورة فوتونية ذو القلب الصلب

محمد سالم جاسم الطائي

مديرية تربية محافظة ميسان || وزارة التربية || العراق

المستخلص: تم تحسين الألياف الضوئية بشكل كبير بواسطة ألياف البلورة الفوتونية بناءً على تصميمات زجاجية مجهرية. من ناحية أخرى، تتيح هذه الألياف حصرًا شديدًا للضوء في منطقة صغيرة جدا، مما يؤدي إلى خيارات بديلة محسّنة بشكل كبير بين الوسط الخفيف والعازل كهربائيا من ناحية أخرى، تسمح ألياف البلورة الفوتونية بتوجيه الضوء عبر النواة الهوائية بدلاً من الزجاج، نتيجة لذلك، الشكل الأخير من الألياف الضوئية يقلل اللاخطية بطرق لا تستطيع تصميمات الألياف التقليدية القيام بها. حيث تم فحص تأثير الزقزقة والتشتت لألياف البلورة الفوتونية ذات النبضات الكاوسية الفائقة خلال فترات النبضات المختلفة في هذا البحث. وفي كل من أنماط التشتت العادية والشاذة. كما تم التحقيق في تأثير الزقزقة والتأثيرات اللاخطية المشتتة للألياف. في هذه الدراسة، فإن النموذج الرياضي لحل المعادلة غير الخطية هو طريقة فورييه المنقسمة. حيث تقل قوة الذروة للنبضات العريضة. عندما يزداد حجم نسبة النبضة الكاوسية الفائقة، يكون انقباض النبض ملحوظًا أيضًا، علاوة على ذلك، تكشف هذه النتائج عن حقائق مهمة، مثل حقيقة أن نظام التشتت الشاذ يتفوق على نظام التشتت المنتظم للنبض. هذه النتائج مفيدة بشكل لا يصدق في معرفة المزيد عن ألياف البلورة الفوتونية وتحسين سرعات البيانات في أنظمة الاتصالات الضوئية الحديثة.

الكلمات المفتاحية: ليف بلورة فوتونية، نبضة كاوسية فائقة، تأثيرات لاخطية، التشتت، الزقزقة، طريقة انقسام الخطوة لفورييه.

Introduction.

photonic crystal fibers are more important in modern system due to their superior properties over traditional fibers, due of its considerable flexibility in design and high nonlinearity, PCF outperforms traditional optical fiber[1]. PCF is an optical fiber having a low regular arrangement refractive index material in the background and a high refractive index material [2]. Light can be guided within the PCF by changing total internal reflection or photonic band-gap guiding such as Birefringence, chromatic dispersion, and other optical characteristics[3]. PCF can assess effective mode area, loss of confinement, and non-linearity. PCFs have exceptional qualities and capabilities due to their unique geometric structure, which make them ideal for sensing applications. PCF is often designed to provide zero dispersion wavelengths (ZDW) at the desired wavelength. As a result, PCF is a better choice than traditional optical fiber for a variety of applications such as supercontinuum generation, biomedical imaging, meteorology, industrial equipment, and many others [4], Figure 1 shows the photonic crystal fiber.

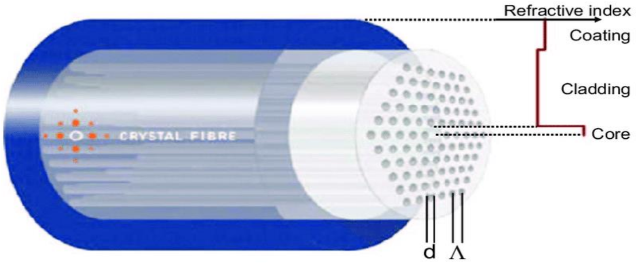

Figure (1) Solid core PCF with microstructure cladding is the most prevalent design4.

One option for expanding capacity is to reduce the canal; another competing option is to increase the path transmission speed. As a result, it is beneficial to concentrate on employing laser sources that generate ultra-short pulses, which might result in a variety of nonlinear effects which must be studied. When various wavelengths have different refractive indices, so the group velocity dispersion (GVD) arises. The data rate is limited by pulse broadening. The GVD effect is integrated into photonic crystal fiber through a variable represented by β_2. Because the refractive index is affected by the intensity, it creates nonlinearity and induces nonlinear chirp in the pulse[5, 6]. The main nonlinear effect is self-phase modulation [7]. When group velocity dispersion (GVD) and chirp are combined, the outcome is a pulse response that is radically distinct from nonlinear effects, the action is also determined by dispersion regions such as the normal (NDR) and abnormal (ADR) regions of dispersion. The value of β_2 for abnormal dispersion region (ADR) will be lesser than zero, whereas the value of β_2 in normal dispersion region (NDR) is larger than zero. One investigates super-Gaussian pulse and their distinct transmission qualities in both the dispersive and chirp effects regions for various pulses durations and super-elevation properties. These pulses tend to expand much more Gaussian pulses because their leader and tailed edges are sharper [8]. The shape of super Gaussian pulses is comparable to that of a square digital pulse, which is one benefit of using them.. The results of a study of superGaussian pulse dispersion and chirp effects, the nonlinear Schrodinger equation(NLSE) is used to examine photonic crystal fibers phenomena like as two types ofgroup velocity dispersion, and chirp. Because of the complicated nature of the superGaussian pulse, this equation is not analytically solvable. As a result, numerical approaches are employed [9]. The Fourier split stages is the most often used well-known numerical technique for solving it[10]. The answer is computed in many tiny stages throughout the length of the optical cable with this approach [11].

Simulation Theory.

The Gaussian distribution may be used to estimate the majority of laser pulses. The input field for super Gaussian pulse has the form shown below [6].

$$U(0,t) = \exp\left[-\frac{1}{2}\,(\frac{t}{T_o})^{2m}\right] \text{..........................} (1)$$

Here(t) is a time reference that moves with the group velocity pulses, T_o symbolizes half the pulse width, while (m) is the factor that defines the sharpness of the pulse peaks. Because raising (m) reasons the spectrum of a pulse to widen, the pulse becomes more broadened as the value of m rises.

NLSE, which is developed using numerical approaches, is used to explore the features of super-Gaussian pulses in the context of group- velocity -dispersion (GVD) alone or in connection with other phenomena such as nonlinear effect. The mathematical representation of NLSE is given as follows:

$$i\frac{\partial U}{\partial z} + \frac{i\alpha}{2}U - \frac{\beta_2}{2}\frac{\partial^2 U}{\partial t^2} + \gamma\ |U\ |^2 U = 0 \text{.............} (2)$$

Eq. (2) illustrates the transmission of an incident electromagnetic wave under the effects of dispersion (β_2), loss(α), and nonlinearity(γ). The variables U and z denote the amplitude pulse and the fiber distance traveled, respectfully. By setting loss(α) and nonlinearity(γ) to zero, The impact of group velocity dispersion (GVD) on light signal is investigated on its own split-step Fourier methods (SSFM) [12] .One of the better numerical methods for applying in nonlinear Schrodinger equation (NLSE) . Equation (1) is a better choice in the following format for implementation:

$$\frac{\partial U}{\partial z} = (\widehat{D} + \widehat{N}) \text{.......................................} (3)$$

Since $\widehat{D}$ is a function that represents fibre dispersion and loss in the assumptions of a linear media, and $\widehat{N}$ adjusts to nonlinear effect of fibre.

$$\widehat{D} = -\frac{\alpha}{2} - \frac{\beta_2}{2}\frac{\partial^2}{\partial t^2} \text{......................................} (4)$$

$$\widehat{N} = i\gamma\ |U\ |^2 \text{...} (5)$$

The split-step Fourier method (SSFM)can solve nonlinear Schrodinger equation(NLSE) numerically by supposing that pulse transmission occurs in extremely short steps with value h. There are two phases to this operation, In stage one, just dispersion is active, and N value is zero; while, in stage two, D is deactivated, and just nonlinear effect is active in the fibre [13]. Photonic crystal fiber

Material is obtained up of number sections, each section of length - h. Upon transmission in a certain part h, Dispersion operates initially for $h/2$ of a distance, The nonlinear effect is applied to the entire section at the midway planes, The electromagnetic field is subsequently propagated over the remaining h/2 distance. This completes the pulse transmission in section h, and the procedure is repeated with the entire length of photonic crystal fibre to conclude the resolution of the non-linear Schrodinger equation (NLSE) [14].

Results and discussion.

A photonic crystal fiber of the type is considered, with a wavelength of 1.55 μm. The values of $\alpha = 0.02\ dB/km, \beta_2 = 0.15\ ps2/km$, chirp (C)= 0, while the nonlinear coefficient is $\gamma = 0.5\ W^{-1}Km^{-1}$. For different values of T_o, such as (2.5, 3.5, and 4.5) ps, the super Gaussian pulse is transmitted. It is preferable to optimize data rate by lowering T_0 in optical fiber systems. The effect of reducing T_0 is demonstrated in this research.

3.1The effect of various m values on the super- Gaussian pulse

For beginning, we'll use a super-Gaussian pulse with a width of T_o = 4.5 ps. Using Eq. 1, the shapes of such a pulse for different values of m are displayed in Figure 2. The pulse edges become wider as the quantity of m increases. When a result, as the quantity of m grows larger, the dispersion of super Gaussian pulses expands as well.

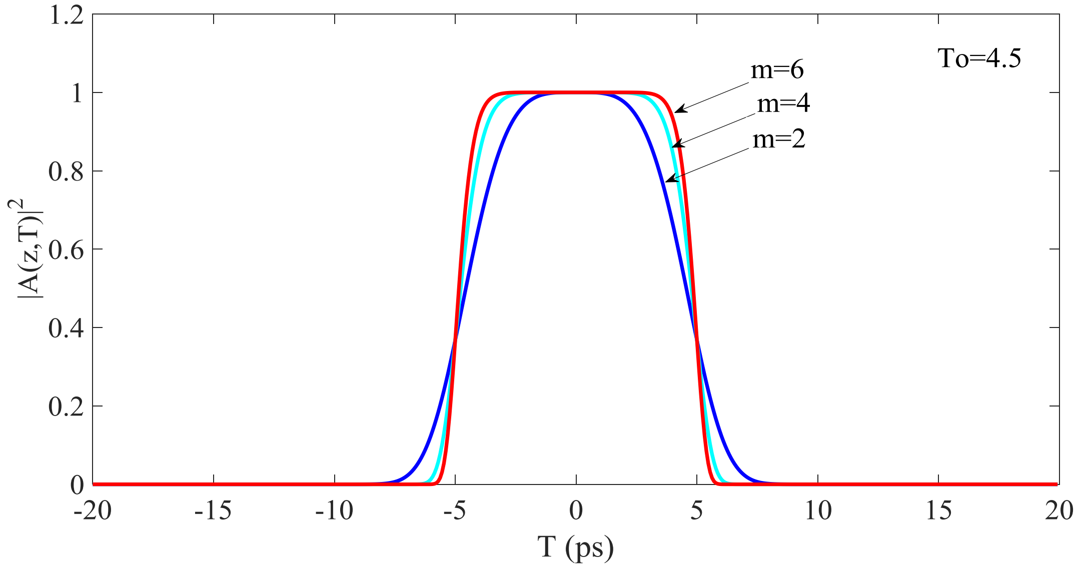

Figure (2) The effect of various m values on the super- Gaussian pulse.

Peak intensity fluctuation along the the fiber for m = 2, 4, 6

With a variation of T_0, the evolution characteristic of super- Gaussian pulses shifts. T_o is reduced to 3.5ps and 2.5 ps in terms of enhancing transmission of data, The pulse's evolution behavior is investigated for a range of m values. For m = 2, Figure 3 depicts the propagation of a super-Gaussian pulse.

Figure 3 also indicates that when the value of T_o lowers, the peak amplitude reduces. For lowest values of t_0, this denotes that the optic disperses the pulse more dramatically. Only pulse widening is shown in Fig. 2, but greater values of m result in pulse constriction, as illustrated in Figures 4 and 5. In Figure 4, with T_o = 3.5 ps and 4.5 ps, the super Gaussian pulse begins to compression in the first path length before broadening. The distance to which the pulse compressed reduces as the value of T_o reduces, with the worst case occurring at T_o = 2.5 ps.

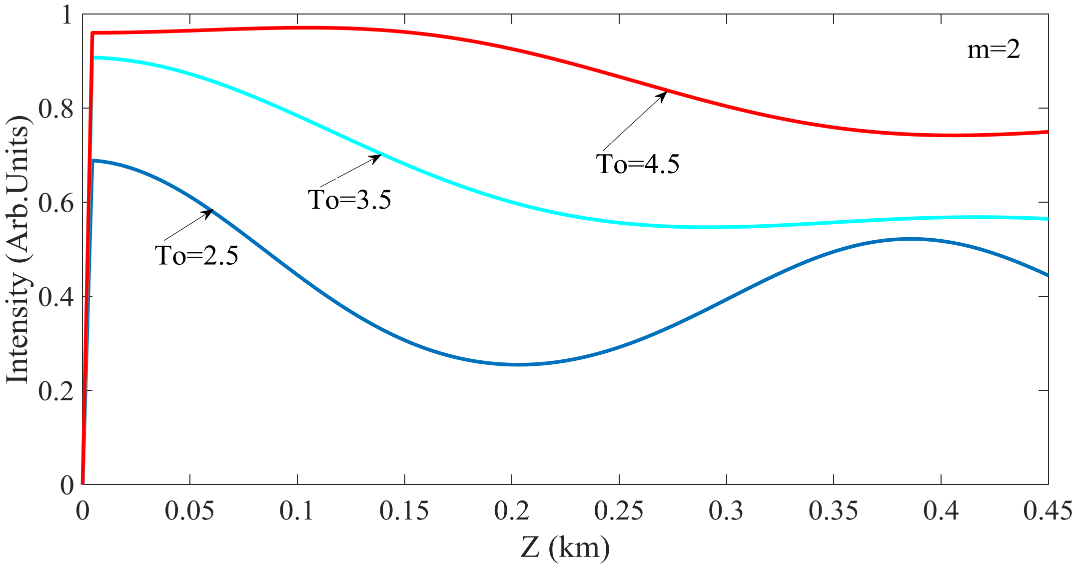

Figure (3) Peak intensity fluctuation along the length of the fiber for m = 2

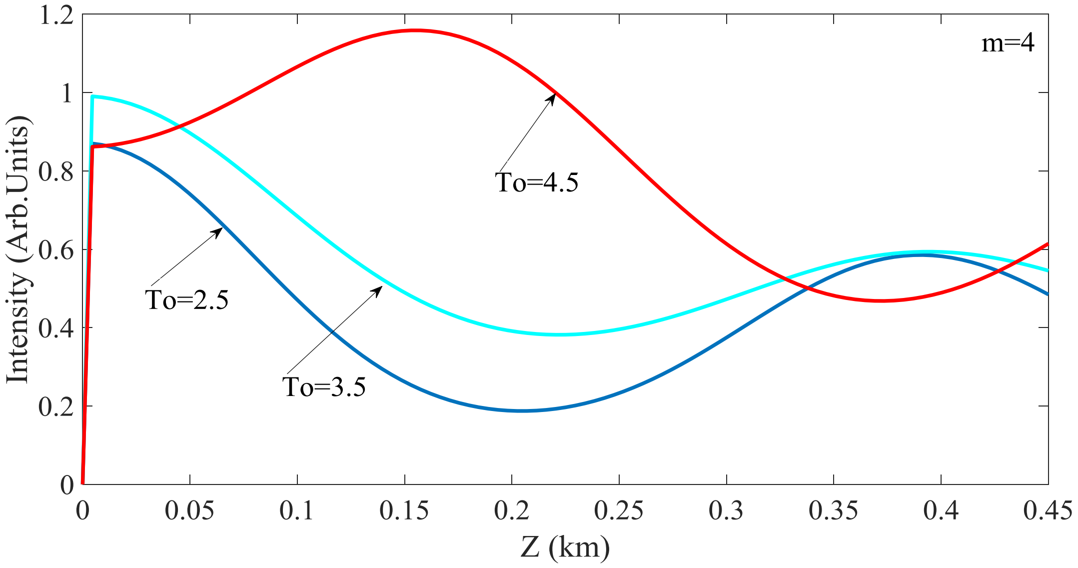

Figure (4) Peak intensity fluctuation along the length of the fiber for m = 4

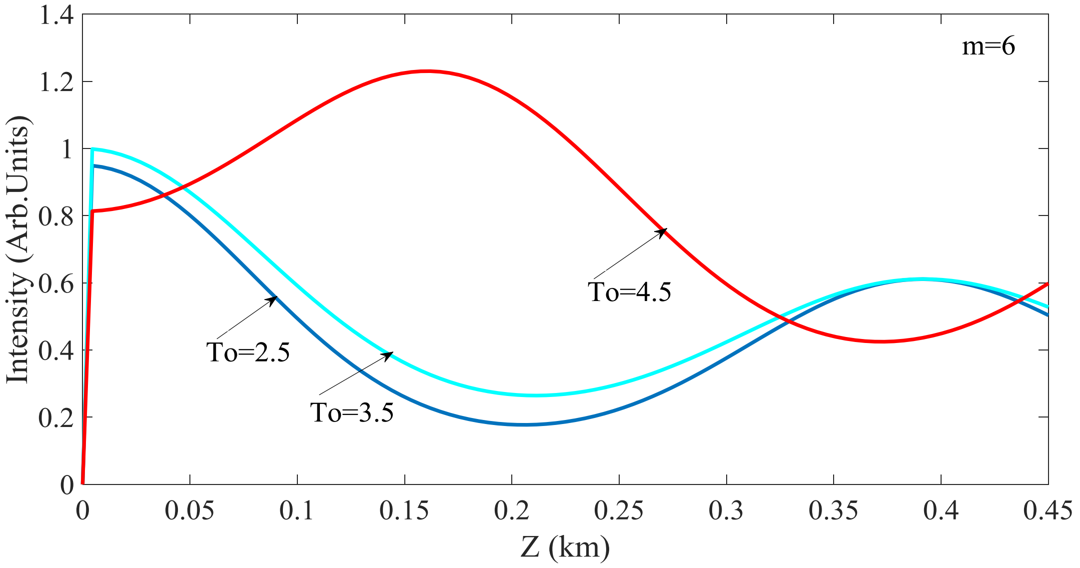

Figure (5) Peak intensity fluctuation along the length of the fiber for m = 6

At T_o = 4.5 ps exhibits remarkable behavior, with only compress observable in this scenario for the duration under investigation. However, the consequence of choosing T_o = 4.5 ps is that the output rate is lower than when using T_o = 3.5 ps or 2.5 ps. When comparing Figures 4 - 5, it can be seen that the amplitude of the maximum output grows as the value of adjusted increases. Although the amplitude of peak power rises in Figure 5, further study reveals that the broaden of pulse more at m = 6 than at m = 4 at where at m = 6, the sharper edges result in the same distance. Peak output intensity versus distance is displayed in Figure 6 for m = 2, 4, and 6 for a stable value of T_o of 3.5 ps.

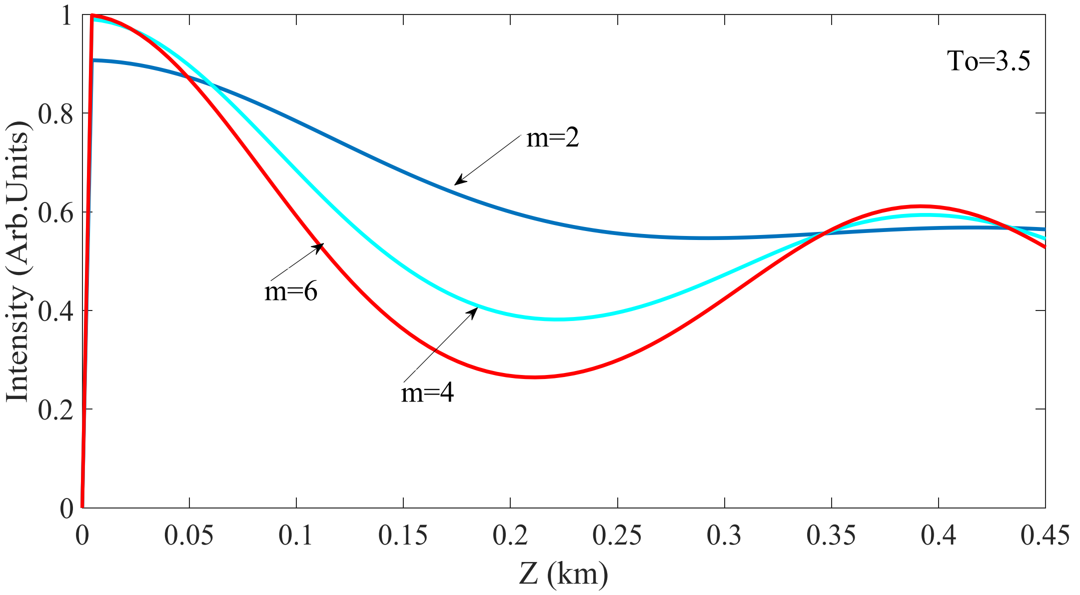

Figure (6) shown the Peak output intensity against distance (z) for m = 2, 4, 6, and t_0 = 3.5 ps

The induce of dispersion widening of the super- Gaussian pulse at long distances rises when the amount of m is raised, as seen in Figure 6. This occurred because as the value of m increases, the super

Gaussian pulses' edges get sharper, and as a consequence, the pulse's spectrum widens, resulting in additional spreading of the pulse. Only the dispersion dominating mode is relevant for the topic above. Fiber effects, involving nonlinearity, occur together in the practical scenario, and the pulse pattern is substantially different when all three effects are present at the same time, as detailed below. Furthermore, various outcomes are seen depending on the procedure region, in other words normal versus abnormal dispersion regimes.

Comparison between ADR GVD and NDR GVD at T_O = 2.5 ps

For to = 2.5 ps and P = 35 mw, Figure 7 shows the propagation of a single super-Gaussian pulse in normal dispersion region (NDR) against anomalous dispersion region (ADR) in the presence of loss across a 0.25 km length. However, in ADR, the two chirps caused by GVD and nonlinearity have different sign, thus they contend with everyone, resulting in less widening than GVD alone in NDR. This reveals an important and significant phenomenon: ADR is a superior region for pulse restoration than NDR. Figure 7 illustrates the identical example with to = 3.5 ps. The similar actions of the super Gaussian pulse is seen. Looking at Figures 7 and 8, it is clear that extending the pulse width raises the maximum output of the pulse. Likewise, the pulse widening in ADR is smaller than that in NDR.

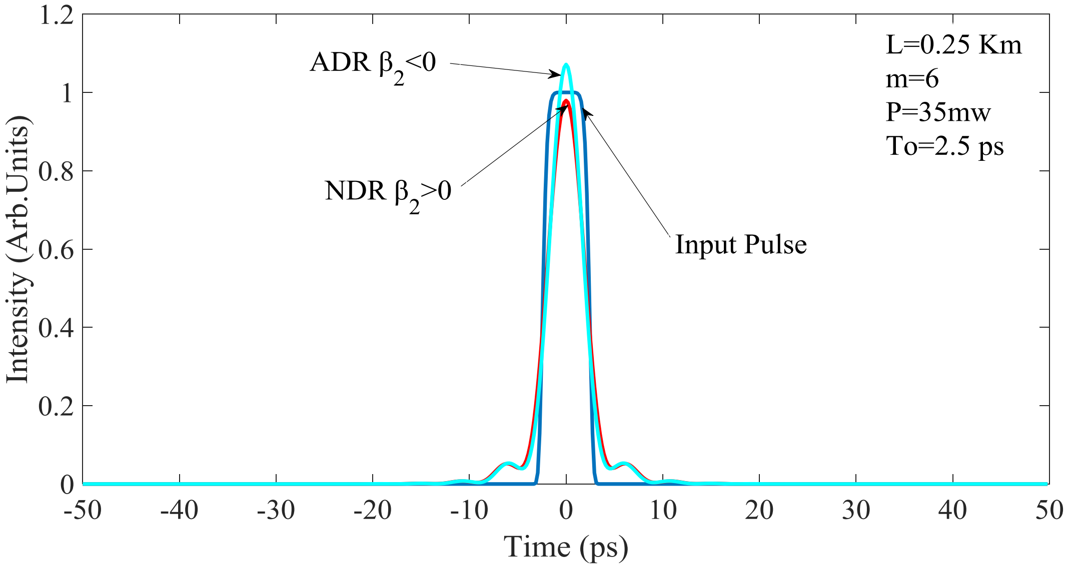

Figure (7) shows a comparison between ADR GVD and NDR GVD at T0 = 2.5 ps.

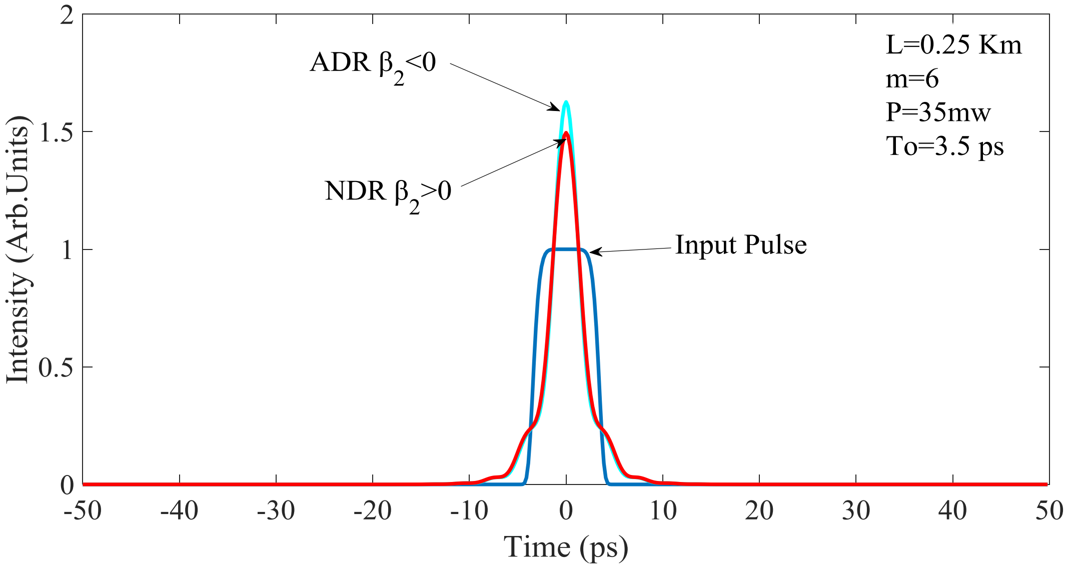

Figure (8) shows a comparison between ADR GVD and NDR GVD at T0 = 3.5 ps.

Comparison super-Gaussian pulse with different values of chirp

A super-Gaussian pulse is the case study according equation below [15, 16].

$$U(0,t) = \exp\left[-\frac{1+iC}{2}\,(\frac{t}{T_o})^{2m}\right]$$

Where C=0, -2, 2, -4, 4, Figure 9 is obtained.

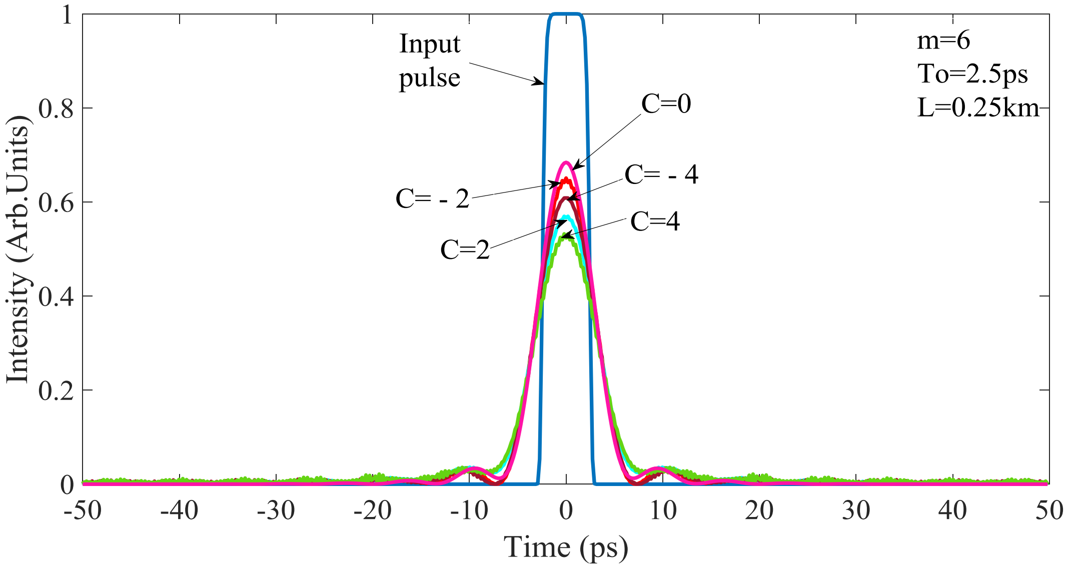

Figure (9) shows Super-gaussian pulse at the beginning and end of the photonic crystal fiber

The high amplitude of the pulse in the case of C = 0 is obvious, by dispersion effect, the conservation of energy causes a reduction in pulse amplitude. The widening impact generated by the GVD is increased as the amplitude of the chirp change in the situations C = = ±2, ±4 and the amplitude was decrease.

Conclusion.

The findings of an investigation of the degrading effects of photonic crystal fiber on super-Gaussian pulses that under impact of dispersion for various pulse width values have indeed been provided. Normal and anomalous dispersion modes have both been considered. The split-step Fourier approach is used to solve the nonlinear Schrödinger equation for such pulse traveling through photonic crystal fiber in order to obtain these results. The results show that NDR favors widening, thus the pulse broadens more than GVD, but in ADR of GVD, the pulse broadens less. When compared to GVD alone, the maximum output of the pulse rises. These results clearly indicate that ADR is superior to NDR in single mode optical fiber for pulse restoration, and the characteristics of the regime in which the pulse was propagated the numerical investigation of the super-Gaussian pulse traveling in the linear regime validated the theoretically expected pulse widening and chirp effect. It was also demonstrated that pulse widening causes a decrease in pulse amplitude owing to energy conservation. These findings clearly suggest that ADR is superior to NDR in photonic crystal fiber for pulse recovery. This work depicts the growth pattern of super-Gaussian optical pulse transmission in ADR and NDR of standard single - mode optic, as well as the different values of chirp in super-Gaussian pulse.

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