Received: 19 October 2024 | Revised: 7 March 2025 | Accepted: 13 May 2025 | Published online: 3 June 2025

RESEARCH ARTICLE

Journal of Optics and Photonics Research
2025, Vol. 00(00) 1–6
DOI: 10.47852/bonviewJOPR52024590

BON VIEW PUBLISHING

# The Mutual Support Between Bright and Dark Pulses in Photonic Crystal Fibers

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**Abstract:** This paper presents an in-depth study of the formation and propagation of single optical pulses in photonic crystal fibers, with a particular focus on the dynamic interaction between dark pulses and bright soliton-like pulses under different dispersion conditions. The dark pulse, propagating in the normal dispersion region, interacts with the bright pulse in the anomalous dispersion region. The results demonstrate that precise adjustment of the relative phase between these two pulses leads to the formation of a stable single wave with unconventional properties. This interaction represents a novel mechanism for controlling the formation of optical pulses in nonlinear systems, opening up prospects for innovative applications in high-speed optical communications and optical signal processing. In addition, the paper examines the impact of frequency oscillation on the performance of optical communication systems, with a detailed analysis of the propagation of super-Gaussian noise pulses in single-mode fibers. Mathematical modeling shows that these pulses are subject to significant nonlinear distortions due to the interaction between scattering and nonlinear properties of the medium, such as the Kerr effect and stimulated scattering.

**Keywords:** photonic crystal fiber, super-Gaussian pulse, chirp, bright soliton, dark soliton, nonlinear Schrodinger equation

## 1. Introduction

In recent years, soliton pulses have attracted a lot of attention. Solitons are described as localized waves that are robust against collisions with one another and propagate without changing their form or velocity characteristics [1]. The occurrence of solitary wave solutions suggests a perfect equilibrium between dispersion and nonlinearity, which is typically impossible to produce in general and typically requires quite particular conditions [2]. Mathematically speaking, solitons are specific solutions of a particular class of nonlinear evolution equations, including the sine-Gordon equation, the nonlinear Schrödinger equation, and the Korteweg–de Vries equation, among many others. Significantly, these equations have several physical applications in a wide range of physical domains, including fluid mechanics, condensed matter, electro-magnetics, nonlinear optics, and plasmas, among many others. Short optical pulses must propagate across optical fibers for high-bit-rate optical communication systems to be of current interest. The performance of light-wave transmission systems is limited by chromatic dispersion in single-mode fibers, which becomes more significant as pulses grow shorter as the data rate increases [3, 4]. By taking into account pulse propagation in single-mode dispersive fibers, attempts have been made to theoretically assess the significance of the chirp effects [3–6]. However, Gaussian pulses with linear frequency chirp are frequently used to achieve the desired outcomes. In reality, the laser pulses have significantly sharper leading and trailing edges and are far from Gaussian. Additionally, time-resolved pulse spectrum measurements [7–9] have demonstrated that frequency chirping in directly modulated semiconductor lasers mostly takes place in the vicinity of the leading and trailing edges. To account for the chirp effects, the linear chirp model that was employed in earlier studies [4–6] might not be appropriate. Using a more realistic model for the temporal shape and frequency chirp associated with the incident pulse, this research examines the propagation of pulses represented by bright and dark soliton in dispersive fibers. The super-Gaussian model, which is an extension of the Gaussian model, offers pulses with a configurable rise time. Our findings demonstrate that the leading and trailing edges' sharpness has a significant impact on the dispersive effects. One compares the findings obtained using Gaussian and super-Gaussian models and explores the influence of the pulse form during propagation.

Bright solitons are produced when abnormalities of dispersion (AD) interact with self-phase modulation, while dark solitons are created when AD interacts with self-phase modulation [10, 11]. Hasegawa [12] made the first experimental observations of bright solitons in optical fibers in 1980. A number of theoretical investigations and experimental projects aiming at the deployment of soliton-based fiber communications have been prompted by this finding. Mollenauer et al. [13] have reported the observation of steady fundamental brilliant solitons' propagation across six thousand kilometers. However, due to the difficulties of producing the first narrow dark pulses, until recently, there was no experimental detection of optical dark solitons in fiber optics [14, 15]. There have been reports of using cross-phase modulation (XPM). In a photonic crystal fiber to generate another pulse or to assist the steady transmission of XPM, a dark pulse in the AD range and a bright pulse in the ND range can support one another to produce a single wave [16]. In the AD range, dual support of a bright and dark soliton can also produce sustainable propagation [17]. Additionally, an ND domain brilliant pulse can generate another ND spectrum

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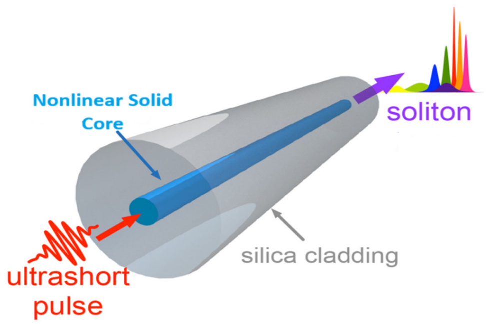
brilliant pulse on a CW background in the AD domain [18]. One presents the production of a modern kind of a single wave in this work. In a photonic crystal fiber (PCF), a carefully shaped super-Gaussian pulse can create a stable dark pulse (intensity dip) when a bright pulse in one dispersion regime (ND) interacts with a dark pulse in another regime (AD) at matched speeds. This highlights how dispersion and nonlinearity can be controlled to engineer exotic optical waveforms. This dark pulse, when combined with the slightly modified brilliant pulse, can propagate as a single wave. It appears that through XPM, the modified AD's brilliant pulse spectrum with the resulting dark wave in the ND spectrum reinforce each other. The noninverted situation, which describes how a dark soliton in the ND area and a brilliant soliton in the AD section cooperate in a nonlinear fluid, has been studied [19, 20]. Nevertheless, pulse propagation in a photonic crystal fiber cannot be considered in the noninverted situation [21]. As the following discusses, our distinct pulses, both dark and brilliant, are not soliton. Consequently, the single wave we display here has to be distinct from those in the noninverted scenario [22] and will analytically investigate brilliant and dark solitons in a hybrid system with a high light-matter connection that is applicable to experiments. One discovers that a range of coexisting moving solitons, such as dark-gray and gray-gray dark solitons and brilliant solitons on zero and nonzero backgrounds, are supported by the matching two-component model. By reducing the two-component issue to a single stationary equation nonlinearity, the analytical form of the solutions is discovered. Although all of the discovered solutions coexist under the same set of model parameters, they approach distinct branches of the polariton dispersion relation for linear waves in a correctly characterized linear limit. A resonance between the margins of the continuous spectrum branches can be linked to the oscillatory-instability threshold of bright solitons with zero background. Bright solitons on the constant-amplitude pedestal are unstable, but "half-topological" dark-gray and non-topological gray-gray solitons are stable in broad parametric ranges below the modulational instability threshold. See Figure 1.

**Figure 1**
**Generate the soliton pulse in photonic crystal fiber**




## 2. Simulation Results

There are two connected nonlinear Schrodinger equations that control the pulse shape in the ND region $v$ and the AD region $u$ in a lossless fiber:

$$i\frac{\partial u}{\partial \varepsilon}+\frac{\partial^2 u}{2\partial r^2}+x_u u(|u|^2+2|v|^2)=0 \tag{1}$$

$$i\frac{\partial v}{\partial \varepsilon}+i\,\delta\frac{\partial v}{\partial \tau}-\frac{\beta}{2}\frac{\partial^2 v}{\partial r^2}+x_v v(|v|^2+2|u|^2)=0 \tag{2}$$

In this case, $\varepsilon$ and $\tau$ stand for the normalized retarded distance and time, respectively. The group velocity difference between the two waves is indicated by the $\delta$. The interplay of these parameters determines whether energy transfers constructively (amplifying effects) or destructively (damping effects), enabling tailored pulse dynamics for applications in optical communications or ultrafast systems. So in Equations (1) and (2),

$$x_u=\frac{2k_{ou}}{k_{ou}+k_{ov}} \tag{3}$$

$$x_v=\frac{2k_{ov}}{k_{ou}+k_{ov}} \tag{4}$$

The beam-propagation technique is used to numerically solve Equations (1) and (2) under the given beginning circumstances [23].

$$u(\varepsilon=0,\tau)=\left(\frac{u_\circ}{\sqrt{x_u}}\right)\operatorname{sech}\left(\frac{\tau}{\tau_\circ}\right) \tag{5}$$

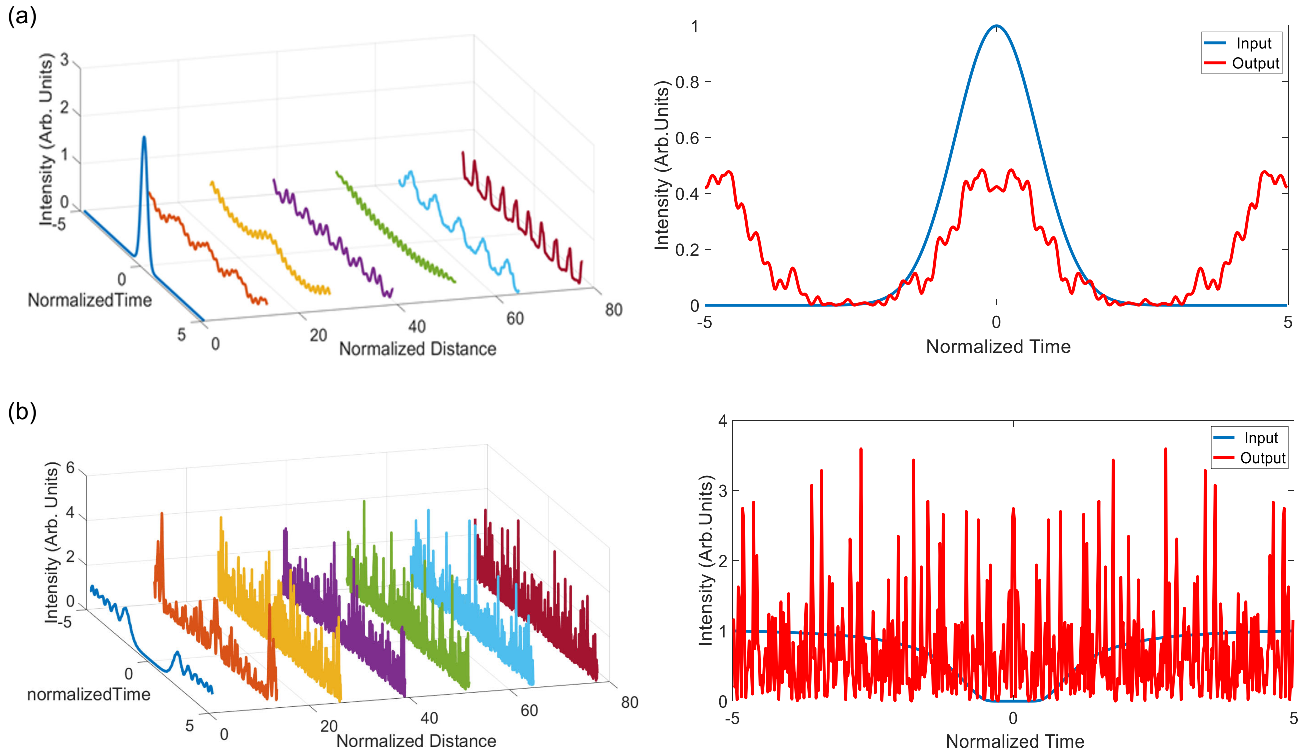
$$v(\varepsilon=0,\tau)=\exp\left[-\left(\frac{\tau}{40}\right)^4\right] \tag{6}$$

Here, $\tau_\circ$ is always selected to be significantly less than 40. Keep in mind that if $u_\circ=1/\tau_\circ$, Equation (5) illustrates a luminous single-soliton pulse. This PCF design leverages its microstructure to operate in ND at 0.835 $\mu m$ and AD at 1.55 $\mu m$, making it versatile for optical systems requiring precise dispersion management at these wavelengths. It is also assumed that the group velocities at these two wavelengths are the same, and hence, $\delta=0$.

To begin, we choose $u_\circ=1/\ \tau=3$ in Equation (5). Figure 2(a) depicts the development of the bright soliton $u$ up to a range of $3\pi$, and Figure 2(b) displays the pulse form of $v$ at a distance of $3\pi$.

In this case, we can see that the long super-Gaussian pulse does not produce a steady-state dark pulse and the bright soliton is annihilated. In contrast, the evolution is completely different if we include u_° in the Equation (5) and increase to u_° = 1/ τ = 5. As can be seen in Figure 2(a), the transmission of the bright pulse in the AD range remains stable within a distance of 3π, although with large variations. In addition, we see that the long super-Gaussian pulse produces a dark pulse. After a distance of π, this dark pulse moves almost without distortion in the ND range. Figure 2(b) shows the pulse shape of this dark pulse and its background at a distance of 3π. According to the study, this dark pulse propagates together with the above light pulse and produces a single wave. To determine whether the dark pulse and the bright pulse in this solitary wave are dark and bright solitons, respectively, one compares the pulse morphology at a distance of 3π in Figure 2. For the bright pulse in our numerical information (shown as a fitted solid line), we fit the core part of the pulse to the dashed line of the bright single-soliton pulse. However, the dark pulse in our data does not fit well with the defined dark soliton. Our results show that dark pulses are longer than dark solitons. We see that in the region of higher power, both the bright and dark pulse phases are flat. In our scenario, this suggests that the bright pulse gives something similar to an iridescent soliton, but in the dark, there are no dark solitons in the pulse. An isolated dark pulse with a constant phase will eventually evolve

**Figure 2**
**The theoretical results when the input end is equipped with a bright one-soliton pulse. (a) The bright pulse's evolution up to a distance of 3$\pi$; any two consecutive curves are separated by a distance of $\pi$/2, (b) the dark pulse's form at a distance of 3$\pi$**




into two dark solitons; however, the XPM light pulse chirp promotes the steady-state propagation of the dark pulse [24–28]. However, the bright pulse (not the bright soliton) can propagate without distortion because the dark pulse also provides chirp to the bright pulse via XPM. Both sets of data show that solitary waves can only form when the incident bright wave is sharp enough to produce dark and bright soliton-like pulses. Essentially, long ultra-Gaussian pulses produce chirping sounds in the initial development stage due to the bright pulse induced by XPM. Due to frequency dispersion, this linear frequency modulation will eventually transform into amplitude modulation of the extended pulse. Through XPM, this amplitude modulation again provides feedback chirp to the bright pulse. The bright pulse is often destroyed by this chirping feedback.

As seen in Figure 3(a), if the first bright pulsing is sufficiently acute, it will reconfigure itself to create another bright wave that resembles a soliton; If not, as Figure 1(a) illustrates, the brilliant pulse is annihilated and transforms into a multihumped wide pulse. The aforementioned amplitude modulation on the long super-Gaussian pulse will aid in the evolution of a sharp dark pulse at the center and in the oscillatory tails as long as the sharp bright pulse can be maintained. The strong dark pulse in the ND region and a bright pulse in the AD region will eventually combine to produce a single wave. Further research is necessary to determine why the dark pulse differs so much from any dark solitons, whereas the light pulse is so similar to a bright one-soliton pulse. Konyukhov et al. [6] addressed phenomena in which a lengthy pulse in the ND range and a bright pulse in the AD range copropagated. A bright two-soliton pulse was formed in the simulation findings of that study by compressing an input Gaussian pulse in the AD range. Furthermore, a wide depression developed in the middle of the extended pulse. To put it another way, there were no isolated waves like in our findings. We've attempted the following inputs.

$$u(\varepsilon = 0, \tau) = \exp\left[-\left(\frac{\tau}{\tau_1}\right)^2\right] \quad (7)$$

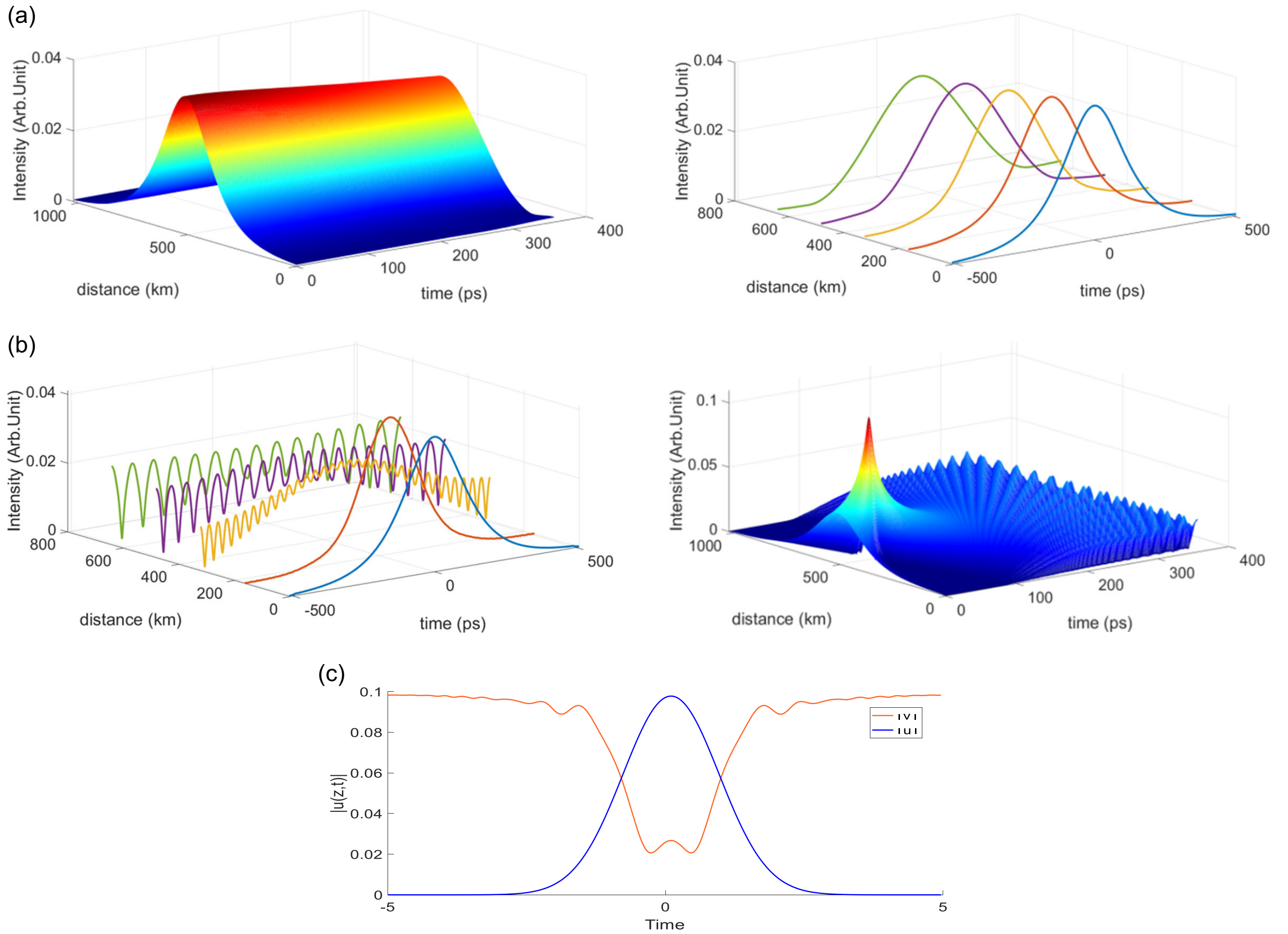
And

$$v(\varepsilon = 0, \tau) = \exp\left[-\left(\frac{\tau}{15}\right)^8\right] \quad (8)$$

which is like those seen in Konyukhov et al. [6]. Our modeling findings up to 5$\pi$ are comparable to those in Konyukhov et al. [6] when $\tau_1 = 7.07$. However, we find that at a distance of 4 $\pi$, a bright pulse that is similar to a one-soliton pulse forms when $\tau_1$ is lowered to 4, i.e., the pulse grows sharper, and on the lengthy pulse, a strong dark pulse is produced. Once more, a single wave forms. These findings not only suggest that a solitary wave in the AD range may be produced by a bright pulse other than a soliton but they also verify that such a strong pulse has to be precise enough to cause a one-off wave.

**Figure 3**

**Numerical outcomes when the input end uses one or more bright soliton pulses. (a) The bright pulse evolves up to a distance of $2\pi$, and any two succeeding curves are separated by a distance of $\pi/2$, (b) the arrangement of the dark pulse at $2\pi$ radians, (c) comparison of the core regions in the numerical simulations for the bright and dark pulses at $2\pi$**




## 3. Conclusion

In this study, the interaction between bright pulses in the anomalous dispersion region and dark pulses in the normal dispersion region within photonic crystal fibers was analyzed, with emphasis on the chirp effect and the formation of standing single waves. The main points drawn from the results are as follows:

1) Formation of bright and dark pulses: The results show that the nonlinear interaction via XPM between the bright and dark pulses leads to the formation of a stable single wave. This wave maintains its stability over long propagation distances (up to $3\pi$), provided that the initial bright pulse is sharp enough. This stability is attributed to the dynamic balance between the self-modulation of the bright pulse (soliton-like) and the feedback of the chirp generated by the dark pulse.
2) The role of chirp in pulse modulation: Frequency changes (chirp) play a crucial role in converting phase modulation into amplitude modulation, especially in super-Gaussian pulses. When the intensity of the bright pulse increases, the chirp generated by XPM produces ripples in the long dark pulse, which promotes the formation of an isolated dark pulse. In contrast, less intense pulses destroy the bright pulse and transform it into a broad multi-peaked pulse.
3) Differences between pulses and classical solitons: Although the resulting bright pulse is similar to a classical bright soliton, the dark pulse is fundamentally different from conventional dark solitons. The dark pulse here is longer and lacks the characteristic steep slope of solitons, suggesting that the stabilization mechanism relies more on mutual interaction with the bright pulse than on self-balancing between dispersion and nonlinearity.
4) Practical applications in optical communication systems: These results provide new insights into improving the performance of high-speed communication systems, where the interaction between bright and dark pulses can be exploited to reduce signal dispersion and increase data transmission efficiency. For example, these single waves may be used in the design of optical repeaters based on the nonlinear properties of crystalline fibers.
5) Limitations and suggestions for future studies: Limitations: The modeling was based on simplifying assumptions such as neglecting optical loss in the fiber, a factor that may affect long-term stability in practical applications.
6) Future suggestions: Study the effect of geometric parameters of crystalline fibers (such as hole geometry and arrangement) on pulse interaction. Explore the possibility of generating hybrid pulses (light-dark) in other nonlinear media, such as nanoscale photonic crystals. Analysis of the effect of phase noise on the stability of single waves in realistic propagation conditions.

7) Contribution to the theoretical understanding of nonlinear phenomena: This study contributes to a deeper understanding of the dynamic interactions between optical pulses in nonlinear media, especially in contexts that go beyond classical soliton models. The results suggest that the combination of bright and dark pulses can open new horizons in research into quantum photonics and advanced optical systems.

In conclusion, this study shows that the interaction between light and dark pulses in optical crystal fibers produces stable single waves with unique properties, with promising applications in improving optical communication systems. However, further research is still needed to understand the exact mechanisms of this interaction and improve the practical conditions for its exploitation.

## Ethical Statement

This study does not contain any studies with human or animal subjects performed by the author.

## Conflicts of Interest

The author declares that he has no conflicts of interest to this work.

## Data Availability Statement

Data are available from the corresponding author upon reasonable request.

## Author Contribution Statement

**Mohammed Salim Jasim AL-Taie:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration.

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**How to Cite:** AL-Taie, M. S. J. (2025). The Mutual Support Between Bright and Dark Pulses in Photonic Crystal Fibers. *Journal of Optics and Photonics Research*. https://doi.org/10.47852/bonviewJOPR52024590