Optics Communications 393 (2017) 95–102

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Characteristics and stability of soliton crystals in optical fibres for the purpose of optical frequency comb generation

M. Zajnulina[a,*], M. Böhm[a,b,c], D. Bodenmüller[a], K. Blow[b], J.M. Chavez Boggio[a], A.A. Rieznik[c], M.M. Roth[a]

[a] innoFSPEC Potsdam, Leibniz Institute for Astrophysics, An der Sternwarte 16, 14482 Potsdam, Germany
[b] Aston Institute of Photonic Technologies, Aston Triangle, Birmingham B4 7ET, United Kingdom
[c] Instituto Tecnologico de Buenos Aires and CONICET, Buenos Aires, Argentina

ARTICLE INFO

Keywords:
Optical frequency combs
Astro-combs
Optical solitons
Soliton crystal
Soliton radiation beat analysis
Generalised nonlinear Schrödinger equation

ABSTRACT

We study the properties of a soliton crystal, a bound state of several optical pulses that propagate with a fixed temporal separation through the optical fibres of the proposed approach for generation of optical frequency combs (OFC) for astronomical spectrograph calibration. This approach - also being suitable for subpicosecond pulse generation for other applications - consists of a conventional single-mode fibre and a suitably pumped Erbium-doped fibre. Two continuous-wave lasers are used as light source. The soliton crystal arises out of the initial deeply modulated laser field at low input powers; for higher input powers, it dissolves into free solitons. We study the soliton crystal build-up in the first fibre stage with respect to different fibre parameters (group-velocity dispersion, nonlinearity, and optical losses) and to the light source characteristics (laser frequency separation and intensity difference). We show that the soliton crystal can be described by two quantities, its fundamental frequency and the laser power-threshold at which the crystal dissolves into free solitons. The soliton crystal exhibits features of a linear and nonlinear optical pattern at the same time and is insensitive to the initial laser power fluctuations. We perform our studies using the numerical technique called Soliton Radiation Beat Analysis.

1. Introduction

Optical frequency combs (OFCs) are discrete optical spectra with lines that are phase-locked and have an equidistant spacing as well as nearly equal intensities over a broad spectral range [1,2]. Since their discovery in mode-locked Ti:Sapphire lasers in the 90's, they have been observed in various nonlinear optical media such as semiconductor micro-resonators [3] and fibre-laser cavities [4]. OFCs show a wide range of application potential in telecommunications for the generation of high-repetition rate picosecond-pulses for ultra-high capacity transmission systems based on optical time-division multiplexing [5–11], spectroscopy [1,12], metrology, frequency synthesis, and optical clocking [13].

In our group, we focus on the deployment of OFCs for the purpose of the astronomical spectrograph calibration. The OFCs generated in mode-locked lasers have been proposed and already successfully tested as calibration sources for high-resolution astronomical spectrographs used for the search for exoplanets or the measurement of the time-variation of the fundamental constants. The spectral line spacings they provide reach up to 50 GHz which is achieved by filtering the mode-locked laser lines (typically ranging from 250 MHz to 1 GHz) by means of a series of Fabry-Perot cavities [4,14–24].

However, observations of galaxy structures and detailed studies of the Milky Way require deployment of spectrographs in the low- and medium-resolution range. For this type of spectrograph, an OFC needs to provide stable spacings from 50 GHz to a few hundreds of GHz which is only hardly achievable in mode-locked lasers due to the laser cavity geometries. As for the semiconductor micro-ring cavities and toroids that are able to provide OFCs with spacing up to a few hundreds of GHz, they suffer from thermal effects degrading the OFC stability which makes them difficult candidates for application in astronomy [25].

In our group, a fibre-based approach for the generation of OFC suitable for spectrographs in the low- and medium resolution range has been proposed and extensively studied experimentally and by means of numerical simulations [25–29]. Contrary to mode-locked lasers used for generation of OFCs, our approach is a single pass consisting of two fibre stages with a conventional single-mode fibre as the first stage and a suitably pumped amplifying Erbium-doped fibre with anomalous dispersion as the second stage. The initial input field is generated by

---

[*] Corresponding author.

http://dx.doi.org/10.1016/j.optcom.2017.02.035
Received 22 November 2016; Received in revised form 11 February 2017; Accepted 13 February 2017
0030-4018/ © 2017 Elsevier B.V. All rights reserved.

two equally intense continuous-wave (CW) lasers spectrally separated by the so called laser frequency separation (*LFS*). The evolution of a OFC begins in the first fibre due to cascaded a four-wave mixing process. In the second fibre, the OFC from the first fibre stage gets broadened due to a further four-wave mixing as well as to a soliton-compression effect based on the extreme optical pulse amplification [25]. Our approach is simple, robust, low-cost, and versatile: it can also be deployed for OFC generation for spectroscopy applications as well as for subpicosecond pulse generation for telecommunication.

The applications in the astronomy requires broadband OFCs with sharp spectral lines. Therefore, it is crucial to precisely understand and control the build-up of the optical pulse temporal shape in the first fibre stage of our approach, because the temporal shapes will determine the bandwidth and stability of produced OFCs. Moreover, the temporal shapes of the first fibre output will directly influence the pulse build-up in the second amplifying stage. Further, any temporal aperiodicity of the optical pulses within the output pulse train would result in the broadening of the OFC lines and, therefore, needs to be prevented to achieve sharp OFC lines at the end.

However, the Generalised Nonlinear Schrödinger Equation (GNLS) with a bichromatic initial condition that we use to model and study our approach is not integrable which hinders us from a thorough understanding of the pulse shape build-up in the first fibre stage. Thus, we apply the numerical technique called Soliton Radiation Beat Analysis (SRBA) to get insight into the pulse formation in the first fibre [30,31]. This technique is capable of dealing with nonintegrable equations with arbitrary initial conditions and allows to retrieve the soliton content if the optical pulses generated in fibre-based systems.

In our previous work ([26]), using the SRBA and a fixed value of the laser frequency separation of $LFS = 78.125$ GHz, we identified a state of free, i.e. separated, solitons for higher laser input powers (> 3 W), an intermediate state that denotes a continuous dissolving of a soliton crystal into free solitons in the moderate input-power region (1.3 - 3 W) and a soliton crystal state for low input powers (< 1.3 W) characterised by a common propagation of several optical pulses with a fixed time separation. We stated that the intermediate state is most suitable for generation of the OFCs for astronomical spectrograph calibration, because it combines the properties of a soliton crystal that guarantees stable spectral spacings of the OFC lines with simple dynamics of separated fundamental solitons.

The discovered soliton crystal state constitutes an unusual nonlinear pattern. The strict temporal periodicity of its components that corresponds to the value of *LFS* makes it an interesting object of studies with high level of potential in applications where fixed pulse temporal separation denoting low level of timing jitter is required. Moreover, the soliton crystal oscillates with the fundamental frequency Z_0 over the propagation distance as we observed in our previous work [26]. For us, the knowledge of the dependence of the soliton crystal properties such as, for instance, its fundamental frequency on different fibre parameters (group-velocity dispersion (GVD), nonlinearity, and optical losses) and on the initial light source characteristics (*LFS* and laser-intensity variations) is necessary for a successful experimental realisation of our approach for generation of OFC for calibration of low- and medium resolution spectrographs.

Here, we present our studies on the soliton crystal properties with respect to the fibre parameters and the initial light source characteristics. We found out that the soliton crystal can be fully described by two quantities, namely by its fundamental frequency and the laser input-power threshold at which the dissolution of the soliton crystal into the state of free solitons takes place. Further, it exhibits features of a linear and nonlinear optical pattern at the same time. Thus, the appearance of the fundamental frequency is a purely linear effect, whereas the crystal has similar properties as separated solitons in terms of the dispersion and nonlinear length which represents its nonlinear nature. Moreover, the soliton crystal is insensitive to laser input power fluctuations which makes its experimental realisation relatively simple to be implemented. Again, we performed our studies using the SRBA technique.

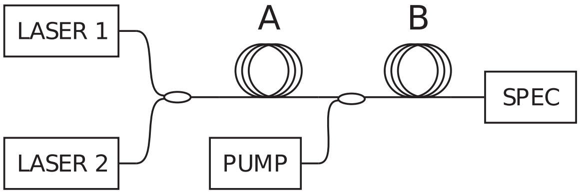

Fig. 1. Schematic representation of the proposed approach for generation of optical frequency combs. LASER 1: fixed CW laser, LASER 2: tuneable CW laser, A: conventional single-mode fibre, B: Er-doped fibre, PUMP: pump laser for B, SPEC: astronomical spectrograph [26].

This paper is structured as follows: in Section 2, we present the experimental setup for generation of OFC in fibres and the corresponding mathematical model, the concept of SRBA and the interpretation of the SRBA power spectra are discussed in Section 3, the results of our numerical studies are presented in Section 4, and a conclusion is drawn in Section 5.

2. Experimental setup and mathematical model

Fig. 1 shows the schematic representation of the experimental setup for generation of OFC for spectral calibration of astronomical spectrographs in the low- and medium resolution range [25–29]. In this figure, A is a conventional single-mode fibre, whereas B is a suitably pumped Erbium-doped fibre with anomalous dispersion. The generation of a comb begins with two equally intense CW lasers (Laser 1 and Laser 2). They are independent, free-running and feature relative frequency stability of 10^{-8} over a one-hour time frame which is sufficient for astronomical applications in the low- and medium-resolution range. Laser 1 has a fixed angular frequency ω_1, whereas Laser 2 has frequency ω_2 that is tuneable. The resulting central frequency is $\omega_c = (\omega_1 + \omega_2)/2$ coinciding with the central wavelength at 1531 nm. The laser frequency separation is given by $LFS = |\omega_1 - \omega_2|/(2\pi)$.

An initial OFC arises in the first fibre due to a cascade of four-wave mixing processes, whereas in the second fibre, the OFC is broadened due to the strong pulse amplification and simultaneous compression. Pulse compression in an amplifying fibres is known from the late 80's and is an alternative technique to the compression in dispersion-decreasing fibres [32–35]. As we discovered in our previous work ([26]), in fibre A, a common soliton crystal state arises out of the initial laser field for low input powers. For high input powers, free, i.e. separated, solitons are formed. In between, there is an intermediate state that denotes a continuous dissolving of the soliton crystal into the free solitons with increasing input power. The soliton crystal constitutes a bound state of several optical pulses that propagate through the optical fibre with a fixted temporal separation. Fig. 2 shows an example of the temporal and spatial evolution of a soliton crystal.

Due to the strict temporal periodicity of crystal's pulse components, its OFC spectrum exhibits sharp spectral lines with stable spacings which makes the soliton crystal a promising nonlinear pattern for high-quality OFC generation. However, a better understanding is still needed about how such a soliton crystal arises. Here, we study the build-up of a soliton crystal in detail. Specifically, we address the question how does the soliton crystal build-up depend on different fibre parameters (GVD, nonlinearity, and optical losses) and the initial light characteristics (*LFS* and laser-intensity variation). We model the nonlinear light propagation in this fibre by means of the GNLS for a slowly varying optical field envelope $A = A(z, t)$ in the co-moving frame [34,36–38]:

$$\frac{\partial A}{\partial z} = i \sum_{j=2}^{3} \frac{i^j}{j!} \beta_j \frac{\partial^j A}{\partial t^j} + i\gamma \left(1 + \frac{i}{\omega_0} \frac{\partial}{\partial t}\right) \times \tag{1}$$

Download English Version:

https://daneshyari.com/en/article/5449480

Download Persian Version:

https://daneshyari.com/article/5449480

Daneshyari.com