EPJ Web of Conferences **309**, 07014 (2024)
EOSAM 2024 https://doi.org/10.1051/epjconf/202430907014

The phase of darkness – measuring the phase of a dark pulse

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Abstract. Dark optical solitons are solutions to the nonlinear Schrödinger equation in normal dispersion media with positive Kerr nonlinearity, exhibiting a discrete π phase jump. These solitons are valuable to applications within telecommunication. Recent advancements have demonstrated the generation of two-colour bright-dark soliton pairs through cross-amplitude modulation in laser cavities, resulting in mode locking. In this study we present for the first time full field characterization of the electric field of a dark pulse. We achieved this by performing Blind Frequency Resolved Optical Gating measurements using the synchronous bright pulse as the gate pulse. The retrieved dark pulse verifies the existence of the expected π phase jump in the phase of the dark pulse, confirming theoretical predictions.

1 Introduction

Dark optical solitons are well-known solutions of the nonlinear Schrödinger equation which are sustained in a normal dispersion medium with positive Kerr nonlinearity [1,2]. They exhibit properties advantageous to several applications with optical communication being one of them [3.4]. The solution to the nonlinear Schrödinger equation for a fully dark soliton predicts that the phase of a dark pulse exhibits a discrete π phase jump [1-3]. If the phase shift is below π, the amplitude of the pulse does not go all the way to zero and the pulse can be referred to as grey soliton and could be expected in dissipative nonlinear systems containing gain and loss. Experimentally, dark Kerr solitons have been generated by exploiting cross-phase modulation (XPM) in optical fibres [5]. Recently, an existence of two-colour bright-dark soliton pair was observed by four-wave mixing and XPM in a Kerr microresonator simultaneously pumped at two wavelengths [6]. We have shown recently that simultaneous two-colour bright-dark pulse generation can be achieved by using cross-amplitude modulation (XAM) in laser cavities coupled by a second-order nonlinear interaction [7,8]. The intracavity XAM by necessity leads to selectivity in longitudinal mode phases and therefore to self-mode locking generating two-colour dark-bright pulse states. XAM is akin to the action of a nonlinear absorber so it is expected that the dark pulse generated in a cavity with normal dispersion would behave as a dissipative dark soliton.

The intensity traces of dark solitons were previously measured using different intensity cross-correlation techniques [4,5,8]. However, the full-field (amplitude and phase) characterization has not been performed, to the best of our knowledge. For instance, frequency resolved optical gating (FROG) could be used for such task. The difficulty is that since dark pulses have low amplitude the standard FROG techniques would not give reliable results. In this work we took advantage of the simultaneous generation of mode-locked trains of two-colour bright-dark pulse states and utilized Blind cross-correlation FROG (Blind XFROG) for complete field characterization of a dark pulse [9].

2 Method

The laser used in this experiment was an in-house built passive mode locked laser based on intra-cavity sum-frequency mixing (SFM) [10], producing a train of synchronous bright and dark pulses. The laser consist of two Nd:YVO_4 lasers interconnected through a periodically poled potassium titanyl phosphate (PPKTP), phase matching SFM between the two wavelengths. As discovered in previous work [8], if the roundtrip time is matched for both cavities, a continuous mode locking regime will be reached. By creating one bright and one dark pulse the laser minimizes the SFM related loss. The laser produced 1064 nm centre wavelength bright pulses with an average power of 100 mW and dark pulses centred at 1342 nm with an average power of 20 mW. Both outputs operated at a synchronized repetition rate of 275 MHz.

The characterization of both electric fields is performed through a Blind XFROG measurement, fully characterizing electric fields of both, bright and dark pulses at once. The experimental set up is shown in Fig. 1.

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https://doi.org/10.1051/epjconf/202430907014

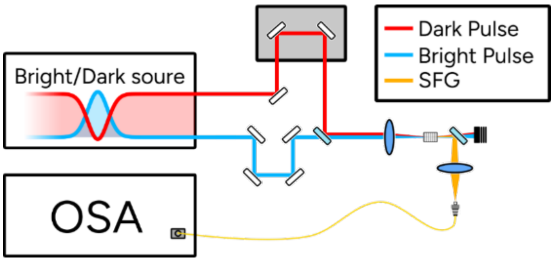

Fig. 1. Experimental set-up of the Blind FROG measurement process.

The set-up is a standard XFROG set-up, with an object and gate pulse with the gate on a delay stage. The measurement device is in our case, due to narrow signal bandwidth and relatively weak signal strength, an Ando AQ6315A Optical Spectrum Analyser (OSA). The weak dark pulse power motivated using the bright pulse as the gate. as the nonlinear FROG signal strength can be increased. This was enabled by the fact that both pulse trains are synchronized and phase-locked.

Due to the low signal-to-noise ratio (SNR) the measurements were retrieved with the Line-Search FROG algorithm which has been shown to perform very well under low SNR conditions [11].

3 Results

The retrieved dark pulse and Blind XFROG trace is shown in Fig. 2 and as can be clearly seen the phase exhibits a near π phase jump across the central part of the pulse, as predicted in [1,3,8].

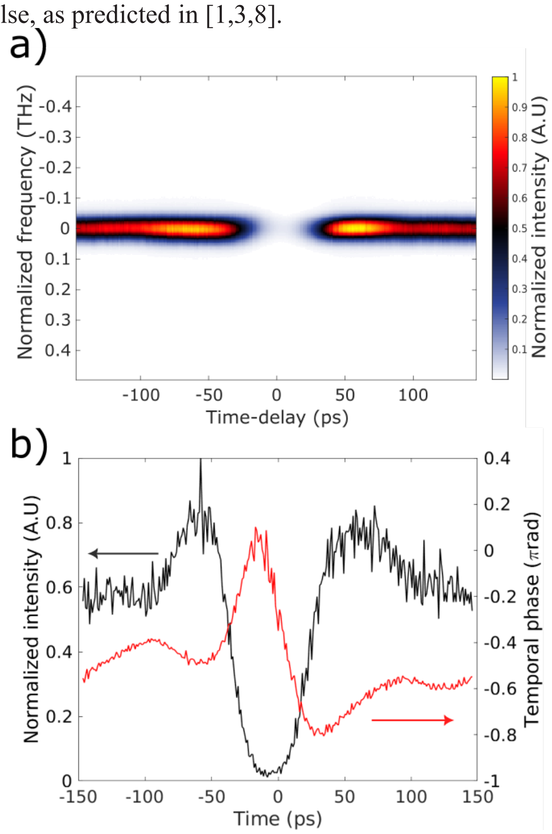

Fig. 2. Measured Blind FROG trace with the bright pulse as gate pulse and retrieved temporal intensity and phase of the retrieved dark pulse.

As the gate pulse used is a bright pulse, we get an expected gap in the XFROG trace signal where the temporal difference between the gate and object pulses is minimised. Here the nonlinear signal produced by the sum frequency mixing between gate and object is near zero as the dark and bright pulse overlaps. The bright pulse simultaneously characterized in the Blind XFROG retrieval is a near transform limited bright pulse with a full width at half maximum (FWHM) of 10 ps. The dark pulse has a full width at half minimum (FWHm) of 60 ps. The retrieved spectral bandwidth of the dark pulse is narrower than the integrated spectrum of the dark pulse laser separately measured with an OSA. The time-bandwidth product of the dark pulse is 0.410 which is not far from transform limit for a sech^2-pulse. The peaks at the edges of the dark pulse in Fig.2 are similar to those expected in bright-dark soliton pair generation under group velocity mismatch (GVM) [6]. The GVM over many roundtrips will then act as a spectral filter limiting the dark pulse bandwidth.

4 Conclusions

In summary we have shown experimental full field characterization of a two-colour bright-dark pulse pair using in-house developed Blind XFROG. We could experimentally verify for the first time, the expected π phase jump across the pulse. The dark pulse generated in the nonlinearly coupled self-mode-locked laser resonators does display the characteristic dark soliton features.

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