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Dynamics of photon fluid flows driven by optical pistons

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Abstract: We investigate the optical analogous of the piston shock problem in gas dynamics. Using fast temporal measurements, we recorded dispersive shock waves formed by the propagation of a bi-chromatic photon fluid along an optical fiber.

OCIS codes: (190.4370) Nonlinear optics fibers, (190.5530) Pulse propagation and temporal solitons.

1. Introduction

The piston problem, i.e. the dynamics in a uniform gas at rest under the action of a moving piston is fundamental problem of physics and a case study in shock wave physics [1]. Shock waves have been thoroughly investigated in many different branches of physics [2]. In conservative systems, shock waves are regularized by the formation, owing to dispersion, of rapidly oscillating non-stationary structures, called dispersive shock waves (DSWs) [3-5].

In this work, we investigate the analogous problem for a photon fluid, which turns out to be strongly influenced by the dispersive character of the medium. Our experiments make use of a fiber optics setup where an all-optically controlled quasi instantaneous discontinuity of frequency of the input light mimics the piston action. This configuration is a specific case of the general Riemann problem that concern propagation with discontinuities [6,7].

2. Analogy with the piston problem and experimental setup

More precisely, to mimic gas compression, we study the propagation, along a highly normal dispersive optical fiber, of a chirped square pulse with an abrupt jump of instant frequency (velocity) at its center (as illustrated in Fig. 1(a)). During the propagation of this dual-frequency pulse, the two parts propagate at different velocities mimicking gas compression. Indeed, the fast pulse part plays the role of a moving piston while the other one (the slow part) plays the role of the compressed gas. The internal collision and squeezing of these two parts eventually lead to the generation of a pair of DSWs connected by an intermediate plateau of constant density (Fig. 1(b)).

In order to generate the suitable bi-velocity square pulse needed to study the genuine Riemann problem, we temporally couple a square shaped pulse and a strong external M-shaped pulse. Both of these pulses are obtained by a direct intensity modulation of CW waves (Fig. 1(c)). The role of this M-shaped pulse is to induce a frequency shift on the square pulse via cross phase modulation (XPM) while propagating along 500 m of highly nonlinear fiber (HNLF). Since the linear slope of the M-shaped pulse abruptly change at its center, this allows to induce a quick shift in frequency at the center of the square pulse. Hence, synthesizing the desired state.

At the output of the HNLF fiber, the M-shaped pulse is spectrally filtered and the chirped square pulse is then injected into 15-Km of dispersion compensating fiber (DCF) (fiber parameters are given in the caption of Fig. 1). The output light is characterized using an optical sampling oscilloscope (OSO).

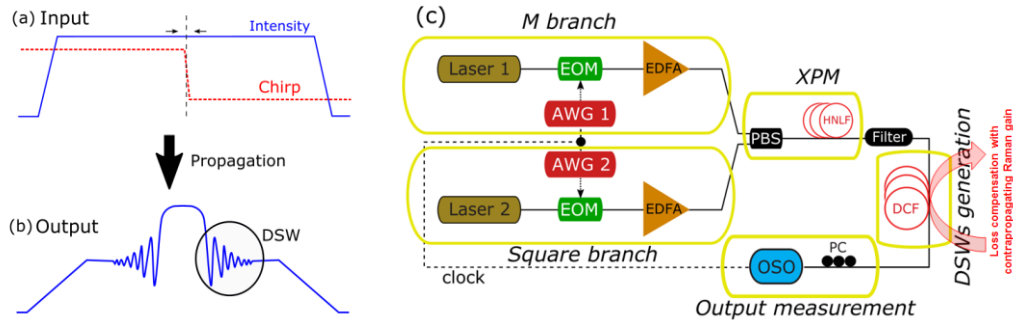


Fig. 1. (a,b) Illustration of the chirped square pulse and the generation of DSWs. (c) Experimental setup. AWG, Arbitrary Waveform Generator; EOM, electro-optic modulator; EDFA, erbium-doped fiber amplifier; PBS, polarization beam splitter; PC, Polarization controller; OSO, optical sampling oscilloscope; HNLF (length 500 m; loss $\alpha = 0.6$ dB/km; zero dispersion wavelength $ZDW = 1551.4$ nm; third order dispersion $\beta_3 = 0.53 \times 10^{-40}$ s³/m; nonlinear coefficient $\gamma = 12$ W⁻¹ km⁻¹). DCF (length 15 km; $\alpha = 0.5$ dB/km; $\beta_2 = 1.7 \times 10^{-25}$ s²/m; $\gamma = 3$ W⁻¹ km⁻¹); Initial condition of M pulse (peak power 7 W, duration 2.4 ns, @1541 nm) and square pulse (peak power 70 mW, duration 1.6 ns, @1545 nm).

3. Compressing Piston:

We performed a series of experiments that demonstrate the generation of DSWs from the chirped pulse. Figure 2 (a) depicts the temporal profile of the 1.3 ns square shaped pulse recorded at the DCF input (HNLF output). The spectrogram in Fig. 2(b) provides us a clear description of the bi-chromatic properties of this pulse. This spectrogram was obtained by performing a heterodyne detection with the help of a tunable CW laser and a 70 GHz photodiode. In the presented case, the total frequency shift induced by the M-shaped pump is 18.5 GHz.

Once injected into the DCF fiber, the square pulse undergoes nonlinear effect and we observed at the DCF output, for an input peak power of 210 mW, the generation of a short central plateau, with several fast and regular oscillations aside (Fig. 2(c)). These oscillations correspond to a regularization of the shock and the formation of a pair of DSW [2]. More interesting, when we reduce the input peak power to almost 8 mW, the pair of DSWs becomes connected by a periodic structure instead of a flat plateau (Fig. 2(d)), we also observe the apparition of vacuum points (points with no photon density). This special case has no equivalent in gas dynamics [7].

The propagation of the chirped square pulse in the DCF was also numerically simulated by integrating the generalized nonlinear Schrodinger equation taking into account our experimental conditions. Our simulations show a good qualitative agreement with observations (not represented here).

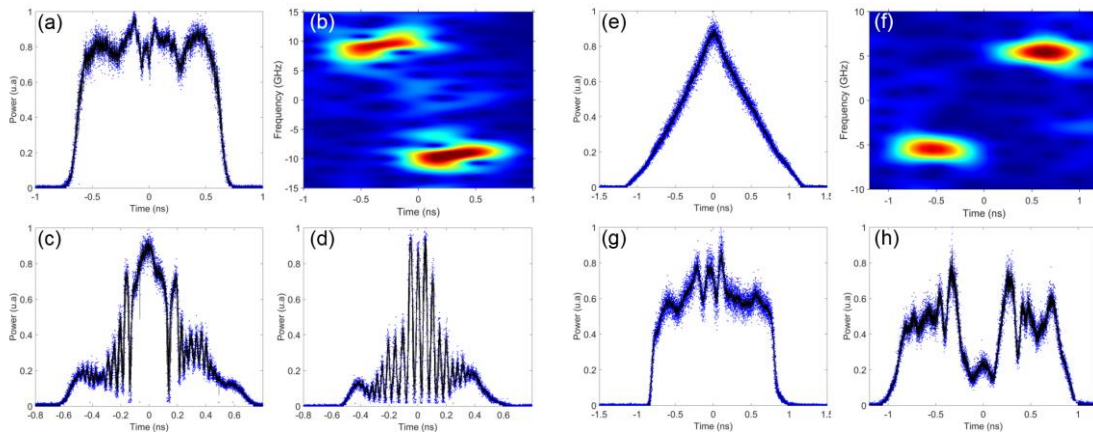


Fig. 2. (a-d) Piston configuration. (a) Intensity profile of the square pulse recorded at the DCF input. (b) Associated Spectrogram. (c,d) Intensity profile recorded at the DCF output for an input peak power of (c) 210 mW and (d) 8 mW. (e-h) Anti-piston configuration. (e) Intensity profile of the triangle shaped pulse used to induce the chirp. Initial condition of the triangle pulse (peak power 5 W, duration 2.4 ns, @1536 nm). (f) Spectrogram associated to the input square pulse (induced frequency shift = 10.5 GHz). (g,h) Intensity profile recorded at the (g) DCF input (h) DCF output. (input peak power = 35 mW).

4. Retracting Piston:

In a second set of experiments, we replaced the M-shaped pump by a triangle shaped one (Fig. 2(e)), which reverses the sign of the velocity profile compared to the previous case (see spectrogram in Fig. 2(f)). Instead of compressing each other, the two parts composing the input pulse ((Fig. 2(g)) undergo a decompression mechanism leading to the formation of a rarefaction waves pair, connected by a small finite plateau (as represented in Fig. 2(h)). This process is analogous to the gas dynamics case when the piston decompresses and exhausts the gas, leading to a low pressure inside a reservoir. Here also, numerical simulations agreed well with experiments (not shown here).

5. Conclusion

We studied the optical analogy of a gas compressed/decompressed by a piston. Our experiments consist in the propagation of a bi-chromatic photon fluid along a highly dispersive optical fiber. We observed generation of dispersive shock waves and rarefaction waves. These results are also well supported by numerical simulations and pave the way to study gas dynamics in relatively accessible optical fiber experiments.

6. References

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