Intra-Pulse Raman Scattering Controlled via Asymmetric Airy Pulses

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Abstract: We study intra-pulse Raman scattering initiated by Airy pulses in optical fibers. Their asymmetric features are revealed from the spectrum of the primary/secondary Raman soliton. Their versatility towards effective frequency tuning is also presented.
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Airy pulses are ubiquitous in dispersive optical systems. They have attracted increasing attention since they were introduced into optics [1]. The dynamics of these pulses has been studied in both the linear and nonlinear regimes [2-10]. However, the experimental investigation of Airy pulses is still relatively unexplored, particularly under the influence of higher order nonlinearities in fibers [11]. Among these nonlinearities, stimulated Raman scattering (SRS) is perhaps the most fundamental; it introduces asymmetry (in time) in the pulse dynamics due to its delayed nature, which leads to a continuous downshift of the frequency of a gradually slowing soliton – the so-called soliton self-frequency shift (SSFS). Since Airy pulses exhibit asymmetric shapes, they may show interesting behavior under the action of the asymmetric Raman response of the fiber. Moreover, clarifying the dynamics of these pulses in the presence of SRS could be beneficial in controlling SSFS as well as in understanding the Airy pulse evolution in more complex nonlinear systems [10]. In this work, we study the SSFS of a pre-shaped Airy pulse in a fiber. Under the influence of the delayed Raman response, the fission of solitons from the main lobe of the input Airy pulse, and their subsequent interactions with the Airy tails, leads to different behaviors for Airy pulses with either a leading or a trailing oscillatory tail, respectively. In our experiments, we demonstrate a novel and convenient method for the control of soliton fission and subsequent SSFS through the offset of the spectral phase associated with the input Airy pulses.

The generalized nonlinear Schrödinger equation is employed to analyze the evolution of Airy pulses in a large effective area fiber (LEAF). Figures 1(a) and 1(b) show the typical nonlinear propagations of two different Airy pulses that are time-reversed with respect to each other. The generated Raman solitons show different nonlinear interactions with the main lobe, as well as with the tails of the two input Airy pulses. Making a comparison for the two inputs, for a *tail-leading* Airy pulse (whose main lobe has a fast leading edge and a slow trailing edge) [Fig. 1(a)], the first generated Raman soliton captures a significant amount of energy thanks to its relatively longer interaction with the main input lobe, a fact that consequently hampers the possibility of generating a secondary Raman soliton. Furthermore, the generated soliton continuously slows down upon propagation, and it never meets the oscillatory Airy tails. In this case, the SSFS process is mostly influenced by the main input lobe. Under the same conditions, but with a *tail-trailing* Airy pulse, the first Raman soliton pulse experiences a shorter interaction with the main lobe [Fig. 1(b)] than the *tail-leading* Airy pulse. The main soliton gains less energy with respect to the previous case, thus leading to the generation of a secondary Raman soliton. Besides the influence that is exerted by the main lobe, the Raman soliton in Fig. 1(b) will eventually overlap with the Airy tails, and gain further energy by means of their nonlinear interaction [12].

In order to confirm our numerical predictions, we perform a series of experiments using a setup similar to that employed in our previous work [4]. A pulse, coming from a fiber laser, has a ~4 nm bandwidth and a ~1549 nm center wavelength. It is modulated by a cubic spectral phase produced by a computer-controlled pulse shaper. The generated Airy pulse is then amplified by an erbium-doped fiber amplifier. Afterwards, we employ a fiber-based polarizer, a 10/90 coupler and a power meter to make sure that the polarization and the average power of the pulse are always the same at the input of a spool of a LEAF fiber (from Corning). The Raman signal generated at the output of the fiber is analyzed by way of an optical spectrum analyzer. The cubic spectral phase is $\exp[i(f - f_0 - f_d)^3/(3\sigma^3)$, where f is the frequency, f_0 is the center frequency, f_d is an offset and σ is relative to the modulation depth).

The offset introduces a quadratic spectral phase term: $\exp[iC(f-f_0)^2]$, where $C=-f_d/\sigma^3$. In this way, the peak power of an Airy pulse at the input can be adjusted by merely altering the offset [4], as typically shown in Fig. 1(c).

In the first set of experiments, we use a cubic phase with $\sigma = -2\times10^{11}$ to produce an Airy pulse with a leading oscillatory edge. The average input power was set at 18 mW. By altering the offset f_d of the cubic phase, different SSFSs could be obtained, as shown in Fig. 1(d), where the whole pattern is almost symmetric with respect to C: larger SSFSs are obtained for larger peak powers in correspondence with the offsets of Fig. 1(c). Near the regime of C=0, the generated Raman solitons are mostly influenced by the main lobe of the Airy pulse. Since the first soliton consumes a significant amount of energy from the main input lobe, it is relatively difficult to generate additional solitons. The secondary Raman soliton appearing for large offsets is caused by the fact that the main lobe is merged with the sub-lobes. Therefore, the dynamics of such a chirped Airy pulse is similar to dynamics of a *tail-trailing* Airy pulse as shown in Fig. 1(b).

Next, we simply changed the sign of σ and performed another set of experiments for an Airy pulse exhibiting a trailing tail. The corresponding results are summarized in Fig. 1(e). With the same input average power as before (18 mW), two Raman solitons (primary and secondary) are now observed to emerge for a large range of offsets, in agreement with our prediction (see Fig. 1(b)). As opposed to the previous case (i.e., an Airy pulse with a leading tail), the dependence of the primary SSFS on the offset C is both asymmetric and non-smooth in nature. This is well understood by the fact that the interaction between the Airy tails and the Raman soliton is also affected by noise. More experimental results show that the smoothness of frequency tuning can be improved with a larger input average power. The energy gain from the tails is effectively able to slow-down the decay of the SSFS, which would otherwise result from a decrease in the input peak power. Therefore, the pattern in Fig. 1(e) looks broader and flatter with respect to that presented in Fig. 1(d).

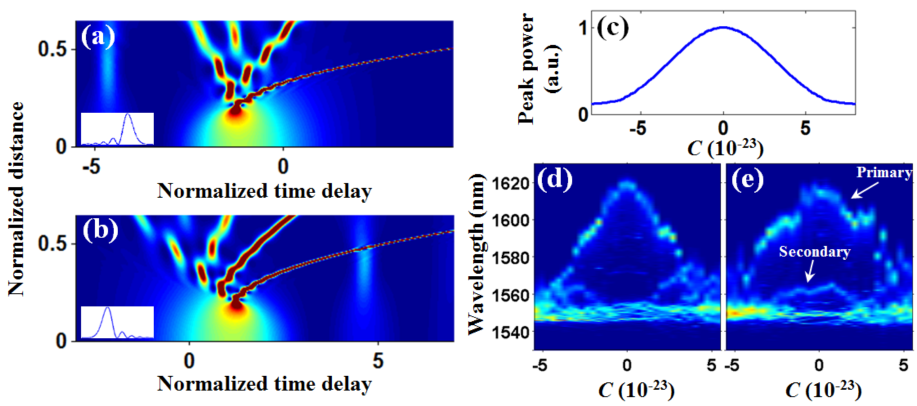

Fig. 1 : (a) and (b) present the numerical nonlinear propagation of different asymmetric Airy pulses with (a) a leading and (b) a trailing tail, and the insets show the profiles of the inputs for each case; (c) Peak power change of an Airy pulse with respect to C - here we assume $\sigma = -2\times10^{11}$; (d) and (e) are the observed Raman frequency shifts dependent on the offset of the cubic phases associated to the input in (a) and (b), respectively.

In conclusion, we have presented a direct observation and comparison of the SSFS of solitons resulting from the fission of Airy pulses with either leading or trailing tails. In our experiment, we proposed an approach to control the Raman frequency shift by merely altering the offset of the cubic phase. New features mediated by Airy asymmetric pulses are revealed. These studies will bring about new possibilities for effective frequency tuning of Raman solitons, important for many applications, such as pulse compression, spectroscopy, etc.

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