Superluminous Three-Wave Solitary Brillouin Structures

Éric Picholle and Carlos Montes

***Abstract*—Self-similar deformation of three-wave stimulated Brillouin scattering (SBS) dissipative structures (“Brillouin quasi-solitons”) yields superluminous behaviors. The authors discuss the relevancy of the various velocities involved in the nonlinear propagation of such complex structures, both in the ideal semi-infinite case and in a real-world Brillouin fiber ring laser experiment. Optical and acoustical group velocities greater than c are shown to occur during pulse propagation in SBS soliton lasers.**

***Index Terms*—Solitons, Sommerfeld & Brillouin, stimulated Brillouin scattering (SBS), superluminal propagation, superluminous propagation, velocity of light.**

I. Introduction

Although many pseudo-paradoxes about “faster-than-light” propagation continue to haunt popular science media, science fiction, and even scientific literature, their solution has been well understood since 1913 and the works of Sommerfeld and Brillouin; indeed, they introduced a crucial distinction between phase, group, signal, front, and energy transport velocities of a light pulse [1] after Sommerfeld’s prediction of group velocities higher than the velocity of light in vacuum, c [2].

Following the distinction introduced by Chiao [3], two main classes of laser pulse propagation with velocities greater than c can be considered, the shape of the pulse being either conserved in a *superluminal* linear interaction (usually in a dispersive medium, near an absorption line [4]) or deformed through a *superluminous* nonlinear interaction between matter and light (for instance a saturated gain mechanism [5], [6] or a coherent scattering process [7]). Gain-assisted superluminal light propagation constitutes an intermediary class [8].

We will hereafter define the group and signal velocities, respectively, as the velocities at which the peak of a wave packet and the half-maximum wave amplitude would move [1], [3]. Nevertheless, even these simple definitions are hardly intuitive in the presence of nonlinear pulse reshaping [6]. The very concept of group of waves lies on an implicit hypothesis that a regular univoquely identifiable pattern is maintained during the propagation [9]. Yet, the splitting of a single wave packet into two daughter packets, or inversely the fusion of two pulses, is nothing unusual in nonlinear optics, yielding various pseudo-paradoxes depending on arbitrary conventions.

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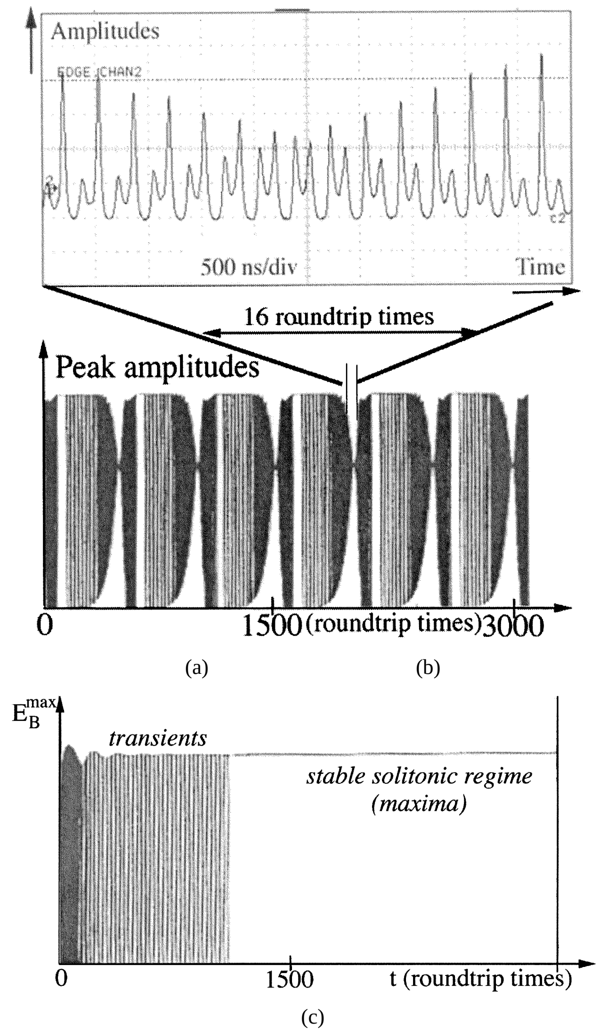

Fig. 1. (a) Periodic exchanges of stability between two subpulses in the output of a Brillouin fiber ring laser (see [10]). (b) Numerical simulation of the same regime; only the maxima (peak amplitudes) are plotted. The group velocity has little sense in the blackened regions where such exchanges of stability take place. (c) Same as (b), but in a different regime; a stable pulsed (quasisolitonic) output is attained after some very long (∼1000 roundtrip times) transients.

For instance, considering that a single group of waves remains itself through a splitting process yields a discontinuity of the group velocity whenever the relative heights of the subpulses are exchanged [Fig. 1(a) and (b)]; reciprocally, the arbitrary distinction of two separated daughter pulses yields a discontinuity on the signal velocity. Other examples can be found in the dynamics of lasers, as in our Brillouin fiber ring experiment, fully described in [10] and [11].

These concepts, nevertheless, recover all their relevancy when the shape of a given pulse is conserved throughout its nonlinear propagation. The group and signal velocities are then equivalent. An obvious example is the well-known first order "nonlinear Schrödinger" (NLS) soliton where the linear group velocity dispersion is exactly compensated by the nonlinear optical Kerr effect [12]. In this paper, we will address a different highly nonlinear regime involving self-similar reshaping, namely, the propagation of sub- or superluminous Brillouin solitary three-wave structures. We will focus the present discussion on their velocity properties; a thorough discussion of the now classical three-wave model of stimulated Brillouin scattering (SBS) can be found in [13] and the general properties of three-wave solitary Brillouin structures in [11], [14]–[16].

II. Stimulated Brillouin Scattering in Ideal Semi-Infinite Optical Fibers

SBS is the coherent (i.e., phase-sensitive) resonant interaction between two optical and one acoustic wave [17]. Single-mode optical fibers are fairly one-dimensional media, in which effective SBS energy transfers can occur when a forward (by convention) "pump" wave $(\nu_p, \mathbf{k_p})$ is backscattered into a counterpropagating "Brillouin" wave $(\nu_B, \mathbf{k_B} \approx -\mathbf{k_p})$ through its electrostrictive interaction with a forward longitudinal acoustic wave $(\nu_a = \nu_p - \nu_B, \mathbf{k_a} = \mathbf{k_p} - \mathbf{k_B} \approx 2\mathbf{k_p})$. In our experiments, the pump wavelength is 532 nm, yielding an hypersonic frequency $\nu_a \approx 33$ GHz and an acoustic damping time γ_a^{-1} in the 10-ns range. This will also be the typical duration of Brillouin pulses created through SBS; the linear group velocity dispersion can thus be neglected in this three-wave model of SBS in fibers, whose numerical simulations account for optical and material losses, Langevin-type "thermal" noise [18], as well as the perturbative optical Kerr effect [13]. Note that this coherent model describes only the reshaping of slowly varying envelopes, and thus neglects carrier effects such as the low-level forerunners following the true front of an ideal finite-support pulse [1], [2].

When a continuous wave (cw) pump wave encounters nothing but a weak thermal acoustic noise in the fiber, only Stokes energy transfers, from the pump to the Brillouin and acoustic waves, can be stimulated. Above the threshold, this instability yields the so-called "Brillouin mirror," highly detrimental to optical telecommunications. More interesting dynamical regimes can be obtained when the fiber is already filled with an intense acoustic wave (usually as a material memory of previous interactions); antiStokes processes are then possible, the pump being rebuilt at the expense of the two other waves. The local SBS gain then depends on the relative phases of the three waves ($g_B \propto \cos(\varphi_p - \varphi_B - \varphi_a)$, conventionally positive in the Stokes regime). For high enough optical intensities, this property induces a very robust self-cleaning process on the phase of the Brillouin wave [7], whose linewidth can thus be as narrow as a few hertz for a megahertz pump width [19].

Here, we are interested in highly nonlinear regimes, where the pump can be strongly depleted within the duration of a short Brillouin pulse or the acoustic damping time. Neglecting both the optical Kerr effect and thermal noise, the coherent three-wave model of SBS admits stable solitary solutions in ideal semi-infinite media (Fig. 2), where the amplification of the leading edge of the backward propagating structure exactly compensates the depletion of the trailing edge (either due to the losses or, in the undamped problem, to anti-Stokes SBS processes).

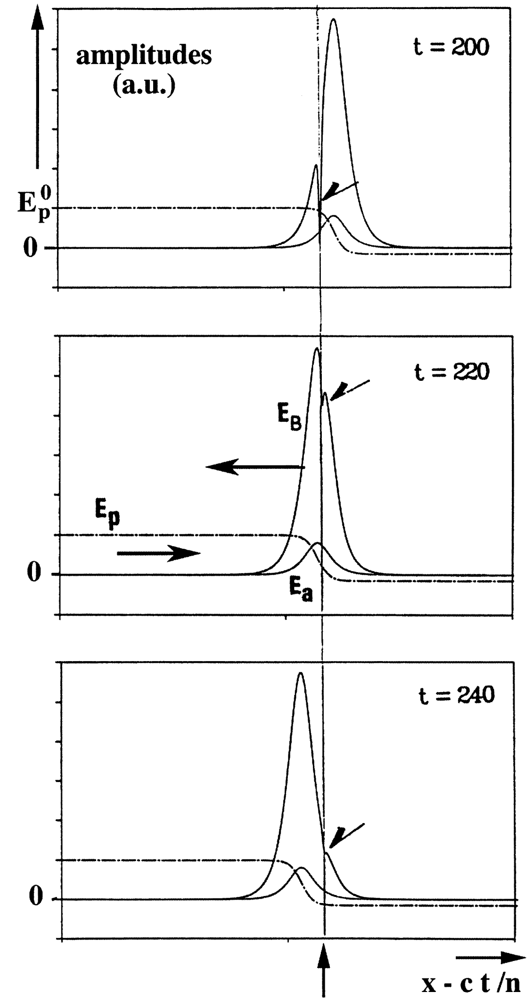

Fig. 2. Spatial distribution of the amplitudes in the three-wave solitary SBS structure in a semi-infinite medium: pump (E_p), Brillouin (E_B), and acoustic (E_a). Additional information superimposed over a superluminous Brillouin solitary wave travels at luminal velocity (i.e., stationary in this travelling frame) and thus drifts toward the pulse's tail. Note the stability of the structure against a strong indentation and its progressive elimination (numerical).

This exact but nonlocal compensation yields a global drift of the structure whose shape remains globally unchanged, or rather endures a constant self-similar deformation. For vanishingly small losses, it can be shown analytically that these structures are actual solitons, in the sense of the inverse scattering transform [20].

The group and signal velocities of these asymptotically stable solitary waves are thus identical and superluminous [7]. Moreover, they are obviously the same everywhere in the structure, including its far leading edge where the Brillouin and acoustic intensities are small enough for the pump to remain essentially undepleted and the interaction linear. The asymptotic Kolmogorov–Petrovskii–Piskunov (KPP) method [21] can thus be implemented to determine the velocity of the whole structure, which depends only on its exponential slope. The softer the leading edge, the wider and the faster the structure [15]. Narrow enough structures even present subluminous behaviors [10], [16].

Note that the backward propagating invariant three-wave structure is actually composed of three components, namely the Brillouin pulse, the associated acoustic pulse, and a pump kink, traveling together with the velocity $v = (1+\epsilon)c/n_{\mathrm{eff}}$, where the effective index is $n_{\mathrm{eff}} \approx 1.46$. Arbitrarily high velocities can be obtained in the ideal dissipationless case as well as for specific relative damping values for the Brillouin (γ_e) and acoustic (γ_a) waves (namely, $\varepsilon = (1-\gamma_e/\gamma_a)^{-1}$ [7], [15]) and for other interaction geometries. With the actual gain and damping parameters of our backscattering experiment, the group and signal velocity of the Brillouin wave packet will thus be $v_B = v = (1+\varepsilon)c/n_{\mathrm{eff}}$, and $|\varepsilon| < 0.3$. The velocity of the acoustic wave packet will be the same, or $v_a = v \approx 3.10^5\ c_a (c_a$ being the linear velocity of sound in silica, or 5960 m/s), and the velocity of the pump wave kink $v_p = -(1+\varepsilon)c/n_{\mathrm{eff}}$.

Energy transport velocities can be defined independently for each wave. It would then be identical to the signal velocity for the Brillouin and acoustic waves; on the other hand, the pump energy is classically transported with a velocity $+c/n_{\mathrm{eff}}$ (thus a difference $(2+\varepsilon)\ c/n_{\mathrm{eff}}$ between signal and energy transport velocities). Yet, these definitions make little sense. The overall process is essentially an energy *transfer* between waves and, as far as the losses can be neglected, the three-wave structure transports no energy but merely localizes it.

According to their quasisolitonic nature, these structures are very stable against very strong phase or amplitude perturbations, as shown in Fig. 2. Thus, since the solution at a later time is not determined by the initial data, they transport *no information* over long distances [22]. For an ideal solitary structure, the only stable information ("here comes the structure") is already present through its infinite wings everywhere in the propagation medium at any time before the arrival of the Brillouin peak. Any additional information will propagate at luminous velocities, drift toward the trailing edge of the structure where it will be killed by the losses, uncompensated there by the strongly depleted pump; if superimposed on the leading edge, it would be erased even more rapidly during its crossing of the main pulse.

No front, hence no front velocity, can be defined for these ideal semi-infinite structures. In this noiseless limit, one can arbitrarily create one by setting both Brillouin and acoustic intensities to zero outside a finite support far from the body of a superluminous structure. This "envelope front" would then propagate with a velocity c/n_{eff}; an initially superluminous structure would thus slow down through some complex transients while it drifts toward this discontinuity [23] and then, for a finite acoustic damping, evolve toward a subluminous attractor [16].

A more realistic approach takes into account the thermal acoustic noise. The effective front of the structure can then be defined as the locus where the exponentially decreasing leading edge of the solitary wave falls below the noise level associated to the amplified spontaneous scattering of the undepleted pump wave. The Brillouin dynamics of this region is quite complicated [24], and it becomes very difficult to distinguish the actual signal from the noise [25]. The effective front velocity is nevertheless identical to the signal velocity of the whole structure, thus eventually superluminous, since the nonlinear phase self-cleaning process discussed above [7] locks the phase structure around the high intensity region, the coherent superluminous pulse thus appearing to continuously "push" away the noise it encounters (*cf. infra*, Fig. 3).

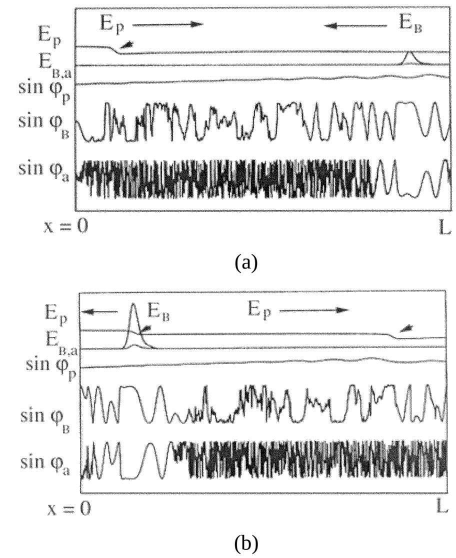

Fig. 3. Spatial distribution inside the Brillouin fiber ring at two different times in presence of strong acoustic noise. Note the phase locking around the high intensity region, the superluminous solitary structure being thus almost insensitive to the amplification of the noise, and its front clearly defined (numerical).

More generally, since the nonlinear self-similar three-wave reshaping process allows neither the transport of information at superluminous velocity, nor of energy, it has very little direct application. It is, nevertheless, of key importance in the stability of the propagation, the robustness of a superluminous, soliton-like structure being considerably increased against any perturbation in the highly nonlinear regimes considered here. For instance, a stable superluminous structure can emerge and escape from a luminal instability that would otherwise yield to chaos when both strong optical Kerr effect and strong group velocity dispersion are involved (as in the stimulated Raman backscattering, a three-wave interaction formally equivalent to SBS but with much lower efficiency and characteristic time [26]).

III. Solitary Structures in a Low-Finesse Brillouin Fiber Ring Laser

Most of the features discussed above can be observed experimentally, *mutatis mutandis,* in Brillouin fiber ring lasers. This class of SBS devices presents a very rich nonlinear dynamics, including periodic [Fig. 1(a)], quasiperiodic, chaotic, or bistable regimes, *etc.,* often attained after very long transients [Fig. 1(c)], in very good qualitative and quantitative predictions of the coherent three-wave model (cf. [11] and references therein).

For long enough ($L > 20$ m) single-mode fiber cavities, the SBS mirror (ultracoherent cw Brillouin laser [19]) is obtained for high finesse and the pulsed quasisolitonic superluminous regime for low finesse cavities [7], following a regular Hopf bifurcation whose control parameter is either the launched pump power I_{cw} or the Brillouin feedback

$R[I_B(L,t) = RI_B(0,t); I_p(0,t) = I_{\rm cw}]$ [27]. The corresponding "free space" soliton is then defined by an effective optical damping taking into account the reinjection losses, or $\gamma_e^{\rm eff} = (\gamma_e - c/2_{n_{\rm eff}} L \ln R)$ [15]. Hereafter, all parameters are taken from the experiment described in [11], namely $L = 80$ m and $I_{\rm cw} = 100$ mW (launched).

The problem of the signal-to-amplified spontaneous noise ratio remains in this cavity configuration, still governed by nonlinear phase self-cleaning process allowing a sound definition of a front "pushed" by the structure at a front velocity equal to the signal velocity (rather than the group velocity when they are distinct, since this mechanism depends on the structure wing slope, which determines the signal width, rather than by the structure peak power or overall energy), as shown in Fig. 3.

An important feature of low-finesse cw-pumped SBS soliton ring lasers is that the nonlinear flight time $T_{\rm flight}$ of the Brillouin pulse is a free parameter. In absence of any special constraint, the device selects the *average* group and signal velocity (still identical for stables pulses) which maximizes the pulse energy [11]. But it can also self-adapt to optimize its stability against external perturbations, such as an interaction with low-frequency radial acoustic waves (namely, cladding Brillouin scattering) corresponding to the mechanical vibration modes of the whole fiber structure. The solitary structure accelerates (respectively, decelerates) when confronted to a periodic perturbation of frequency slightly above (respectively, below) the closest multiple of the linear cavity free spectral range $n_{\rm eff}L/c$, in order to find the fiber in the same vibrational state from roundtrip to roundtrip. Since the signal velocity of a pulse is still related to the slope of its front edge, thus its duration, we have observed strong pulse compression and dilatation (from 18 to 75 ns, for a "bare" duration around 30 ns) during this self-velocity-adaptation process [10].

Only these average group velocities are accessible to direct measurement, yielding $T_{\rm flight} < T_{\rm linear} = c/n_{\rm eff}L$. While they remain fairly close to those theoretically obtained in semi-infinite media for pulse of the same shape and duration (the strong reinjection cutdown being described as "distributed losses"), the actual dynamics within the fiber resonator is much more complicated.

The Brillouin pulse injected at the far end of the fiber (left-side of Fig. 3) is homothetic to the output pulse, but with a severe energy cutdown (by a factor 1-R, or 97%) ; moreover, no conjugate acoustic pulse is reinjected. It is thus very far from the asymptotic solitary structure, and: (a) meets a pump already depleted by its interaction with the pulse (during the previous roundtrip; cf. Fig. 3, top); its width, thus its signal velocity, are almost constant (Fig. 4), while its peak power slowly increases, yielding a decrease in group velocity; (b) near the middle of the cavity, the Brillouin pulse meets the pump kink created when it left the cavity at the end of the previous roundtrip; this brief "collision" has little effect on the pulse widht and height, but corresponds to a very evolutive state characterized by a bump on both signal and group velocities; (c) then interacts with a "fresh," weakly depleted pump, yielding a much more efficient amplification and an increase in group velocity; and (d) finally meets a truly undepleted (or "unprepared") pump which has never interacted with its front wing, already out of the cavity; again, this short interaction has little effect on the pulse itself, but corresponds to a huge increase in group velocity it $(v_g > c)$, with a major effect on the average group velocity.

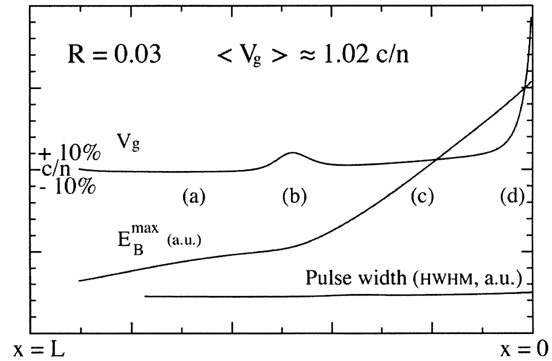

Fig. 4. Spatial evolution of the group velocity, Maximum amplitude, and (almost constant) width of a Brillouin pulse during its backward propagation in a stable, low-feedback, high-gain SBS soliton laser. A slightly subluminous period of slow amplification: (a) is followed by stronger energy transfers in the second half of the fiber, where the pulse meets an undepleted pump. The slightly superluminous average velocity is governed by the unstable regions (b) and (d) (numerical).

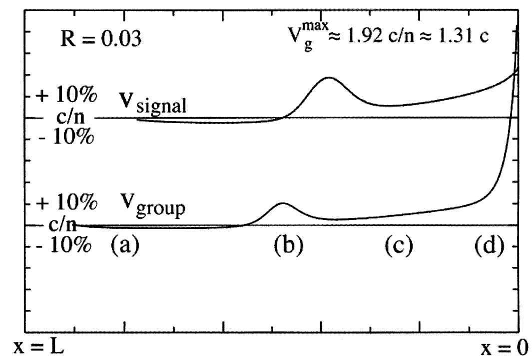

Fig. 5. Same as Fig. 4 $(R = 0.03)$. Dynamical evolution of the group and signal velocities during one propagation cycle inside the fiber (numerical).

The group and signal velocities are almost equal during phases (a) and (c), which correspond to stable propagation regimes, with some amplification but no reshaping. They strongly differ in phases (b) and (d) (Fig. 5), where some major reshaping occurs while the pulse self-adapts to fit a pump step (b) or to meet the fiber boundary. It is interesting to note that, while average group and signal velocities are by definition equal in a stable soliton laser, they present very different dynamics and can locally reach very high values.

Such rapid variations in the group and signal velocities are a fair indicator that the pulse, while globally stable, is subject to major destabilizing factors, overcome by nonlinear self-reshaping. The device depicted in Figs. 4 and 5 operates very close to the SBS laser critical feedback $R_{\rm crit} \approx 0.032$, thus to the bifurcation toward a cw regime [26]. Operation parameters deeper in the stable "solitonic" region yield smoother velocity dynamics (Fig. 6).

IV. Conclusion

The concept of nonlinear pulse reshaping is very general in the context of interactions between matter and light. Stimulated

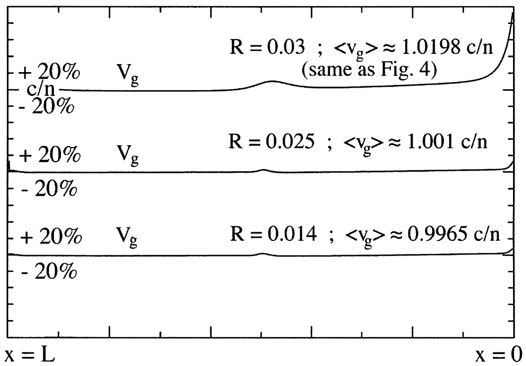

Fig. 6. Dynamical variations of the group velocity for three stable pulsed SBS lasers with different feedbacks values R. Close to the critical feedback (top, $R = 0.3$), the pulse exhibits strong self-reshaping, which is mostly avoided farther from the bifurcation (numerical).

Brillouin scattering is archetypal of a wide class of three-wave interactions which admit soliton-like sub- and superluminous solutions, including the material wave and also stimulated Raman scattering [25] and parametric interaction in quadratic nonlinear media [28]. It would be intriguing to explore the associated "nontraditional forms of matter" nonlinearly coupled to superluminous light structures at the quantum wavefunction level [29], [30]. It can also be noted that nonlinear reshaping of solitonic nature may occur in the frequency space [31].

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