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Brillouin solitons and enhanced mirror in the presence of acoustic dispersion in a small-core photonic crystal fiber

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Abstract: Stimulated Brillouin scattering (SBS) of visible light in a small-core photonic crystal fiber (PCF) resonator of small external Q-factor, experimentally presents trains of subluminescent and superluminescent pulses presenting all the characteristics of dissipative Brillouin solitons. Insertion of the acoustic dispersion, which may be significant in PCF, in the coherent SBS three-wave model modifies the dissipative structures. For special pump wavelengths the acoustic dispersion response may be particularly strong and may lead to an enhanced Brillouin mirror.

keywords Stimulated Brillouin scattering, photonic crystal fibers, acoustic dispersion

1 Introduction

The low stimulated Brillouin threshold in small-core photonic crystal fibers (PCF) [1] allows to envisage numerous applications in amplifiers, sensors and even Brillouin lasers. Well established in standard optical fibers [2]-[7], the spatio-temporal dynamics of Brillouin lasers in PCF is up to now less studied. An important characteristic of such PC fibers is the great variety of acoustic modes which can interact with the light [8]. They are henceforth experimentally and theoretically well defined [9, 10, 11], and it is known that they may induce a modulation instability in PCF lasers [12] [13]. Another characteristic of such acoustic modes, namely their group velocity dispersion, has not been the object of special consideration. The acoustic modes may contain pure longitudinal, transverse and torsional components, but there are the longitudinal components which prevail in the stimulated Brillouin mechanism through electrostriction.

The object of this article is to experimentally show, on the one hand, that in a configuration where only one acoustic mode is concerned, the dynamics of Brillouin lasers in PCF is similar to that of Brillouin lasers in traditional fibers. On the other hand, insertion of acoustic dispersion in the coherent three-wave SBS model [14, 5] may modify the characteristics of such components.

Thresholds of five times higher than theoretical predictions have been observed in the infrared region [9, 10, 11]. We have shown for a continuous source that the Brillouin threshold decreases until the level of standard fibers for a $\lambda_p = 532$ nm source linearly polarized, rendering SBS interesting in PCF [1].

2 Experimental results

The experimental setup is shown in Fig. 1.

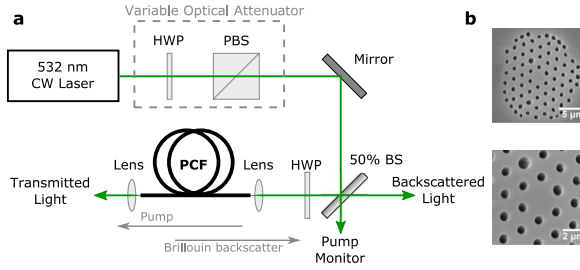


Figure 1: (a) Setup: HWP, half-wave plate; (P)BS, (polarizing) beam splitter. (b) SEM images of PCF microstructured at different magnifications.

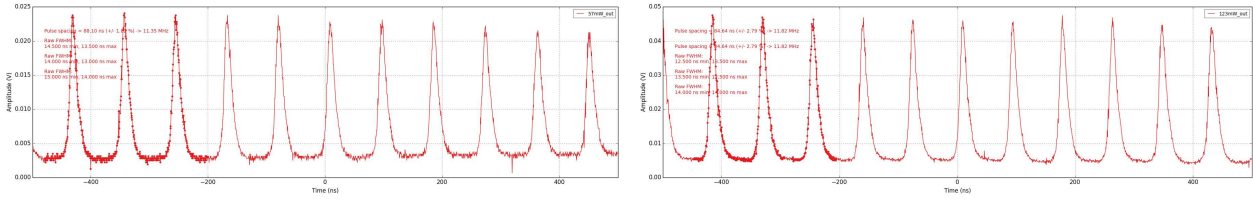


Figure 2: With a cw-pump at 532 nm the temporal backscattered Brillouin response is composed by a train of Brillouin soliton pulses **subluminous on the left hand** side of repetition frequency $f_r = 11.35$ MHz, and temporal spacing $\Delta t_r = 88.10$ ns, with a pump power of $P_p = 152$ mW, and **superluminous on the right hand** side with respectively $f_r = 11.82$ MHz, $\Delta t_r = 84.64$ ns and $P_p = 212$ mW. The periodicity correspond to the go and back trip in the PCF with group velocities slowly subluminous or superluminous. The time pulse width (FWHM) is 14.5 ± 1.4 ns. After ends cleavage, the length of the PCF is reduced to nearly 9 m.

The fiber has a core diameter of $d_c = 3.0 \mu\text{m}$, air-hole pitch $\Lambda = 1.9 \mu\text{m}$, and hole diameter $d = 0.7 \mu\text{m}$, inducing at 532 nm an effective section of $4.73 \mu\text{m}^2$, comparable to the traditional fibers. The Brillouin spectrum is symmetric with a width less than 50 MHz (interferometric resolution). The same fiber presents at 1550 nm an asymmetrical spectrum and a ten times higher threshold [1]. The experimental setup is shown in Fig.1. The cw-pump is issued from a double frequency Ytterbium laser of linear polarization and 15 MHz bandwidth. The fiber is cleaved at the ends in order to provide 4% reflexion at each extremity, reducing the Brillouin threshold to about 130 mW for a 9 m length. We refer to Ref.[1] for more details and spectral recording. Here we are interested in the backscattered temporal dynamics shown in Fig.2.

3 Dissipatif solitons in the PCF laser: acoustic dispersion effect

The trains of subluminous and superluminous pulses experimentally observed present all the characteristics of the dissipatif Brillouin solitons. Their study has been realized in a classical optical fiber ring cavity: generation of dissipative Brillouin solitons [2], morphogenesis, stability and bifurcation diagram [3], self-structuration and asymptotic physical interpretation [4, 6], optical bistability and general classification in the (gain G - feedback R) plane [5], and in a polarization preserving fiber ring cavity [7].

We propose to describe these scenarii in the PCF cavity by using the same coherent three-wave model equations, including optical Kerr effect, which govern the time-space evolution of the complex (pump, Brillouin and acoustic) field amplitudes E_j ($\mathbf{j}=\mathbf{p},\mathbf{s},\mathbf{a}$) [14, 5, 7], by taking into account the fiber modal profile [15]. and for the first time the acoustic group velocity dispersion which may play

a special role in the PCF. The evolution equations for the pump E_p , Brillouin E_b and acoustic E_a envelopes read:

$$\begin{aligned} (\partial_t + v_p \partial_x + \gamma_p) \mathbf{E}_p &= -K_{\text{SBS}} \mathbf{E}_s \mathbf{E}_a + iK_K [|\mathbf{E}_p|^2 + 2|\mathbf{E}_s|^2] \mathbf{E}_p \\ (\partial_t - v_s \partial_x + \gamma_s) \mathbf{E}_s &= K_{\text{SBS}} \mathbf{E}_p \mathbf{E}_a^* + iK_K [2|\mathbf{E}_p|^2 + |\mathbf{E}_s|^2] \mathbf{E}_p \\ \left(\partial_t + v_a \partial_x + i\tilde{\beta}_a \partial_{tt} + \gamma_a \right) \mathbf{E}_a &= K_{\text{SBS}} \mathbf{E}_p \mathbf{E}_s^* \end{aligned}$$

where γ_j ($j = p, s, a$) are the respective damping coefficients, $K_{\text{SBS}} = \sigma [\epsilon_0 c n^7 / (8 \rho_0 c_a)]^{1/2} \omega_p p_{12}$ the Brillouin coupling coefficient, $p_{12} = (\rho_0 / n^4) (\partial \epsilon / \partial \rho) = 0.286$ the silica elasto-optic coefficient, and $K_K = n_2 \omega / (2n)$ the nonlinear Kerr coefficient. The acoustic group velocity dispersion coefficient $\tilde{\beta}_a = v_a (d^2 k_a / d\omega_a^2)$ should be experimentally determined. In a first time we introduce it through an arbitrary dimensionless parameter $\beta_a = \tilde{\beta}_a K_{\text{SBS}} E_{\text{cw}} / 2 = 0.01$. Figures 3 show two couples of Brillouin solitons. The left hand side figure stands for the standard dispersionless fiber and the right hand side couple for the PCF which the perturbative dispersion value $\beta_a = 0.01$. We remark that this perturbative value is sufficient to introduce a pulse velocity variation of about 2%, an amplification of 5%, and a pulse compression of 15% (right hand side Fig.3), which is comparable to the transverse cladding Brillouin scattering effect [16].

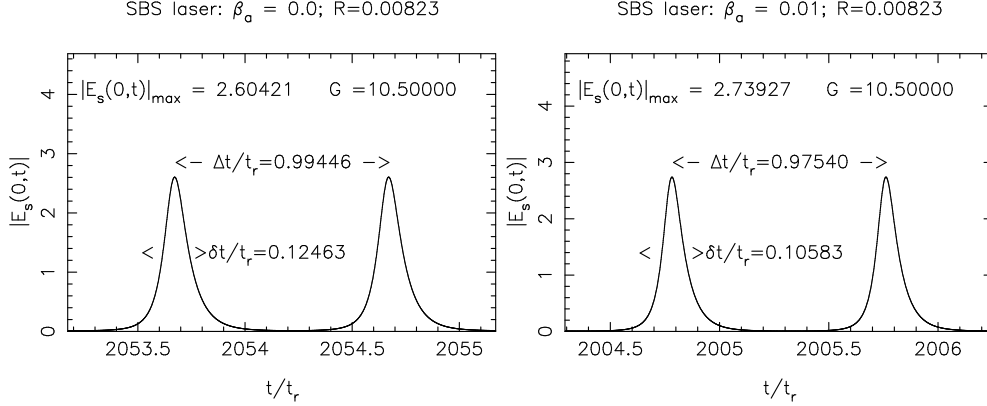


Figure 3: Pairs of consecutive superluminescent Brillouin solitons in the cavity of round trip time $t_r = 2nL/c = 87.3$ ns: on the left hand side for the standard fiber ($\beta = 0$), and on the right hand side for the PCF cavity ($\beta = 0.01$). The Brillouin gain is $G = g_0 I_p L = 10.5$ and the reflexion feedback at the end of the cavity $R = 0.00823$. The amplitudes are normalized to the pump amplitude at the entry of the cavity $E_p(0) = E_{\text{cw}}$

4 Enhanced Brillouin mirror

The group velocity dispersion may become very important at the transition frequencies between surface and volume acoustic modes [8] [12]. In this case it is convenient to formulate the acoustic equation like that used in plasma physics [17], namely

$$\left[(1 + 2i\mu_a \alpha) \partial_t + \varepsilon \partial_x + i\tilde{\beta}_a (\partial_{tt} - \varepsilon^2 \partial_{xx}) + \gamma_a \right] \mathbf{E}_a = K_{\text{SBS}} \mathbf{E}_p \mathbf{E}_s^*$$

where $\varepsilon = c_a / c$, $\mu = \gamma_a / \tau_0 = \gamma_a / K_{\text{SBS}} \mathbf{E}_p(0)$, and $\alpha = 1 / (2\omega_a \tau_0)$. The pulsation regimes are transient and with a cw-pump we numerically obtain asymptotic regimes of a **new** enhanced Brillouin mirror with the acoustic amplitude increasing in the pump direction as show Figures 4.

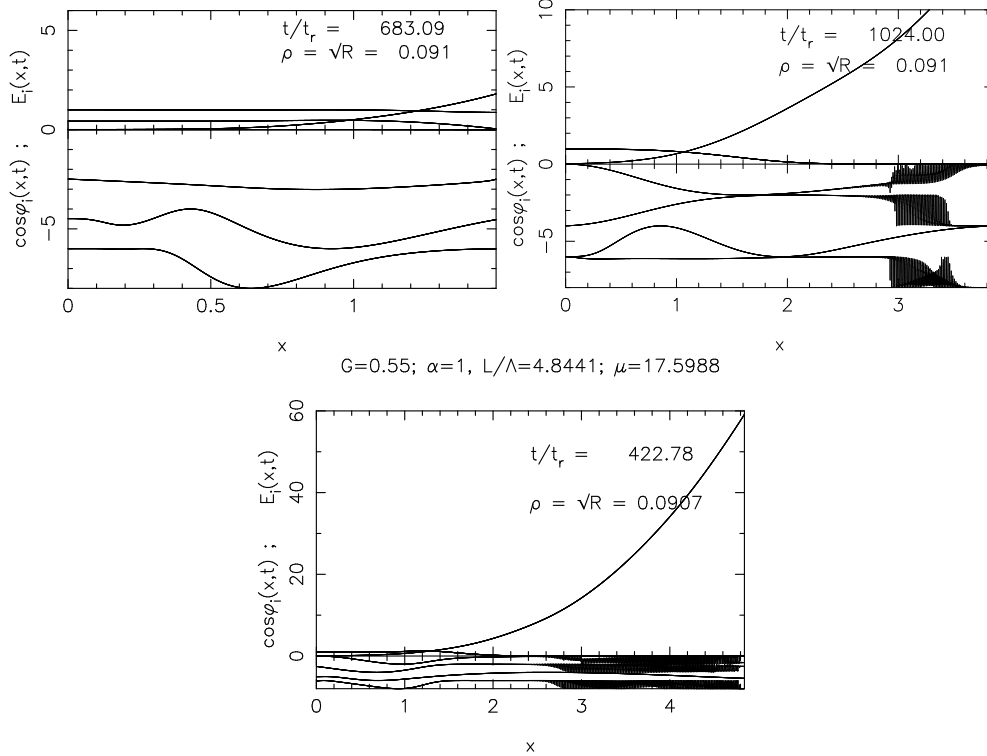


Figure 4: Spatial amplitude distributions for the enhanced Brillouin mirror generated through high acoustic dispersion in the PCF. Gain G and feedback R parameters included in the figures. The amplitudes are normalized to the pump amplitude at the entry of the cavity $E_p(0) = E_{cw}$.

5 Conclusion

The PCF Brillouin lasers are capable to show the same rich scenario of the three-wave Brillouin dynamics in a standard fiber laser. A complementary study is necessary to precise the acoustic parameters. It is possible that for particular pump wavelengths the acoustic dispersion present so high values that the regime studied in plasma physics [17] should be pertinent. It leads to an enhanced Brillouin mirror.

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