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Polarization instabilities and antiphase dynamics in a Brillouin fiber ring laser

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The usual configuration of the Brillouin fiber ring laser is slightly modified to investigate the influence of polarization effects on the system dynamics. Experiments reveal behaviors that drastically contrast with those observed when the polarization of the light remains linear. The Stokes emission may exhibit periodic and quasiperiodic instabilities with an antiphase phenomenon involving two polarization eigendirections. The frequency detuning between the Stokes wave and the cavity resonances seems to play a key role in the system dynamics. [S1050-2947(97)51109-7]

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The discussion concerning the dynamics of stimulated Brillouin scattering (SBS) in optical fibers now deals with two main topics: (i) the study of SBS in the presence of weak external feedback, and (ii) the study of the behavior of Brillouin fiber ring lasers. In the first case the feedback simply arises from Fresnel reflections at the fiber ends. In the second case the fiber is inserted in a ring resonator, which allows us to reach larger feedbacks [1–3]. In both cases a large variety of dynamical features has been reported. In the presence of weak feedback, experimental investigations have been performed with polarization preserving and polarization scrambled fibers [4–7]. They have revealed the Stokes emission to exhibit deterministic dynamics with periodic, quasiperiodic, and chaotic instabilities. On the contrary, studies related to the dynamical behavior of Brillouin ring lasers are almost always performed with polarization maintaining fibers [8–10]. This avoids random changes in the state of polarization of the beams and allows the authors to consider that the light remains confined to a well-defined fiber mode. The comparison between theory and experiment is then possible within the framework of the now well-established three-wave SBS model, which assumes that both the Stokes and the pump waves remain linearly polarized.

The aim of this paper is to present experimental results concerning the behavior of a Brillouin fiber ring laser when additional degrees of freedom due to the polarization of the fields are able to alter its dynamics. Even if it is commonly admitted that the Brillouin gain is a factor of 2 higher when linear polarization is maintained [11], one can consider that polarization effects have not yet been extensively studied in Brillouin fiber ring lasers [12]. In particular and unlike several other lasers [13–18], the aspects related to the system dynamics remain largely unexplored when the polarization of the light beams no longer remains linear.

In order to investigate how the degrees of freedom associated with polarization may influence the laser dynamics, we have slightly modified the experimental setup commonly used. This has allowed us to carry out polarization-resolved experiments in which the laser intensities along two polarization eigendirections are simultaneously monitored. Before detailing these modifications and their consequences on the system dynamics, let us briefly recall the main characteristics and behaviors of the ''usual'' Brillouin ring laser. This will then permit us to directly and easily compare the situations in which polarization remains linear to those in which the state of polarization is scrambled.

Our experimental setup is schematically shown in Fig. 1(a). It is basically analogous to Brillouin fiber ring lasers previously studied in the literature [19–21]. The pump laser is a titanium-sapphire laser operating at 800 nm. It emits a linearly polarized beam characterized by a 500-kHz linewidth. Its frequency can be linearly swept over a range adjustable from 10 MHz to 30 GHz. The pump laser is optically isolated from the Brillouin laser by a Faraday isolator and the incident pump power can be controlled by an acousto-optic modulator (AOM). Input and output fiber coupling are achieved through 20×microscope objectives, the maximum power injected being typically in the range 100–150 mW. The bow-tie polarization preserving fiber has a cutoff wavelength of 630 nm for monomode propagation and is cabled in order to limit environmental perturbations. The input end of this fiber is adjusted so that the direction of polarization of the pump beam coincides with one of the main axis (i.e., the fast or the slow axis) of the fiber. The light beam then maintains its polarization all along the fiber. Finally the output end is rotated so that the direction of po-

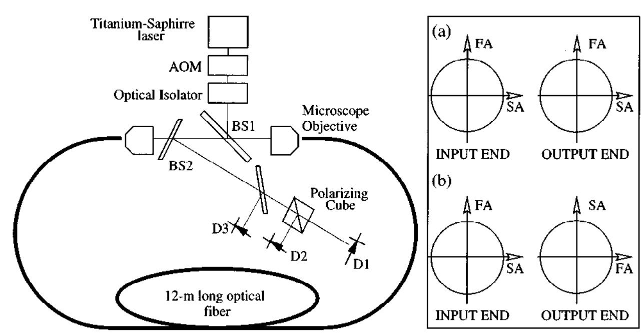

FIG. 1. Schematic representation of the experimental arrangement and of the corresponding fiber orientations. FA and SA stand for fast and slow axes, respectively. In case (a) of the ''usual'' setup, the detection part only consists of one detector recording the total Stokes power. In case (b) of the modified setup, the detectors D1 and D2 allow a polarization-resolved analysis, while photodiode D3 records the evolution of the total Stokes power.

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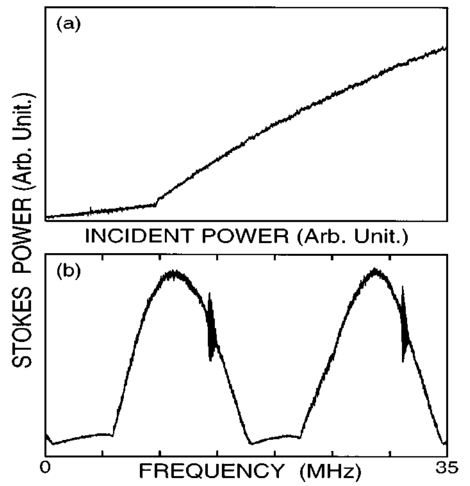

FIG. 2. ''Usual'' Brillouin fiber ring laser. Experimental Stokes signal recorded while slowly sweeping (a) the incident pump power and (b) the frequency of the pump laser. The acquisition time is about 0.01 s in each case.

larization at the output end becomes parallel to the direction of polarization at the input end. One has thus constructed a ring resonator in which the light always remains linearly polarized. The optical fiber being 12 m long, the free spectral range (FSR) of the ring cavity is 17 MHz. This value is comparable to the width of the Brillouin gain curve (60 MHz full width at half maximum at 800 nm) and only a few modes can thus experience gain. As already discussed in Refs. [8] and [9], these conditions lead to a Stokes emission that always remains stable and monomode as the input pump power increases [see Fig. 2(a)]. If the frequency of the pump laser is slowly swept, the stability of the Stokes emission is only affected during mode hops that appear with a periodicity equal to the cavity FSR [see Fig. 2(b); full explanations are given in Ref. [8]].

To observe polarization effects, we have rotated by 90° the output end of the fiber so that the fast axis at the input end is now parallel to the slow axis at the output end [see Fig. 1(b)]. It follows that the polarizations of the pump and of the Stokes waves no longer remain linear and the detection part has accordingly been modified in order to permit a polarization-resolved analysis. The two orthogonal polarization directions are separated by a polarizing cube, the power of the Stokes wave along the fast and slow axes, being monitored, respectively, by detectors D1 and D2. Another detector (D3) is used to record the evolution of the total Stokes power. These detectors are silicium photodiodes that have a 200-MHz frequency bandwidth and are connected to a 125-MHz oscilloscope. Let us emphasize that the reflectivity of the first beam splitter (BS1) is polarization dependent, whereas the reflectivity of the second one (BS2) is low (4%) and polarization independent. Otherwise, we estimate that about 10% of the pump power emerging from the output end of the fiber is recoupled at the input end. Because of unavoidable drifts, this value can increase to about 15%, but whatever the situation may be, the pump depletion is never negligible.

As already performed in the case of Fig. 2(a), an overview of the dynamics of our modified Brillouin laser can first be

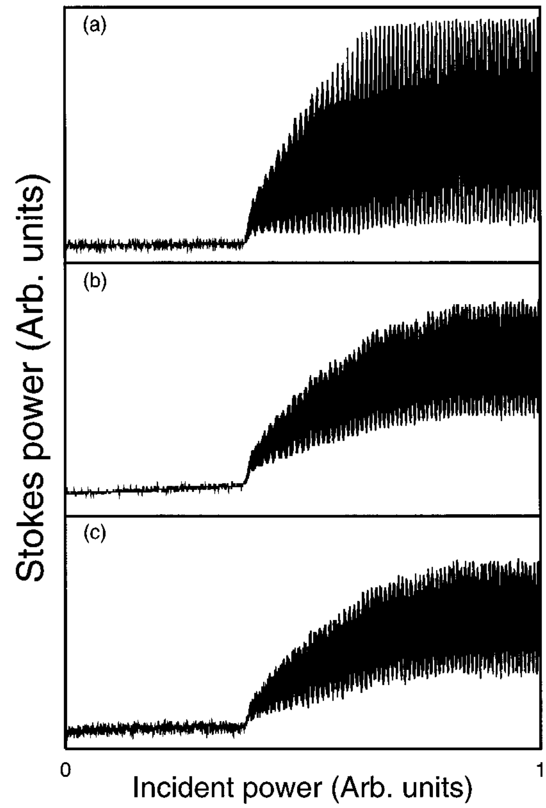

FIG. 3. Modified Brillouin fiber ring laser. Experimental Stokes signals recorded while slowly sweeping the incident pump power: (a) total Stokes power (detector D3), (b) Stokes power along the fast axis (detector D1), and (c) Stokes power along the slow axis (detector D2)

obtained by slowly sweeping the input power with the AOM. As shown in Fig. 3, the system behavior drastically contrasts with the behavior previously observed. The total Stokes power is now strongly unstable, the modulation depth associated with the appearance of the instabilities being nearly 100% whatever the incident pump power may be [Fig. 3(a)]. This destabilization of the total Stokes power is obviously accompanied by a simultaneous destabilization of the Stokes powers detected along the two orthogonal polarization directions [Figs. 3(b) and 3(c)]. As depicted in Fig. 3, the instabilities appear just above the laser threshold but one should mention that, depending on the experimental conditions, this is not always the case. As in Fig. 2(a), it is thus possible to record very stable Stokes emissions or to observe a destabilization of the Stokes emission well above the laser threshold. However, the two last features can be easily interpreted if we now consider the results of an experiment in which the frequency of the pump laser is swept.

The experimentally observed variable being the total Stokes power, unavoidable environmental perturbations (i.e., mainly fluctuations in the coupled power, the reinjection rate and the optical length of the cavity) lead to the observation of three characteristic situations when the frequency of the pump laser is swept over two cavity FSR's (Fig. 4). Before discussing these behaviors, let us explain why twice as many resonances (i.e., twice as many frequencies of the pump laser for which the Stokes power is maximum) appear in the now-studied laser than in the usual one [Fig. 2(b)]. This can be

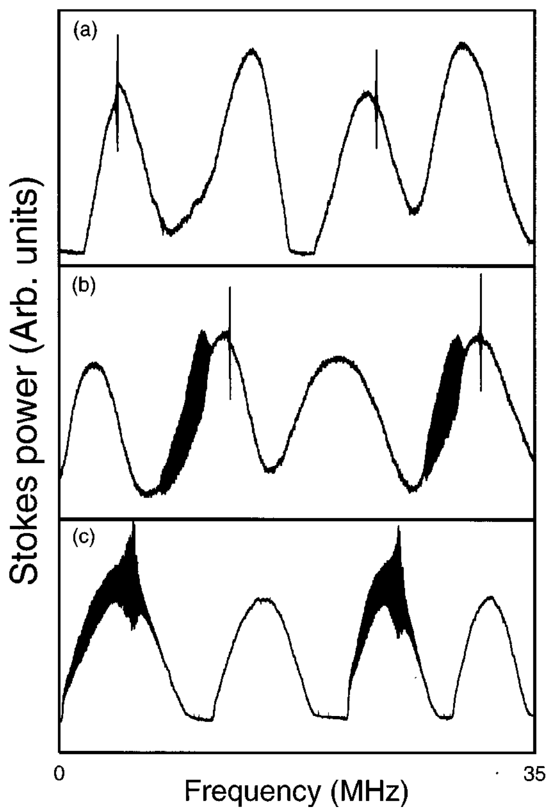

FIG. 4. Modified Brillouin fiber ring laser. Three typical recordings showing the evolution of the total Stokes power (detector D3) while slowly sweeping the frequency of the pump laser.

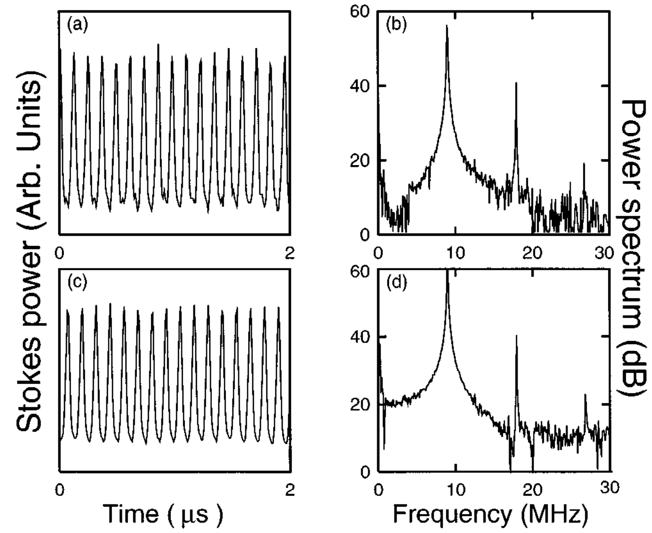

FIG. 5. Periodic instabilities of the Stokes power and associated power spectra: (a),(b) detector D1; (c),(d) detector D2.

easily understood if one considers that the linearly polarized pump field now covers not one round-trip but two round-trips (one along the fast axis and the other one along the slow axis) inside the cavity in order to replicate itself. Variations of the intracavity pump field with the laser frequency are obviously accompanied by analogous variations of the Stokes power and lead to the global behavior evidenced in Fig. 4. The fact that the amplitude of two consecutive peaks is not constant [see in particular Figs. 4(a) and 4(b)] comes from the anisotropy of the resonator losses and from a slight difference in the parallelism of the main axis of the fiber. Even though the mode hops are sometimes lost in other instabilities (Fig. 4), they always appear periodically spaced with a period of 17 MHz, the FSR of the usual system. The position of the mode hop obviously depends on experimental conditions (i.e., mainly the laser frequency and the cavity length) and it can be completely different from one recording to another. For instance, the mode hops are at the top of the big peaks in Fig. 4(b) but at the top of the small peaks in Fig. 4(a). As in the usual system [see Fig. 2(b) and Ref. [8]], the instabilities associated with the mode hops are due to a mode beating arising at a frequency of 17 MHz. This means that, for the Stokes wave, the modal structure of the resonator remains unchanged by the modification we have introduced in the Brillouin laser. The polarization state of the Stokes wave then replicates at each cavity round-trip but, unlike the usual laser, does not remain linear.

The signal shown in Fig. 4(a) has been recorded in conditions of relatively low feedback and incident pump power. Apart from the instability linked to mode hops, it is therefore devoid of any other kind of instabilities. However, a new type of instability appears at high enough feedbacks and pumping levels. Before detailing their nature, let us note that they always appear on the peak on which the mode hop occurs. This clearly indicates that the frequency detuning between the Stokes wave and the cavity resonances plays an important role in the system dynamics. Depending on the experimental conditions, the instability range appearing when the pump frequency is swept can be obviously more or less important. All this information being given, one can now understand why either stable or unstable behaviors can be recorded when the incident pump power is swept. During this sweeping the frequency detuning between the pump laser and the cavity resonances is arbitrary and the Stokes frequency can then be located at any point inside the ranges presented on Fig. 4. When the incident pump power is increased one can then observe various situations.

Both the incident power and the frequency of the pump laser being now held constant, we are going to consider the nature of the instabilities evidenced in Figs. 4(b) and 4(c). Slight drifts in the experimental parameters lead to the observation of periodic and quasiperiodic oscillations, which are simultaneously recorded by the detectors D1 and D2. The fundamental frequency of the periodic instabilities (Fig. 5) is approximatively equal to half the FSR of the usual laser: 8 MHz. The signals simultaneously recorded [Figs. 5(a) and 5(c)] clearly show antiphase dynamics between the two orthogonal polarizations. This feature has already been observed in other kinds of lasers and in particular in multimode lasers [13–15]. It could indicate the coexistence of two coupled laser systems presenting a strong competition effect. The fact that the fundamental frequency of the instabilities is around 8 MHz shows that they are correlated to a phenomenon involving a double round-trip of the light inside the cavity. So, they do not arise from a mode beating but from another physical reason, the origin of which is difficult to extract from the experimental data. A theoretical investigation aiming to model our system will probably be necessary to understand the physical mechanisms giving rise to such a

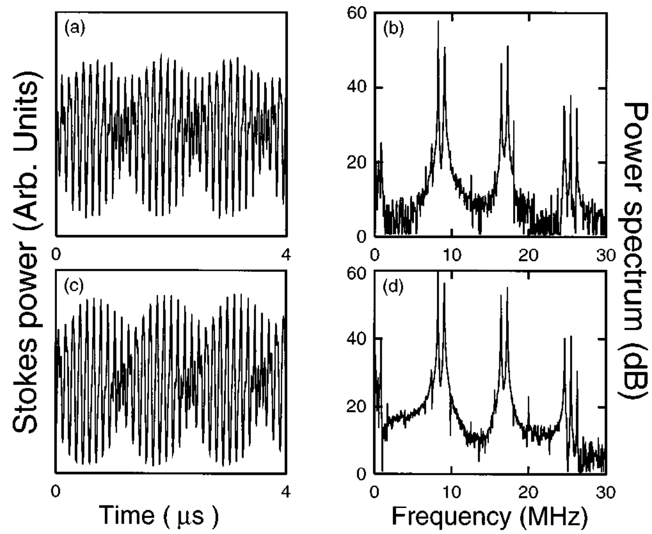

FIG. 6. Quasiperiodic instabilities of the Stokes power and associated power spectra: (a),(b) detector D1; (c),(d) detector D2.

frequency. However, if we consider that it can be a relaxation frequency of the laser [19], its appearance is not so surprising, since this frequency is preferably exited in lasers exhibiting the antiphase phenomenon [13]. The quasiperiodic oscillations (Fig. 6) appear in a very particular situation. They can be recorded when a mode hop superimposes itself on the periodic instabilities, as in Fig. 4(c). The amplitude of the 8-MHz signal is then slowly modulated by a low-frequency envelop [Figs. 6(a) and 6(c)] arising from a beating associated with the superposition of the two unstable signals. Let us note that, as in the case of periodic oscillations, one can observe an antiphase motion between the two orthogonal polarization directions.

In summary, we have slightly modified the configuration of the usual Brillouin fiber ring laser in order to investigate how the degrees of freedom associated with polarization may influence its dynamics. Polarization-resolved experiments have revealed the existence of antiphase dynamics between the two orthogonal polarization directions, a feature already observed in several kinds of lasers. Moreover, our experiments have pointed out the importance of the frequency detuning between the Stokes wave and the cavity resonances. The influence of this parameter will have to be taken into account in further theoretical works aiming to extend the three-wave SBS model by including polarization effects. Obviously other studies will have to be undertaken to supplement the present one. To that effect, we are now testing other experimental configurations with different orientations of the fiber ends and different birefringences.

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