# Evidence of Chaotic Stimulated Brillouin Scattering in Optical Fibers

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We report first evidence in support of chaotic stimulated Brillouin scattering under cw pump conditions involving a single Stokes and pump signal. A single-mode optical fiber is used as the nonlinear medium. The inclusion of external optical feedback modifies the form of the chaotic dynamics and results in a rich variety of classifiable precursor dynamical features.

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Pulsating instabilities and chaos are of current interest throughout physics and, in particular, quantum optics. While observations of these phenomena are now extensive in systems with external optical feedback, notably lasers,[1] passive bistable systems,[2] and to a lesser extent systems with counterpropagating pump beams,[3] there are few if any reports[4] of such behavior in nonlinear processes for which this restriction is lifted. In this paper we consider stimulated scattering phenomena and provide, to our knowledge, first evidence indicative of chaotic dynamics in one of these basic processes, namely, stimulated Brillouin scattering (SBS). A single-mode optical fiber is used to generate SBS under cw single-mode pump conditions,[5] resulting in first-order Stokes emission only. We find both the transmitted pump and backscattered SBS to exhibit chaotic behavior under all operating conditions investigated, including those close to the threshold for SBS; the SBS exhibits massive instabilities with modulation depths $\sim 100\%$.

The few reports to date, mainly theoretical, on the dynamics[6–14] of SBS principally concern the generation of instabilities, usually limit-cycle behavior, through more complex interactions involving either more than one pump beam,[12,13] external cavity feedback,[9–11] and/or higher-order Stokes–anti-Stokes generation.[12] Experimental findings, often in regard to plasma interaction,[10,12] have been constrained to short-pump-pulse excitation,[7,10,13] posing limitations to quantitative statements of long-term dynamical behavior; an exception being the observation of limit-cycle behavior in fibers with external optical feedback.[11] Of the theoretical contributions, an exception is the analytical findings of Blaha *et al.*[14] providing evidence of unstable behavior in SBS involving a single pump and Stokes signal in a semi-infinite medium.

Our experimental arrangement is schematically shown in Fig. 1. The cw emission of a single-mode argon-ion laser at 514.5 nm, with an instantaneous ($\leq 1$ msec) linewidth of $\sim 15$ kHz (Coherent Innova 100) was used as a pump source providing variable output power stabilized to $\pm 2\%$. Two 10× microscope objectives $L_1$ and $L_2$, were used to couple the light into and out of the optical fiber, respectively. The fiber comprised a pure $SiO_2$ core of diameter 4.8 $\mu$m with a $B_2O_3$-doped $SiO_2$ cladding. It was optically isolated from the argon laser using a Faraday isolator (OFR Model IO-5-532) giving an isolation factor of 35 dB between them. The pump signal and backscattered signal, comprising the SBS signal together with residual scatter, were sampled via the beam splitter in Fig. 1. These signals together with the signal transmitted through the fiber were detected using photodiodes (HP-type BPX65) $D_1$, $D_2$, and $D_3$ which have a rise time of $\leq 0.5$ nsec. A transient digitizer (LeCroy TR 8828C) having a data sampling rate of 5 nsec interfaced with a Masscomp Computer (MC5600) was used for temporal recording and subsequent signal processing to provide power spectra and phase-portrait reconstruction. Results were cross checked from independent recordings on a Tektronix 7104 oscilloscope for both temporal measurements and direct phase-portrait reconstruction of the SBS versus transmitted pump signals (oscilloscope in the $x$-$y$ mode) and on a Hewlett-Packard spectrum analyzer (HP8590A) for corresponding spectral analysis. Feedback from the end faces of the fiber was eliminated using an index-matching liquid. Single-mode propagation in the fiber was ensured by looping a small section of the front end of the fiber thereby suppressing higher-order modes and was confirmed by observation of the spatial form of the transmitted signal. A Fabry-Perot interferometer with variable spacer confirmed throughout only first-order Stokes SBS emission.

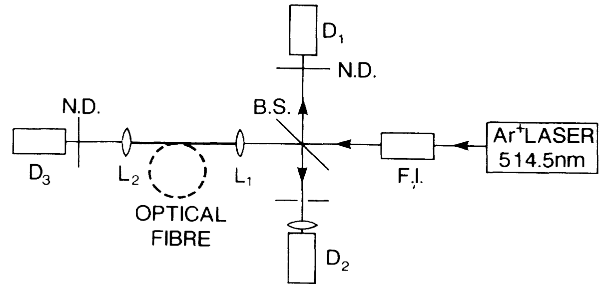


FIG. 1. Schematic setup of experimental arrangement. F.I. is Faraday isolator, N.D. is neutral density filters, and $D_1$, $D_2$, $D_3$ are photodetectors.

At low input power the backscattered signal increased linearly with input power due to Fresnel reflection up to the threshold launch power for SBS (~100 mW for a 200-m fiber). The signal thereafter increases rapidly and nonlinearly with launch power, the conversion efficiency to SBS being ~40% for a launch power of ~300 mW accounting for losses arising from looping the fiber. Corresponding fiber transmission measurements showed a nonlinear response for input power ≥ 100 mW and for pump powers ≥ 200 mW gave a saturated maximum of 20 mW. These general features are in agreement with the findings of others.[5] The threshold power for SBS can be estimated from small signal theory of stimulated scattering and is given as[5] $GL_e \approx 21$, where $G$ is the SBS gain factor and, for a pump-laser linewidth $\Delta\nu_L$ much less than the Brillouin scattering linewidth $\Delta\nu_B$ ($\Delta\nu_B \sim 145$ MHz at 514 nm), is given as $KP_L/\lambda^2\Delta\nu_B A$, where $K$ is a constant depending upon the physical and optical properties of the fiber and $A$ is the effective cross-sectional area of the guided mode. The effective interaction length $L_e$ is given as $L_e = \alpha^{-1} \times [1-\exp(-\alpha L)]$, where $\alpha$ is the absorption coefficient experimentally determined to be $4.6\times10^{-3}$ $\text{m}^{-1}$ (20 dB/km), and $L$ the length of the fiber. Using physical properties data for fused silica and an estimated value of $A = 0.9\times10^{-11}$ $\text{m}^2$, the above relation gives a threshold pump power $P_L \sim 82$ mW. Accounting for losses arising from looping the fiber, the launched power for obtaining SBS is increased by an experimentally measured factor of 1.6–1.8, giving a threshold power for SBS ~130 mW in reasonable agreement with experimental findings.

Representative recordings of the chopped input signal and SBS signal close to threshold and for a higher pump power along with the transmitted signal are shown in Fig. 2, traces (a)–(d), which demonstrate the magnitude of the instability. Trace (a) shows the effectiveness of the optical isolator in ensuring a stable dc steady-state input signal. In trace (b) the unmodulated portion of the reflected signal is that arising from spurious Fresnel backscatter of the incident pump. For higher pump power [trace (c)] this contribution is masked by the large SBS signal, which as in trace (b) shows sustained instabilities with modulation depth of ~100%. Similar results were obtained for all input powers, limited to a maximum value of ~700 mW by the laser output power. Trace (d) shows an example of the transmitted pump signal corresponding to the SBS signal of trace (c). The ratio of the unstable to the underlying stable portion of the transmitted signal provides a measure of the SBS conversion efficiency of 40%, consistent with the measurement above. These general features were confirmed for various fiber lengths from 38 to 300 m with an expected increase in the SBS threshold for reduced fiber length; ~500 mW for the 38-m fiber.

Representative forms of the dynamical instability in the SBS and the transmitted pump signals for a 100-m-length fiber taken without the chopper and for a launch power of 280 mW are shown in the digitized recording of Fig. 3 showing the time series, power spectrum, and reconstructed phase portraits. The latter were obtained by a two-dimensional plot of data points $x_i$ ($i=1, 2, \ldots, 16000$) vs $x_{i+K}$ for an appropriate value of delay $K$. The time recording of the SBS [trace (a)] shows erratic and aperiodic emission over a broad time scale down to ~50 nsec. The corresponding power spectrum exhibits pure broadband features suggestive of fully developed chaos with a spectral bandwidth ~30 MHz which may be compared with the Brillouin gain bandwidth of ~145 MHz. The reconstructed phase portrait [trace (c)] exhibits motion on an outward spiraling and folding trajectory, particularly evident from observing the temporal evolution of the trajectory. The corresponding recordings of the pump signal transmitted through the fiber [traces (d)–(f)] exhibit similar features though over a reduced spectral bandwidth. The phase portrait essentially mirrors that of the SBS due to the parametric nature of the nonlinear interaction, providing further evidence of the deterministic rather than stochastic nature of this process; also corroborated by the continuous form of the trajectories spiraling and folding motion, within the digitization resolution. More generally the spectral broadening was found to depend upon the input pump power, varying from ~10 close to threshold to ~20 MHz at twice the input power. The general features of traces (a)–(f) are typical of those obtained for a wide range of pump powers and were found to be highly reproducible. Interestingly, no evidence of precursor routes to chaos was found.

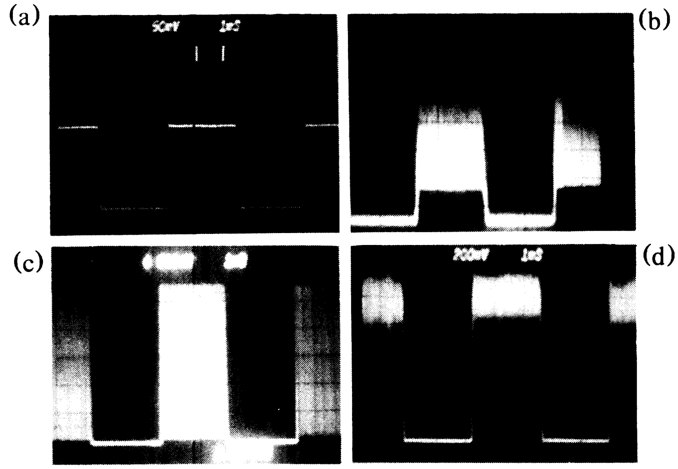


FIG. 2. Temporal recordings of chopped signal (a) input signal detected by $D_1$, (b) backscattered signal detected by $D_2$ for a launch power of 0.12 W, (c) backscattered signal detected by $D_2$ for a launch power of 0.33 W, and (d) transmitted signal detected by $D_3$ for a launch power of 0.33 W. Time scale is 1 msec/division throughout. Fiber length is 200 m.

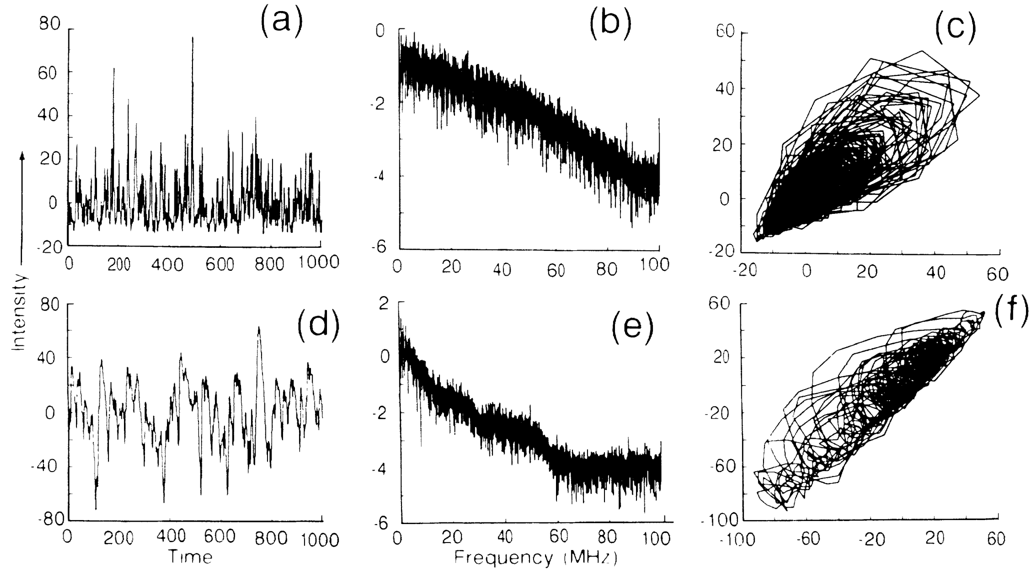


FIG. 3. Sample time series, power spectrum, and phase portraits taken from 16-K digitized recordings of the SBS signal (row 1) and transmitted pump signal (row 2). The time-series traces (a) and (d) comprise 1000 data points (step interval 5 nsec). Corresponding power spectra [traces (b) and (e)] are for 16-K data points with a vertical scale gain of 10 dB/ division. Traces (c) and (f) are the corresponding phase portraits comprising 2000 data points constructed with a delay of 15 and 3 step intervals, respectively. Fiber length is 100 m.

In further investigations of these phenomena we also considered the influence of external feedback on the dynamics of the SBS process. Feedback was provided by removal of the index-matching fluid from the fiber ends to give a nominal reflectivity of ~4% from each of the end faces. In marked contrast with the results above, and for all conditions of operation, the temporal instabilities occur in random bursts of 1–3 msec dispersed within stable regions of operation, attributable to environmentally induced fluctuations of the effective length of the fiber cavity. The SBS and transmitted pump signals were nevertheless found to exhibit a rich variety of reoccuring and classifiable dynamical features; some samples are shown in the phase-portrait traces of Fig. 4 and full details will be published elsewhere. Limit-cycle behavior [trace (a)], dominant at the higher launch powers (500 mWsec), ranged in period from 200–300 nsec (cavity round-trip time $t_c \sim 1$ $\mu$sec) with evidence of correlation[11] with $t_c$ for the 38-m fiber. The torroidal phase portrait [trace (b)] provides evidence of two-frequency oscillation while period-two and period-three bifurcations of the basic limit cycle [trace (a)] have also been observed. Traces (c) and (d) suggest a weakly chaotic motion indicative of the breakdown of a two torus which is further supported by the observed lifting of the broad background in their power spectra relative to (a) and (b). Significant further analysis of the experimental data for fibers with and without index matching will be required in order to resolve this question. This work is currently in progress. The attractor in trace (d) is similar to those obtained without optical feedback (Fig. 3).

Our observations in support of fully developed chaos in SBS in the absence of external optical feedback indicate the key role of the electrostrictively induced distributed optical feedback in the fiber, inherent to the process of SBS, is also instrumental in promoting this dynamical behavior. Significantly, the inclusion of external optical feedback modifies the chaotic dynamics and also allows for various stable oscillatory dynamical signatures. Preliminary results of our numerical analysis, based on the coupled nonlinear field (Stokes and pump) and material equations, in an extended medium without external feedback confirm the existence of chaotic spatial-temporal behavior, found to be dependent on both the gain and dispersion features of the nonlinear interaction. Further considerations of amplified spontaneous Brillouin scattering, nonlinear polarization coupling,[15] and the acoustic cylindrical eigenmodes of the fiber[16] are currently in progress; although the role of the latter would not appear significant since no evidence of forward Brillouin scattering has been found.

In conclusion, we have demonstrated the unique merit of a single-mode optical fiber in identifying the rich dynamical behavior in SBS under cw conditions of operation. More generally its application should prove valuable to investigations of other stimulated scattering phenomena and nonlinear processes which conventionally have required high pump intensities and so pulsed pump sources.

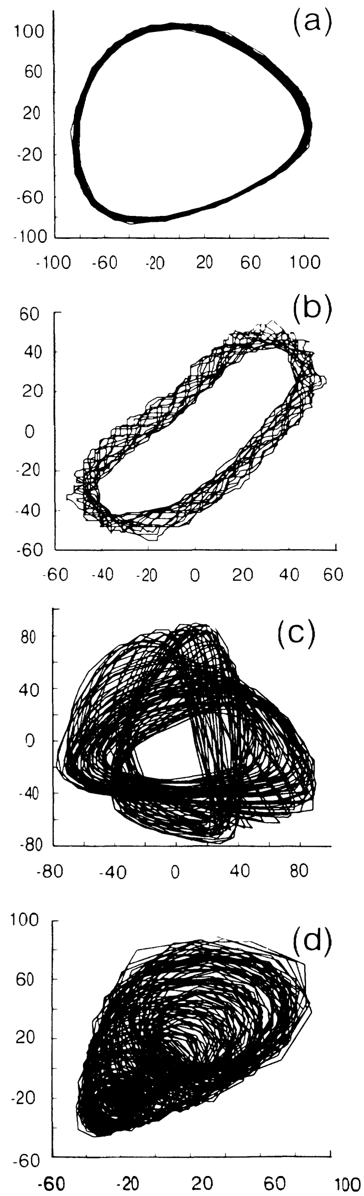


FIG. 4. Some representative phase portraits of the transmitted pump signal [traces (a)–(c)] and SBS signal [trace (d)] from the fiber in the presence of optical feedback (a) limit cycle and (b) torroidal motion. Traces (c) and (d) are examples of chaotic attractors. 2000 data points of 16-K recordings are shown throughout. Fiber length is 100 m.

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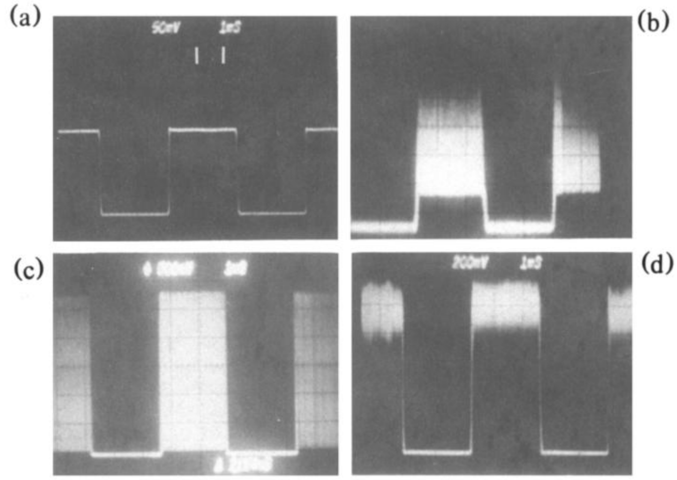


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