Statistical properties of the monochromatic laser radiation partially depleted through the stimulated Brillouin scattering in a single mode optical fiber.

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We performed numerical simulations in order to explore statistical properties of the monochromatic laser radiation partially depleted through the stimulated Brillouin scattering process in a single mode optical fiber. We give a clear physical insight into the problem and, for what is to our knowledge the first time, reveal how the probability function of the transmitted laser power evolves as key parameters of the model vary, leading to a modification of Stokes field statistics.

Introduction

Stochastic fluctuations of the scattered Stokes power as well as similar fluctuations of the pump power transmitted through the fiber (residual power) are commonly recorded in SBS experiments [1]. Initiated by spontaneous noise these fluctuations can be observed even under CW excitation of the fiber by a well-stabilized monochromatic pump. We have already reported [2] statistical properties of the scattered Stokes radiation. A Stokes power probability function has been described for a wide range of SBS regimes. We explored nontrivial evolution of the Stokes field statistics above the SBS threshold and demonstrated that modification of the Stokes field statistics is responsible for broadening and hole burning of the spectra of SBS power observed in the experiment [3]. Whereas it has already been done for Stokes signals, the statistics of the pump field transmitted trough the fiber has not been investigated yet and is reported here for the first time. Concretely, we reveal how the probability function of the pump power evolves as the key parameters of a one-dimensional SBS model vary, leading to the modification of the Stokes field statistics. To complete the picture these new results are presented in conjugation with corresponding data related to the Stokes radiation. Our interest to the problem is warmed up by recent observations of the residual pump power spectra [4].

SBS model and numerical procedure

Numerical simulations were based on the set of one-dimensional SBS dynamical equations for complex amplitudes of the pump wave $E_L(z,t)$, the Stokes wave $E_S(z,t)$ and the hypersound wave $\rho(z,t)$ [1]. Boundary conditions correspond to the injection of a monochromatic CW pump wave at $z=0$, i.e. $E_L(0,t)=\sqrt{P_0}$, $E_S(L,t)=0$. Other parameters in the calculations are related to SBS in typical telecommunication fiber at pump wavelength of $\lambda_L \sim 1\mu m$: $g = 2.5\cdot 10^{-9}\,cm/W$ is SBS gain, $T_2 = 10\,ns$ is the acoustic phonon lifetime, $S = 25\mu m^2$ is the fiber mode area. The initiating noise was considered as a Gaussian random process with zero mean and δ-correlated in space and time. For any given fiber length L the threshold power is referred as $P_{th} = 20S/gL$ [1].

Two dimensionless parameters $N = P_0/P_{th} = T_0/10T_1$ and $\gamma = T_1/T_2$ are defined as ratios between key temporal parameters of the SBS process: the time that light takes to travel through the fiber $T_0 = n/cL$, the time associated with the effective SBS amplification length $T_1 = 2nS/cgP_0$ and the hypersound decay time T_2. For a given pair $\{N, \gamma\}$ we calculated twenty different stationary realizations of pump - Stokes field time series $\{E_L(L,t), E_S(0,t)\}$ each with duration of $20\mu s$. Then these data were processed to build probability functions of pump and Stokes powers $W(P_L)$, $W(P_S)$ averaged over realizations.

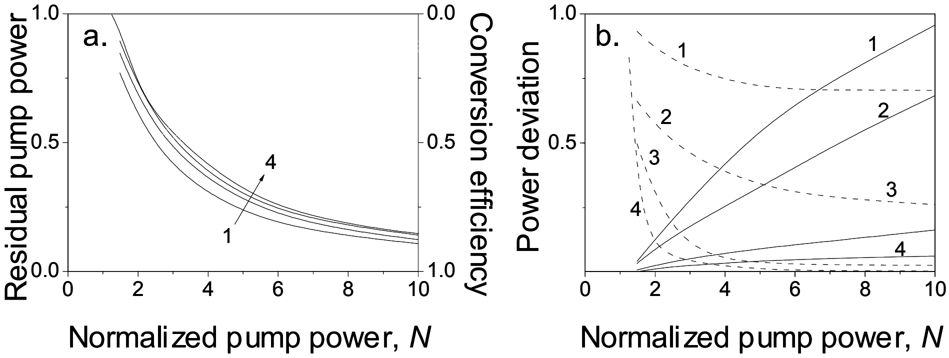

Fig.1. (a) Normalized residual pump power η and pump-to-Stokes conversion efficiency, (b) pump and Stokes (dashed line) normal power deviations as functions of N for parameter $\gamma = 10, 1, 0.1, 0.01$ (curves 1–4).

Results and discussion

Parameter N (input pump power level P_0 in units of time above threshold) determines the degree of pump depletion that is due to power conversion from pump to the Stokes wave. The pump-to-Stokes conversion efficiency grows logarithmically with N and so the normalized residual pump power $\eta = \langle P_P(L,t)\rangle / P_0$ decreases as shown in Fig.1(a). As presented in Fig.1(b), the Stokes wave generated near threshold ($N \approx 1$) exhibits large chaotic power fluctuations with a normal deviation $\Delta_S \approx 60 \sim 100\%$, while pump wave remains no modulated. The pump depletion leads to energy exchange between the counter-propagating pump and Stokes waves that to some extent suppresses Stokes power fluctuations and generates fluctuations of the pump power with a normal deviation of $\Delta_L \approx 60 \sim 100\%$ (at $N > 5$). At a given $N > 1$ the depth of both pump and Stokes fluctuations is determined by the parameter γ. For $\gamma << 1$ fluctuations are quickly inhibited as pump depletion grows, while for $\gamma >> 1$ fluctuations remain large even under high pump-to-Stokes conversion efficiency. Fig.2 shows qualitatively different behaviors of Stokes and pump powers calculated for $N = 10$ ($\eta \approx 13\%$) in two limit cases: $\gamma = 10$

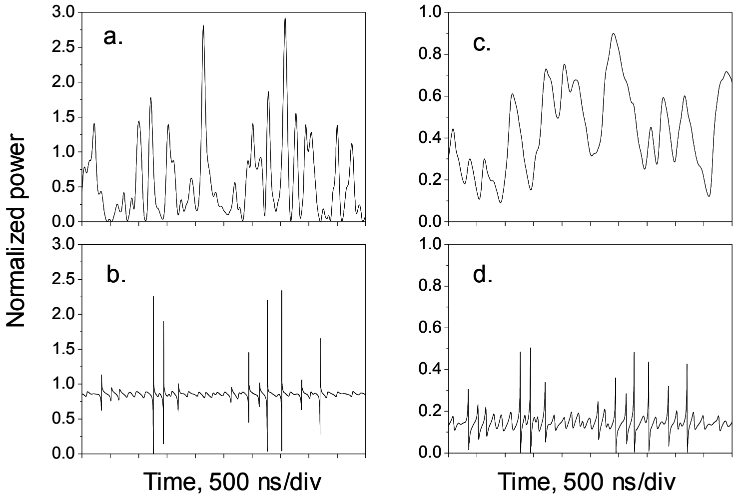

Fig.2. Typical temporal behavior of the Stokes power $P_S(0,t)/P_0$ (a, b) and residual pump power $P_L(L,t)/P_0$ (c, d) are shown for two limit cases at $N=10$: $\gamma=10$ (a, c), $\gamma=0.01$ (b, d).

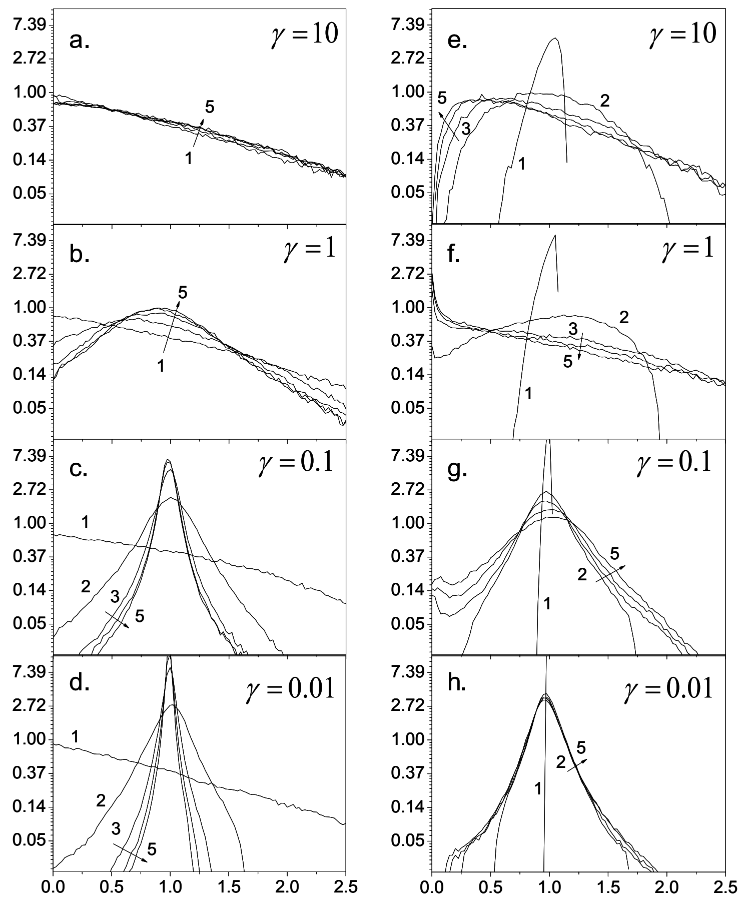

Fig.3. Probability functions of the Stokes (a-d) and transmitted pump (e-h) powers.
Curves 1-5: $N = 1.25, 2.5, 5, 7.5, 10$

($\Delta_S \approx 70\%$, $\Delta_L \approx 95\%$) and $\gamma = 0.01$ ($\Delta_S \approx 0.4\%$, $\Delta_L \approx 6\%$), respectively. The last feature demonstrates a specific role of the acoustic wave memory that smoothes coupling between pump and Stokes power fluctuations within the acoustic phonon lifetime.

The probability functions for the Stokes and pump powers in logarithmic scale are shown in Fig.3 with N and γ as parameters. Note that Gaussian random process with zero mean has exponential power distribution function $W\left(P/\langle P\rangle\right) = \exp\left\{-P/\langle P\rangle\right\}$ represented in Fig.3 by the straight line. One can see that Stokes and pump fields demonstrate completely different evolutions of their probability functions. At any value of γ near threshold ($N \approx 1$), the Stokes field has a Gaussian statistics, while the pump probability function is concentrated near unity exhibiting a specific cut-off from the right side. Two things explain these last features: near SBS threshold the monochromatic pump is still weakly modulated; the input power level P_0 determines the upper limit of pump fluctuations. Above threshold with the increase of N, the pump fluctuations become deeper and the pump probability function exhibits broadening. The broadening is more significant than greater γ, i.e. the role of acoustic memory is less important. At $\gamma > 1$, as $N \to \infty$ the statistics of the pump field asymptotically approaches a Gaussian. In contrast, at $\gamma < 1$ the pump probability function saturates to some triangular curve with maximum near unity. For comparison, the statistics of the Stokes field above threshold remains Gaussian only for $\gamma >> 1$ (e.g., $\gamma = 10$). In other cases the Stokes statistics drastically is modified as N grows. There are two special cases when the pump and Stokes statistics are nearly similar. At $\gamma >> 1$ and $N \to \infty$ they are both Gaussian. At $\gamma \ll 1$ both probability functions have similar shapes.

Conclusion

We numerically investigated the statistical properties of a monochromatic pump field depleted through SBS in single mode fiber. The pump power probability function was found to exhibit nontrivial evolution above SBS threshold. We explored two factors responsible for formation of the pump field statistics: effective coupling between Stokes and pump power fluctuations above SBS threshold, and acoustic wave memory that smoothes this coupling within the acoustic phonon lifetime.

Acknowledgements

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