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Study of the longitudinal distribution of power generated in a random distributed feedback Raman fibre laser with unidirectional pumping

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Abstract. **The longitudinal distribution of the Stokes-component power in a Raman fibre laser with a random distributed feedback and unidirectional pumping is measured. The fibre parameters (linear loss and Rayleigh backscattering coefficient) are calculated based on the distributions obtained. A numerical model is developed to describe the lasing power distribution. The simulation results are in good agreement with the experimental data.**

Keywords: *Raman laser, random feedback, Rayleigh backscattering, fibre.*

6. Introduction

The positive feedback, which is necessary for lasing, is generally implemented by integrating a cavity into a laser; however, there are some other opportunities. Even in 1966 lasing based on a nonresonant feedback was demonstrated by Ambartsumyan et al. [1], who replaced one of the mirrors of a ruby laser cavity by a diffuse scatterer. Then Letokhov [2] proposed and theoretically investigated a laser with scatterers randomly distributed in space and characterised by negative absorption. Later this scheme, referred to as a ‘random laser’, became of great interest for researchers. Since that time many versions of random lasers with a feedback implemented as a result of multiple scattering of generated photons from particles randomly distributed in a gain medium have been considered [3]. Recently the concept of random feedback has been implemented in fibre lasers [4]. Distributed gain was formed in a long (84 km) optical fibre due to stimulated Raman scattering (SRS), and a feedback was formed as a result of Rayleigh backscattering from density fluctuations randomly distributed over the fibre core. Since the structure of doped quartz glass (the fibre core consists of) inevitably contains random submicron fluctuations, one can use a standard telecommunication fibre to design a ‘random’ Raman fibre laser.

To date, significant progress has been achieved both in the development of new versions of fibre lasers based on this principle and in the description and understanding the mechanisms of their operation. In particular, cw narrow-band Raman lasers with a random distributed feedback based on Rayleigh scattering, working at 1.55 [4, 5] and 1.2 μm [6], have been developed, as well as multiwavelength [7, 8] and tunable [9, 10] lasers. Their spectral properties were also described [11].

There is much interest in the longitudinal distribution of lasing power in such lasers. Differing radically from the distribution in Raman lasers having a conventional linear cavity with point reflectors (mirrors), which are located at the fibre ends, it is important for both understanding the mechanisms of random lasing and for potential applications of these lasers in telecommunication and sensor systems. Recently, the longitudinal distribution of lasing power in a symmetric configuration (which is simplest for consideration and was implemented for the first time in [4]) was experimentally and theoretically investigated in [12]. To this end, two pump lasers were applied, whose radiation was introduced into the middle of a fibre segment to propagate in the opposite directions from the middle of the segment to its ends. In this case, the Raman gain coefficient is maximum in the middle of the fibre and decreases to the same extent to its ends, while lasing power is maximum at the point $|z| = L_{\rm RS}$, where the gain decreases to the loss level. This system is characterised by symmetry for counterpropagating generated waves in the case of reflection with respect to the fibre midpoint [12]. Another basic scheme of a random laser is an asymmetric configuration with one pump laser, whose radiation is introduced into one of the fibre end faces. Obviously, the lasing power distribution in a system with unidirectional pumping should differ significantly from that in a symmetric system; however, it has not been investigated to date.

In this paper, we report the results of detailed experimental study of the longitudinal distribution of lasing power in a Raman fibre laser with a random distributed feedback in different configurations with one pump laser. The Rayleigh backscattering coefficient and linear loss in the fibre are found from the experimental data. The longitudinal power distributions were numerically calculated based on the system of balance equations; the results obtained are in good agreement with the experiment.

7. Experimental setup

To investigate experimentally the longitudinal lasing profile, we designed the scheme of an Raman laser with a random feedback. A 84-km segment of standard telecommunication fibre SMF-28 with randomly distributed inhomogeneities,

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which was composed of nine spliced pieces of different length, played the role of a gain medium. A spectral-selective coupler was used to introduce 1455-nm pump laser radiation either from the left edge of the system (Fig. 1a) or into its centre (Fig. 1b).

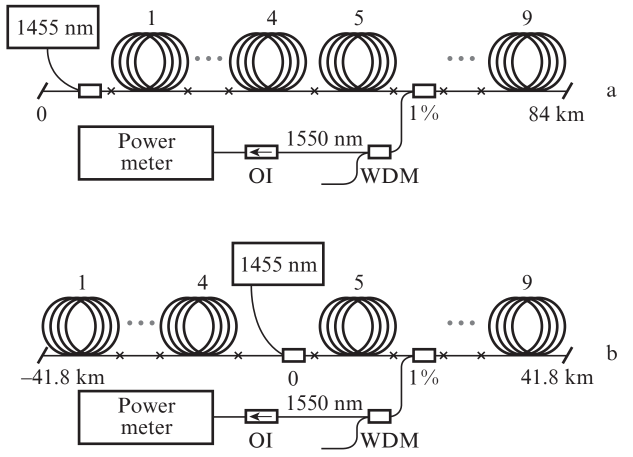

Figure 1. Experimental setup: (a) unidirectional-pumping scheme and (b) scheme with pumping into the middle of the fibre (WDM and OI stand, respectively, for a 1455/1550 wavelength division multiplexer and an optical isolator).

The lasing threshold in both schemes was ~1.6 W, a value that is in good agreement with the earlier experimental results and theoretical estimates [4, 12]. Lasing was observed near the Raman gain peak (about 1555 nm); the lasing spectrum width depended on power and amounted approximately to 1 nm.

Measurement modules were successively spliced into each gap between fibre segments and to both laser outputs. Each module consisted of a 1 % coupler, wavelength division multiplexer (WDM) 1455/1550, and an optical isolator (OI). The Stokes wave power was measured by a module without introducing spurious reflections into the system. The measurement module was installed successively in two directions (to measure the power of the waves propagating both to the right and to the left).

To increase the number of points in the distribution, the pump propagation direction was changed after measuring power in each of eight gaps between the fibre segments, and then measurements were repeated at each point. Since all nine segments had different lengths, this symmetric reflection of the system with respect to its centre doubled the amount of data.

8. Measurement results

The measured longitudinal power distributions for the unidirectional-pumping scheme (Fig. 1a) are shown in Fig. 2. They differ radically from the distributions observed in the symmetric configuration [12]. The wave that is codirectional with the pump wave has a flat distribution, which can be seen well on the linear scale (Fig. 2b). The distribution peak is spaced from the pump laser by the gain length L_{RS} and is located at the point where the loss of laser radiation wave is equal to its gain [4]. The backscattered wave sharply increases near the fibre end face, where the pump power is maximum. Note that the power of the backscattered wave (which is directed oppositely to the pump wave) increases by five orders of magnitude after the passage through the fibre, whereas the power of the laser wave that is codirectional with the pump wave is changed much more smoothly (by less than an order of magnitude).

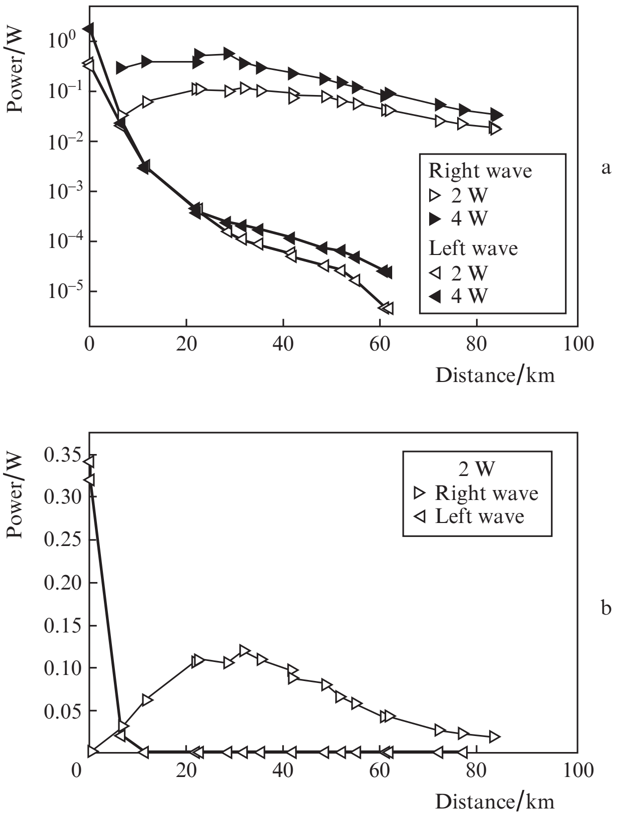

Figure 2. Longitudinal power distributions in the scheme with unidirectional pumping from the left edge at pump powers of (a) 2 and 4 W (logarithmic scale) and (b) 2 W (linear scale).

Further studies were performed with a laser of another experimental configuration, where the point of pump input is shifted to the centre of fibre segment by 42 km from its beginning (see Fig. 1b). In this configuration the pump wave is completely absent in the left half of the cavity, which makes it possible (as will be shown below) to determine independently the optical loss and, what is more important, find the Rayleigh backscattering coefficient (the ratio of the power backscattered and trapped by the fibre to the total scattered power).

In this configuration the longitudinal distributions of the counterpropagating-wave power (Fig. 3) become more symmetric in comparison with the distributions for unidirectional pumping from the left edge, which are presented in Fig. 2. However, they are less symmetric than the distributions in the fully symmetric scheme with two pump sources [12]. Indeed, a high-power backward Stokes wave propagates in the left half of the laser, although pump radiation is absent in it. Having undergone Rayleigh backscattering, this wave serves as a seed for the forward Stokes wave. Thus, a forward wave is generated more efficiently than in the previous scheme: at a pump power of 4 W, the power in the distribution peak is 1 W, in contrast to a value of 0.5 W, which is obtained for pumping from the fibre end face. However, in this case, the maximum power of the generated backward wave decreases: one has 1.4 W in the scheme with pumping from the middle of the fibre segment in contrast to 2 W in the scheme with pumping from the end face. This fact is important for practical applications.

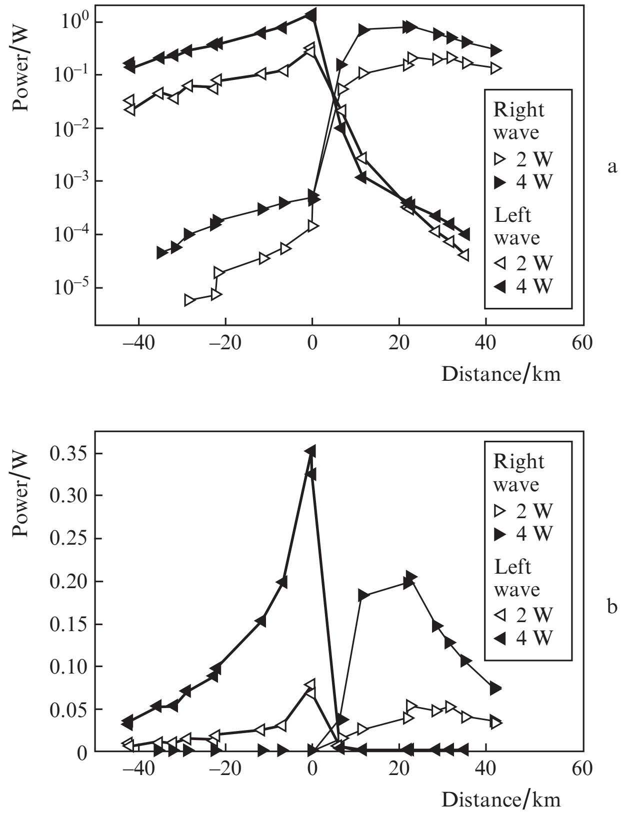

Figure 3. Longitudinal power distributions in the configuration with pumping into the fibre centre on (a) logarithmic and (b) linear scales.

It is of interest to observe the behaviour of the power-peak position for the forward laser wave (this peak characterises the gain length L_{RS} in the system under study). With an increase in the pump power, the peak should approach the input point for the pump radiation in view of its depletion because of the Stokes component generation. The law of this shift for a symmetric two-arm configuration (the gain length L_{RS} is inversely proportional to the pump power) was analytically obtained and experimentally confirmed in [12].

The measured longitudinal distributions were used to derive the dependence of the gain length L_{RS} on the pump power P for unidirectional pumping (Fig. 4). In this scheme L_{RS} decreases more slowly: the phenomenological law of decrease was found to be described by $P^{-0.7}$. This fact can be important from the practical point of view. Indeed, a decrease in L_{RS} to values smaller than the fibre length leads to a loss of output power, because at $z > L_{\text{RS}}$ the lasing power drops exponentially. An increase in the pump power leads to a further shift of the L_{RS} point to the pump input point and to an increase in the length of the fibre segment where the Stokes wave undergoes only linear loss. Thus, the output laser efficiency deteriorates. The more slowly L_{RS} decreases with an increase in the pump power, the higher the lasing efficiency.

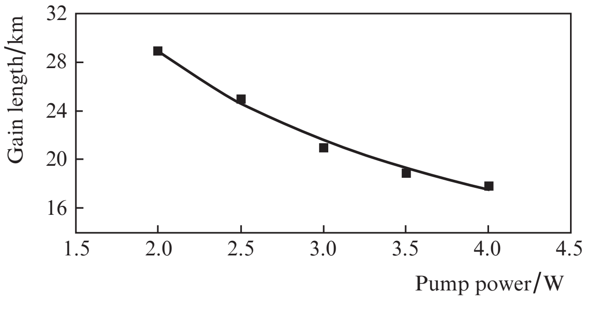

Figure 4. Dependence of the gain length L_{RS} on the pump power: (squares) experimental data and (solid line) approximation by a power law of the $P^{-0.7}$ type.

9. Calculation of the optical loss and backscattering coefficient

If the power distribution in the configuration with one pump wave introduced into the centre of the scheme (Fig. 1b) is known, some fibre parameters can be determined. Indeed, in the left arm, since the pump wave is absent, the backward wave with a power P_{S}^{-} undergoes only exponential decay; the exponential factor α_{S} is determined by the optical loss in the fibre:

$$P_{\text{S}}^{-}(z < 0) = P_{\text{S}}^{-}(z = 0)\exp(z\alpha_{\text{S}}). \tag{1}$$

Here, z is the coordinate along the fibre, which is counted from the point of pump radiation input and increases toward the right. The optical loss α_{S} was found by approximating the experimental data (Fig. 5, upper curve) to be 0.058 km^{-1}; this value is in agreement with manufacturer's data (α_{S} = 0.045 km^{-1}).

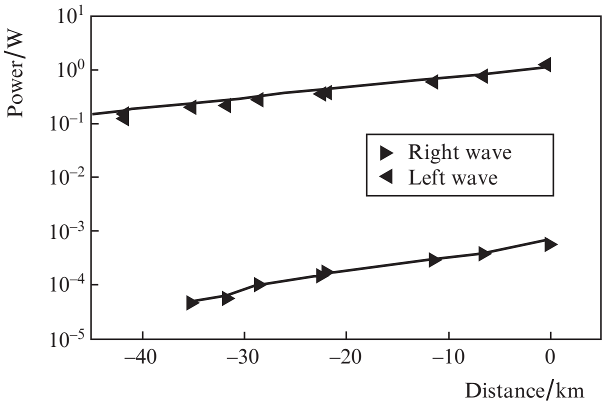

Figure 5. Power distributions for the right and left waves in a fibre segment without amplification: (triangles) experimental data and (solid lines) results of calculation from formulas (1) and (2).

Then the measured distribution power of the Stokes wave power in the left arm can be used to find the Rayleigh backscattering coefficient Q, a parameter that is determined by the geometric sizes of the fibre and is equal to the ratio of radiation power backscattered and channelled by the fibre to the power scattered into the solid angle 4π. Indeed, the power P_{S}^{+} of the forward wave formed in the left arm from the backward wave P_{S}^{-} due to the Rayleigh backscattering is described by the expression

$$P_{\text{S}}^{+}(z + L) = \frac{1}{2}QP_{\text{S}}^{-}(z + L)\{1 - \exp[-2\alpha_{\text{S}}(z + L)]\}. \tag{2}$$

Here, $L = 41.8$ km is the total arm length. Thus, one can calculate the longitudinal distribution of the forward wave in the left arm using the Rayleigh backscattering coefficient as a free parameter. The value $Q = 1.05\times10^{-3}$ provides the best agreement between the experimental data and the analytical calculation results (Fig. 5, lower curve). Note that manufacturer's data on the Rayleigh backscattering, 82 dB ($Q = 7\times10^{-4}$), some differ from the experimental value.

10. Numerical model

The longitudinal power distribution throughout the laser can be calculated using the well-known system of balance equations, which describe the lasing power in an Raman fibre laser [13]:

$$(\alpha_\mathrm{P} + \mathrm{d}/\mathrm{d}z)P_\mathrm{P}^+ = -g_\mathrm{S}P_\mathrm{P}^+(P_\mathrm{S}^+ + P_\mathrm{S}^- + 4h\nu_\mathrm{S}\Delta\nu)\nu_\mathrm{P}/\nu_\mathrm{S},$$

$$(\alpha_\mathrm{S} \pm \mathrm{d}/\mathrm{d}z)P_\mathrm{S}^\pm = g_\mathrm{S}P_\mathrm{P}^+(P_\mathrm{S}^\pm + 2h\nu_\mathrm{S}\Delta\nu) + \varepsilon_\mathrm{S}P_\mathrm{S}^\mp.$$

Here, the P and S subscripts denote the pump and Stokes components, respectively; the "+" and "–" superscripts correspond to the forward and backward waves; ν_i is frequency; $\Delta\nu$ is the gain spectrum width, which amounts to few tens of nanometres; and α_i and g_S are, respectively, the loss and Raman gain coefficient. The Rayleigh backscattering coefficient $\varepsilon_\mathrm{S} = \alpha_i Q$ takes into account the Rayleigh-scattering feedback, as a result of which the right and left waves are mixed. The boundary conditions corresponding to the scheme with pumping into the middle of the fibre have the form

$$P_\mathrm{P}(0) = P_0,\quad P_\mathrm{S}^+(0) = R_L P_\mathrm{S}^-(0),\quad P_\mathrm{S}^-(L) = 0.$$

Here, P_0 is the pump power and $R_L = \frac{1}{2}Q[1 - \exp(-2\alpha_\mathrm{S}L)] = 5\times10^{-4}$ is the total reflection coefficient of the Rayleigh mirror formed by the left arm of the system. The left-arm distributions were reconstructed from formulas (1) and (2). The simulation results are in good agreement with the experimental data (Fig. 6, solid line).

As was noted above, the presence of the left arm is significant, despite the small reflection coefficient R_L of the Rayleigh mirror formed. Indeed, on the assumption that $R_L = 0$ (i.e., with the left arm removed from the system), the power distribution changes significantly (Fig. 6, dashed line) and becomes inconsistent with the experimental data.

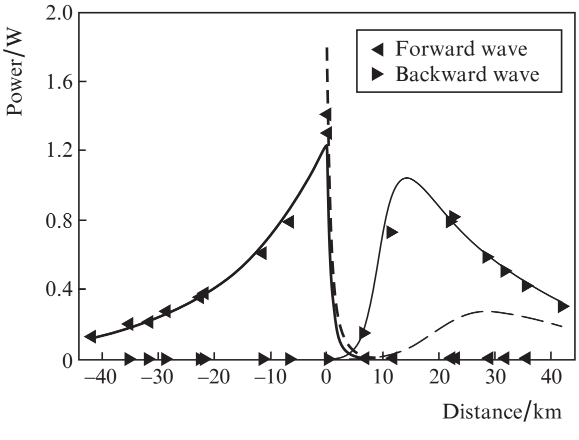

Figure 6. Comparison of the numerical and experimental models: experimental data (triangles) and the results of numerical calculation taking into account and disregarding the random distributed feedback in the left arm (solid and dashed lines, respectively).

Thus, in contrast to the single-arm configuration, the scheme with a single pump point in the middle of the fibre results in higher powers of the forward wave and lower powers of the backward wave.

11. Conclusions

The power distributions in the single-arm configuration of Raman laser with a random distributed feedback were experimentally and numerically investigated. The Rayleigh backscattering coefficient of the fibre was calculated based on the distributions measured. These distributions are described well within the balance model, despite the fact that it takes into account neither dispersion nor nonlinear effects, which most likely play an important role in the formation of the spectrum of a random Raman laser, as well as a conventional Raman fibre laser [14]. Note that the knowledge of longitudinal power distributions makes it possible to optimise laser parameters for further applications, for example, the use of a laser as a distributed amplifier of optical signals.

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