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Experimental investigation of spectral characteristics of an erbium-doped fibre amplifier operating in the recirculation regime

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Abstract**. The spectral profiles of the gain in an erbium-doped fibre amplifier, incorporated into a recirculating fibre ring, are experimentally investigated. The fibre ring was excited by a superfluorescent fibre source. A procedure for measuring the spectral gain profile is developed, and the criterion of gain-profile uniformity evaluation in the case of broadband radiation is proposed. The influence of the shape of the input radiation spectrum, the pump level, and the composition of the active fibre on the uniformity of the spectral gain profile is studied. It is found that, the uniformity reaches its maximum at a certain pump level. It is shown that, to obtain a maximum number of recirculation cycles for a broadband optical signal, one has to optimise parameters of the fibre amplifier together with parameters of the fibre source of radiation in the active recirculation interferometer.**

Keywords: *fibre amplifier, gain spectrum, recirculation interferometer.*

Active optical ring devices based on a fibre ring with a built-in fibreoptic amplifier currently attract a considerable interest of researchers. A wide range of applications, including fibreoptic data storage, signal-processing systems, fibre sensors of the latest generation (gyroscopes, hydrophones) [1, 2] is now expected for these devices.

Depending on the relation between the coherence time τ_c of the radiation source and the fibre ring round-trip time T, the following two operating modes of such fibre rings can be distinguished. When the narrowband excitation is used ($\tau_c \gg T$), the fibre ring works as a fibreoptic ring cavity. In the case of broadband excitation ($\tau_c \ll T$), the ring works as a recirculating delay line.

In this paper, we study a fibre ring with the fibreoptic amplifier operating in the recirculation regime. In our earlier paper [3], we implemented this regime in an angular velocity sensor based on a recirculating fibre ring interferometer (RFRI) with an erbium-doped fibreoptic amplifier embedded into a recirculating ring. With an appropriate gain, one can compensate for round-trip losses in such an interferometer and increase the sensitivity by signal accumulation due to multiple round trips (recirculation cycles) of radiation through the ring. As it was shown theoretically [4], an active RFRI could have the sensitivity two orders of magnitude higher than that of a conventional Sagnac interferometer. However, the advantage achieved experimentally [3] was lower than the theoretical prediction. That discrepancy could originate from the fact that it is impossible to achieve large numbers of recirculations of light within a ring due to distortions of the spectral gain profile of a fibreoptic amplifier near the lasing threshold.

Indeed, the number of signal recirculations in a ring with a fibreoptic amplifier is determined by the cavity finesse [4] $F = \pi R/(1 - R^2)$, where $R = ag < 1$ is the round-trip amplitude transmission of the ring, a are passive losses in the ring, and g is the amplitude gain of the fibreoptic amplifier. In most of the applications, the dependence of these parameters on the wavelength λ of light is ignored. In reality, however, the spectral gain profile $g(\lambda)$ of an erbium-doped fibreoptic amplifier usually has a noticeable nonuniformity within a broad band of a source signal. Moreover, the dependence $g(\lambda)$ may be determined by the shape of the signal spectrum. Because this factor does not allow us to obtain a large number of recirculations of the spectral components of light within the entire signal band, we should optimise the parameters of the fibre source – fibre amplifier system. The purpose of this optimisation is to obtain a uniform profile $g(\lambda)$ for RFRI components.

In this work, we experimentally investigated the influence of several factors on the spectral gain profile of an erbium-doped fibreoptic amplifier operating in a recirculation mode with input radiation supplied by a superfluorescent fibre source (SFS).

An optical scheme of the experimental setup is shown in Fig. 1. Two types of SFS based on ytterbium – erbium-doped fibre providing radiation of different spectral shapes with a power-weighted mean bandwidth of about 20 nm were used as sources of broadband radiation with the average wavelength equal to 1550 nm. The fibreoptic amplifier (components *6*, *7*, *8* in Fig. 1) was fabricated using an ytterbium – erbium-doped fibre. The amplifier was pumped by multimode 0.97-μm diode lasers. Radiation of these lasers was coupled into the fibre through directional couplers. The gain of the fibreoptic amplifier was controlled by varying the current of pump diodes. To implement the recirculation mode, the amplifier was placed in series with an attenuator and a directional coupler in a ring delay line. The directional coupler (*5*) with the coupling ratio fixed within the entire spectral range of measurements served as

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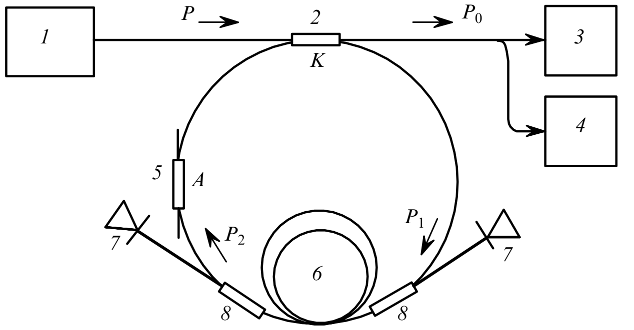

Figure 1. Scheme of the experimental setup: (*1*) fibre radiation source, (*2*) directional coupler, (*3*) spectrum analyser, (*4*) power meter, (*5*) attenuator, (*6*) active fibre, (*7*) diode lasers used to pump a fibreoptic amplifier, (*8*) couplers – multiplexers.

an attenuator. The coupler (*2*) had the power coupling ratio $K = 0.5$. The couplers were made of an isotropic single-mode fibre.

The spectral profile $G(\lambda)$ of the power gain of the fibreoptic amplifier in the case of broadband radiation with a given spectrum $P(\lambda)$ was found as the ratio of signal powers at the output and at the input of the fibreoptic amplifier at a certain wavelength: $G(\lambda) = P_2(\lambda)/P_1(\lambda)$ (Fig. 1). In our experiment, the spectra $P_0(\lambda)$ and $KP(\lambda)$ of signals at the output of the coupler (*2*) were measured with a spectrum analyser, and the average powers P_0 and KP of these signals were measured with a photodiode power meter. These measurements were performed at the same output of the coupler with the amplifier pump switched on and off. Note that, when the pump is switched off, the fibre of the amplifier totally absorbs input radiation. The signal $P_0(\lambda)$ is related to the signal at the output of a fixed attenuator (the transmission coefficient A of the attenuator is assumed to be independent of λ). By varying A, one can study the influence of the pump level on the gain spectrum within a broad range with no lasing in the ring. Note that the proposed method of determining the spectral profile $G(\lambda)$ within a certain wavelength band $\lambda_1 - \lambda_2$ corresponding to the wavelength band of the input signal of the fibreoptic amplifier allows, in our opinion, the behaviour of this amplifier used as a part of an RFRI to be described in a more adequate way.

Let us derive $G(\lambda)$ as a function of measured spectra $P_0(\lambda)$ and $KP(\lambda)$. According to the scheme shown in Fig. 1, we can write the set of equations

$$P_1(\lambda) = (1 - K)P(\lambda) + AKP_2(\lambda), \tag{1}$$

$$P_0(\lambda) = KP(\lambda) + (1 - K)AP_2(\lambda). \tag{2}$$

From equations (1) and (2), we derive the expression for the spectral gain profile

$$G(\lambda) = \frac{P_2(\lambda)}{P_1(\lambda)} = \frac{P_0(\lambda) - KP(\lambda)}{A[KP_0(\lambda) + (1 - 2K)P(\lambda)]}, \tag{3}$$

which was used in computer analysis of measured spectra. Below, we will consider the amplitude spectra of the fibreoptic amplifier $[g(\lambda) = [G(\lambda)]^{1/2}]$ and SFS $[e(\lambda) = [P(\lambda)]^{1/2}]$.

The spectral profiles of the amplitude gain of the phosphosilicate fibre amplifier obtained at different pump levels (i.e., different average gains g_s) are shown in Fig. 2 as an example. In this case, the SFS spectrum was nonuniform (about 5 dB). The power of SFS radiation at the input of the fibreoptic amplifier was 100 μW, the magnitude of additional losses in the ring was $A = 7.2$ dB ($A[\mathrm{dB}] = 10\lg A^{-1}$). The average gain $g_s = [(P_0 - KP)/A(KP_0 + (1 - 2K)P)]^{1/2}$ calculated by using the readings of the power meter is the parameter of the curves. The curve corresponding to $g_s = 2.74$ was measured for the maximum possible pump level near the ring lasing threshold at which the operating mode of the fibreoptic amplifier still remained stable (prethreshold regime). It is evident from Fig. 2 that profiles $g(\lambda)$ are noticeably nonuniform, especially for low pump levels. When the pump level increases, the peaks growing with the pump appear in spectral profiles $g(\lambda)$. The self-excitation of the ring within a narrow spectral range takes place at a certain pump level around one of the peaks (the short-wavelength peak in Fig. 2). This peak is marked with the arrow in Fig. 2.

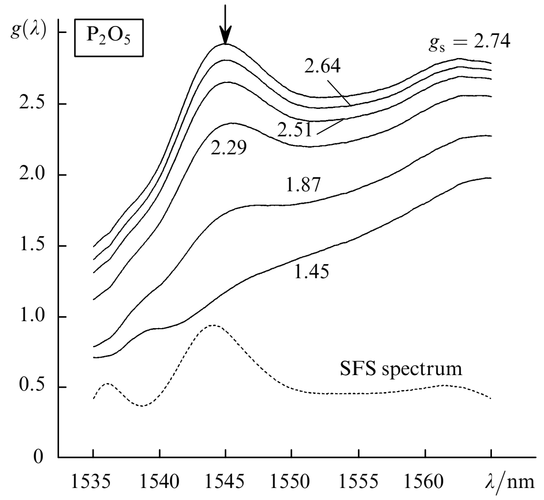

Figure 2. Spectral gain profiles for different average amplitude gains g_s of the phosphosilicate fibre amplifier.

In the subsequent analysis, the profile nonuniformity was defined by the parameter $\delta = g_0/g_{\max}$, where g_0 is the gain averaged over the measured spectrum in the wavelength band $\lambda_1 - \lambda_2$, and $g_{\max}$ is the maximum value of this gain. The wavelength band was chosen approximately equal to the weighted mean of the SFS amplitude spectrum bandwidth. Note that g_0 and g_s represent the same parameter of a fibreoptic amplifier measured by different methods (there is a slight difference between the values of g_0 and g_s, which arises, apparently, due to the methods of their definition; this issue will not be addressed here). The quantity δ characterises the potential of the recirculation regime of a ring cavity and defines the average number of recirculation cycles in the ring (for a uniform profile, $\delta = 1$).

To reveal the dependence of δ on the pump level in a broader range, we measured the spectral gain profiles for losses A in the ring equal to 0.5, 7.2, and 13 dB, with other parameters of SFS and fibreoptic amplifier being fixed. Fig. 3 shows δ as a function of g_s in a wide range of the average gain. It is displayed as consecutively placed three groups of data points whose coordinates were derived from the spectra measured for the above-specified losses (the points corresponding to the prethreshold regime for the relevant values of losses are marked by arrows). One can see that the spectral nonuniformity is the greatest for low losses and, consequently, for a low amplifier pump level. The points corresponding to different values of A form a relatively smooth curve with a well-pronounced maximum of δ at $g_s \simeq 2.65$. In our experiment, the pump level corresponding to maximum δ was slightly lower than the level of prethreshold pump (the maximum possible average gain).

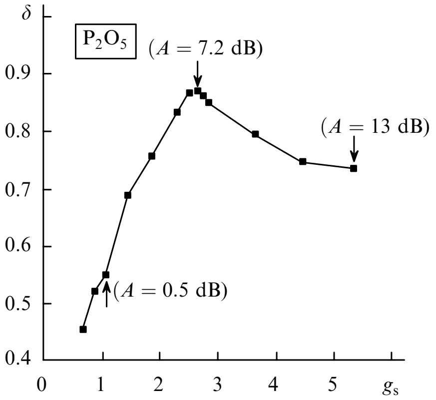

Figure 3. Nonuniformity of the spectral profile of the amplitude gain of the phosphosilicate fibre amplifier as a function of the pump level (the average gain g_s).

Then we studied the influence of the uniformity of the SFS spectrum on the spectral profile of the fibreoptic amplifier. Fig. 4 displays the profiles of the gain spectra for the same phosphorsilicate fibre, measured by an SFS with the nonuniformity of radiation spectrum equal to 1.5 dB. Our investigations have shown that the uniformity of the profile of the fibreoptic amplifier gain is not very sensitive to the shape of the SFS spectrum. An SFS spectrum with a flat shape was preferable under conditions of our experiment.

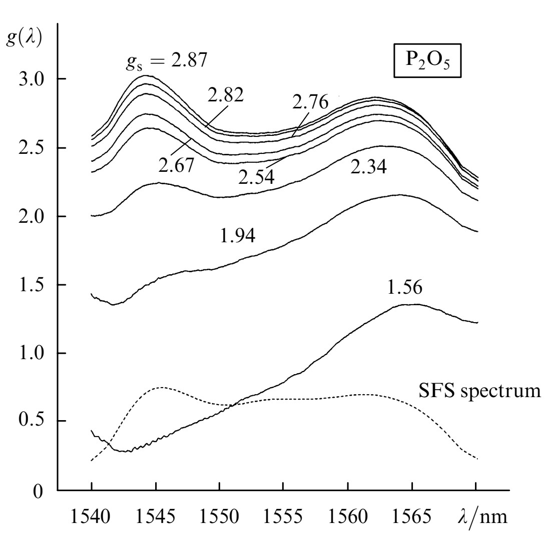

Figure 4. Spectral gain profiles for different average amplitude gains g_s of the phosphosilicate fibre amplifier in the case of an SFS with a uniform spectrum.

To examine the influence of the active fibre composition, we measured the gain spectra of an aluminate-fibre amplifier (Fig. 5) for different pump levels and a uniform SFS spectrum. The spectral profile for this fibre noticeably differs from that typical of a phosphosilicate fibre (Fig. 4).

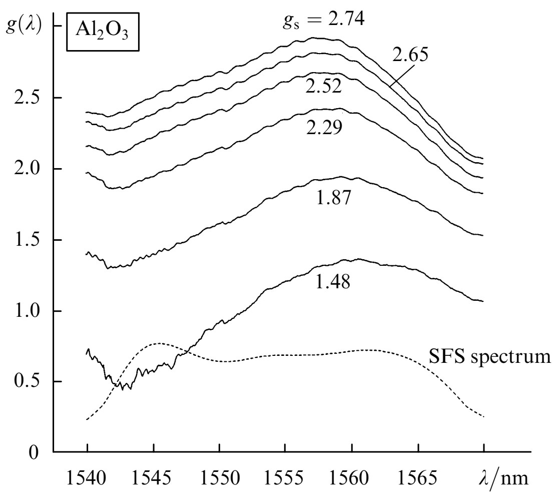

Figure 5. Spectral gain profiles for different average amplitude gains g_s of the aluminate fibre amplifier in the case of an SFS with a uniform spectrum.

Fig. 6 shows the dependences of the profile uniformity parameter δ on the pump level plotted by using the profiles presented by Figs 2, 4, 5. The maximum uniformity of the profile (curve *2*) was achieved with a phosphosilicate fibre and a uniform SFS spectrum. At the same time, the maximum value of $\delta = 0.93$ was achieved at a pump level noticeably lower than the lasing threshold of the ring, i.e., away from the optimal RFRI pump regime. Preliminary experiments show that a careful choice of the fibre length in the fibreoptic amplifier is required for the optimisation.

The profiles of the spectra $g(\lambda)$ obtained at different pump levels are approximately similar to the profiles measured by conventional methods [1]. For low pump levels, the long-wavelength part of the profile is dominating.

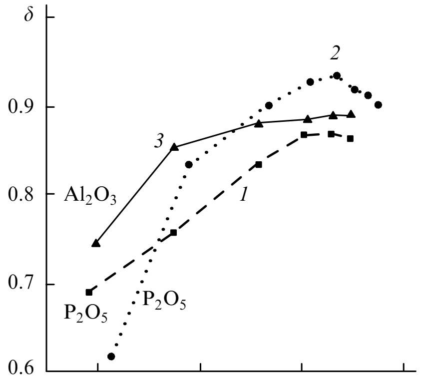

Figure 6. Nonuniformity of spectral profiles of the amplitude gain for phosphosilicate and aluminate fibre amplifiers as a function of the pump level (the average gain g_s) in the case of an SFS with nonuniform (*1*) and uniform (*2, 3*) spectra.

As the pump level increases, the short-wavelength part rises and gradually becomes dominating. This effect can be attributed to the difference between the spectral dependence of the absorption cross section $\sigma_{\rm ab}(\lambda)$ and that of the gain cross section $\sigma_{\rm am}(\lambda)$ within the working range of erbium ions pumped through the third level, as well as to the distribution of ground- and excited-state populations $n_1(z)$ and $n_2(z)$ along the active fibre (see [1]). Due to these factors, the maximum uniformity of the profile $\sigma(\lambda)$ is achieved at a certain pump level. The spectra $\sigma_{\rm ab}(\lambda)$ and $\sigma_{\rm am}(\lambda)$ depend also on the composition of silica glass (phosphate or aluminate glasses), which leads to differences in gain profiles $g(\lambda)$ of fibres of different materials.

The phosphosilicate fibre amplifier employed for the experiments presented here was also used in our earlier work [3] on an RFRI done with an SFS having a uniform radiation spectrum. The results of this work allow us to explain the discrepancy between theoretical calculations and the measurements for the slope of the RFRI output curve noticed in [3]. Calculations were performed with an assumption that the profile of the fibreoptic amplifier gain was uniform. Two issues were emphasised in the analysis of the experimental data in [3]. First, the slope of the output curve in the prethreshold regime was much lower than it was expected because the RFRI ring started to lase already at relatively small values of the parameter R ($R \sim 0.9$). Second, the dependence of the curve slope on the fibreoptic amplifier gain in the region of the prethreshold regime noticeably differed from the calculated (linear) function.

Both of these facts become clear if we take into account the nonuniformity of the gain profile and the nonoptimality of the fibreoptic amplifier pump in the prethreshold regime. Analysis performed in this work showed that the fibreoptic amplifier had a nonuniform gain spectrum. Parameters of this spectrum [the function $\delta(g_{\rm s})$] are characterised by curve (*2*) in Fig. 6. Thus, the condition $\delta < 0.9$ was met in experiments [3] for the prethreshold regime. Taking into consideration the dependence of R on λ for a broadband signal, we can assume that the average number of recirculation cycles should be determined by the spectrum-averaged value of $R_{\rm s}$, which is related to δ. We can show that $R_{\rm s} = ag_{\rm s} \simeq g_0/g_{\max} = \delta$ in the prethreshold regime. We then find that $R_{\rm s} \simeq 0.9$ under conditions of experiments [3], and the number of recirculation cycles is not very large, which explains a moderate enhancement of the RFRI curve slope.

The nonlinear behaviour of the curve slope with the increase of the fibreoptic amplifier gain in experiments [3] can be explained by the dependence of δ on the gain. As follows from Fig. 6, the value of δ reaches its maximum at a certain average gain. An increase in this parameter resulted in a noticeable lowering of δ relative to its maximum value, thus reducing the number of recirculation cycles with respect to what was expected and making the curve slope a nonlinear function of the fibreoptic amplifier gain.

Thus, to increase the sensitivity of active RFRIs, we need to improve the uniformity of the profile of the intracavity fibreoptic amplifier gain. In accordance with the results presented above, at least two requirements should be met. First, the pump level providing maximum δ should be chosen. Second, this pumping level should correspond to the prethreshold regime of the ring. A sufficiently uniform profile can be achieved by using methods suggested earlier for an erbium-doped fibre amplifier [1, 5]. One of these methods involves using a combination of active fibres of different composition and length. At the same time, the reciprocity of amplifier properties for counterpropagating waves should be provided for a fibreoptic amplifier in an RFRI. This problem requires an additional investigation.

Practical applications of an amplifier in an RFRI require the stability of the gain profile, especially within the spectral range where the ring may lase. We should bear in mind that the profile stability is the property of a system consisting of an SFS and a fibreoptic amplifier. In our experiments, we revealed a relatively weak dependence of the profile uniformity on the shape of the SFS spectrum (as well as on the average SFS power, according to preliminary studies). At the same time, the dependence of the gain profile on the number of recirculation cycles in the fibreoptic amplifier was demonstrated. Nevertheless, the influence of these factors on the stability of the gain profile requires further examination.

Thus, in this work we have experimentally investigated the spectral gain profiles of an erbium-doped fibre amplifier operating in a recirculation regime with input radiation supplied by a superfluorescent fibre source based on an ytterbium – erbium-doped fibre. We proposed a procedure to measure the spectral profile of a fibreoptic amplifier and to estimate its uniformity in the case of a broadband SFS. The uniformity of the spectral profile of the fibreoptic amplifier was studied as a function of the spectral shape of input radiation, the pump level, and the composition of the active fibre. We have shown that the uniformity of the spectral gain profile reaches its maximum at a certain pump level. We demonstrated the necessity to optimise a set of parameters of an SFS – fibreoptic amplifier system for the maximum uniformity of the spectral profile. An optimised SFS – fibreoptic amplifier system with a uniform gain profile would allow a large number of signal recirculation cycles to be achieved, which is the necessary condition for a radical improvement of the sensitivity of recirculation fibre ring interferometers.

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