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Increase in the output power of radiation with a wavelength of about 1650 nm using dual-polarised Raman amplification

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Abstract. **Nonlinear distortions of radiation at the Raman amplifier output in the regimes with one and two orthogonal polarisations (single- and dual-polarised amplification) in an extended optical fibre are compared. At an output power of 3.5 W and a wavelength of 1650 nm the nonlinear distortions for dual-polarised amplification are smaller, due to which a narrower spectrum can be provided for output radiation. As a result, one can measure more exactly, for example, the methane concentration using a remote lidar system. A somewhat higher power of an undistorted signal (~4 W) without deteriorating the spectral properties of output radiation is obtained in the dual-polarised amplification regime at the aforementioned wavelength.**

Keywords: *lidar, Raman amplifier, polarisation, pumping, methane.*

1. Introduction

The aircraft lidar systems used to determine the methane concentration in the atmospheres of the Earth and other planets call for laser sources with a power above 1–3 W in the wavelength range corresponding to methane absorption lines (1640–1660 nm), with a narrow emission spectrum, narrower than the methane absorption line width: ~0.1 nm. The power in the emitted pulse maximum for the spacecraft lidars used for global monitoring of methane concentration should exceed 20–30 W [1]. Currently, there are no such high-power commercial radiation sources. The aforementioned wavelength range is of interest not only for lidar technologies; it is also widely used in medicine, communication tools, and scientific research [2–5]. These devices with a high-purity emission spectrum can make up the deficiency of high-power laser sources in the range between the wavelengths typical of erbium-based fibre amplifiers and the wavelengths used in modern thulium-based amplifiers and lasers [6].

In this paper, we report the results of studying the possibility of increasing the output power of a Raman amplifier without deterioration of the spectral characteristics of its output radiation due to the amplification of two input orthogonally polarised signals (dual-polarised amplification) and their subsequent summation.

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2. Simulation and theoretical estimates

The output power of Raman amplifiers and converters in the wavelength range under consideration depends, in particular, on the polarisation effects occurring in the extended active fibre of the amplifier. The polarisation effects in a Raman amplifier were estimated in [7]. A depolarisation coefficient k_{pol}, which depends on the signal and pump polarisations, was introduced to take into account the depolarisation of signal and pump beams. The coefficient k_{pol} is 1 for coinciding polarisations, 0.5 for depolarised pumping, and zero for mutually orthogonal signal and pump polarisations. The total gain of a Raman fibre is $g_{R\,tot} = g_R k_{pol}$, where g_R is the gain for coinciding signal and pump polarisations. We performed a comparative theoretical simulation of dual- and single-polarised amplification in a Raman amplifier.

The power at the Raman amplifier output was determined by solving the equation for the nonlinear signal–pump interaction [8]:

$$P_S(z) = \left(P_{S0} + \frac{\omega_S}{\omega_p}P_{p0}\right)\exp(-\alpha z)\left\{1 + \frac{\omega_S P_{p0}}{P_{S0}}\right.$$
$$\left.\times\exp\left\{\frac{g_R k_{pol}}{\alpha}\left(\frac{\omega_p}{\omega_S}I_{S0} + I_{p0}\right)[\exp(-\alpha z) - 1]\right\}\right\}^{-1}. \qquad (1)$$

Here, P_S is the power of the signal Stokes component, which depends on coordinate z; ω_S and ω_p are, respectively, the signal and pump frequencies; α is the optical-signal damping coefficient in the fibre; and P_{S0}, P_{p0}, and I_{S0}, I_{p0} are, respectively, the signal and pump powers and intensities at the beginning of the fibre (at $z = 0$). The Stokes signal power at the fibre amplifier output, P_{SL}, is given by the expression $P_{SL} = I_{SL}A_{eff}$, where A_{eff} is the effective fibre core area and L is the fibre length. The results of calculating the output power P_{SL} from formula (1) as a function of input power for different coefficients k_{pol} are shown in Fig. 1.

The calculations were carried out using the following parameter values: $\alpha \approx 0.22$ dB km^{-1} (or 5.2×10^{-5} m^{-1} for a wavelength of 1.55 μm in the domain of small fibre losses), $P_{p0} = 4.3$ and 1 W (the pump powers were chosen to be the same as used in the experiment), and the Raman conversion factor for quartz fibre with depolarisation disregarded is $g_R = 0.7 \times 10^{-13}$ m W^{-1}. The dependences of the output power on the input power at a low pumping level, presented in Fig. 1b, are almost linear. At the same time, one can see in Fig. 1a that, the closer the input signal and pump polarisations to each other (i.e., the larger the k_{pol} value), the more strongly the amplifier output power rises; even at weak input signals,

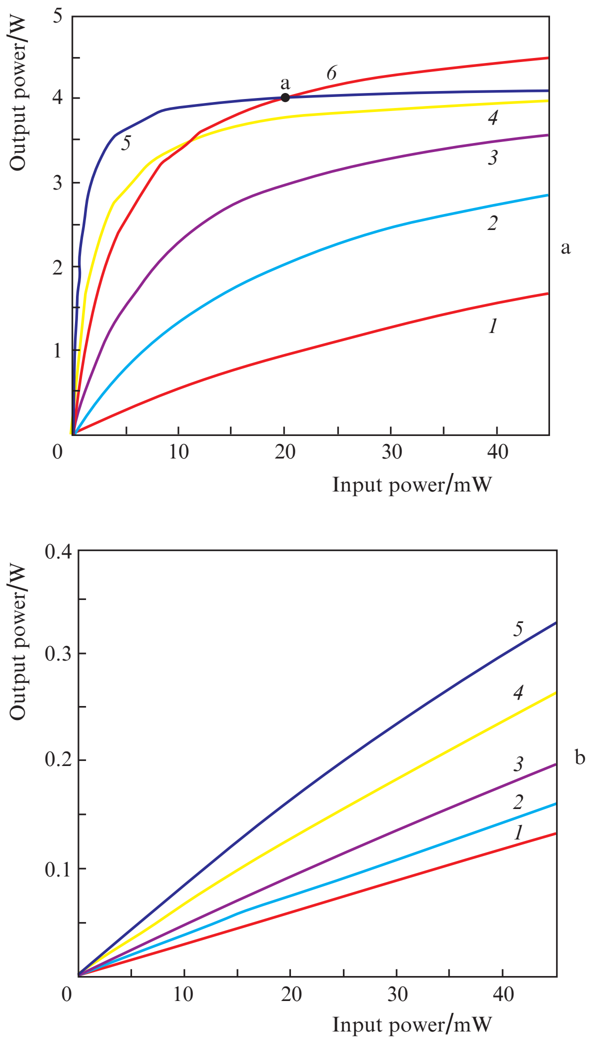

Figure 1. Dependences of the Raman power at the output of extended (800-m-long) fibre on the input power for $k_{\rm pol}$ = (*1*) 0.21, (*2*) 0.27, (*3*) 0.32, (*4*) 0.39, (*5*) 0.45, and (*6*) 0.56. (a) The total pump power is 4.3 W for curves *1*–*5* (single-polarised amplification) and 5 W for curve *6* (dual-polarised amplification). (b) The pump power is 1 W (single-polarised amplification).

there arises a saturation region, in which nonlinear distortions increase and the output signal spectrum broadens. It was found experimentally (see below) that the output signal spectrum broadens with an increase in the pump power above 4.3 W. This spectral broadening is explained by nonlinear distortions caused by the self-modulation of the radiation propagating in an extended fibre [9].

To exclude the radiation spectrum broadening, an attempt was made to divide the input signal into two components with orthogonal polarisations in order to implement amplification in a region more distant from the saturation domain. Under these conditions, if the total pump power is increased to 5 W, with a pump power of 2.5 W per each polarisation, the output power of Stokes optical signal would be ~4 W (point 'a' on curve *6*, Fig. 1a). This can be qualitatively explained as follows: the pump power per each polarisation in the dual-polarised amplification regime is lower by about half, and the gain linearity may be higher. The total power of two amplified orthogonally polarised signals may be equal to the power of the output signal with one polarisation. Since the amplification linearity and threshold of nonlinear effects are higher for two less intense orthogonal polarisations of the output signal, the total spectrum of two amplified signals may also be narrower than that obtained without splitting signal into polarisation components. Two signals with orthogonal polarisations in an active fibre exhaust pump power differently; therefore, the coefficients $k_{\rm pol}$ for them will be somewhat different, depending on the amplifier design features. Thus, the pumping in the amplifier will be most likely used more efficiently.

3. Experimental results

To compare the signals formed at the amplifier output, we investigated the amplification scheme for a distributed feedback (DFB) laser with linear polarisation of radiation (Fig. 2). The linearly polarised radiation of this laser was split into two channels using a polarisation beam splitter (PBS). Orthogonally polarised beams propagated in each channel; an additional segment of panda-type fibre was inserted in one of the channels to eliminate mutual coherence of radiation. The length L of this segment was chosen from the condition

$$L \gg L_{\rm coh} = c/(2\Delta\nu), \qquad (2)$$

where $L_{\rm coh}$ is the DFB-laser coherence length, c is the speed of light, and $\Delta\nu \approx 1$ MHz is the lasing spectrum width. Then both radiation channels were combined using a polarisation beam combiner (PBC). After the insulator the radiation was supplied to a preamplifier and then to a final Raman amplifier; the output radiation of the latter can be supplied to a photodetector, optical spectrum analyser, or optical power meter.

Note that both the preliminary and final amplifiers were designed according to the counterpropagating pump scheme; unpolarised pump radiation was introduced conventionally into active fibre of the optical multiplexer. The radiation spectrum at the final amplifier output was recorded, as well as the power and signal from the photodetector, before which calibrated cells with methane can be installed to estimate additionally the radiation spectrum width. The signal parameters in this scheme were compared both in the presence of a splitter–combiner and in its absence (i.e., when radiation propagated directly from the master laser to the ISO insulator, as shown by a dashed line in Fig. 2). First the output characteristics of the amplifier as functions of input signals were measured; they were found similar to those obtained by theoretical simulation (Fig. 1). It was established that, within the measurement error, the curves for dual- and single-polarised amplification almost coincide (Fig. 3) and are close to curve *3* in Fig. 1a. Since under conditions of dual-polarised amplification the values of input signal and pump power for each polarisation are about two times smaller than for the single-polarised regime, the coincidence of curves in Fig. 3 can be explained by the fact that the $k_{\rm pol}$ values are larger for polarisation-separated radiation components. A calculation based on formula (1) showed that $k_{\rm pol} \approx 0.56$, whereas for the single-polarisation radiation $k_{\rm pol} \approx 0.32$ [Fig. 1a, curve (*3*)]. In the case of two polarisations, the pump power was ~2.15 W for each polarisation, and the output signal, calculated from formula (1), was multiplied by 2, because the output powers of two amplified orthogonally polarised signals were summed.

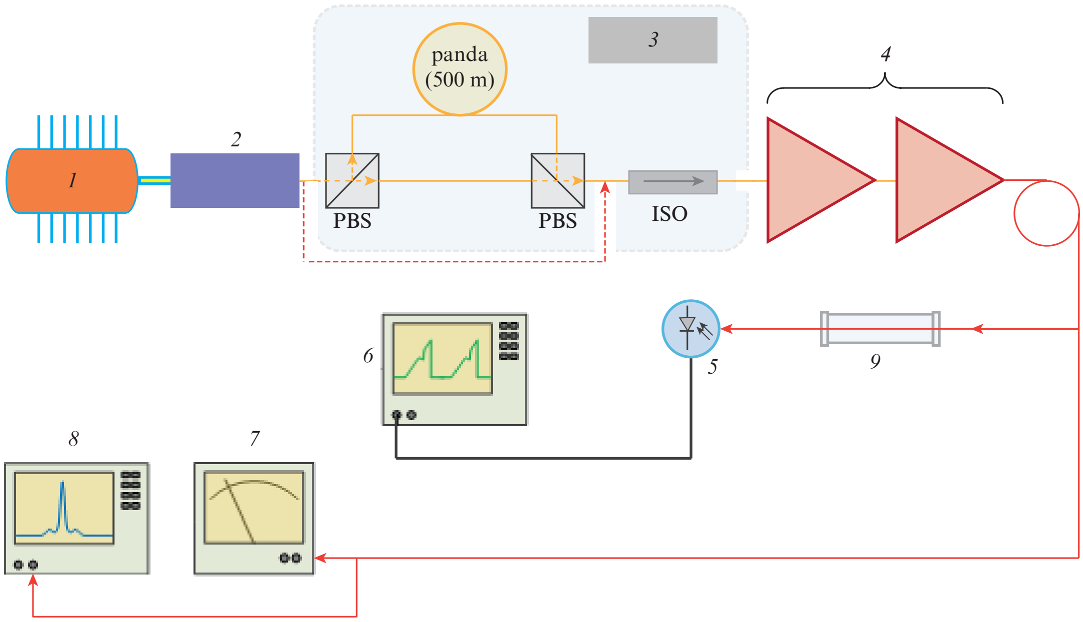

Figure 2. Block diagram of the setup: (*1*) scanned-wavelength master laser; (*2*) polarisation controller; (*3*) optical depolariser; (*4*) two-cascade Raman amplifier; (*5*) photodetector; (*6*) oscilloscope; (*7*) optical power meter; (*8*) optical spectrum analyser; (*9*) cell with methane.

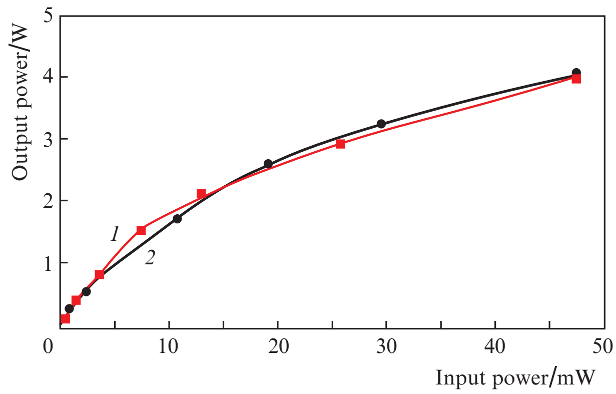

Figure 3. Experimental dependence of the output power on the input power at a pump power of 4.3 W for (*1*) dual-polarised and (*2*) single-polarised amplification.

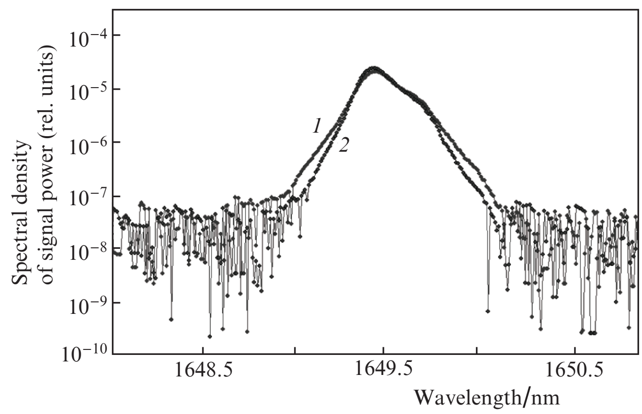

Figure 4. Radiation spectra at the Raman amplifier output for the cases (*1*) without and (*2*) with separation in polarisations.

The experimental spectra of output signals are shown in Fig. 4. Note that laser radiation was periodically scanned over wavelength with a scan range of ~0.5 nm and a period of ~20 ms. The spectra were recorded at an optical signal power of ~40 mW at the final amplifier input. It can be seen that the spectral width for the case with splitting radiation into polarisations is somewhat smaller than for the case without splitting. This fact indicates that nonlinear distortions are smaller for two amplified orthogonally polarised signals.

This conclusion is confirmed by comparing the oscillograms of photodetector output signals recorded for a methane-containing cell placed in the beam path after the final amplifier (Fig. 5). A calibrated cell filled with methane was installed between the photodetector and the output fibre end face. Oscillograms were recorded for two pump powers of the output amplifier: 4.3 and 1 W. The input signal powers at the final amplifier input were maintained at the same level: ~40 mW. At a pump power of 4.3 W the power at the final amplifier output was ~3.5 W in both cases (with and without splitting in polarisations). One can see in Fig. 5a that the dip in the methane absorption line for polarisation-split radiations is larger than for non-split radiations (points A and B, respectively). Since the spectrum in the former case is somewhat narrower, the methane absorption line is recorded more accurately, with a narrower time or wavelength (in the scan range) integration domain; therefore, the gas concentration can be measured more accurately. Without splitting in polarisations, the amplifier operates near the saturation region, where nonlinear phenomena may lead to spectral broadening of radiation; therefore, the methane absorption line will be integrated in a wider domain of the wide spectral emission line. At a low pump power of the amplifier in both cases under consideration, amplification occurs on linear portions of the output amplifier characteristic, where the radiation spectrum is less distorted; therefore, the oscillograms for these cases appear approximately equal (Fig. 5b).

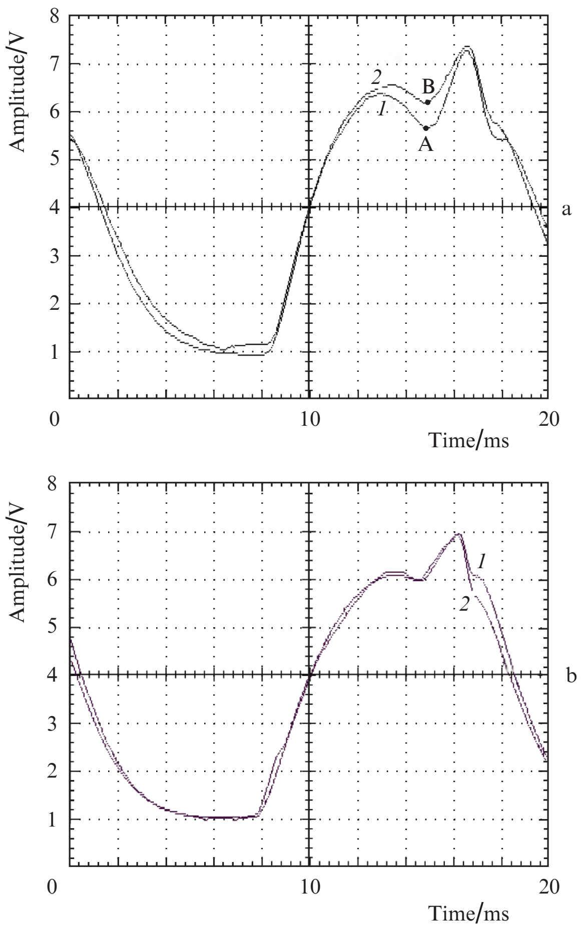

Figure 5. Oscillograms of lidar signals at the photodetector output in the presence of a cell with methane in the beam path for the cases with (*1*) and (*2*) without separation of radiation in polarisations, at pump powers of (a) 4.3 and (b) 1 W.

With an increase in pump power for dual-polarised amplification, the amplifier output power turned out to be ~0.5 W (or 10%–12%) higher than in the case of single-polarised amplification, where the radiation power was 3.5 W. The radiation spectrum width was the same in both cases. The simulation results approximately coincide with experimental data, and the gain in power due to the splitting into two signals with orthogonal polarisations is not very large. However, even this small increase in power may somewhat increase both the accuracy of background methane sensing and widen the lidar range, especially when the case in point is aircraft sensing with at flight height up to ~10 km.

4. Conclusions

It was shown that dual-polarised amplification in a Raman amplifier increases its output power from ~3.5 to ~4 W without broadening the output radiation spectrum, which increases, for example, the energy potential of lidar for remote sensing methane concentration in air. The results of simulating the splitting of the input optical signal into two signals with orthogonal polarisations and amplification of this signal are in good agreement with the experimental data.

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