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Generation of linearly polarised light near 1.4 μm in a cascaded, random distributed feedback Raman laser

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Abstract. **We have demonstrated efficient generation of linearly polarised light by a random distributed feedback laser based on stimulated Raman scattering in a 1.8-km-long fibre, pumped by linearly polarised radiation of an ytterbium-doped fibre laser with a lasing wavelength near 1.06 μm. Cascaded generation up to the fifth Stokes component (1.4 μm) with wavelength tuning by changing the pump wavelength is obtained. The output power of the fourth Stokes component reached 5 W at λ = 1.34 μm. The problems related to the further mastering of the long-wavelength region are discussed.**

Keywords: *fibre optics, Raman laser, random distributed feedback, cascaded generation, Rayleigh scattering, polarisation-maintaining fibre.*

1. Introduction

Lasers based on stimulated Raman scattering (Raman lasers) with random distributed feedback (DFB) [1, 2] are lasers of new type, where processes of stimulated Raman and Rayleigh scattering of light in passive fibres provide, respectively, distributed gain and random feedback. The feedback, being very small, is nevertheless sufficient to implement lasing in passive fibres of kilometre length, because the Raman integral gain is proportional to the fibre length and pump power. When using relatively short fibres (less than 1 km) and high pump powers, random DFB Raman lasers have demonstrated high-power (10–200 W) generation of unpolarised [3] and linearly polarised [4] light with absolute optical conversion efficiency of pump power into the Stokes component of about 90%, a value close to the quantum limit (95%) of Raman lasers based on germanosilicate fibres.

Recently, cascaded generation of linearly polarised light in a random DFB Raman laser based on a 1-km-long polarisation-maintaining (PM) fibre was demonstrated in [5]. The optical conversion efficiency of pump radiation from an ytterbium-doped fibre laser (YDFL) with a wavelength 1.05 μm into the first and second Stokes components reached 75% and the conversion efficiency into the third Stokes component was 70%, i.e., close to the corresponding quantum limit. The high efficiency and simplicity of the schemes of Raman lasers with random DFB make them promising for various applications, including lasing in the telecommunication spectral region. Cascaded generation from the first to the sixth Stokes components in an YDFL-pumped Raman laser with random DFB (based on a 10-km long fibre) with an increase in the pump power was recently demonstrated in [6]. However, because the fibre was long, its conversion efficiency was low (less than 15% at a wavelength of 1.36 μm) and the generated power did not exceed 1.8 W. In addition, the output radiation was unpolarised.

In this paper, we report the results of studying the possibility of mastering the long-wavelength spectral region using the scheme of a random DFB Raman laser (proposed by us in [5]) on the basis of PM fibre. Due to an increase in the passive-fibre length from 1 to 1.8 km, cascaded Raman generation of linearly polarised light up to the fifth Stokes component (with a wavelength close to 1.4 μm) was obtained at the same pump power (to 15 W). The optical pump conversion efficiency into the first three Stokes waves was at a level of 55%–60%. The output power of the fourth Stokes component at a wavelength of 1.34 μm reached 5 W, a value corresponding to an optical conversion efficiency of 33%. The generation in the long-wavelength spectral region was limited by other nonlinear effects, which compete with the Raman process in the range of fibre zero-dispersion wavelength (ZDW) (~1.4 μm); this limitation was also observed in [6]. Some ways to solve this problem are discussed below.

2. Experimental setup

A schematic of the experimental setup is shown in Fig. 1; it is similar to that reported in [5]. Pumping was performed by an YDFL, designed according to the master oscillator–power amplifier scheme. The laser generated single-mode linearly polarised light with an output power up to 15 W. An YDFL

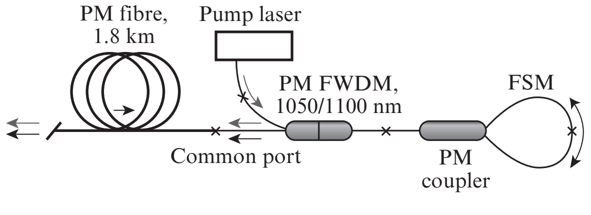

Figure 1. Schematic of the experimental setup:
(PM fibre) polarisation-maintaining fibre; (PM FWDM) polarisation-maintaining filtering WDM; (FSM) fibre Sagnac mirror.

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with a ring cavity and selector based on fibre Bragg grating (FBG) with high reflectance was used as a master oscillator. The radiation wavelength varied from 1040 to 1080 nm using an FBG with an appropriate Bragg wavelength. Since the output radiation of the master laser was unpolarised, a fibre polarisation beam splitter was installed at its output to select one linearly polarised component, which was then launched into a two-stage ytterbium-doped PM fibre amplifier. The random DFB Raman laser was designed according to the forward pumped scheme. The laser was formed on a 1.8-km-long passive PM fibre (Fujikura SM98-PS-U25D). The output end face of the fibre was cleaved at an angle larger than 10° to exclude the Fresnel back reflection. A broadband fibre Sagnac mirror (FSM), based on a PM fibre coupler, was spliced to the other fibre end face. The FSM reflectance $R = 4\kappa(1 - \kappa)$, depending on the coupling ratio κ, decreased with an increase in the wavelength from 93% ($\lambda = 1.1$ μm) to 6% ($\lambda = 1.4$ μm) (Fig. 2).

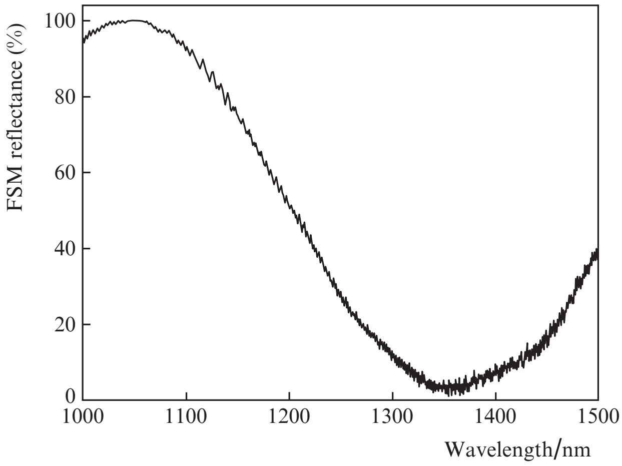

Figure 2. Dependence of the fibre Sagnac mirror reflectance on the light wavelength.

Pump radiation was coupled into a 1.8-km-long passive fibre through a polarison-maintaining filtering wavelength division multiplexer (PM FWDM); lasing was provided by the existence of the Raman gain at the Stokes wavelength and a feedback. The latter was implemented, on the one hand, by the reflection of the ring mirror and, on the other hand, by the Rayleigh backscattering inside the long passive fibre. The output power and spectra were measured from the side of the angle cleaved fibre end using, respectively, a power meter and an optical spectrum analyser (OSA).

3. Results

An increase in the input pump power from 1 to 15 W led to successive (from the first to the fifth) generation of Stokes components. A change in the pump wavelength caused corresponding tuning of the lasing wavelength. Figure 3a shows the output radiation spectra at the maximum input pump power for pump wavelengths of 1040.6, 1064.4, and 1080.1 nm. One can see that the Stokes components exhibit a narrow generation line with FWHM values of ~1, ~1.7, ~3, and ~4 nm for the first, second, third, and fourth orders, respectively, at the maximum generation power of these components. The aforementioned values are in agreement with the data obtained for a Raman laser with random DFB in a 1-km-long fibre [5]. However, when the wavelength of a current Stokes component approaches the zero dispersion wavelength of the passive fibre in use (~1.4 μm), a broadband generation line of the fifth Stokes component arises (Figs 3a–3c). A similar effect was observed in a 10-km-long Raman fibre laser with random DFB, which generated unpolarised light [6].

The power of the spectral components of generated light was determined in the following way. First, the relative distribution of the output power over emission lines was found using an OSA. Then, the OSA was replaced with a power meter to measure the total power at the output of the scheme. The thus obtained values of the output power were used to calibrate the powers of residual pump radiation and Stokes components in different cascades. It can be seen in Figs 3d–3f that the power evolution up to the fourth cascade is qualitatively similar to that in short random DFB Raman lasers, which generated both unpolarised [7] and polarised [5] light. Before the Raman lasing threshold, there is only pump radiation at the output, whose power is reduced by approximately 35% after the transmission through the 1.8-km-long fibre. When reaching the threshold, the power of the first Stokes component begins to exponentially rise, while the pump power depletes, until the pump radiation is practically entirely converted into the Raman signal. The power of the first Stokes component increases until reaching the second lasing threshold, after which the power of the second Stokes component begins to exponentially rise, while the first-component power decreases, etc. However, the fifth Stokes component starts being generated near the fibre ZDW, despite the fact that the power of the previous component does not reach its maximum (Figs 3d–3f).

The decrease in the generation threshold for the higher order Stokes components is related to the influence of nonlinear effects, primarily, the four-wave mixing, which becomes much more pronounced in the vicinity of ZDW. The competition between the nonlinear effects and Raman gain leads to a strong decrease in the Raman conversion efficiency when generating the next Stokes orders and an increase in the spectral continuum in the range of fibre anomalous dispersion. It can be seen in Fig. 3 that the generation threshold of the higher order Stokes components increases with a change in the pump wavelength from 1040 to 1080 nm. This behaviour can be explained by the influence of several factors: the weakening of the Rayleigh scattering with an increase in wavelength, the decrease in the Raman gain, and the drop of the ring Sagnac mirror reflectance from 93% at $\lambda = 1.1$ μm to 6% at 1.4 μm (see Fig. 2). As a result, the generation power of the corresponding Stokes components significantly increases when the pump radiation is converted to longer wavelengths.

The optical conversion efficiency, calculated as the ratio of the power of the corresponding Stokes component to the input pump power, was found to be about 62%, 59%, and 54% for the first, second, and third components, respectively, at $\lambda_p = 1064.4$ and 1080.1 nm (Figs 3e, 3f) and slightly smaller at $\lambda_p = 1040.6$ nm (Fig. 3d). The generation power changed from 2 to 7 W for different Stokes orders and reached 5 W for the fourth Stokes component at a wavelength of 1.34 μm (Figs 3c, 3f), which corresponds to a conversion efficiency of 33%. Due to the limitation of the pump power and the competition with four-wave mixing, the generation power on the fifth Stokes component near 1.36 μm was 0.8 W (Figs. 3a, 3d).

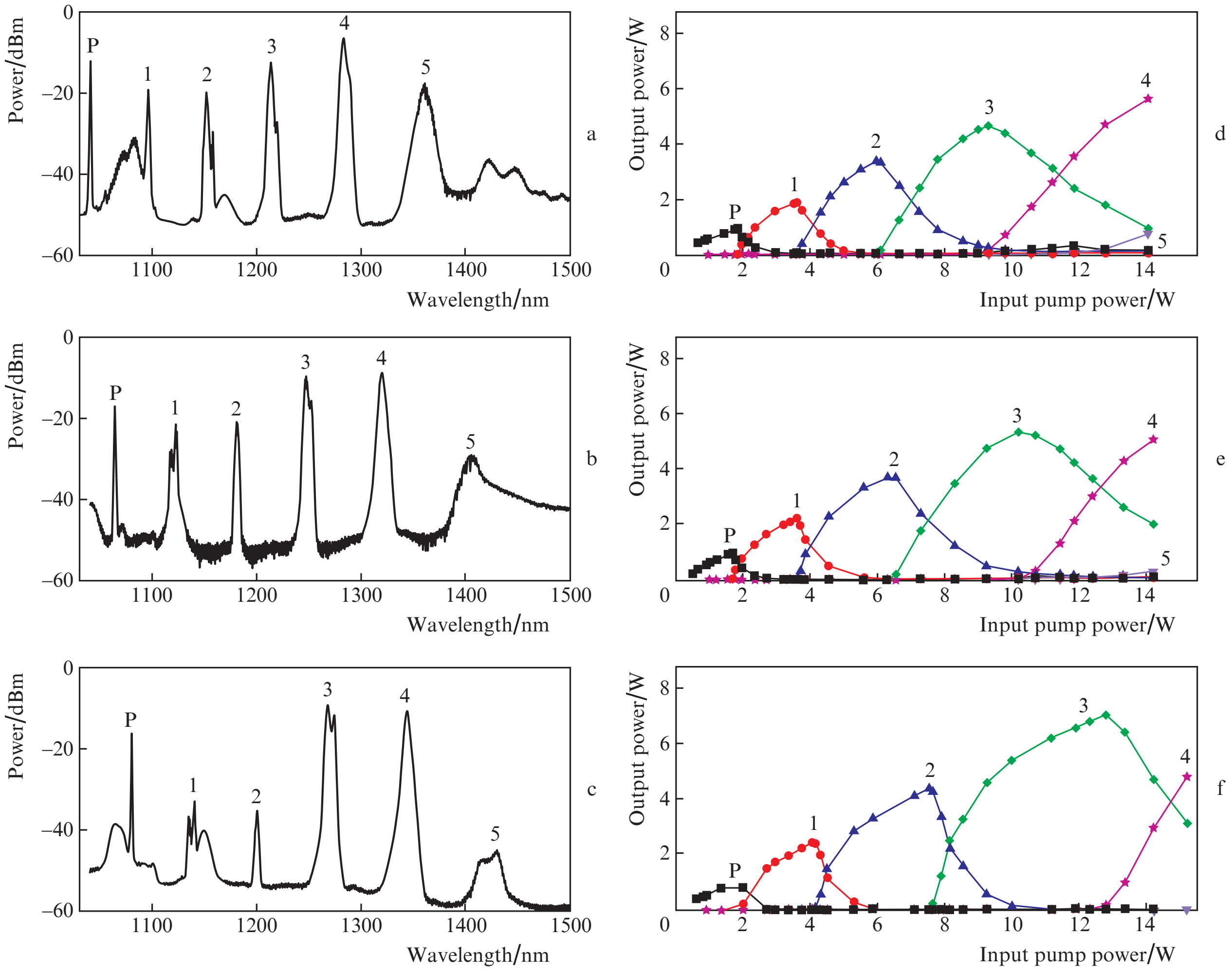

Figure 3. (a–c) Output spectra of the random DFB Raman laser in a 1.8-km-long fibre at input pump powers P_p = (a, b) 14.1 and (c) 15.2 W for pump wavelengths λ_p = (a) 1040.6, (b) 1064.4, and (c) 1080.1 nm and (d–f) dependences of the output powers of different Stokes components and residual pump power on P_p for λ_p = (d) 1040.6, (e) 1064.4, and (f) 1080.1 nm. Letter 'P' stands for the pump wavelengths and powers and numbers 1–5 indicate the wavelengths and powers of the Stokes components.

The obtained values of the power and conversion efficiency greatly exceed those reported in [6], because we used a much shorter fibre. In addition, our scheme (based on PM fibre components) makes it possible to generate stable linearly polarised light. As was demonstrated in [4, 5], the extinction ratio in this scheme exceeds 22 dB and is not reduced with an increase in the generation power on different Stokes components.

4. Discussion

The results of our study showed that efficient cascaded generation may occur in the normal-dispersion region of a long optical fibre. In addition, generation of narrow-band Stokes radiation is also observed when pumping far in the anomalous dispersion region of the fibre [1]. However, the competition between nonlinear effects in the vicinity of ZDW (~1.4 μm) gives rise to a broadband spectral continuum and reduces the efficiency of cascaded Raman generation. This problem must be solved to further master longer wavelengths.

One of the ways is to use a narrow-band FBG recorded on the fifth Stokes component wavelength. An insertion of this FBG between the PM FWDM and broadband Sagnac mirror in the scheme presented in Fig. 1 was expected to promote the narrow-band generation of the fifth Stokes component. Figure 4 shows the output spectra under pumping at a wave-

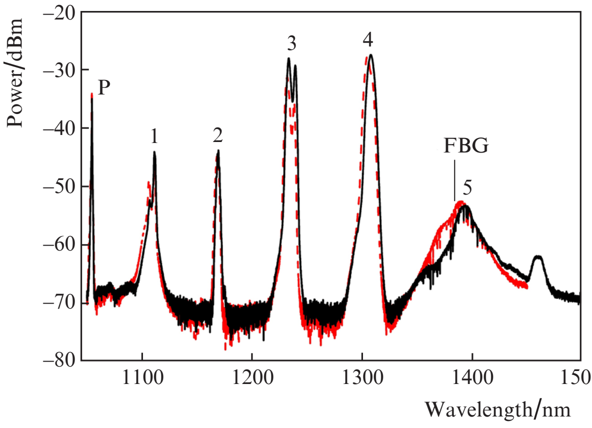

Figure 4. Output spectra of the random DFB Raman laser in a 1.8-km-long fibre pumped by linearly polarised 1055-nm light with an FBG at 1384 nm (solid line) and without FBG (dashed line).

length of 1055 nm, measured without the FBG and with the FBG recorded at 1384 nm. It can be seen that the spectral continuum near 1.4 μm is retained in the presence of the FBG; therefore, it is generated in a single pass through a long passive optical fibre.

In addition, the number of Stokes cascades can be increased by shortening the optical fibre with a simultaneous increase in the pump power or by applying a passive fibre with a red-shifted (e.g., to 2 μm) ZDW.

5. Conclusions

Efficient cascaded Raman generation of linearly polarised light due to the Raman gain and Rayleigh feedback in a passive 1.8-km-long PM fibre pumped by linearly polarised radiation was demonstrated. Stokes components up to the fifth order (with a wavelength near 1.4 μm) were obtained. The optical pump conversion efficiency into the first three Stokes components was at a level of 55%–60% and the conversion efficiency into the fourth component (at $\lambda = 1.32$ μm) was about 36%. When tuning the fourth component to a wavelength of 1.34 μm, its power reached 5 W with a conversion efficiency of ~33%. The power of the fifth Stokes component at a wavelength of 1.36 μm amounted to ~1 W. An increase in wavelength to ~1.4 μm led to the generation of a broadband continuum in the anomalous dispersion region of the fibre, which was caused by other nonlinear effects, in particular four-wave mixing, which limited the cascaded Raman generation at wavelengths above 1.4 μm.

The laser scheme presented here is of interest for the fundamental research, as well as for sensor and telecommunication applications, where efficient sources of linearly polarised light are required. In particular, the spectral range of 1.34–1.36 μm is quite appropriate to use in the above-described random DFB Raman laser in the scheme of a fibre distributed Raman amplifier with second-order pumping [8] or in a distributed Brillouin sensor system [9]. Currently, the scheme of the cascaded Raman laser based on a conventional FBG cavity at all intermediate Stokes components has a higher efficiency (to 65% [10]); nevertheless, it is much more complicated and does not allow one to generate linearly polarised light.

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