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Mode selection in a directly diode-pumped Raman fibre laser using FBGs in a graded-index multimode fibre

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Abstract. **We examine the selection of the fundamental transverse mode in a directly multimode-diode-pumped Raman laser with a cavity formed by fibre Bragg gratings (FBGs) in a graded-index fibre. The application of FBGs recorded by femtosecond radiation in the central region of the fibre core provides an unprecedentedly high (for lasers of this type) beam quality ($M^2 < 1.2$) at a lasing power above 5 W.**

Keywords: *fibre laser, Raman laser, graded-index fibre, fibre Bragg grating, diode pumping, mode selection.*

1. Introduction

Raman fibre lasers, whose principle of operation is based on stimulated Raman scattering, are considered to be promising radiation sources, tunable in a wide wavelength range. Passive single-mode optical fibres are generally used as a gain medium of Raman lasers, where pumping is performed into the fibre core by single-mode fibre lasers. Single-mode ytterbium-doped double-clad fibres serve as an active medium for the highest power pump lasers. The latter, in turn, are pumped into the cladding by high-power multimode laser diodes (LDs). In contrast to the rare-earth-doped lasers, designed for specific spectral ranges, Raman lasers can operate at practically any wavelength spaced from the pump wavelength by the Stokes shift and be tuned within the wide Raman gain profile. Raman lasers are characterised by a small quantum defect; short time response to the pump-induced gain, low level of spontaneous-emission; and the absence of photodarkening, which is a serious problem for fibre lasers generating at wavelengths close to ~1 μm (in particular for the ytterbium-doped fibre laser (YDFL) [1]).

At the same time, the Raman laser generation at wavelengths below 1 μm is hindered because of the absence of high-power single-mode pump sources in the short-wavelength region (in particular, the lower limit of YDFL generation wavelength is ~980 nm [1]). An alternative approach is to directly pump Raman lasers by commercially available multimode LDs, whose power in the range of 915–980 nm exceeds 100 W per module. A multimode pump beam can efficiently be coupled into the relatively large core of a multimode passive optical fibre with a refractive index gradient (graded-index fibre) [2], which can also cleanup the pump beam as a result of the Raman conversion [3].

In the first studies of the Raman lasers based on graded-index multimode fibres, neodymium-doped solid-state multimode lasers were used as pump sources. The development of the technology of multimode LDs stimulated investigations of the possibility of using these sources to implement Raman generation in graded-index fibres. In one of the first studies in this field, we demonstrated a cw Raman laser with direct pumping by a laser diode with a wavelength ~940 nm [4]. The output power of the Raman laser at 980 nm amounted to 2.9 W at a slope pump conversion efficiency into the Stokes wave of about 25%. The laser cavity was formed in a 4.5-km-long graded-index fibre by a high-reflecting fibre Bragg grating (FBG) and the normally cleaved fibre end. The generated output beam had a much higher quality than the diode pump beam due to the beam cleanup under Raman conversion in the graded-index fibre and additional mode selection by the FBG with a narrow reflection spectrum.

Recently, Yao et al. [5] showed that the output power and slope efficiency of a diode-pumped Raman laser can be increased up to 20 W and 80%, respectively, using a relatively short (1.5 km) graded-index fibre and a double-pass pump scheme with a higher power, obtained by combining two 975-nm LD beams. An even higher power (~80 W) was implemented in a 0.5-km graded-index fibre for a similar laser cavity configuration at a pump power of ~150 W, introduced from a multimode 980-nm LD [6]. However, the laser wavelength (~1020 nm) demonstrated in both studies is not of much interest, because a much higher power can be obtained at this wavelength with the aid of a conventional YDFL.

The possibility of multimode pumping of Raman lasers based on passive double-cladding fibres was simultaneously studied. The lasing power of ~100 W was obtained by applying a multimode YDFL for pumping into the fibre cladding [7]. When using multimode LDs for pumping, the lasing power did not exceed 6 W; however, the beam quality ($M^2 = 1.9$) exceeded that obtained with Raman lasers based on graded-index fibres. The further development of Raman lasers pumped by multimode LDs into the fibre cladding calls for improving the fabrication technology of special double-clad fibres, which now have higher losses than commercially available graded-index fibres.

To advance into the short-wavelength range, we developed a Raman laser in a graded-index fibre with diode pumping in

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the vicinity of 915 nm [8], which has a higher (as compared with the Raman laser described in [4]) output power (~4 W) and slope efficiency exceeding 40%. Large values of laser parameters at a shorter generation wavelength (954 nm) were obtained due to the optimisation of the graded-index fibre length proceeding from the given level of pump power: ~50 W.

In this paper, we report the results of studying the possibility of performing the mode selection of Raman laser radiation in graded-index fibres using an FBG. It is shown that, at output power levels on the order of 1 W, the beam quality can significantly be improved in comparison with that obtained in the other studies on Raman lasers with direct diode pumping, up to the generation at the fundamental transverse mode.

2. Experimental setup

To protect high-power multimode LDs, the radiation was launched (as in [8]) using bulk optics (Fig. 1). The pump radiation of a high-power multimode diode was coupled into the core of a Corning 62.5/125 fibre (numerical aperture NA = 0.275) using collimating lenses L1 and L2 with an efficiency higher than 70%. In contrast to [8], the launched pump power at 915 nm was increased to approximately 60 W, which allowed us to reduce the graded-index fibre length from 2.5 to 1.1 km. Selective mirrors M1–M3 were used to separate the Raman generation and pump beams. The powers of the Raman generation and the unabsorbed part of the pump beam were measured by three optical power meters OPM1–OPM3.

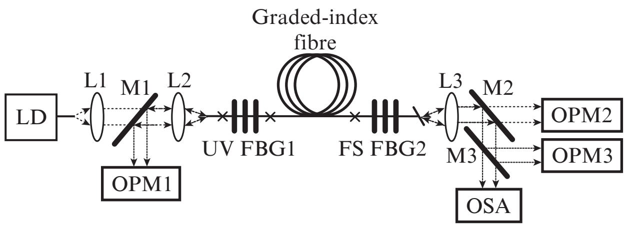

Figure 1. Schematic of the experimental setup.

The linear cavity, as in the previous experiments [4, 8], was formed by a highly reflective (R_1 ~80%) FBG1, recorded in the interference scheme by a UV beam in the core of graded-index Corning 62.5/125 fibre (see [9]), and the normally cleaved fibre end (Fresnel reflection coefficient R_2 ~4%). In addition, to improve the selection of the fundamental mode of graded-index fibre, an FS FBG2 was spliced at the laser output (it was point-to-point recorded in the central region of the fibre core by a femtosecond (FS) laser beam [10]). For comparison, a UV FBG2, recorded (as well as the FBG1) by UV radiation, was also used at the output. In this case, the output end of the fibre was cleaved at an angle larger than 10° to reduce the feedback induced by the Fresnel reflection. The 1.3-mm-long FS FBG with a period $\Lambda = 0.645$ μm operated in the second order with a reflectance of ~4% and a spectral width $\Delta\lambda = 0.21$ nm at a wavelength of 954 nm. Note also that the graded-index fibre (in contrast to that described in [10]) had a standard cladding 250 μm in diameter; therefore, to improve the FS FBG quality, the acrylic cladding was removed from the fibre before the recording.

Figure 2 shows the reflection spectra of the UV FBG1 and output FS FBG2, measured using a single-mode fibre coupler with a coupling ratio of 50 : 50. The FBGs recorded in the graded-index multimode fibre were by turn spliced to one of the single-mode ports of the coupler. Note that the information about the reflectance for higher order modes is lost under these experimental conditions; nevertheless, the reflection spectrum of the output FS FBG2 exhibits several resonances at wavelengths smaller than 954 nm, which correspond to the lower order modes.

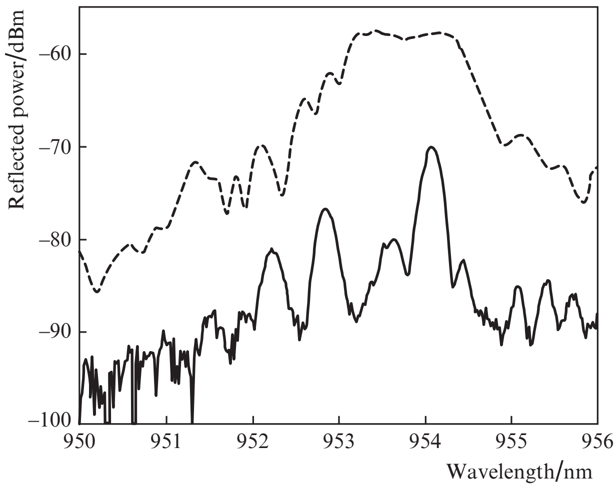

Figure 2. Reflection spectra of (dashed line) UV FBG1 and (solid line) output FS FBG2.

3. Experimental results

First we will compare the generation spectra of a 2.5-km-long Raman laser for output mirrors of several types (Fig. 3a). When using mode-nonselective Fresnel reflection from the output end of the fibre, one can observe generation of a relatively homogeneous spectrum ~1 nm wide (dashed curve). In the case of output UV FBG2 (which was also used in [8]), one can observe a three-peak structure with peaks spaced by ~0.6 nm, which corresponds to the reflection of three individual groups of graded-index fibre modes with small transverse indices (dot-dashed curve). The 954-nm component corresponds to the fundamental mode; the mode-group number increases with decreasing wavelength. The reflection spectrum is narrow for each group of modes; therefore, the generation spectra of different mode groups are well resolved. When using the highly reflective UV FBG1, the reflection spectrum is relatively wide, as a result of which individual resonances cannot be resolved. In the case of output FS FBG2, one observes a two-peak generation spectrum with a distance of ~1.2 nm between the peaks (solid curve). It can be seen that the second group of modes (at a wavelength of 953.6 nm), spaced by 0.6 nm from the main one, is not involved in lasing. Note also that the amplitude of the peaks related to the groups of higher order modes is relatively small. When the FS FBG2 is used, the peak at 953 nm is unstable in time and does not always manifest itself in the generation spectrum.

As in [8], the generation efficiency significantly decreased when the UV FBG2 was used as the output mirror instead of the normally cleaved fibre end. At the same time, a replacement of the normally cleaved fibre end at the output with the

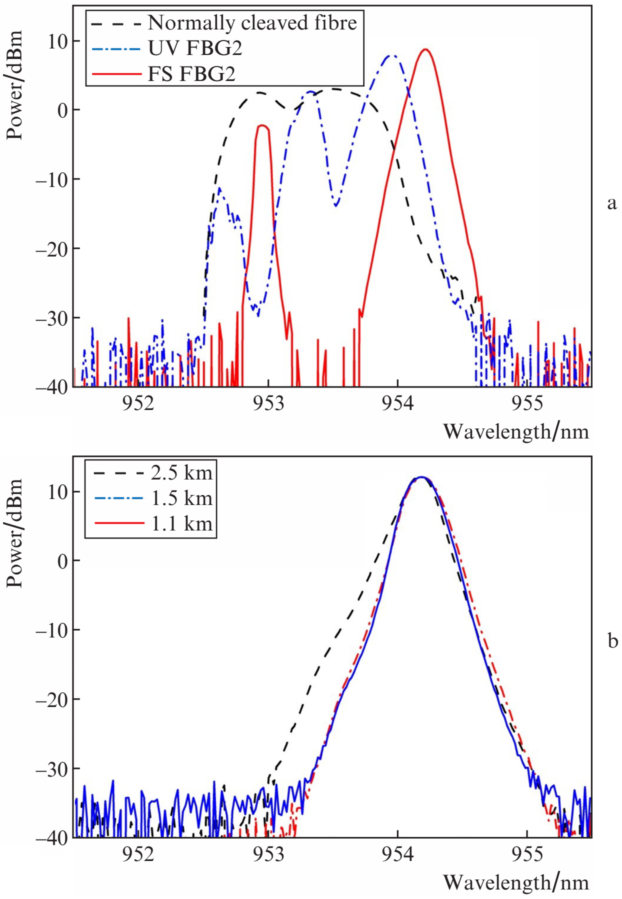

Figure 3. (a) Generation spectra of the Raman laser with a length $L = 2.5$ km at the output power $P_{out} = 1.9$ W for output mirrors of different types: normally cleaved fibre end, UV FBG2, and FS FBG2. (b) Generation spectra of the Raman laser with output FS FBG2 at the output power $P_{out} = 4.8$ W and laser lengths $L = 2.5$, 1.5, and 1.1 km.

FS FBG2 barely changed the lasing power. This fact, along with the good mode selection, suggests that this cavity configuration has good prospects.

In the further experiments the laser length was reduced to 1.1 km. It can be seen in Fig. 3b that the generation spectrum at a fixed output power of 4.8 W only slightly changed with a decrease in the cavity length. Note that the periodic occurrence of the additional peak at a wavelength of 953 nm (corresponding to higher order modes) was observed only in the 2.5-km-long laser. Stable single-mode lasing was implemented when the graded-index fibre length was reduced to 1.1 km. Independent measurements of the output beam in the laser with a 1.1-km-long cavity revealed its quality factor M^2 to be better than 1.2 at output powers in the range from 5 to 10 W. This fact indicates that the lasing is close to single-mode.

4. Discussion

Our measurements revealed correspondence between the FBG reflection spectra and the generation spectra (see Figs 2 and 3a). Let us describe in more detail the reflection spectrum of the multimode FBG in the graded-index fibre [11]. This spectrum consists of a set of equidistant peaks, the distance $\Delta\lambda$ between which can be approximately written as $\Delta\lambda = \lambda^2 \mathrm{NA}/(\pi d n_1^2)$, where λ is the FBG reflection wavelength, d is the fibre core diameter, and n_1 is the cladding refractive index. Based on the characteristics of the fibre in use (NA = 0.275, $d = 62.5$ μm, and $n_1 = 1.45$) and the wavelength value $\lambda = 954$ nm, we find the distance between the peaks for separate mode groups to be $\Delta\lambda = 0.61$ nm, which is in good agreement with the distance between the peaks in the generation spectrum obtained with the UV FBG2 installed at the output of the Raman laser. At the same time, the doubling of the distance between the peaks as a result of applying the FS FBG2 at the output can be explained by the absence of the reflection peak for the second-group mode (because of the small overlap integral for the field of this mode with the grating recorded in the central part of the fibre core.

It is known (see, e.g., [12]) that the mode-group number in a graded-index fibre can be characterised by the quantity $g = 2p + |m| - 1$, where p and m are, respectively, the radial and azimuthal mode numbers. The radial (ρ) and azimuthal (ϕ) field distributions for modes LP_{mp} are described by the Laguerre polynomials $L_p^{|m|}$:

$$E_{p,m}(\rho,\phi) \sim \exp(\mathrm{i}m\phi)\exp(-\rho^2/2\rho_0^2)\, L_{p-1}^{|m|}(\rho^2/\rho_0^2)\rho^{|m|}/\rho_0^{|m|+1},$$

where ρ_0 is the radius of the fundamental-mode field. Hence, the first two mode groups are not degenerate and contain modes LP_{01} and LP_{11}, while the third group includes two modes: LP_{02} and LP_{21}.

To estimate the smallness of the overlap integral of the fibre mode fields and the photomodification region in the FS FBG2, we should note that the fundamental-mode diameter $2\rho_0$ in the graded-index Corning 62.5/125 fibre can be estimated according to [12] as ~9.8 μm, and the photomodification region has the form of an ellipse in the fibre cross section, with characteristic sizes of principal axes of about 1 and 8 μm respectively (see, e.g., [13]). Note that, despite the comparable values of the mode diameter and the photomodification region size in one of the directions, the overlap integrals are small for modes with nonzero azimuthal index m. Thus, only the modes with index $m = 0$ are maximally overlapped with the FBG recorded near the fibre center; therefore, only the reflection peaks corresponding to these modes (LP_{01} in the first group and LP_{02} in the third group) arise in the reflection spectrum of the FS FBG2 and, correspondingly, in the generation spectrum of the Raman laser when this grating is installed at the output.

5. Conclusions

The use of highly reflective UV FBG1 and output FS FBG2 (recorded in the core of a graded-index fibre) as mirrors in the Raman laser cavity with direct pumping by a multimode LD provides a high laser beam quality ($M^2 < 1.2$) at output powers of more than 5 W. This beam quality is much better than that demonstrated for Raman lasers with direct multimode diode pumping using bulk optics and multimode graded-index fibre ($M^2 > 2.9$) [5, 6], as well as double-cladding fibres ($M^2 = 1.9$) [5]. The cavity configuration in the FBG-based Raman laser allows one to pass to the all-fibre scheme, and laser power and efficiency can be increased by combining a smaller length and higher pump power in one fibre and using special measures to suppress higher order modes during Raman generation.

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