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Seven-core fibre Raman laser with intercore coupling

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Abstract. **This paper reports results of a study aimed at producing a Raman fibre laser based on a multicore fibre with high-reflectivity fibre Bragg gratings inscribed in its peripheral cores using femtosecond laser pulses. We present spectral and power characteristics of a Raman laser whose output power at a wavelength of 1090 nm is 2.5 W. The laser emission linewidth has been shown to decrease as a result of the reduction in nonlinear effects owing to the larger effective mode area in the multicore fibre in comparison with a standard single-mode fibre Raman laser.**

Keywords: *Raman laser, femtosecond refractive index modification, multicore fibre.*

1. Introduction

Raman fibre lasers are promising laser light sources emitting at wavelengths unattainable with fibre lasers based on active fibre doped with rare-earth ions. To date, various Raman laser configurations have been demonstrated, including those with random distributed feedback (RDFB) due to Rayleigh scattering in single-mode fibre [1]. Replacing single-mode fibre by a twin-core fibre in which the distance between the guiding cores is so small that there is transfer of light between the cores allows the emission linewidth of such a Raman laser to be reduced severalfold [2]. The emission linewidth of such a laser, 0.55 nm, proved to be considerably smaller than the 1.8-nm linewidth of an RDFB Raman laser with a similar configuration based on single-mode (single-core) fibre at an output power of 7 W. The decrease in laser linewidth was shown to be due to the spectrally selective properties of the twin-core fibre with intercore coupling and the weaker impact of nonlinear effects (self-phase and cross-phase modulation) owing to the increase in the effective mode area in proportion to the number of cores.

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Point-by-point femtosecond laser writing of fibre Bragg gratings (FBGs) [3], a process that allows FBGs to be inscribed in particulawr cores of a multicore fibre with high positioning accuracy, makes it possible to produce new Raman laser configurations with the use of such fibre. In particular, as shown by Skvortsov et al. [4] the use of a narrow-band reflector based on an FBG inscribed in one core of a twin-core fibre, instead of a broadband Sagnac loop mirror, enables a twofold decrease in the emission linewidth of an RDFB Raman laser. In this paper, we report a method for additional spectral filtering by inscribing two high-reflectivity FBGs offset along the fibre in different cores at the cavity input, which leads to the formation of a Michelson interferometer if there is intercore coupling. Moreover, as shown by Skvortsov et al. [4] the use of FBGs in cavities of RDFB twin-core fibre Raman lasers improves lasing stability in comparison with RDFB Raman lasers with a Sagnac loop mirror [2]. In connection with this, it appears promising to further increase the number of cores for designing new Raman laser configurations with improved spectral characteristics.

In this paper, we report spectral characteristics of a seven-core fibre Raman laser with high-reflectivity FBGs inscribed in the peripheral cores at the cavity input and output using point-by-point femtosecond laser writing.

2. Experimental

The seven-core fibre was fabricated at the Dianov Fiber Optics Research Center, Russian Academy of Sciences (Moscow) and had the following parameters: mode field diameter at a wavelength near 1090 nm, 6.4 μm; core-to-core spacing, 17.3 μm; passive loss in the fibre at a wavelength of ~1.1 μm, no higher than 2 dB km^{-1}; Raman gain coefficient at the Stokes wavelength (~1090 nm), about 0.3 W^{-1} km^{-1}.

Figure 1 shows a schematic of a Raman laser based on this multicore fibre. Linearly polarised pump light with a wavelength of ~1049 nm and power of up to 12.5 W was launched into the central core of the seven-core fibre through an isolator with a high optical damage threshold (above 10 W). High-reflectivity ($R > 90\%$) FBGs with a resonance wavelength of ~1090 nm, corresponding to the Stokes wavelength, were inscribed in all the peripheral cores, as shown in Fig. 1. The single-core fibre was fusion-spliced to the central fibre core, which had no FBG. This allowed us to avoid nonresonant pump losses in the input FBGs.

The light leaving the seven cores was separated by a Thorlabs F230FC-B collimator. To separate the pump light and stimulated Raman scattering (SRS) radiation, we used a Thorlabs GR50-1210 diffraction grating. Thus, the output light had the form of 14 spatially separated beams, and we

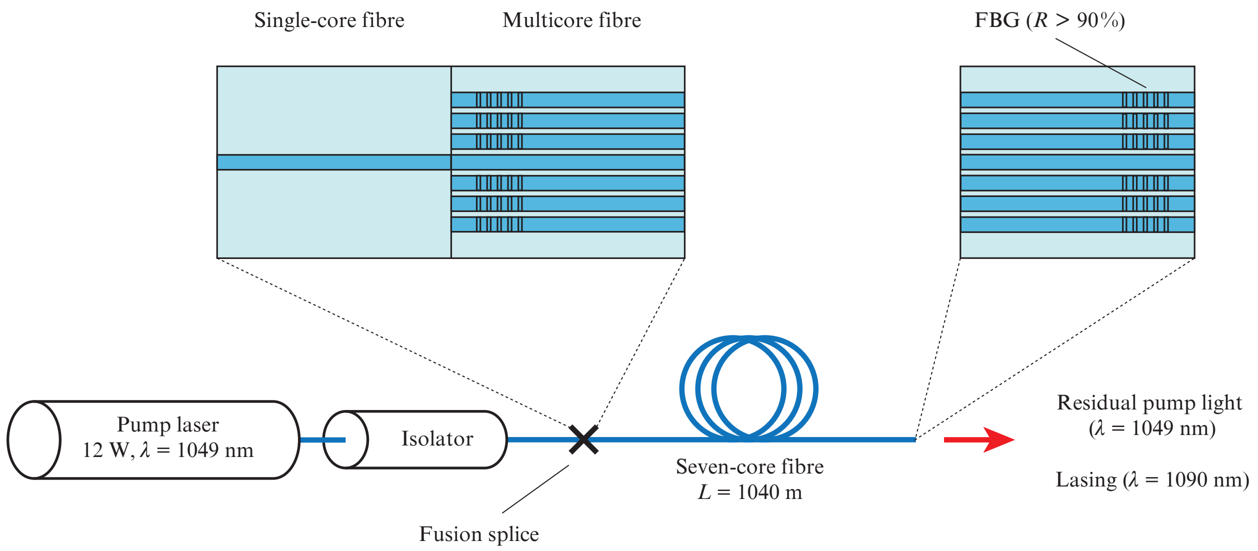

Figure 1. Schematic of the seven-core fibre Raman laser.

used a diaphragm to isolate each of them in spectral measurements. The laser output spectrum was obtained using a Yokogawa AQ6370 optical spectrum analyser with a resolution of 20 pm.

Figure 2 shows the stimulated Raman (~2-W power) and residual pump (~0.3-W power) spectra. The difference between the pump and laser wavelengths is 12.3 THz, which approaches the detuning corresponding to the maximum stimulated Raman gain in GeO_2 fibre.

The output Stokes power and transmitted pump power as functions of input pump power are shown in Fig. 3. The lasing threshold of the Raman fibre laser was reached at a pump power of 3 W. The relatively high threshold power of the Raman laser with a cavity based on high-reflectivity FBGs is due to the decrease in the stimulated Raman gain coefficient because of the increase in the effective mode area of the coupled cores [5]. The total output SRS power (with allowance for all the fibre cores) at a maximum pump power of 12.5 W was 2.55 W, whereas the maximum output power of the central core was about 2.25 W.

Figure 4a shows Stokes Raman spectra of the central core at different output powers. With increasing output power, the laser emission linewidth increases, which is characteristic of single-core fibre Raman lasers as well and is due to the influence of nonlinear effects (self-phase and cross-phase modulation) on the laser linewidth [2, 6]. Increasing the effective mode area reduces the influence of these effects owing to the reduction in the nonlinearity coefficient, leading to a decrease in the laser emission linewidth. At a maximum output power of the central core near 2.25 W, its 3-dB emission bandwidth does not exceed 320 pm. According to previously reported experimental data and an analytical model [6], the emission bandwidth of single-core fibre at a similar laser configuration and the corresponding output power was ~800 pm. Figure 4b shows Stokes Raman spectra of a peripheral core at different output powers. The central part of the spectra (1090 nm) has a dip due to the high-reflectivity FBG in the peripheral core at this wavelength. In addition, the spectra demonstrate interference effects, whose origin remains to be studied in detail.

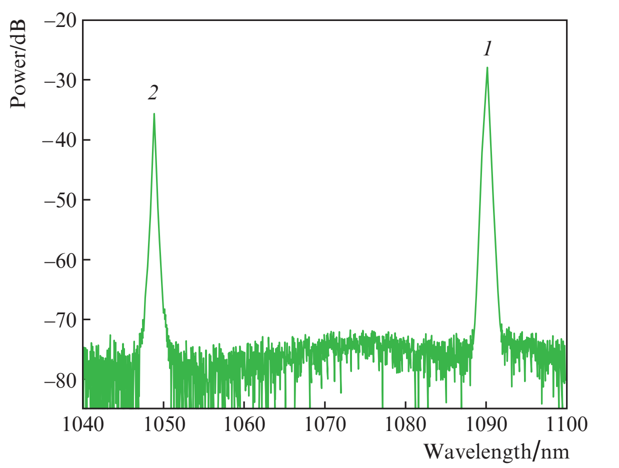

Figure 2. (*1*) Stimulated Raman (~2-W power) and (*2*) residual pump (~0.2-W power) spectra.

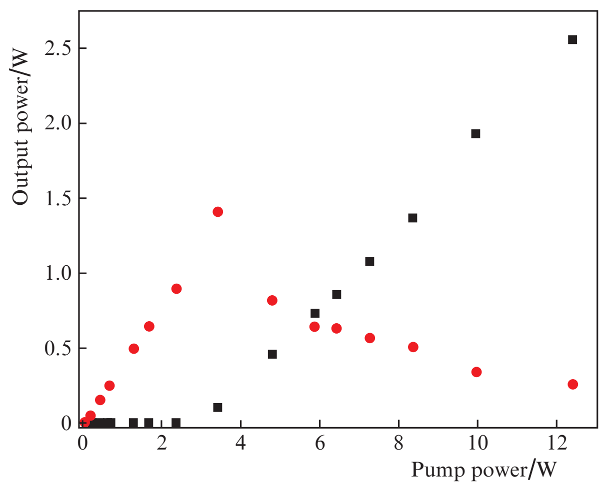

Figure 3. Output SRS power (■) and transmitted pump power (●) as functions of input pump power.

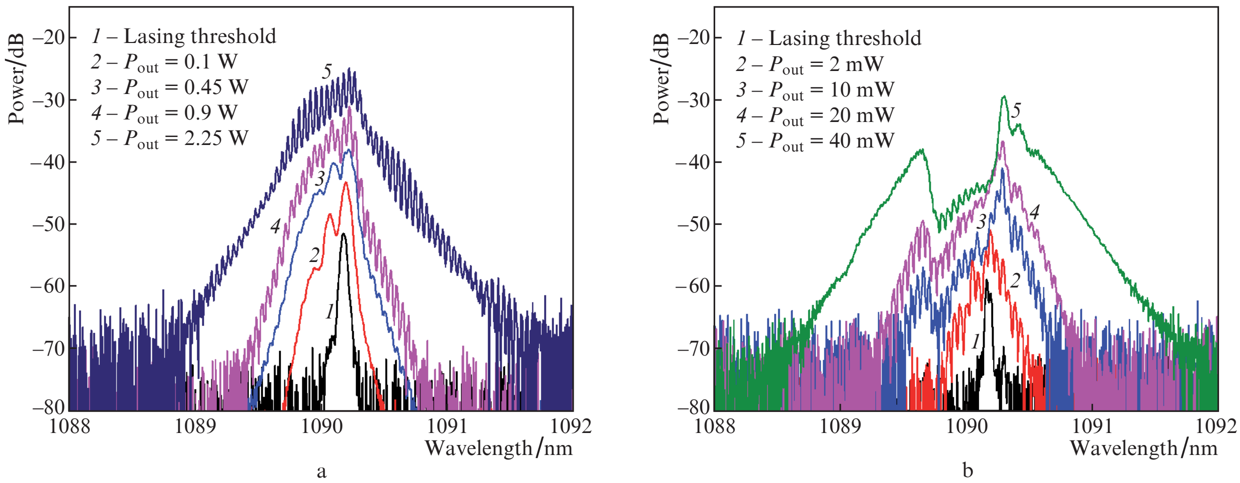

Figure 4. (Colour online) Stokes Raman spectra of (a) the central core and (b) a peripheral core at different output powers.

3. Conclusions

Selective inscription of high-reflectivity FBGs only in the peripheral cores of a multicore fibre has made it possible to obtain efficient Raman generation with an output power of ~2.5 W at a Stokes wavelength of 1090 nm, which opens up new possibilities for further optimization of multicore fibre laser configurations. Investigation of spectral characteristics of a Raman fibre laser based on a seven-core fibre with FBGs inscribed in its peripheral cores has demonstrated an appreciable decrease in the emission linewidth of the laser (in comparison with a single-core fibre Raman laser) owing to the increase in its effective mode area, which leads to a decrease in nonlinearity coefficient and, accordingly, a weaker influence of nonlinear effects on the laser emission linewidth.

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