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FBG array-based random distributed feedback Raman fibre laser

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Abstract. **We have demonstrated the possibility of making a Raman laser with a random distributed feedback ensured by an array of 57 fibre Bragg gratings with random phases and amplitudes inscribed in a 13-m-long polarisation-maintaining passive fibre. The linearly polarised cw output power at a wavelength of 1092.3 nm reaches 5.7 W. The laser linewidth at the highest output power is about 80 pm. In the nearthreshold regime, we observe single-frequency lasing with a linewidth under 100 kHz as determined by self-heterodyne measurements.**

Keywords: *fibre laser, Raman laser, fibre Bragg grating, random distributed feedback.*

1. Introduction

Recent years have seen great interest in disordered-structure-based random distributed feedback (RDFB) lasers. One example of such lasers is light sources in which RDFB is due to Rayleigh scattering by fluctuations in the refractive index of the medium and gain is due to stimulated Raman scattering (SRS) in optical fibre [1]. Such lasers typically have a cavity several hundred metres to tens of kilometres long. It has been shown that, in addition to the standard telecom range (~1.5 μm [1]), Rayleigh scattering feedback allows for Stokes wave generation at wavelengths shorter than 1 [2], ~1.1 [3], ~1.2 [4] and ~1.4 μm [5] and that the cascade generation of higher Stokes components offers the possibility of tuning the Rayleigh scattering RDFB Raman laser wavelength over a wide range: 1.1–2 μm [6, 7]. Note that the use of polarisation-maintaining fibres allows one to obtain a linearly polarised laser output at a high pump-to-Stokes conversion efficiency, weakly dependent on the Stokes component number (70%–80%) [6]. Without any additional spectral selection, the RDFB laser emission linewidth is determined by the Raman gain profile and ranges from 1 to 3 nm [1–7]. The great length of the cavity and the relatively broad emission spectrum are the key drawbacks of such a laser.

To reduce the laser linewidth, various spectral filters are usually used. For example, using this approach Sugavanam et al. [8] demonstrated an RDFB Raman fibre laser with a linewidth of ~50 pm. With a tunable filter, one can gradually tune the emission wavelength within the broad Raman gain band [9]. Moreover, the frequency nonselectivity of Rayleigh scattering feedback allows one to obtain a uniform tuning characteristic at power changes by ~0.1 dB. Also possible in such lasers is multiwavelength operation. El-Taher et al. [10] demonstrated the generation of a series of narrow spectral lines within a Raman gain band owing to the use of 22 fibre Bragg gratings (FBGs) differing in resonance wavelength as spectral filters. RDFB Raman lasers have found application in many areas: from distributed sensors [10, 11] to fibre-optic communications [12, 13].

There is another type of RDFB, in the form of a sequence of FBGs written with random spacings (FBG array) or with random phase shifts along the FBG (random FBG). Generally, such lasers can operate in multi- or single-frequency mode, depending on the cavity length and pump power. Such an approach to the fabrication of the RDFB laser cavity allows the cavity length to be considerably reduced. In particular, one of the first reports [14] described erbium-doped fibre lasers based on 20- and 30-cm-long random gratings, with an emission wavelength of 1534 nm. Each grating consisted of random-length segments with random phase shifts between them, which was ensured by the grating fabrication technique. The emission linewidth was 0.5 pm. Abdullina et al. [15] demonstrated a single-frequency ytterbium-doped fibre laser operating near 1030 nm, with a distributed feedback based on a 4.1-cm-long random FBG consisting of ten segments and having two sets of random characteristics: phase and amplitude. The measured laser linewidth was under 100 kHz. Lizarraga et al. [16] proposed and demonstrated a random erbium-doped fibre laser emitting at ~1535 nm in which feedback was ensured by a grating array. The number of FBGs in the laser was varied from 7 to 31. The length of each grating was 5 mm, the spacing between the gratings was chosen at random in the range 4.2–5.8 mm, and the total fibre length was 1.5 m. The output spectrum showed two longitudinal modes for the laser with seven gratings and five to seven competing modes at a larger number of gratings.

Gagné and Kashyap [17] demonstrated the first Raman laser with an RDFB based on a 1-m-long random FBG,

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which had a total number of random phase shifts near 1500. The laser emitted at a wavelength of 1576 nm and was pumped at a wavelength of 1480 nm. The laser linewidth in single-frequency mode was 430 kHz at the lasing threshold and reached 0.3 nm at the maximum output power (15 mW) and a slope efficiency of 0.8%. The fabrication of an RDFB laser cavity requires no high accuracy, unlike in the case of a uniform distributed feedback (DFB) laser, which requires writing a long, high-quality FBG. In particular, Westbrook et al. [18] used a 12.4-cm-long FBG in a DFB laser and obtained Raman lasing in both a commercial germanosilicate fibre and a highly nonlinear fibre with increased germanium concentration. The laser emitted at a wavelength of 1584 nm under pumping at a wavelength of 1480 nm. The output power, laser linewidth and threshold power were 150 mW, 7.5 MHz and 39 W in the case of the commercial fibre and 350 mW, 4 MHz and 4.3 W in the highly nonlinear fibre, respectively. The threshold power of the DFB laser (in the case of the standard fibre) considerably exceeded that in Ref. [17].

Thus, in the case of a random FBG-based distributed feedback Raman laser, there are no stringent requirements for the cavity fabrication process, in contrast to a uniform FBG-based DFB laser, and its length can be several orders of magnitude shorter than that of Rayleigh scattering random Raman lasers.

In this paper, we describe a Raman laser with an RDFB based on an FBG array written in a polarisation-maintaining passive germanosilicate fibre. This configuration has advantages over the random FBG scheme [17]: an array of short FBGs can be written using standard equipment, and increasing the spacing between gratings makes it possible to reduce the lasing threshold and improve the laser efficiency.

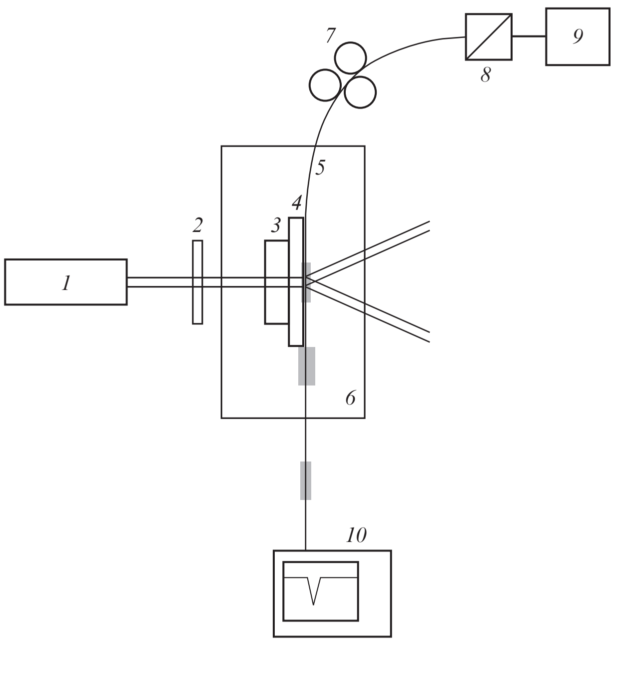

Figure 1. Schematic of the FBG inscription process: (*1*) UV laser; (*2*) focusing cylindrical lens; (*3*) piezoceramic element; (*4*) phase mask; (*5*) optical fibre; (*6*) linear translation stage; (*7*) polarisation controller; (*8*) polariser; (*9*) spontaneous light source; (*10*) optical spectrum analyser. The grey rectangles represent FBGs with a random amplitude and phase.

2. Experimental

Figure 1 shows a schematic of the experimental setup used to inscribe FBGs and assess their characteristics. In the process of grating inscription, a motorised linear translation stage (*6*), carrying an optical fibre (*5*) and a phase mask (*4*) adjusted to a Bragg wavelength of 1093 nm, was moved across an argon UV laser beam (*1*). The 244-nm laser radiation was focused by a cylindrical lens (*2*) to the fibre core. The interference of diffracted beams produced FBGs with a uniform refractive index profile and a modulation period determined by the phase mask. To stabilise the FBG resonance wavelength, the fibre sections in which the gratings were inscribed were fixed at the same tension, which subsequently led to a shift of the Bragg wavelength to shorter wavelengths when the FBG was in an unconstrained state. The exposure time during the FBG inscription process was determined by the translation speed, which was set by a random number generator so that the gratings ranged in reflectivity from 10% to 15%. As the fibre was translated for writing the next grating, a random phase shift was produced between the gratings. The positioning accuracy was ~1 mm. The total number of gratings was 57, the centre-to-centre spacing between them was ~230 mm, and the grating length was ~40 mm. Thus, the total cavity length was about 13 m. No detailed optimisation of the grating array was performed, and the number of gratings was prompted by the following considerations: at a factor of 2 smaller number of gratings and the pump power available, the lasing threshold would not be reached, whereas increasing the number of reflectors increased background losses, which reduced the output pump power and laser efficiency.

Figure 2 shows the transmission spectrum of the FBG array written in a polarisation-maintaining germanosilicate fibre (Fujikura SM98-PS-U25D; core diameter, 6.6 ± 0.5 μm). The spectrum was measured for orthogonal polarisations, as schematised in Fig. 1. As a broadband emitter, we used an ytterbium-doped fibre-based spontaneous light source (*9*). After passing through a polariser (*8*) and polarisation controller (*7*), the light was detected by a Yokogawa AQ6370 optical spectrum analyser (*10*) with a 20-pm resolution. The depth of the minimum in the transmission spectrum was

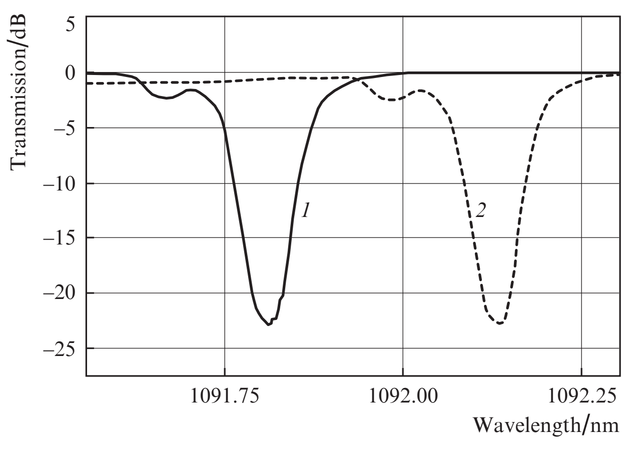

Figure 2. Transmission spectra for light polarised along the (*1*) fast and (*2*) slow axes of a fibre with a random FBG array.

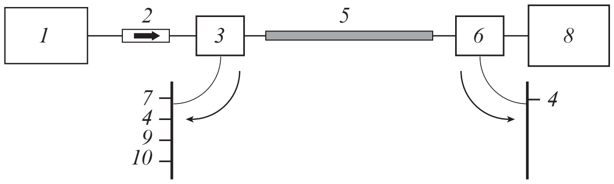

Figure 3. Schematic of the RDFB Raman laser:
(*1*) 1045.2-nm pump source; (*2*) isolator; (*3*,*6*) WDM couplers; (*4*,*8*) power meters; (*5*) random FBG array with λ = 1092.3 nm; (*7*) optical spectrum analyser; (*9*) oscilloscope; (*10*) polarimeter.

–23 dB and its –10-dB bandwidth was under 0.1 nm. The total background loss in the long grating was measured to be ~30%.

The FBG array was used to make an RDFB Raman laser, schematised in Fig. 3. Light from a 1045.2-nm pump source (*1*) passes through an isolator and WDM coupler (*3*) and then enters the fibre in which the random FBG array was written. Another WDM coupler (*6*) separates the Stokes wave and the pump light transmitted through the FBG array (*5*). As a cw pump source, we used a laser system comprising a master oscillator and ytterbium-doped fibre amplifier. Tuning the Bragg wavelength of the grating in the cavity enables the pump laser to emit in the range 1040–1070 nm [19]. Unlike in Ref. [17], the Raman laser does not have any reflecting grating for pump light recirculation.

Figure 4 illustrates the effect of the input pump power on the pump power transmitted through the fibre and the powers of the Stokes waves copropagating and counterpropagating with the pump light, measured by the power meters *4* and *8*.

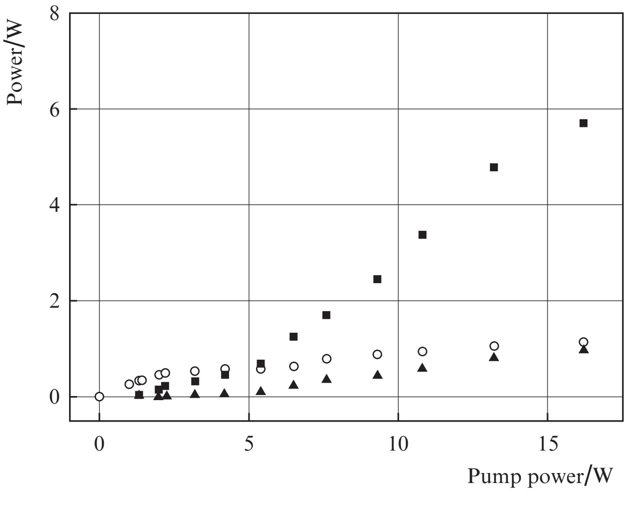

Figure 4. Effect of the input pump power on the pump power transmitted through the FBG array (○) and the powers of the Stokes waves copropagating (▲) and counterpropagating (■) with the pump light.

When its threshold power (~1.3 W) was reached, the laser began to emit at the Stokes SRS wavelength in continuous mode. Figure 5 shows an oscilloscope trace of the backward Stokes wave intensity near the threshold power. In the scheme under consideration, the Stokes power reaches 5.7 W, which is two orders of magnitude above that reported previously [17]. The reason for this is that, in our case, the germanosilicate fibre in which the Stokes wave is amplified is an order of magnitude longer. The slope efficiencies for the backward and forward Stokes waves were 34.8% and 5.8%, respectively. The reason for this distinction is that, in the case of backward Stokes wave generation, the wave is amplified in the undepleted pump region, whereas the forward wave is amplified in the pump depletion region, as in the case of a Rayleigh scattering RDFB Raman laser [20].

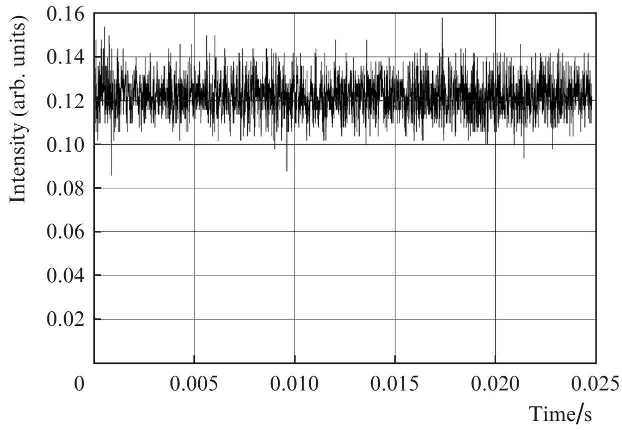

Figure 5. Oscilloscope trace of the backward Stokes wave intensity in the RDFB Raman laser.

The Stokes wave was linearly polarised because in our experiment we used a linearly polarised pump light and polarisation-maintaining fibre. The extinction coefficient, measured with a ThorlabsTPX 5004 polarimeter, was 19.2 dB. Using polarised pump light, we reduced the lasing threshold, because the threshold power for depolarised light is twice as high [21].

Figure 6 shows backward Stokes wave spectra at various pump powers. The spectra were obtained using a spectrum analyser. In the nearthreshold regime, the lasing wavelength was ~1092.3 nm and the measured –3-dB Stokes bandwidth corresponded to the width of the instrumental function of the spectrum analyser (20 pm). The Raman gain coefficient,

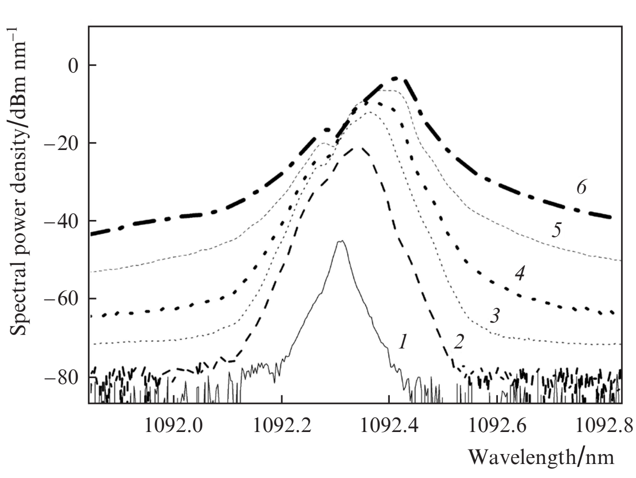

Figure 6. Backward Stokes wave spectra at pump powers of (*1*) 1.3, (*2*) 2, (*3*) 4.2, (*4*) 6.5, (*5*) 10.8 and (*6*) 16.2 W.

dependent on the difference between the pump and laser frequencies, $\Delta\omega$, is known to have a maximum in germanosilicate fibre at $\Delta\omega \approx 440$ cm^{-1} (see e.g. Ref. [22]). In our case, $\Delta\omega = 410$ cm^{-1}, but this does not lead to a large efficiency loss owing to the relatively flat shape of the Raman gain band around the maximum [22]. Raising the pump power from 1.3 to 2 W causes considerable broadening of the lasing spectrum, indicative of multimode lasing. At pump powers above 2 W, the bandwidth varies only slightly, in the range 60–80 pm.

To more accurately determine the nearthreshold laser linewidth, we used self-heterodyne measurements [23]. The Stokes wave passed through a Mach–Zehnder interferometer having one of its arms ~1.8 km long, which ensured a resolving power of ~100 kHz. The shorter interferometer arm included an acousto-optic modulator with a carrier frequency of 150 MHz.

Figure 7 shows a beat spectrum obtained with an Agilent N9010A rf signal analyser, which has a 10-kHz resolution under the conditions in question. At a pump power of 1.3 W, the full width at half maximum of the beat signal is 140 kHz, which corresponds to a spectral linewidth under 100 kHz. Under these conditions, the Stokes power was 12.5 mW. Increasing the pump power by hundreds of milliwatts produces a beat signal at frequencies differing from the carrier frequency, which is due to the onset of lasing on other longitudinal modes and shows up as an increase in spectral linewidth.

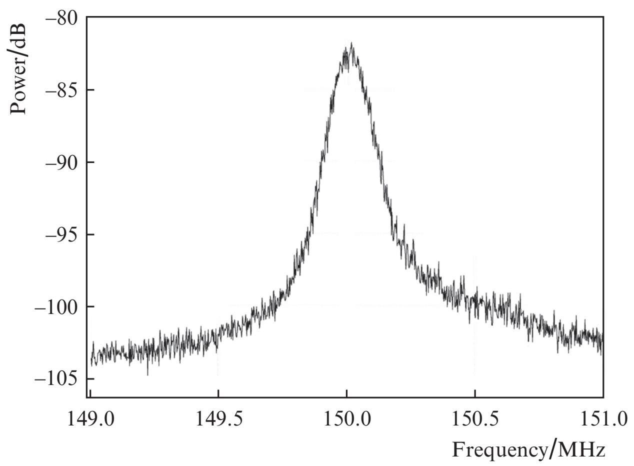

Figure 7. Beat spectrum of the backward Stokes wave of the RDFB Raman laser.

3. Conclusions

We have demonstrated a Raman laser with a distributed feedback based on an array of relatively short FBGs with random phases and amplitudes, written without using any specialised technique for producing a long grating with phase shifts along it. At a pump power of ~16 W, the Stokes power at a wavelength of 1092.4 nm reached ~5.7 W. The threshold power for lasing was 1.3 W, and the corresponding laser linewidth was no greater than 100 kHz (~0.0004 pm). At the highest pump power, the measured linewidth was ~80 pm. Owing to an order of magnitude larger effective Raman laser length in comparison with previous work [17], we obtained a lower lasing threshold, higher slope efficiency and narrower spectral laser linewidth. Optimised RDFB Raman lasers can find a variety of applications: having a narrow spectral linewidth and rather high power, such lasers can be used for remote FBG sensor interrogation and as light sources in distributed sensor systems. Moreover, this configuration can be adapted to the 1.5 μm range, which will allow such lasers to be employed in telecommunication systems. Their high-power, narrow-band output can be efficiently converted to the visible range via frequency doubling in a nonlinear crystal or periodically poled fibre (see e.g. Ref. [24]).

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