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Two-frequency fibre Raman laser

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***Abstract*. A new scheme of a fibre Raman laser emitting at two wavelengths is proposed. The scheme uses a one-stage Raman converter with the output Bragg grating with the reflectivity above 99 %. Lasing at two wavelengths is achieved due to the overlap of the output emission spectrum with the reflection spectrum of the output Bragg grating.**

Keywords: *stimulated Raman scattering, fibre laser, Bragg grating.*

1. Introduction

At present fibre Raman converters (lasers) are widely used for pumping Raman and erbium-doped fibre amplifiers [1, 2]. Fibre Raman sources emitting at two or several wavelengths were proposed to extend the gain spectrum of fibre Raman amplifiers and reduce their noise [3, 4]. As a rule, such devices use a single fibre as an active medium, and lasing at several wavelengths is achieved by mounting a corresponding number of pairs of Bragg gratings forming the converter resonator. Note that, because different gratings are used in the scheme, phase relations between different wavelengths change randomly. This is caused by external perturbations (thermal, acoustic, and mechanical), which cannot be identical for gratings written in different sections of a fibre. In addition, such perturbations change the optical length of the fibre section between the gratings. Therefore, radiation emitted at different wavelength is not mutually coherent. At the same time, it is interesting to develop a two-wavelength radiation source, which can be considered as a generator of high-frequency oscillations at the difference frequency of the emitted wavelengths. Such a generator with two semiconductor radiation sources was demonstrated in Ref. [5].

In this paper, we propose a new scheme of a fibre Raman laser emitting at two wavelengths. The laser resonator is formed only by one pair of gratings, which allows us to assume that radiation at these wavelength is mutually coherent.

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2. Optical scheme of the experiment

Our study of the optical properties of two-stage Raman converters showed that their emission spectrum at the frequency of the first (intermediate) Stokes shift consists of two peaks separated by 0.2 – 1 nm. Because the first resonator of the converter is formed by two Bragg gratings with reflectivities close to 100 %, it is reasonable to assume that radiation emitted from this resonator 'covers' the reflection spectrum of the output grating at the adjacent wavelengths. This effect can be explained by the broadening of the emission spectrum in the resonator caused by nonlinear processes. In this case, the emission spectrum proves to be broader than the reflection spectrum of the output Bragg grating. We intend to use this effect for the generation of two wavelengths in a one-stage Raman converter with a resonator formed by two Bragg gratings with high reflectivities.

Figure 1 shows the optical scheme of a two-frequency laser. A Yb^{3+}-doped double-clad fibre laser was pumped at 980 nm by a 4-W semiconductor laser. The resonator of the Yb^{3+}-doped fibre laser was formed by two Bragg gratings: the input grating with the reflectivity $R \approx 1$ and the output grating with the reflectivity $R = 0.2$. The ytterbium laser emitted up to 2.5 W at a wavelength of 1080 nm. The radiation of this laser was coupled into a Raman laser based on a fibre with a germanosilicate core, the molar concentration of germanium dioxide in the core being $\sim 4\,\%$. We used in experiments the SiO_2/GeO_2 fibre samples of length 200, 620, and 1000 m. The resonator of the Raman laser was formed by two Bragg gratings with reflectivities $R \approx 1$ at 1136 nm. The width of the reflection spectrum of the output grating was smaller than that for the input grating. The transmission spectra of both gratings of the Raman laser are shown in Fig. 2. We also used an additional Bragg grating with the high reflectivity at 1080 nm at the Raman laser end, which returned an unabsorbed part of radiation from the Yb^{3+}-doped fibre laser to the resonator of the Raman laser.

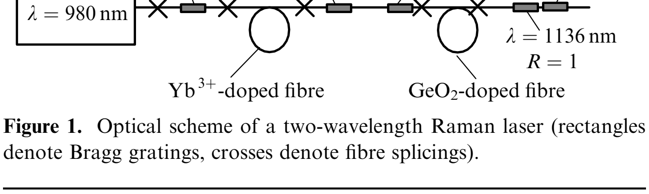

Figure 1. Optical scheme of a two-wavelength Raman laser (rectangles denote Bragg gratings, crosses denote fibre splicings).

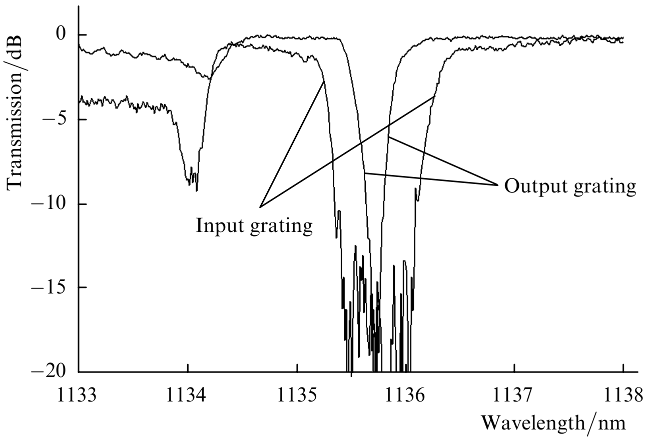

Figure 2. Transmission spectra of Bragg gratings forming the Raman laser resonator.

3. Experimental results

The Raman laser emitted at two wavelengths separated by ~ 0.5 nm. The emission spectrum of this laser recorded with a resolution of 0.1 nm is shown in Fig. 3. Note that the relation between the intensities of the peaks in Fig. 3 is determined by the accuracy of coincidence of the reflection maxima of the input and output Bragg gratings. The intensities of the emission peaks can be equalised by the temperature tuning of the reflection spectrum of one of the gratings.

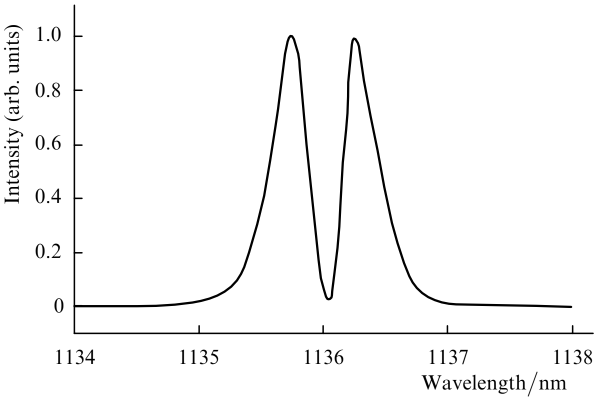

Figure 3. Output emission spectrum of the Raman laser.

Figure 4 shows the dependences of the output power of the two-wavelength Raman laser on the power of a semiconductor pump laser for SiO_2/GeO_2 fibres of three different lengths used in the resonator of the Raman laser. The maximum lasing efficiency was achieved for the fibre of length 200 m. In this case, the maximum output power was 1.7 W, which corresponds to the 42 % conversion of radiation from the multimode pump laser and, hence, to the 65 % conversion of radiation from the multimode ytterbium laser. Note that this lasing efficiency is virtually not inferior to the results obtained for a laser with the output grating optimised for achieving the maximum output power. (The maximum conversion efficiency for fibres of this type is 73 % neglecting the 'covering' of the reflection spectrum of the output grating [6].)

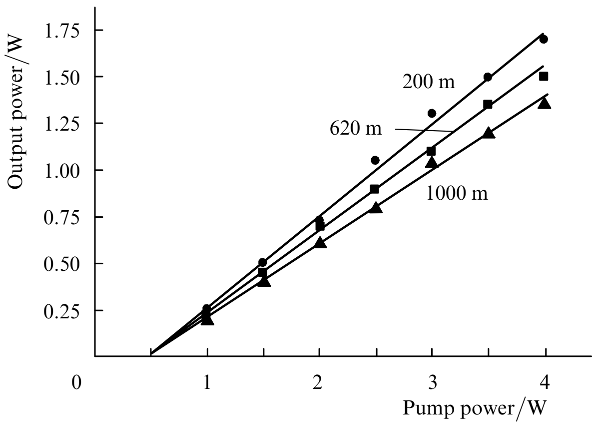

Figure 4. Dependences of the output power of the 1136-nm Raman laser on the power of the 980-nm pump semiconductor laser for three different lengths of fibres in the Raman laser resonator.

4. Dynamic parameters of the device

The two-wavelength Raman laser developed in this work has interesting dynamic properties. It is known that the removal of a stabilising grating from the resonator of the Yb^{3+}-doped fibre laser can result in pulsed lasing. This can be explained qualitatively as follows. In the absence of the output grating in the Yb^{3+} laser, a feedback is provided by a grating placed at the output of the Raman converter. When the efficiency of conversion of radiation from the Yb^{3+} laser is high, the feedback becomes so weak that lasing can be quenched. However, when the output power of the Yb^{3+} laser is low, the Raman conversion efficiency becomes negligibly small and the feedback and lasing are recovered. As a rule, in this case, the Raman laser operates in the self-mode-locked regime at the frequency corresponding to the round-trip transit time for radiation in the laser resonator.

The removal of a stabilising output grating from the optical scheme of the Yb^{3+}-doped fibre laser in the case of a two-wavelength Raman laser resulted in a different dynamic picture. Figure 5 shows the oscillogram of pulsed radiation from the two-wavelength laser (the length of the SiO_2/GeO_2 fibre was 620 m). One can see that pulses of two types are observed. The repetition rate of most intense pulses is

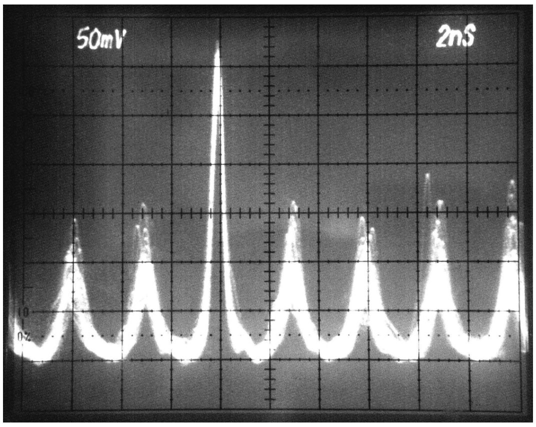

Figure 5. Oscillogram of the pulsed regime of the two-wavelength Raman laser.

$\sim$ 160 kHz, which corresponds to the round-trip transit time in the laser resonator. The repetition rate of pulses of a lower intensity is about 330 MHz, and there is no pedestal from cw radiation. Note that this repetition rate is equal to $c/2\Delta L$, where ΔL the optical path difference appearing due to the phase difference for different emission wavelengths:

$$\Delta L = L\frac{\Delta\lambda}{\lambda}. \qquad (1)$$

Here, ΔL is the resonator length equal to 640 m taking the ytterbium laser length into account; $\Delta\lambda$ is the difference of the wavelengths emitted by the Raman laser; and λ is the emission wavelength of the Raman laser.

When the SiO_2/GeO_2 fibre of length 1000 m was used in the resonator of the Raman laser, the modulation frequency decreased approximately to 200 MHz, which corresponds to the calculation (1). In this case, the temporal stability of pulses improved. However, stable pulsed lasing was not observed when the fibre length was 200 m. It seems that a substantial part of radiation from the ytterbium laser reflected from the output grating remains unconverted in this case and the feedback for the Yb^{3+} laser does not disappear completely. Therefore, to obtain the pulse repetition rate up to $\sim$ 1 GHz, it is better to decrease the spectral interval $\Delta\lambda$ between the laser wavelengths than the fibre length L in the resonator of the Raman laser.

5. Conclusions

We have shown that a one-stage Raman laser with a highly reflecting output Bragg grating can emit simultaneously at two wavelengths. The spectral interval between the emission wavelengths is determined by the parameters of Bragg gratings and can be from fractions of nanometre to a few nanometres. The use of the same Bragg gratings for the generation of two wavelengths suggests the mutual coherence of radiation at these wavelengths. A direct proof of the mutual coherence by measuring beats of signals at different wavelengths requires the use of special equipment because the difference frequency exceeds 100 GHz in our case.

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