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Fibre laser with an intracavity polariser based on a long-period fibre grating

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***Abstract*. An all-fibre Er-doped laser emitting linearly polarised radiation is built. The laser uses a long-period fibre grating as a polarisation-dependent absorbing filter. The use of such an intracavity filter provides the degree of polarisation of output radiation as high as 98 % for a differential lasing efficiency of 45 %.**

Keywords: *optical fibre, refractive-index grating, fibre laser.*

1. Introduction

Fibre lasers with linear polarisation are used as light sources in telecommunication systems and in detectors of various physical quantities. One of the methods of obtaining polarised radiation emitted by fibre lasers involves the use of standard fibre polarisers either inserted in the laser cavity (for suppressing the generation of undesirable polarisation) or mounted outside it. Such polarisers include discrete elements introducing additional optical losses,which is undesirable, especially in the case of a polariser located in the fibre laser cavity. Another drawback is the relatively high cost of the polarisers. In addition, standard polarisers are intended, as a rule, only for certain spectral ranges used in telecommunication systems. For this reason, the application of all-fibre polarisation-sensitive element in a fibre laser is of considerable interest.

In modern fibre laser systems, the cavity is formed by photoinduced refractive-index gratings which serve as narrow-band mirrors determining the laser wavelength [1]. For a given laser wavelength, narrow-band spectral filters induced in the optical fibre can be used for suppressing one of the polarisations in the output radiation. The role of such a filter can be played, for example, by a Bragg fibre grating written in a birefringent optical fibre and characterised by resonance reflection at different wavelengths for different polarisation states [2]. The main disadvantage of such a filter is that the reflected radiation with an undesirable polarisation is not coupled out from the cavity and may decrease the population inversion in the medium, thus reducing the laser efficiency. In addition, in the presence of other reflecting elements (e. g., the end of the fibre), a resonator for radiation with an undesirable polarisation may be formed.

This problem can be solved by using a tilted Bragg grating. Such a grating couples out radiation of the fundamental mode of the fibre in a narrow spectral range and serves as an absorbing spectral filter [3]. The application of such a filter written in a birefringent fibre makes it possible to introduce optical losses at a certain wavelength for one of the radiation polarisation states without changing the transmission of radiation with the orthogonal polarisation. However, the fabrication of tilted Bragg gratings is a complicated technical problem requiring the use of special equipment.

It was shown earlier [4] that a long-period refractive-index fibre grating written in a birefringent fibre may also be used as a polarisation-dependent absorbing spectral filter. A long-period grating couples, at the corresponding resonance wavelength, the fundamental mode HE_{11} of a single-mode fibre with one of the modes HE_{1n} ($n = 2, 3, \ldots$) propagating in its cladding. In this case, the energy transfered into the cladding mode is absorbed upon further propagation along the fibre, leading to the formation of an absorption peak in the transmission spectrum of the fibre with a grating [5]. The resonance coupling between the fundamental and cladding modes in a birefringent fibre is achieved at different wavelengths for different polarisation states. These wavelengths must be separated by large intervals for coupling with radiation having a certain polarisation, while radiation with the orthogonal polarisation propagates without losses [4].

In this work, we demonstrated the efficient generation of radiation with linear polarisation in an Er-doped fibre laser having a long-period fibre grating written in a birefringent fibre.

2. Laser scheme

A laser with linearly polarised output contained birefringent fibre with a core doped with Er ions having a concentration of the order of 10^{19} cm^{-3}, with germanium dioxide as the profiling element. The cutoff wavelength of the first higher mode in the fibre was $\sim$ 860 nm. Birefringence at the fibre core is due to nonaxisymmetric stresses at the boundary between the core and the cladding, which emerge during the 'collapse' of the fibre preform with a high concentration of germanium dioxide in the core. In our case, the molar concentration of germanium was $\sim$ 18 %, which led in birefringence in the core $\sim 2.5 \times 10^{-4}$. Birefringence was measured by the spectral beats method. In order to prevent

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the clusterisation of Er ions, the fibre core was also doped with aluminium oxide with a molar concentration of ~ 0.5 %.

The scheme of the highly Er-doped fibre laser investigated by us is presented in Fig. 1. The active fibre was pumped by radiation of a semiconducting laser diode at 980 nm with a maximum power of 70 mW. The highly reflecting mirror in the cavity of the Er-doped laser was formed by the Bragg fibre grating with a resonance wavelength of 1540 nm and a reflection coefficient exceeding 99 %. In order to eliminate the polarisation dependence of the reflection spectrum of such a grating, it was written in a photosensitive fibre with a small birefringence, which was then spliced with the active fibre of length 10 m. The cleaved end of an Er-doped fibre served as the output mirror with a reflection coefficient of about 4 % (Fresnel reflection). In such a laser configuration, the output radiation wavelength was determined by the resonance wavelength of the Bragg grating.

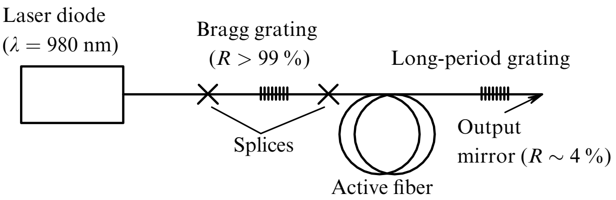

Figure 1. Scheme of a fibre laser emitting linearly polarised radiation.

The photoinduced long-period refractive-index grating used in our experiments was written directly in an active fibre, which allowed us to avoid additional optical losses emerging during the splicing of cavity elements. The 31-mm long grating was written by the step-by-step method [6] using the second harmonic radiation of the argon laser ($\lambda = 244$ nm). The spatial modulation period of the refractive index was chosen so as to ensure the resonant coupling between a higher cladding mode having a large overlap integral and the core mode and amounted to 142 μm.

Fig. 2 shows the transmission spectrum of the written grating. One can see that all the absorption peaks of the grating are split in nonpolarised light, which corresponds to the resonance coupling of modes with crossed polarisation states. Fine tuning of the resonance wavelength of the long-period grating to the laser radiation wavelength was achieved using the method of hydrofluoric-acid etching of a fibre with a grating written in it [7]. Using this method, the absorption peak near 1500 nm corresponding to the coupling between the HE_{11} and HE_{19} modes for the fast fibre axis (see Fig. 2) was displaced to a laser generation wavelength of 1540 nm.

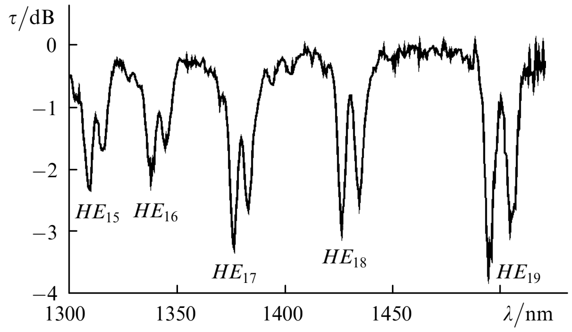

Figure 2. Transmission spectrum τ of a long-period grating measured in nonpolarised light.

Fig. 3 shows the transmission spectra of the grating, measured in the crossed polarisation states of probe radiation. One can see that the absorption peak depth in the transmission spectrum of the grating exceeded 10 dB for both polarisation states. The spectral width of the peaks determined by the number of the grating periods was approximately 8 nm, which made it possible (for polarisation splitting ~ 7.5 nm) to effectively absorb one of the polarisation states of radiation without considerable losses (less than 1 dB) in the other state.

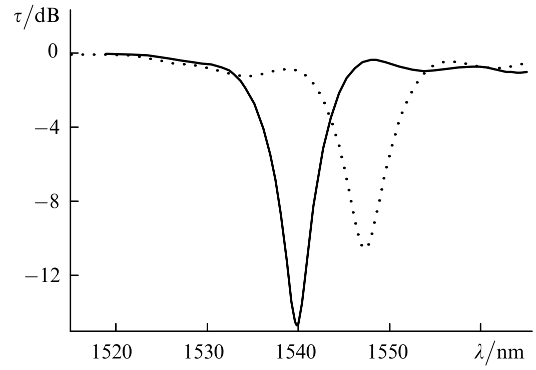

Figure 3. Transmission spectrum τ of a long-period grating measured in crossed polarisations corresponding to fast (solid curve) and slow (dotted curve) axes of the fibre.

3. Results and discussion

Polarisation properties of the output radiation were studied with the help of a Glan prism used as an external analyser. Fig. 4 shows the output laser power as a function of the angle of rotation of the analyser (curve *1*). This dependence displays clearly manifested deep oscillations with a period ~ 180°, indicating a high degree of polarisation of the output radiation (not less than 98 %). To eliminate the effect of the long-period grating on the properties of output radiation, it was immersed in a liquid with a refractive index close to that of the fibre cladding. Such an immersion suppresses the absorption peaks of the grating almost completely [8]. One can see from Fig. 4 (curve *2*) that laser

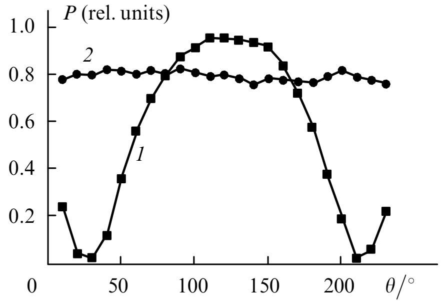

Figure 4. Laser output power P as a function of the rotational angle θ of the analyser for a long-period grating without (*1*) and with immersion (*2*).

radiation becomes depolarised. Note, that the power of nonpolarised radiation decreases by half after the passage through the analyser and amounts to approximately 80 % of the maximum power of polarised radiation. Thus, the total laser power is reduced by a factor of 1.6 after the separation of one of polarisations with the help of the long-period grating. This is apparently associated with additional losses introduced by the grating (side peak in Fig. 3).

Note, that the presence of side peaks in the transmission spectrum of the grating is due to the fact that the fabrication was carried out with a constant modulation amplitude of the refractive index along the grating [9]. Special profiling of the modulation amplitude (apodisation of the grating) suppresses these peaks [10].

The dependence of the output power of polarised laser radiation on the pump power is shown in Fig. 5. One can see that the scheme under investigation has a relatively low lasing threshold (~ 5 mW). The differential efficiency relative to the pump power was 45 %, which corresponds to the quantum differential efficiency of about 70 %. These parameters can be improved by optimising the spectral characteristics of the long-period grating.

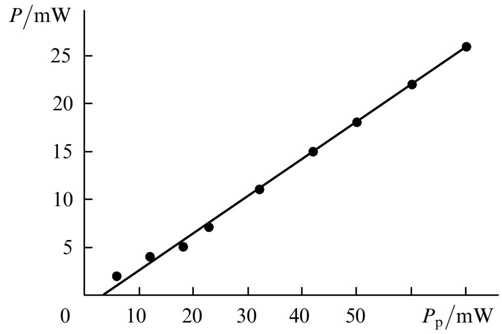

Figure 5. Dependence of the laser output power P on the pump power P_p.

4. Conclusions

A simple scheme of all-fibre Er-doped laser emitting linearly polarised radiation is proposed and investigated. The laser cavity was formed by a Bragg fibre grating determining the lasing wavelength and by the cleaved end of an fibre. A long-period photoinduced grating was used as a polarisation-sensitive fibre element. The advantages of the proposed scheme include small optical losses in the laser cavity, relative simplicity of preparing long-period fibre gratings, and the possibility of choosing and tuning the laser radiation wavelength. In addition, this scheme allows one to switch between the polarisation states of output radiation. This can be done by shifting the resonance wavelength of the long-period grating corresponding to the transverse polarisation towards the wavelength of laser radiation or by tuning the resonance wavelength of the Bragg grating. In the latter case, the polarisation switching is accompanied by a change in the laser wavelength. Possible methods of spectral tuning of fibre gratings were considered in Refs [11, 12].

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