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All-fibre ytterbium laser tunable within 45 nm

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***Abstract*. A tunable ytterbium-doped fibre laser is fabricated. The laser is tuned by using a tunable fibre Bragg grating (FBG) as a selecting intracavity element. The laser is tunable within 45 nm (from 1063 to 1108 nm) and emits $\sim$6 W in the line of width $\sim$0.15 nm, the output power and linewidth being virtually invariable within the tuning range. The method is proposed for synchronous tuning the highly reflecting and output FBGs, and a tunable ytterbium all-fibre laser is built.**

Keywords: *fibre Bragg grating, tunable ytterbium-doped fibre laser*.

1. Introduction

Lasers based on optical fibres doped with rare-earth ions are unique highly efficient sources of cw IR radiation that can be tuned in a broad spectral range. Most of the tunable fibre lasers contain bulk cavity elements for selecting the emission wavelength, which unfortunately restrict the lasing efficiency. A fibre Bragg grating (FBG) written in the core of an optical fibre by UV light represents a resonance reflector with a narrow reflection spectrum at the Bragg wavelength $\lambda_{\rm Br} = 2n\Lambda$, where n is the effective refractive index of the fibre and Λ is the period of the light-induced refractive-index modulation (see, for example, [1, 2]).

The resonance wavelength of a FBG can be tuned by subjecting the optical fibre to mechanical stress resulting in a change in the grating period Λ. The axial load applied to the fibre changes the resonance wavelength of the FBG by the value

$$\Delta\lambda = \lambda_0(1 - P_{\rm e})\varepsilon, \qquad (1)$$

where $P_{\rm e} = 0.22$ is the photoelasticity coefficient; ε is the relative elongation of the fibre; λ_0 is the resonance wavelength of the written FBG. The tuning range provided by stretching the fibre is limited by its weak tensile strength (the typical threshold value of ε is $\sim$0.01). The tuning range produced by compressing the fibre is considerably broader and also limited by the fibre strength, but in this case the threshold value of ε is greater ($\varepsilon \approx -0.23$). Axial loads can be produced either by compressing the fibre in a holder [3] or bending a plate with the fibre glued to it [4]. The first method requires the use of a rather complex design. The second method provided record broad tuning ranges achieving 110 nm in the 1.55-μm region ($\varepsilon \approx -0.09$) [4]. However, the tuning range of a 1.55-μm erbium-doped fibre laser with such a FBG used as a cavity element did not exceed 35 nm [5], while the tuning range of a 0.9-μm neodymium-doped fibre laser did not exceed 15 nm [6].

A 976-nm diode-pumped double-clad ytterbium-doped fibre laser has a high efficiency at the $^2F_{5/2} \rightarrow {}^2F_{7/2}$ transition of the Yb^{3+} ion in the region between 1.08 and 1.11 nm [7]. The realisation of the continuous tuning of an ytterbium all-fibre laser will expand considerably the field of its applications; however, no attempts have been made so far in this direction.

In this paper, we present the results of using a FBG as an intracavity element for tuning an ytterbium fibre laser. The laser tuning was performed in the range from 1063 to 1108 nm. The method is proposed for synchronous tuning the highly reflecting and output gratings and a tunable ytterbium all-fibre laser is built.

2. Experimental

A tunable FBG was written in a Flexcore-1060 optical fibre that was preliminarily kept in the hydrogen atmosphere at a pressure of $\sim$100 atm. The FBG writing was performed by the holographic method by using the 244-nm second harmonic of a high-power argon laser [8, 9]. Figure 1 shows the typical reflection spectrum of the FBG. A part of the fibre with the written FBG was glued to a $\sim$5-mm-thick organic glass plate. The bending of the plate elongates the fibre by $\varepsilon = -0.5d/r$ (where r is the radius of curvature of the plate), resulting in a change in the resonance wavelength of the FBG [4].

Figure 2 shows the scheme of the tunable ytterbium fibre laser. The pump radiation from multimode laser diode (*3*) with a fibre pigtail is focused by lenses (*4*) and (*5*) through dichroic mirror (*6*) to double-clad fibre (*2*) with the ytterbium-doped core. A fibre of length 20 m with the 110×110-μm square light-guiding cladding and the fundamental mode distribution diameter $\sim$7 μm was used. The absorption of pump radiation was $\sim$1 dB m^{-1} at a wave-

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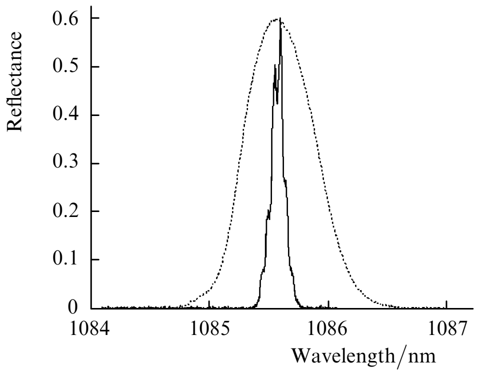

Figure 1. Typical FBG reflection spectrum (the maximum FBG reflectance at $\lambda_0 \approx 1093$ nm in the free state is $R_0 \approx 60\,\%$) (dashed curve) and the corresponding output emission spectrum of the ytterbium fibre laser (solid curve). The compression coefficient is $\varepsilon \approx -0.01$.

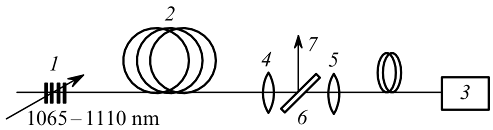

Figure 2. Scheme of a tunable ytterbium fibre laser: (*1*) tunable FBG; (*2*) ytterbium-doped optical fibre; (*3*) pump laser diode with a fibre pigtail; (*4, 5*) lens; (*6*) dichroic mirror; (*7*) output radiation of the ytterbium laser.

length of 976 nm. The laser resonator was formed by the fibre end-face (broadband reflector with the reflectance $\sim$4 %) and tunable FBG (*1*). The dichroic mirror is transparent for pump radiation at 976 nm and has a high reflectance in the lasing spectral range. The fibre laser was pumped through the fibre end-face. Compared to pumping through the tunable FBG, this scheme eliminates the absorption of pump radiation in the cladding of a standard Flexcore-1060 fibre and in the fibre part glued to the plate. The parameters of the ytterbium laser emission reflected by the dichroic mirror were controlled by a power meter and measured with a spectrum analyser.

We studied several FBGs with reflectances from 60 % to 90 % at $\lambda_0 = \lambda_{\rm Br}$ $(\varepsilon = 0) \approx 1093$ nm. The output power of the ytterbium laser with different FBGs varied insignificantly.

To increase the pump power coupled into the active fibre and obtain the optimal transmission coefficient of the output mirror, we fabricated tunable ytterbium all-fibre laser (Fig. 3). An ytterbium fibre fabricated by using the GTWave technology (assembled from a fibre with the ytterbium-doped core and an additional fibre without the

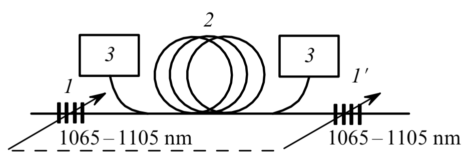

Figure 3. Scheme of a tunable ytterbium all-fibre laser: (*1, 1′*) synchronously tunable highly reflecting and output FBGs, respectively; (*2*) ytterbium-doped GTWave fibre; (*3*) pump laser diodes.

core, which are enclosed in a common polymer jacket) was pumped by two laser diodes from the two ends of the additional fibre [10]. The active fibre length was 25 m and the diameter of the fundamental-mode distribution was $\sim$7 μm. The highly reflecting and output gratings forming the laser cavity were spliced to the ytterbium optical fibre. The resonance wavelength of the FBG was $\lambda_0 = 1105$ nm. The reflectances of the highly reflecting and output FBGs were $\sim$90 % and $\sim$15 %, respectively. The gratings were glued to a common plate, which provided the synchronous tuning of both FBGs upon bending the plate.

3. Results

Figure 4 shows the dependence of the output power of the ytterbium fibre laser on its emission wavelength for the scheme presented in Fig. 2. A tunable FBG was written for reflection at the wavelength $\lambda_0 \approx 1093$ nm and had the initial reflectance $R_0 \approx 60\,\%$. The wavelength region $\lambda < \lambda_0$ is related to the fibre compression, while the region $\lambda > \lambda_0$ corresponds to the fibre stretching. The typical output spectrum of the ytterbium laser with this grating obtained upon weak compression ($\varepsilon \approx -0.01$) is shown by the solid curve in Fig. 1. In this scheme, we obtained tuning from 1063 to 1108 nm, i.e. within 45 nm, the output power being almost constant upon tuning within 40 nm. Upon stretching close to the fibre rupture, $\varepsilon > 0.01$, the output power decreased by more than 10 %, while upon fibre compression ($\varepsilon \leqslant -0.05$), the output power weakly increased. The widths of the FBG reflection spectrum ($\sim$0.7 nm at the −3-dB level) and the emission spectrum of the laser ($\sim$0.15 nm) were not changed considerably upon compression, but the reflectance increased from the initial value $\sim$60 % to $\sim$75 % after strong compression ($\varepsilon \approx -0.05$). The use of FBGs with different initial reflectances ($R_0 = 60\,\% - 90\,\%$) also resulted in weak variations of the output power because cavity losses were mainly determined by the transmission coefficient of the fibre end-face. The maximum output power of the ytterbium fibre laser pumped by the $\sim$10-W radiation was $\sim$6 W.

The use of a FBG with the reflectance 15 % instead of the fibre end-face in the laser scheme shown in Fig. 3 provides the optimisation of the output power for the specified pump power. Figure 5 shows the change in the output power of the ytterbium fibre laser during its tuning. Upon synchronous tuning of the highly reflecting and

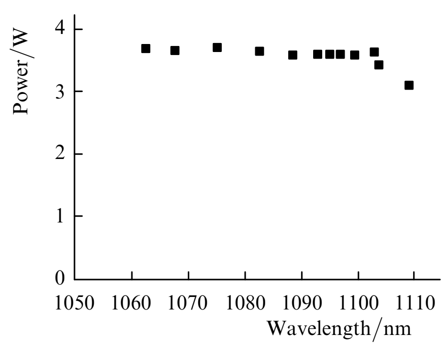

Figure 4. Dependence of the output power of the ytterbium fibre laser on the emission wavelength tuned with the help of a FBG (the reflectance of the FBG in the free state at $\lambda_0 \approx 1093$ nm is $R_0 \approx 60\,\%$) for the pump power $\sim$7 W.

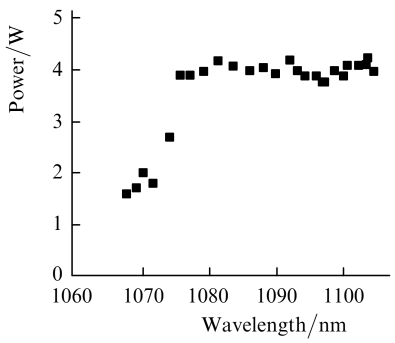

Figure 5. Dependence of the output power of the ytterbium all-fibre laser on the emission wavelength changed with the help of synchronously tuned highly reflecting and output FBGs (the reflectances of FBGs in the free state at $\lambda_0 \approx 1105$ nm are $R_0 \approx 90\,\%$ and $R_{\rm out} \approx 15\,\%$).

output FBGs due to fibre compression, the output power almost did not change when the laser wavelength decreased by 30 nm; however, upon further fibre compression (when $\Delta\lambda$ achieved $\sim$40 nm), the output power decreased more than by half. The measurement of the spectra of FBGs showed that this occurs due to the mismatch of the resonance wavelengths by $\sim$0.3 nm, while the full width of the reflection spectrum of the highly reflecting FBG at the -3-dB level is $\sim$0.6 nm. The output power achieved by using the output FBG was somewhat higher than that in the case of using the fibre end-face.

During tuning the drift of the laser wavelength was observed immediately after its change. Upon detuning by 15 nm from the resonance wavelength λ_0, the laser wavelength was stabilised after $\sim$5 min and then long-term fluctuations for $\sim$1000 h became smaller than 0.1 nm.

4. Discussion

Thus, by using a tunable FBG to change the wavelength of the ytterbium fibre laser, we obtained the maximum output power $\sim$6 W and the tuning range 45 nm upon pumping by $\sim$10 W. The output power of the laser and the width of its emission spectrum ($\sim$0.15 nm) changed insignificantly upon tuning, whereas the reflectance of the FBG increased by $1.2-1.3$ times upon fibre compression from $\varepsilon = 0$ (free state) to $\varepsilon \approx -0.05$ (strong compression). We have found that the polarisation of the output radiation is random and almost does not change upon tuning.

A weak dependence of the output power on the reflectance of the highly reflecting FBG is explained by the fact that cavity losses were mainly determined by the high transmission coefficient of the fibre end-face used as the input mirror. In addition, the output power can be determined by the spectral dependence of the unsaturated gain when the laser wavelength is considerably changed [7]. However, this effect was not observed due to uniform saturation and a great excess of the gain over losses.

A considerable decrease in the output power of the ytterbium all-fibre laser observed upon the synchronous tuning of the highly reflecting and output FBGs and a change in the laser wavelength by more than 30 nm is explained by the relative mismatch of the resonance frequencies of FBGs upon fibre compression, which can be eliminated by the additional matching of the highly reflecting and output FBGs to each other. The laser of this type is promising for applications in all-fibre schemes.

5. Conclusions

We have fabricated a 6-W tunable ytterbium fibre laser which can be tuned within 45 nm in the 1.1-μm region by using a tunable FBG. We have also built a tunable ytterbium all-fibre laser in which two synchronously tunable FBGs (highly reflecting and output) are used.

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