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Single-frequency, linearly polarised fibre laser with spectrally asymmetric fibre Bragg grating mirrors

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Abstract. **A new design of a single-frequency fibre laser at a wavelength of 1.55 μm with linearly polarised output radiation is developed and investigated, in which a uniform Bragg grating written in an SMF-28 fibre is used as one mirror and the other mirror is a grating written in a Panda fibre with a small overlap of reflection spectral bands of mirrors and the possibility of fine tuning of the lasing spectral line. The length of the active part of the laser cavity formed by a fibre doped with the low-concentration Er^{3+} erbium ions is 10 cm. At a pump power of 60 mW and a wavelength of 1.48 μm, the lasing power reaches 100 μW and the width of the spectral line is less than 100 kHz.**

Keywords: *erbium, single-mode fibre, single-frequency laser, fibre Bragg grating, ring cavity.*

1. Introduction

The development of fibre lasers with high-quality single-frequency radiation is relevant for fabricating a variety of local and distributed fibre sensors, as well as coherent communication and information processing systems [1, 2]. High-quality single-frequency laser radiation means radiation with extremely low amplitude and phase noise, linear polarisation, and output power of about 0.1 to 1 mW, sufficient for operation of photodetectors with an acceptable dynamic range of allowable optical signal loss in fibre systems.

Many research teams, as well as manufacturers (see, e.g., [1–6]), make and study single-frequency distributed-feedback (DFB) fibre lasers using technologies similar to those used in the manufacture of semiconductor DFB lasers. These technologies are based on writing fibre Bragg gratings (FBGs) in a single-mode core highly doped with an activator, the phase of the grating period being shifted by π in the middle of the small-length (~10 mm) cavity. The short cavity length makes it easy to obtain a single-frequency lasing regime, and for oscillation on a single polarisation mode, an active highly doped fibre is taken with a Panda-type light guiding core (PM fibre).

The quality of the obtained single-frequency radiation depends on the parameters of a single-mode highly doped fibre and the well-developed FBG writing technology. The advantage of the production technology of such single-frequency fibre lasers consists in the reproducibility of their properties and the seriality of the manufacturing process. As a rule, these are single-frequency single-mode PM fibre lasers with a high concentration of the doping impurity of Er^{3+} ions and a short cavity. For practical use, the low output power of such lasers is amplified up to 1–10 mW (for sensors) and up to 1–2 W (for coherent pulse reflectometers – distributed sensors). The necessity to use output optical power amplifiers negates the potential cheapness of single-frequency fibre lasers; their cost is too high for applications in fibre-optic sensor systems for which an output power level of 0.1–1 mW is sufficient.

It should be noted that there are a number of works where erbium fibre lasers with increased output power were implemented in a configuration with DFB and a classical cavity (such as a Fabry–Perot resonator) on a single-mode fibre with a high concentration of Er^{3+} ions and a cavity length of up to 50 mm [3]. However, clustering effects lead to up-conversion processes and, as a rule, to pulsed lasing; therefore, obtaining a stable continuous-wave single-frequency regime becomes a problem. A number of design issues in order to obtain a continuous single-frequency lasing regime have been studied using ytterbium single-frequency DFB lasers, where the concentration of the active impurity of Yb^{3+} ions is high and no clustering effects are present. Thus, in Ref. [4], a phosphorus-silicate glass matrix was chosen as the core material of a single-mode fibre doped with germanium to increase photosensitivity. A single-frequency ytterbium fibre DFB laser was fabricated and studied using 16-mm π-shifted FBGs in the cavity and at an operating wavelength 1030 nm, the laser line width is smaller than 8 kHz in the continuous-wave highly stable mode with the output power of ~10 mW.

A brief review of the achievements and technical methods for obtaining a stable single-frequency lasing regime tested on highly doped erbium and ytterbium fibres and lasers [3–6] allowed us to use the following key techniques in this work to achieve a continuous-wave single-frequency regime in an erbium-doped fibre laser:

1) the choice of a single-mode fibre waveguide doped with a low concentration of Er^{3+} ions (~500 ppm) without clustering effects, with the active part of the cavity 10 cm long;

2) for generating a single polarisation mode, as in Ref. [5], the output FBG mirror was written in a PM fibre, docked (fused) to the active part of the cavity; and

3) for fine tuning to the single-frequency laser mode, the temperature adjustment of the shift of the spectral transmission edge of the second FBG cavity mirror was used, which was first tested in [5] to obtain single-frequency lasing in an ytterbium fibre laser.

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The design closest to our laser construction scheme with fine-tuning to a single-frequency generation regime and the mechanism for isolating one longitudinal mode of a composite cavity using distributed Bragg mirrors is described in Ref. [6]. However, ytterbium single-mode fibre was used there as an active highly concentrated medium, and the obtained single-frequency radiation at a wavelength of 1030 nm is less demanded in practice than the radiation from erbium fibre lasers at a wavelength of about 1550 nm, which falls into a wide wavelength range for telecommunication and sensor applications.

The aim of this work is to develop and study the combined design of single-frequency erbium fibre lasers for an operating wavelength of about 1550 nm using the above methods to obtain single-frequency low-noise output radiation with linear polarisation and output power in the range 0.1–1 mW. It is important that, at the same time, the usual 'manual' laser manufacturing and tuning technology used in research laboratories is preserved, while the concentration of the dopant Er^{3+} ions in the core of a conventional single-mode fibre is reduced by almost an order of magnitude. By increasing the length of the laser fibre cavity and high reflection coefficients of the FBG mirrors, narrow generation lines with a half width of $\Delta\nu_{1/2}$ in the range of 10–100 kHz are achieved, which is sufficient for the applications of the developed lasers, including coherent reflectometry.

2. Design and operation features of a single-frequency fibre laser

The single-frequency erbium fibre laser is schematically shown in Fig. 1. The active part of the laser cavity 10 cm long is formed by a single-mode fibre with a circular core with a diameter of 4 μm, activated by Er^{3+} erbium ions with a concentration of ~500 ppm without clustering effects. The absence of the latter excluded the formation of high-lying energy levels due to the interaction of erbium ions and the transition to radio-frequency pulsation of optical power under pumping. The FBG mirrors were fusion spliced to the ends of the active part of the cavity (the sites of fusion in Fig. 1 are indicated by the letter F). The gratings were written in CORNING SMF-28e^{+} optical single-mode fibres (SMFs) and polarisation-maintaining (PM) fibres PM 1550. The 15-mm circular-core optical gratings were highly reflective (HR), having a reflectance of more than 99%. The total spectral width of the grating reflection band at half maximum is $\Delta\lambda_{\rm FWHM}$(SMF) = 0.15 nm. The PM fibre gratings were made partially transmitting and, with a length of 20 mm, had reflection coefficients of 96%–98% with a spectral width of $\Delta\lambda_{\rm FWHM}$(PM) = 0.10 nm. The FBG reflection peaks in the birefringent PM fibre are spaced at 0.35 nm, which corresponds to birefringence $\Delta n_{\rm bf} = 3.2 \times 10^{-4}$. The resonance wavelength of the grating in the SMF corresponds to the reflection peak of the fast axis of the grating in the PM fibre and is shifted in the process of writing by about 0.1 nm to the short-wavelength side. It was then adjusted by temperature to obtain optimal lasing conditions for both output optical power and the exact wavelength of generation.

The laser was pumped by the radiation of a laser diode at a wavelength $\lambda_{\rm p} = 1.48$ μm through an optical multiplexer (OM). The pump radiation was launched into the cavity from the side of the PM fibre FBG mirror, which provided linearly polarised lasing. Another additional factor ensuring the linear polarisation of the output laser radiation was the fact that the active part of the cavity with fusion spliced FBG mirrors was constructively fixed in a straightened state on a flat thermally stabilised ($T_{\rm stab}$) supporting surface. With its length of 10 cm, the spatial configuration of the generated radiation remained stable, and the output radiation was linearly polarised. A fine adjustment of the lasing wavelength was implemented by changing the temperature $T^0_{\rm reg}$ of the SMF FBG mirror. The temperature $T^0_{\rm reg}$ of this mirror depended not only on the distance between the maxima of the reflection peaks of the FBG mirrors, but also on the transmittance peak of the composite cavity and its optical Q factor, which affects the photon lifetime in the cavity and the width of the laser output spectral line. The temperature sensitivity $\Delta\lambda/\Delta T$ of the grating at a wavelength of $\lambda_{\rm g} = 1.55$ μm was approximately 0.012 nm C$^{\circ -1}$.

An optical circulator (OC) at the output of the multiplexer was used to couple out the laser radiation at a wavelength of about 1.55 μm and to provide optical isolation from the spectrum analyser and the laser line width meter.

In our design of a single-frequency fibre laser, as in [6], we additionally used the important possibility of changing the temperature $T^0_{\rm reg}$ of the mirror of one of the spatially separated FBGs, in this case, on the SMF. This extends the ability to adjust the power and lasing line width of the fibre laser of this design while maintaining the linear polarisation of the output radiation.

3. Results and discussion

To select a single longitudinal mode by frequency in a fibre laser with the cavity length $L \approx 15$ cm, it is necessary to provide a significant gain deficiency in the wavelength range $\Delta\lambda \sim 0.005$ nm, which is facilitated by fairly sharp spectral transmission peaks of the composite cavity in the radiation

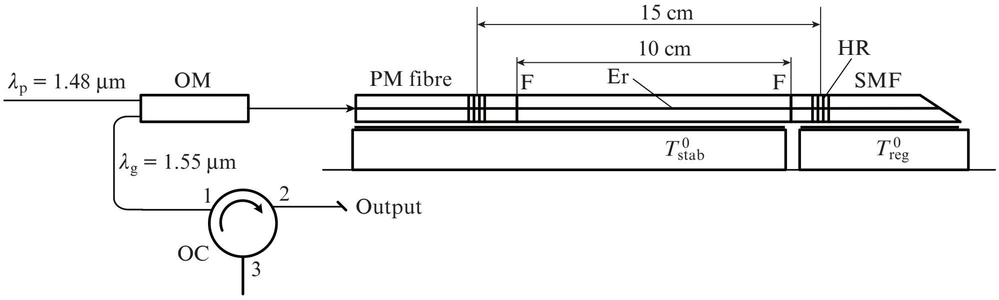

Figure 1. Single-frequency fibre laser design.

amplification regime. The resulting transmission spectrum of two spectrally mismatched FBG mirrors is similar to the transmission spectrum of a uniform grating with a phase shift by π in the middle of the length [1–3]. An additional factor in isolating a single spectral line and suppressing other neighbouring lines is that, when amplified in the active part of the cavity, the spectral line of enhanced spontaneous luminescence (superluminescence) is narrowed at a maximum.

The narrow-band lasing spectra were studied using a spectrum analyser (ANDO AQ6317) with a resolution of 0.01 nm. Figure 2 shows the spectrum at a pump power of 60 mW; the maximum output power was about 100 μW (–10 dBm). It can be seen that when the power varies from –80 to –10 dBm, the emission spectrum is regular, without visible side resonance peaks in the range 1549.8–1550.8 nm near the centre lasing wavelength. This observation may indirectly indicate a developed regime of single-frequency lasing. To confirm that the lasing spectrum is single-frequency, an analyser with a high spectral resolution is required. We investigated the output spectrum of the fibre laser using a ring fibre cavity with high finesse ($F \approx 200$) and spectral resolution $\Delta\nu \approx 160$ kHz (instrument function). The length of the loop circuit of the ring cavity $L_{\rm rr}$ made of a single-mode SMF-28 fibre was 10 m. For the formation of a high-finesse ring cavity, an X-type single-mode directional coupler with splitting ratio of 1:200 was used.

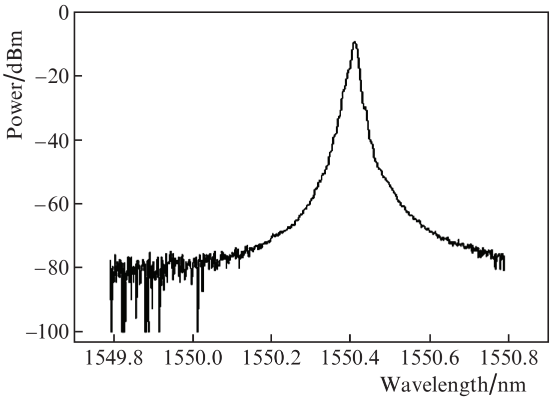

Figure 2. Spectrum of narrow-band oscillation of a fibre laser recorded in a wide dynamic power range by a spectrometer with a resolution of 0.01 nm.

Figure 3 shows one transmission period of the ring cavity used as a scanning analyser of the emission spectrum of the single-frequency fibre laser. A linear scan of the length of the ring cavity was performed by applying a linearly varying voltage to a piezoelectric cylinder with a cavity fibre wound around it (~20 turns with a diameter of 80 mm). The trajectory of the linear voltage variation is superimposed on the scanning spectrum in order to clearly indicate the time interval during which the scanning regime is linear. The distance between the two spectral peaks corresponds to the free dispersion region of the ring cavity FSR = $(c/n)L_{\rm rr}$ and amounts to 20 MHz, which indicates the frequency scale on the horizontal axis of the sweep. It also follows from Fig. 3 that there are no other resonances in the linear sweep period that could indicate the simultaneous lasing in a composite cavity at other frequencies. In this case, a spectrum with one spectral line indicates a single-frequency mode of the fibre laser generation. Figure 4 shows a scan of one spectral peak of the studied fibre laser radiation on a larger frequency (time) scale. It can be seen that the contour of the laser spectral line has no clearly distinguished frequencies or other resonances. The spectral curves in Figs 3 and 4 prove the fact of the fibre laser single-frequency generation at one longitudinal mode of its own cavity. This lasing regime is reliably reproduced in the process of fine-tuning the temperature $T^0_{\rm reg}$ of the SMF highly reflecting FBG mirror (keeping fixed the temperature $T^0_{\rm stab}$ of the second grating).

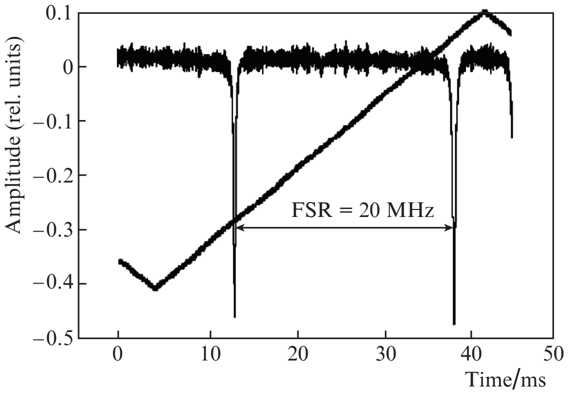

Figure 3. One period of scanning the emission spectrum of a fibre laser by a ring fibre cavity analyser with a free dispersion region FSR = 20 MHz, which demonstrates a single-frequency lasing regime with suppression of side mode frequencies exceeding 20 dB.

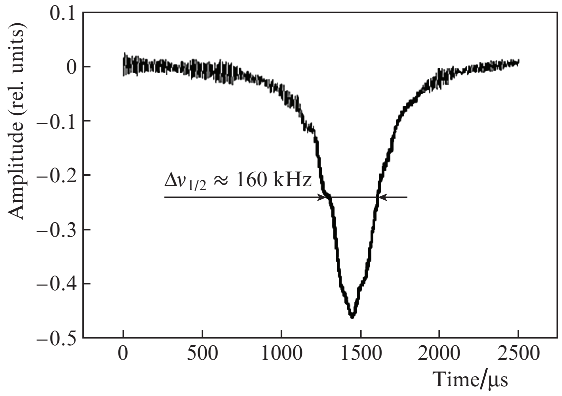

Figure 4. Fine structure and detailed frequency sweep of a single lasing line with a width of $\Delta\nu_{1/2} \approx 160$ kHz (instrument function of the ring cavity) of the single-frequency fibre laser at an output power of 100 μW.

The obtained continuous-wave single-frequency generation of the proposed fibre laser was stable in the spectral position of the lasing frequency – the frequency sweep did not exceed 10 MHz and was determined by the properties of the electronic thermostat. In the design of the fibre laser, we used one of the typical stabilisers/regulators of temperature, a Wavelength Electronics temperature controller. Note that the developed single-frequency fibre laser has a low level of intrinsic amplitude noise (especially at frequencies below 1 kHz), which is a consequence of the absence of $1/f$-type noise, which is usually typical for single-frequency injection semiconductor DFB lasers (see, e.g., [7], Fig. 13).

The output power characteristic of the fibre laser generation is shown in Fig. 5. In this work, we studied one of the possible (see, e.g., [1]) principles for producing single-frequency laser radiation. The main goal of the work was the achievement and proof of single-frequency lasing at one longitudinal mode of its own cavity, obtaining a stable linear polarisation of the output radiation and achieving an output optical power acceptable for practical use – at least 100 μW. The use of heterogeneous optical elements of the laser led to the fact that the optical loss and mode matching at the junctions of the elements were not optimal. As a result, not all pump radiation power is efficiently used (see Fig. 5). We believe that in the future, when selecting laser elements, the pump efficiency can be increased, and it is quite possible to obtain single-frequency lasing with an output power on the order of 1 mW. The achieved output power level of 100 μW of single-frequency linearly polarised radiation at a wavelength of about 1.55 μm is sufficient for constructing fibre sensors with small (~10 dB) allowable losses in the fibre system. The optical power at the photodetector in the range of 10–20 μW is sufficient for their normal operation at a signal-to-noise ratio of ~1000. The saturation power of PROM-type photodetectors is about 200 μW, and the generation powers of a single-frequency fibre laser obtained above are practical even without the use of additional fibre-optic amplifiers.

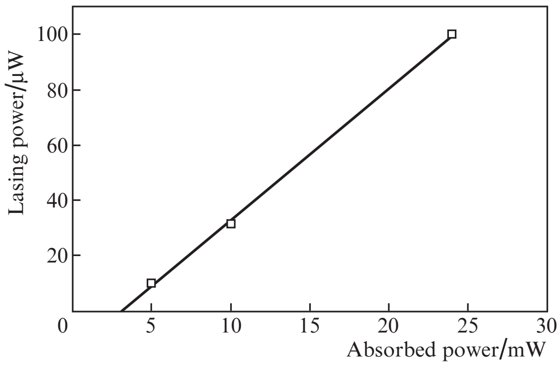

Figure 5. Dependence of the output power of the single-frequency fibre laser on the absorbed pump power at a wavelength of 1.48 μm.

4. Conclusions

A combined design of single-frequency fibre laser whose cavity consists of 15 cm long single-mode fibre doped with Er^{3+} ions of moderate concentration (~500 ppm) with spatially and spectrally separated mirrors on short-length FBGs was developed and studied. The gratings were written in a conventional SMF-28e$^+$ fibre and in a polarisation-maintaining PM fibre and were fusion spliced to the cavity fibre. The linearly polarised radiation was coupled out from the laser through the FBG formed in the PM fibre and having a reflection coefficient of ~98%. Fine-tuning to the single-frequency lasing regime was implemented by changing the temperature of the HR FBG mirror in the SMF fibre, which operated similar to a π-shifted grating in a typical DFB laser. It was shown that the spectral mismatch of FBG mirrors in the laser design makes it easy to obtain a single-frequency regime and achieve a maximum lasing power. Measurements with a high-Q ring cavity showed that the half-width of the spectral line $\Delta\nu_{1/2}$ of a single-frequency fibre laser was determined by the instrument function of the scanning interferometer and did not exceed ~100 kHz at a lasing power of 100 μW.

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