10 W widely tunable narrow linewidth double-clad fiber ring laser

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Abstract: A highly efficient and widely tunable narrow linewidth ytterbium-doped double-clad fiber laser with a linearly polarized output power of 10 W is demonstrated. The laser wavelength was tunable over a range of 24 THz from 1032 nm to 1124 nm by using a diffraction-grating pair in Littrow-Littman configuration in a unidirectional ring-cavity. The laser linewidth was smaller than 2.5 GHz for all power levels and all laser wavelengths. Additionally, an operating mode without any measurable amplified spontaneous emission with a linearly polarized output power of up to 3 W was realized.

OCIS codes: (140.3480) Lasers, diode-pumped; (140.3510) Lasers, fiber; (140.3560) Lasers, ring; (140.3600) Lasers, tunable

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1. Introduction

In the last few years fiber laser devices became of strong interest for a variety of applications in industry and science because of their high efficiency and reliability. With fiber lasers based on rare-earth doped silica fibers very high output powers up to 110 W have been demonstrated [1,2]. Such output powers in combination with a diffraction limited beam quality can be achieved using novel fiber designs like double-clad fibers [3]. Moreover, because of the broad gain bandwidth of those fibers, tunable narrow linewidth laser systems have been demonstrated [4]. Especially with ytterbium-doped fibers highly efficient systems with tuning ranges up to 70 nm and output powers up to 5 W were described [5,6].

However, the emission properties of fiber lasers with its high power density in the core, can be altered due to nonlinear scattering processes, like Raman and Brillouin scattering. Particularly, stimulated Brillouin scattering results in an intensity dependent feedback. Thus, in linear fiber cavities this effect increases intensity fluctuations and can causes self q-switching in high-power fiber lasers [6,7,8]. This effect is mostly attenuated by using unidirectional fiber ring-cavities, where back-scattered Brillouin-photons are suppressed. Therefore, in this setup intensity dependent stimulated Brillouin scattering could even reduce intensity fluctuations.

In this letter, we report what is believed to be the first realization of a ytterbium-doped fiber ring laser setup with a linear polarized output power of 10 W, which combines widely wavelength tunability with a narrow laser linewidth of 2.5 GHz. Moreover, laser operation without measurable amplified spontaneous emission (ASE) is demonstrated.

2. Experimental setup

In Figure 1 the setup of the unidirectional ring-cavity is shown. The ytterbium-doped double-clad silica fiber with a Large Mode Area (LMA) design had a length of 20 m. The core of the fiber, which was doped with 1000 ppm ytterbium, had a diameter of 10 µm and a numerical aperture of 0.07. Hence the core was transverse single-mode for wavelengths above 1 µm. The fiber loss was measured to be < 0.02 dB/m at a wavelength of 1200 nm. The surrounding cladding with a diameter of 400 µm and a numerical aperture of 0.38 acted as waveguide for the pump light and was D-shaped, improving the pump light absorption [9]. Both end facets of the fiber were polished under an angle of 10° in order to prevent laser action due to Fresnel back-reflections in the fiber core.

As pump source we used a fiber coupled 980 nm laser diode (DILAS MF98-25) with a maximum output power of nearly 32 W. In that wavelength region the ytterbium-doped fiber has maximum pump light absorption. Additionally, the small quantum defect between the pump and the laser wavelength enables a very high efficiency. The pump light was focused by two lenses into the pump-core at one end of the active fiber. The laser radiation and the pump light were separated by the dichroic mirror M1 in front and a filter behind of the active fiber, respectively. Mirror M2 guided the laser beam emitted at the pump side to a combination of a polarization beam splitter (PBS1), a half-wave plate and a second polarization beam splitter (PBS2). The beam splitters in combination with the half-wave plate served as output couplers for the clockwise (PBS2) and counter-clockwise (PBS1) propagating laser radiation, respectively. The emission properties of the laser depend strongly on the circulation direction, which could easily be adjusted by a suitable orientation of a Faraday-rotator. The double-grating arrangement, depicted in the left part of Figure 1 was used to realize a tunable narrow linewidth operation and consisted of a fixed grazing incidence diffraction grating and a second one in Littrow mount [10]. Wavelength tuning is accomplished by rotating the Littrow-grating (Tuning grating) around its vertical axis. Both holographic diffraction gratings were gold-coated and had an inverse groove spacing of 1200 mm^{-1}. The gratings were 35 mm long and 15 mm in height. The diffraction-efficiency was optimized by means of a half-wave plate up to 95% and the wavelength resolution was optimized by means of a telescope. The back-diffracted beam from the gratings was deflected by PBS2 via M3 and M4 to the other end of the fiber. At this end a single lens was used to couple the laser beam into the core of the fiber. In order to achieve a stable continuous wave laser operation an

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additional half-wave plate and quarter-wave plate were placed inside the resonator. With these wave plates the polarization of the laser beam was adjusted to compensate the birefringence of the fiber in order to optimize the output power for a given out-coupling ratio. Otherwise nonlinear polarization rotation in the fiber can lead to power fluctuations or even mode-locked operation of the laser [11].

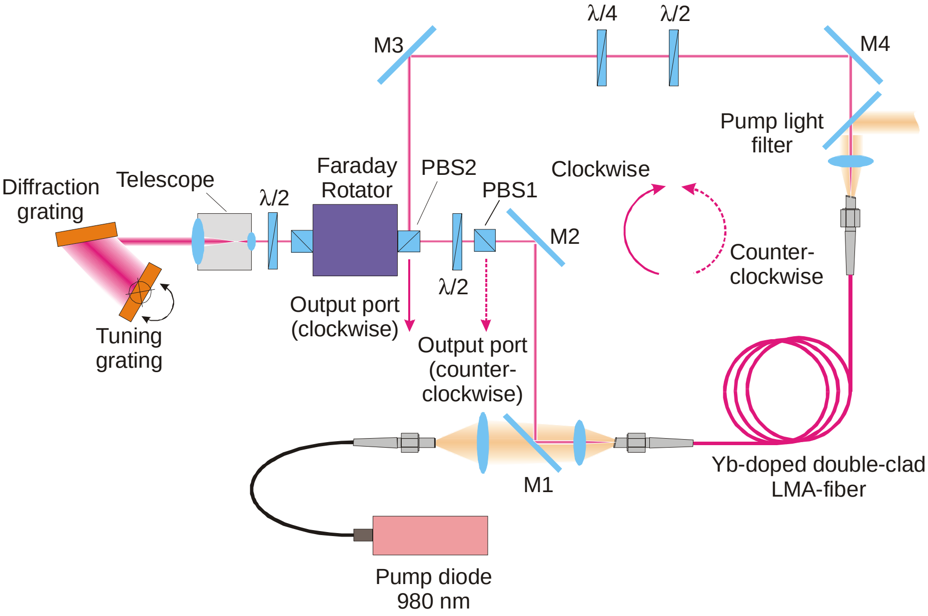

Fig. 1: Experimental setup: see text for details.

3. Results

The 980 nm absorption of the ytterbium-doped fiber is very strong (~0.5 cm^{-1} at maximum) but also quite narrow (FWHM: ~2 nm). Therefore, the pump light absorption depends strongly on the wavelength of the pump diode. In order to eliminate effects resulting from the power dependent wavelength drift of the pump diode for all experiments only the absorbed pump power is considered. This value is determined by measuring the residual pump power at the end of the fiber, taking a typical coupling-efficiency of 75% into account. In maximum about 80% of the pump light was absorbed.

Primary, the experimental results for clockwise circulation direction are described. In Figure 2 the output power of the laser versus the absorbed pump power for a laser wavelength at the center of the tuning range at 1080 nm is shown. We achieved a linearly polarized output power of more than 10 W at an absorbed pump power of 18.6 W, which corresponds to a pump power of 31.7 W. The slope efficiency was 68%. The output power increased linearly with increasing absorbed pump power and no saturation was observed. Therefore, further power-scaling by means of higher pump power is expected.

Figure 3 shows the dependence of the output power (upper part) and the slope efficiency (lower part) on the laser wavelength. The dependence of the output power is shown for four different pump power levels. However, due to a degradation of the pump diode the maximum available pump power for the following experiments was 29 W. At this pump power the laser wavelength was tunable from 1032 nm to 1124 nm, corresponding to a tuning range of 24 THz. Reducing the pump power the tuning range decreased slightly to 21.5 THz. The slope efficiency with respect to the absorbed pump power is nearly constant for signal wavelengths between 1040 nm and 1100 nm. The maximum slope efficiency of 85% was achieved at a laser wavelength of 1035 nm.

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The increasing slope efficiency with decreasing laser wavelengths can be explained by taking the quantum defect and the emission cross section of ytterbium-doped silica fibers into account [12].

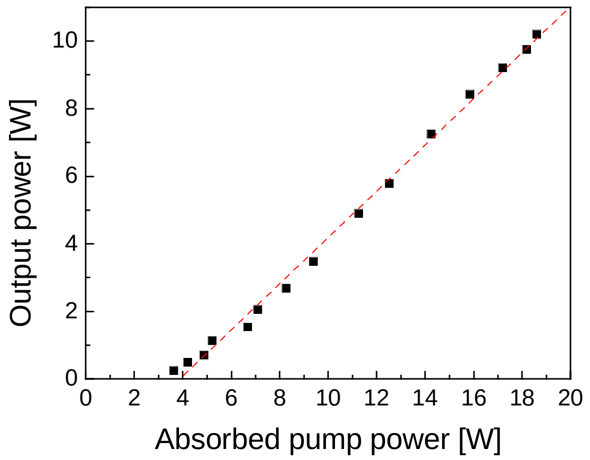

Fig. 2: Laser output power versus absorbed pump power for a signal wavelength of 1080 nm.

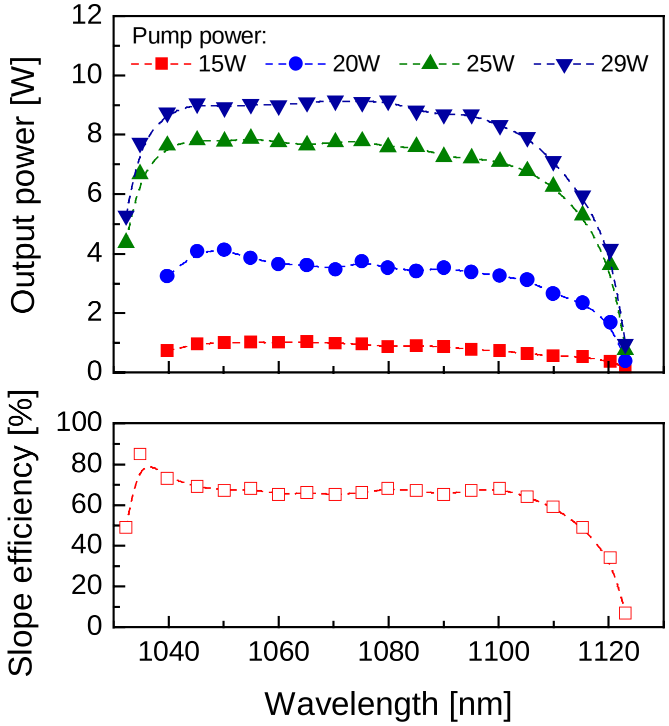

Fig. 3: Output power and slope efficiency versus emission wavelength. The tuning curves are shown for four different pump power levels.

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By using a confocal Fabry-Perot interferometer with a free spectral range of 10 GHz the pump power dependence of the laser linewidth was measured. For a pump power just above the threshold the laser linewidth was approximately 330 MHz and increased up to 2.5 GHz for the maximum available pump power of 29 W. For all pump power levels the laser linewidth varied only slightly with the laser wavelength.

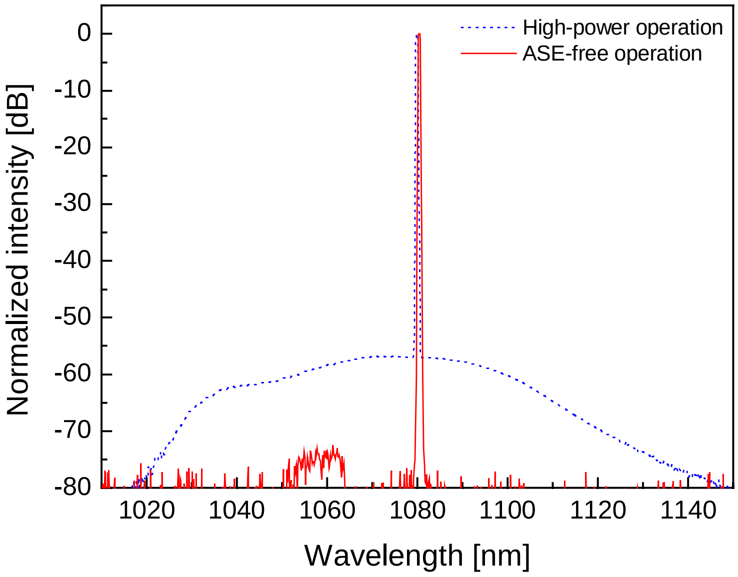

Fig. 4: Emission spectra at the center of the tuning range for high-power operation and ASE-free operation. The broad signal around 1060 nm is an artefact of the spectrum analyzer.

Rotating the Faraday-rotator by 180° about its vertical axis, the circulation direction of the laser light can easily be inverted from clockwise to counter-clockwise direction. Since for counter-clockwise circulation, the laser beam was coupled out right behind the diffraction grating pair an output signal without any measurable amplified spontaneous emission (ASE) can be extracted. In this operation-mode the tuning range was not changed in comparison to the high-power operation (clockwise circulation). At a laser wavelength of 1080 nm a linearly polarized output power of 3 W for an absorbed pump power of 16.8 W was achieved. The slope efficiency was reduced to 23 % because of the higher losses in the cavity for the counter-clockwise circulation. The wavelength-dependence of the output power and the slope efficiency is similar to that of the high-power operation-mode.

The emission spectra of the fiber laser were recorded applying an optical spectrum analyzer with a resolution bandwidth of 0.05 nm. Figure 4 shows the spectra for clockwise (dashed line) and counter-clockwise (solid line) circulation of the radiation at laser wavelengths around 1080 nm and a pump power of 29 W. The peak intensity of both curves are normalized to 0 dB. For the ASE-free mode of operation the suppression of the ASE was at least 20 dB larger than for the high-power operation-mode. The relative amount of the ASE on the total output power for either modes of operation was calculated from the optical spectra and is shown in Figure 5. Compared to a minimum fraction of 0.01% in case of the high-power operation, this amount is more than two orders of magnitude lower in the whole tuning range for the ASE-free operation-mode. A extremely low relative amount of ASE of roughly $1.0*10^{-4}$% was measured in the wavelength range between 1045 nm and 1090 nm. Note, that in this wavelength region the measurement was limited by the sensitivity of the spectrum analyzer (see Figure 5).

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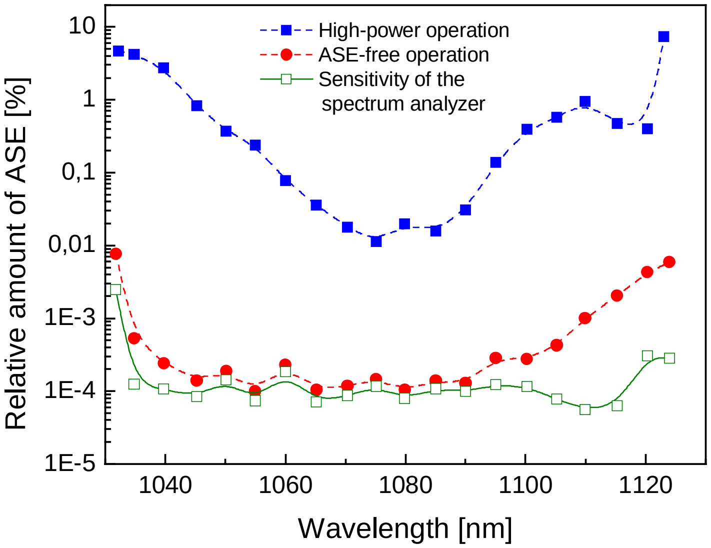

Fig. 5: Relative amount of the ASE on the output power for high-power and ASE-free operation, both for a pump power of 29 W. The measurement sensitivity of the optical spectrum analyzer is illustrated by the solid curve with the open squares.

4. Conclusion

In conclusion, we presented a widely tunable narrow linewidth ytterbium-doped double-clad fiber laser with a linearly polarized output power of 10 W and a slope efficiency of 68% at a wavelength of 1080 nm. By using two intra-cavity gratings in Littrow-Littman configuration the laser wavelength was tunable over a range of 24 THz from 1032 nm to 1124 nm. The laser linewidth was smaller than 2.5 GHz for all power levels and all wavelengths. Moreover, by reversing the circulation direction of the laser radiation inside the cavity an ASE-free linearly polarized output power of up to 3 W with a slope efficiency of 23% at a wavelength of 1080 nm was achieved.

Regarding the emission properties this highly efficient laser system is extremely suitable as a seed source for tunable amplifiers for the generation of narrow linewidth high-power radiation or as pump source particulary for pumping optical parametric oscillators to generate radiation in the 3.4 µm region [13].

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