2. Experimental set-up and results

The experimental installation is schematically shown in Fig. 2. The pump radiation at 976 nm is guided through a fibre beam combiner into a 3-m long active double-clad ytterbium fibre with a 10-µm core (NA = 0.08). Yb-doped fibre laser has free-space optical elements on both ends of its linear cavity. The laser radiation is directed onto them through the fibre ends cleaved at 8 degrees and collimators. One of the ends of the fibre laser cavity is terminated with a discrete polariser and a spectrally selective reflector consisting of a prism and a mirror. The polariser combined with the polarisation-maintaining fibre used in the cavity ensures linearly polarised laser radiation. Spectrally selective reflector allows tuning of the laser radiation wavelength within the spectral gain band of the active medium.

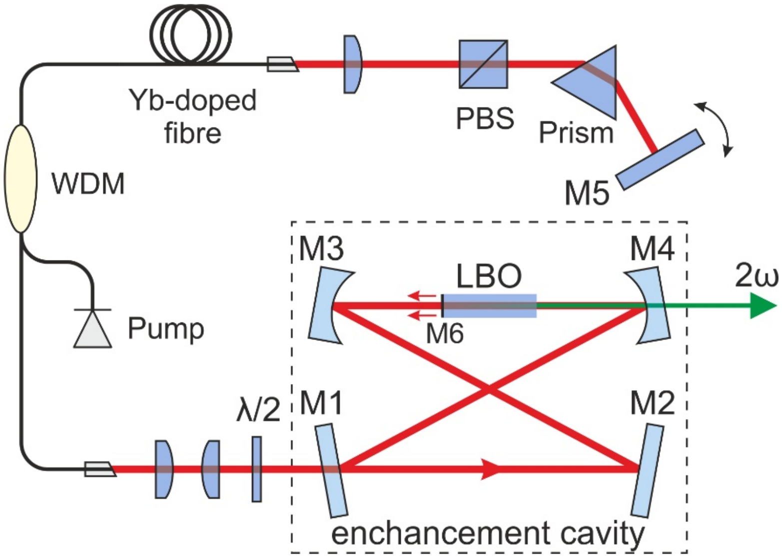

Fig. 2. Experimental set-up of the Yb-doped fibre laser with a partially coupled enhancement cavity: M1–M4 – mirrors of the enhancement cavity; M5, M6 – end mirrors of the fibre laser linear resonator.

At the other end of the fibre laser's linear cavity, free-space elements include a high-Q four-mirror resonator with a non-linear LBO crystal inside, as well as a focusing element and a polarisation element for mode and polarisation matching of the input radiation to the parameters of the four-mirror resonator. Three of the high-Q resonator mirrors are totally reflective to the fundamental laser harmonics, while the resonator input mirror has transmittance of several per cent, which depends on the radiation wavelength. The 20-mm long non-linear LBO crystal with anti-reflection-coated working surfaces orthogonal to the beam is positioned between two spherical mirrors with equal radii of 75 mm. The crystal is placed inside a high-temperature thermostat to ensure type I non-critical phase-matched second harmonic generation at the temperature of around 150 °C stable to ± 0.05 °C. The anti-reflection coatings of the non-linear crystal cover wavelengths within ranges 1030–1100 nm and 515–550 nm. Spherical mirror M4 of the four-mirror resonator is dichroic: it reflects radiation with wavelengths within 1030–1100 nm and transmits radiation at wavelengths between 515 and 550 nm.

The anti-reflection-coated surface of the non-linear crystal closest to the input mirror of the enhancement cavity plays the role of the fibre laser output coupler (mirror M6, Fig. 2). As it turned out, reflection (0.2%) from this surface is sufficient to establish feed-back in the fibre laser resonator. All other flat surfaces of laser resonator elements (fibre ends, polariser faces, etc.) are inclined relative to the resonator axis so that radiation reflected from them cannot enter the fibre laser resonator. Location of the fibre laser output coupler within the enhancement cavity poses natural limits on the reflectivity of this mirror: the more reflective it is, the lower will be the Q-factor of the four-mirror cavity. Therefore, to maximise the enhancement cavity's Q-factor, reflectivity of this mirror must be minimal. At the same time, too low reflectivity of the fibre laser output coupler may reduce the output power of the fibre laser. It is necessary to note that for some models of CW fibre lasers [15] it is indicated that the optimal reflectivity of the output coupler for them should be below 1%. To confirm this indication, a separate special study would be required. Nevertheless, the results of the present work demonstrate that in the proposed optical layout, an output coupler with reflectivity 0.2% effectively increases the power of laser radiation in the partially coupled enhancement cavity.

The high-Q four-mirror cavity in a bow-tie configuration provides enhancement of the fundamental radiation power to the level of over 30 W when pumped with 6.2 W at 976 nm. The radius of the beam waist within which the non-linear crystal is positioned is close to the optimum given by the Boyd-Kleinman theory [16] for the used crystal and amounts to approximately 30 μm. The laser radiation spectrum is narrowed down by the prism to 0.5 nm, which is within the spectral width of the non-linear crystal phase matching, equal to 1.8 nm. In analogy to [14], the fibre laser operates in those longitudinal modes of the fibre laser cavity, which are also resonant for the enhancement cavity. To fulfil this condition, it is sufficient for the fibre laser resonator to be much longer than the enhancement cavity. In this study, the fibre laser resonator is more than 6 times as long as the enhancement cavity.

The second harmonic radiation is predominantly generated in one direction, towards mirror M4. The power of the second harmonics generated in the opposite direction (towards mirror M3) is comparatively low and does not exceed several mW. This effectively means that the fundamental radiation inside the partially coupled enhancement cavity is present as a unidirectional running wave.

The maximal achieved power of the second harmonic radiation at 536 nm is 880 mW in TEM_{00} mode (Fig. 3). The corresponding overall power conversion efficiency from pump power (976 nm) to green power (536 nm) is more than 14%. The wavelength of the fundamental harmonics is tuned within the 1042–1090 nm range by rotating mirror M5. The wavelength of the second harmonics is synchronously tuned by adjustment of the temperature of the non-linear crystal. The dependence of the second harmonic power upon wavelength is shown in Fig. 4. The same Fig. 4 also demonstrates the dependence of transmittance of input mirror M1 of the four-mirror cavity upon wavelength. Within the generation range of 1042–1090 nm, this transmittance varies from 2% to 16%, and the maximum of the second harmonic output power is reached at the wavelength of 1072 nm, for which the transmittance of input mirror M1 is equal to 5%. The demonstrated tuning range of the second harmonic wavelength was 521–545 nm, and the output power of the green radiation at the extremes of this spectral range was 420 and 220 mW respectively. Significant reduction of the second harmonic output away from the central wavelength corresponding to the maximum (536 nm) occurs because of non-optimal transmission of input mirror M1 at other wavelengths. Without the enhancement cavity (an output mirror with transmission of 4% was used in its stead), power excursion of the fundamental radiation did not exceed 40% of the maximum as the generation wavelength of the fibre laser was tuned within the 1035–1100 nm.

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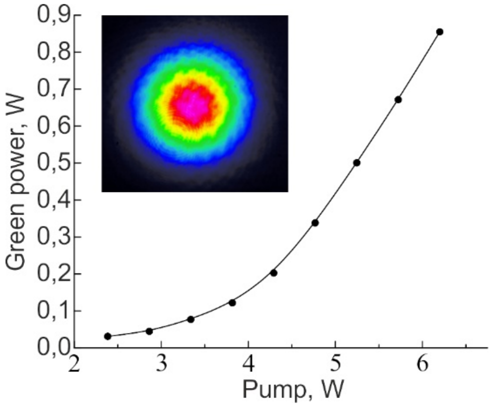

Fig. 3. Second harmonic output power dependence on pump power (976 nm). The inset picture shows the beam profile of the second harmonic radiation.

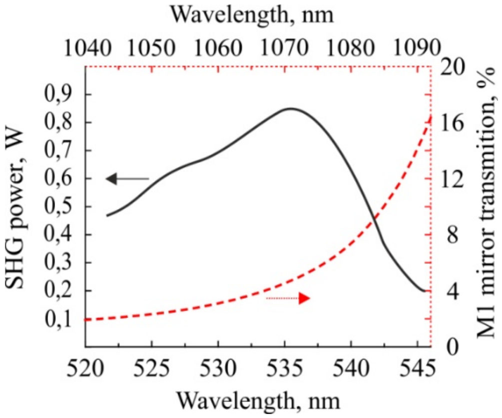

Fig. 4. Dependence of the second harmonic output power and transmission of the input mirror of the enhancement cavity on wavelength.

At green output power level of up to ~500 mW, instability of the output radiation power did not exceed 2–3%/s and was in our opinion primarily caused by imperfections of the experimental set-up (open layout, air movements, mechanical instability of unconnectorized fibre ends, etc.). At the output power level over 500 mW, the output spectrum of the laser became increasingly unstable and the fundamental wavelength could jump by as much as 0.4–0.6 nm, indicating insufficient spectral selectivity of the prism at higher power levels. Fundamental wavelength hops led to greater second harmonic power instability, which could be as high as 15–20%. A more spectrally selective element (for example, a diffraction grating) will be able to suppress fundamental wavelength hops at higher powers and reduce the green output power instability at least to within several per cent.

It is pertinent to note that in the studied configuration, coupling of the enhancement cavity to the laser resonator is comparatively strong, since generation occurs at those laser frequencies, which are also resonant for the enhancement cavity. Otherwise, the laser radiation would not reach the non-linear crystal, being almost totally reflected from the input mirror of the enhancement cavity.

In the studied configuration, transmission of the output mirror of the laser resonator remains constant (0.2%). However, the power of radiation reflected from it increases as the radiation power inside the enhancement cavity grows. Correspondingly, effective reflectivity of the output mirror placed inside the cavity is also variable and depends on the intra-cavity power, which in its turn depends on the relative amount of energy exiting the cavity because

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of second harmonic generation. Therefore, effective transmittance of the output mirror in the studied configuration depends on the relative energy coupled out of the cavity as the second harmonic radiation. This is the key feature of an output mirror contained within an enhancement cavity.

The essential difference of the proposed configuration from the one described in [14] is that no fundamental radiation must be coupled out of the enhancement cavity in order to provide feed-back. When this is necessary (as it is in [14]), two mirrors of the enhancement cavity cannot be totally reflective, thus reducing finesse of the cavity in the configuration "resonator within resonator".

Among other differences of the proposed approach from the one discussed in [14], one can mention a substantially lower second harmonic generation threshold relative to the pump radiation power. In the proposed configuration it amounts to 2.4 W, whereas in [14] it was as high as 6 W. Furthermore, a non-linear crystal with Brewster faces used in [14] creates additional losses (~19%) for the s-polarised second harmonic radiation because of its reflection from Brewster faces.

3. Conclusion

The proposed technique of fibre laser radiation frequency doubling in a partially coupled enhancement four-mirror cavity offers relatively high efficiency of variable-wavelength second harmonic generation combined with a comparatively simple set of required components. Among the major advantages of the proposed technique are relatively low second harmonic generation threshold and comparatively high efficiency of the second harmonic generation at relatively low pump power. Tuning of the radiation wavelength is done by rotating a quartz prism, and an anti-reflection-coated face of the non-linear crystal serves as the output coupler of the fibre laser resonator. The proposed approach may be used not only for second harmonic generation of non-single-frequency CW radiation in a enhancement cavity, but also for other types of non-linear conversion of CW and pulsed radiation in a high-Q cavity, such as parametric oscillation, Raman conversion, etc. The proposed method does not require automatic adjustment of the enhancement cavity length. Laser generation occurs at frequencies, which are common for the fibre laser resonator and the enhancement cavity. The developed configuration may be also used for non-linear conversion of pulsed radiation in an enhancement cavity, and the duration of input pulses may be as short as 1 ps (spectral width of such pulses does not exceed the spectral width of phase matching in the employed non-linear crystal). This configuration also allows easy automatic tuning of the second harmonic wavelength within a broad spectral range by synchronous tilting of the resonator's end mirror and adjustment of the non-linear crystal temperature.

Feeding the fibre laser radiation into an enhancement cavity through a low-reflectivity output coupler located inside this cavity represents a new promising approach to non-linear transformation of radiation in a partially coupled enhancement cavity.

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