CW Yb-fibre laser with wavelength-variable efficient intracavity frequency doubling in partially coupled enhancement cavity

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ABSTRACT

This paper presents the results on second harmonic generation in a tuneable Yb-fibre laser with an enhancement cavity partially coupled to the laser resonator. The maximal second harmonic output power was 880 mW at 536 nm when pumped with 6.2 W at 976 nm. The output radiation line width of the second harmonics of the Yb-fibre laser did not exceed 0.5 nm with a tuning range of 521–545 nm and the output power at the ends of this range 220 and 450 mW respectively. Further presented is an analysis of different frequency doubling configurations both with and without an enhancement cavity in a broad range of output powers of the fundamental radiation.

Keywords: fiber laser, nonlinear optics, second harmonic generation, enhancement cavity

1. INTRODUCTION

Frequency doubling optical configurations relying on enhancement cavities have demonstrated their high efficiency in a variety of different lasers [1–7]. Application of such cavities to fibre lasers made it possible not only to efficiently convert non-single-frequency radiation [8, 9], but also to remove the need of automatic alignment of the enhancement cavity length to the wavelength of the incident radiation. Due to relatively long resonators of fibre lasers, spectral density of longitudinal modes in these resonators far exceeds that in the enhancement cavities. Therefore, certain frequencies of the fibre laser resonator coincide or nearly coincide with transmission peaks of the enhancement cavity. For these frequencies, the enhancement cavity is resonant and provides efficient power enhancement inside the cavity. Practicality of such configurations was demonstrated earlier for cases when the enhancement cavity is external to the fibre laser resonator and when the enhancement cavity is contained within the fibre laser resonator (see Fig. 1(a) and 1(b)).

The present work proposes a new approach to second harmonic generation in fibre lasers: in our case, the enhancement cavity is partially coupled to the fibre laser resonator owing to a small shared optical path, at the same time belonging both to the fibre laser resonator and to the enhancement cavity (Fig. 2). This became possible because the fibre laser output coupler was placed inside the enhancement cavity.

2. EXPERIMENTAL SETUP

The experimental installation schematically shown in Fig. 3 is composed of two coupled resonators: the linear fibre laser resonator with an active optical fibre as its gain medium and a ring enhancement cavity with a non-linear LBO crystal inside. The linear resonator of the fibre laser is terminated on one side by totally reflective mirror M5 and on the other side, by a normal to the beam and weakly reflective (0.2%) facet of the non-linear LBO crystal located within the enhancement cavity. The pump radiation at 976 nm is guided through a beam combiner into the inner cladding (diameter 125 μm, NA = 0.46) of a 3-m polarisation-maintaining double-clad optical fibre having a 10-μm core (NA = 0.08) doped with ytterbium ions.

The fibre ends through which the intra-cavity radiation passes onto discrete elements were cleaved at 8° in order to avoid parasitic back-reflection into the fibre. A prism was placed in front of end mirror M5, which allowed spectral tuning of the fundamental radiation by rotation of that mirror.

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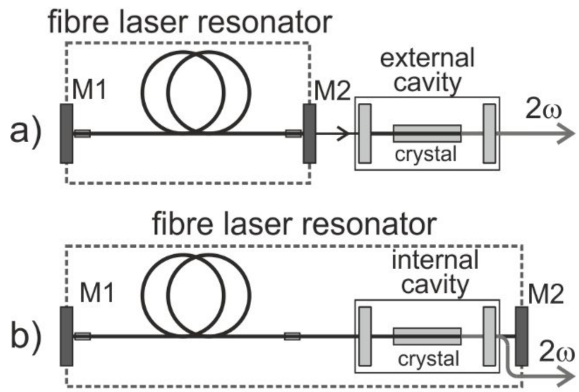

Fig. 1. Configurations of second harmonic generation with the enhancement cavity external (a) and internal (b) to the fibre laser resonator.

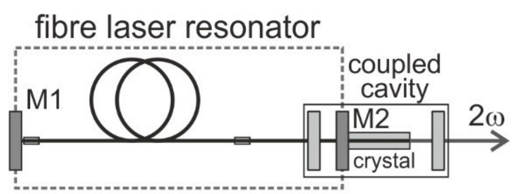

Fig. 2. Diagram of second harmonic generation in a fibre laser where the enhancement cavity is only partially coupled to its resonator.

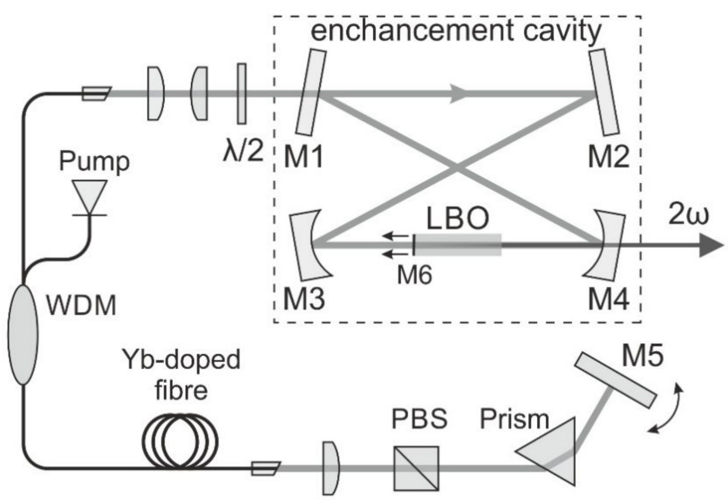

Fig. 3. Experimental set-up of the Yb-doped fibre laser with a partially coupled enhancement cavity: M1–M4 – mirrors of the enhancement cavity; M5, M6 – end mirrors of the fibre laser linear resonator.

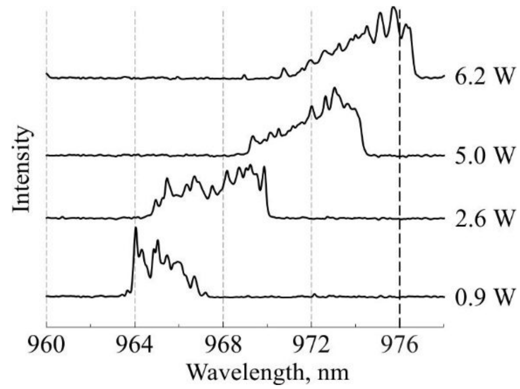

Fig. 4. Pump radiation spectra at different output powers.

Between the collimating lens and the prism, a polariser (PBS) was installed to ensure linear polarisation of the laser's radiation. At the other end of the linear fibre laser resonator, was located a four-mirror enhancement cavity, whose only two surfaces orthogonal to the beam were the anti-reflection-coated faces of the non-linear cavity having reflectivity of around 0.2%. A half-wave phase plate in front of the enhancement cavity was used to match the laser polarisation to the requirement of the most efficient second harmonic generation in the non-linear crystal.

The enhancement cavity was formed by flat mirrors M1, M2 and spherical mirrors M3, M4 with equal curvature radii of 75 mm. Mirrors M2–M4 were totally reflective in the wavelength range of 1000–1100 nm, transmittance of input mirror M1 varied between 2% and 15% within the laser's working wavelength range of 1040–1090 nm correspondingly.

A 20-mm LBO crystal was cut for non-critical phase matching of type II, the temperature inside the oven where it was kept being about 150 ± 0.1 ºC. The crystal's working faces had anti-reflection coating for 1064 and 532 nm.

To narrow down and tune the laser radiation line, we tested a dispersion prism and a birefringent filter [10, 11], both having sufficiently high radiation damage threshold to allow high-intensity beams. Our experiments have shown that the chosen prism only worked well up to a certain laser output power (~500 mW for the second harmonic radiation), above which irregular wavelength hops by as much as 0.5–1 nm were observed. This indicates insufficient spectral selectivity of the prism at relatively high laser radiation power. It should also be noted that because of comparatively low angular dispersion of the prism, the optical path between the fibre end and mirror M5 had to be correspondingly long. In the present work, it was approximately 1 m. A birefringent filter consisting of a single birefringent Brewster plate and a polariser allowed tuning the laser's fundamental radiation within a 40-nm range. In this case, however, wavelength hopping in the laser's output spectrum emerged at even lower output power level as compared to the prism.

3. SHG IN PARTIALLY COUPLED ENCHANCEMENT CAVITY

In Ref. [8] it was shown that in the configuration "resonator within resonator", the fibre laser feedback was provided by a reflective mirror located behind the enhancement cavity, *i.e.* this cavity had two partially reflective mirrors: one for coupling the fundamental radiation into the enhancement cavity, and the other for coupling it out. The fundamental radiation in this configuration was generated at those frequencies, which were resonant for both the fibre laser resonator and the enhancement cavity.

In the configuration of partially coupled cavities, the fundamental radiation is also generated at frequencies resonant for both the fibre laser resonator and the enhancement cavity. However, in our case the fibre laser feedback was provided by a reflective mirror located *inside* the enhancement cavity. One of the anti-reflection-coated faces of the non-linear crystal orthogonal to the beam played the role of this mirror within the enhancement cavity. To verify operability of the laser's output mirror having reflectivity of only 0.2%, the optical layout shown in Fig. 5 was adopted. In this layout, the front anti-reflection-coated face of the non-linear crystal was directly used as the output mirror of the fibre laser without the enhancement cavity. Our experiments have established that fibre laser generation emerged when this face of the non-linear crystal was aligned so as to return the reflected radiation back into the fibre. It is necessary to point out that the effective reflectivity of this anti-reflection-coated surface is higher inside the enhancement cavity than it is outside because inside the enhancement cavity, a higher-power beam is incident upon this surface due to the power-enhancement factor of the cavity. This is why the effective reflectivity of such anti-reflection-coated surface placed inside the enhancement cavity may reach several per cent and be close to the optimal one predicted in [12].

The parameters of the used four-mirror enhancement cavity were selected for optimal focusing of intra-cavity radiation onto the 20-mm LBO crystal [13], the waist radius w_0 of the focused beam being approximately 30 μm. The calculated spectral width of phase matching for the utilised crystal amounted to 1.8 nm [14] and comfortably exceeded the laser radiation line width (0.5 nm). The angle of incidence of the beam onto the spherical mirrors in the enhancement cavity was around 10º, thus leading to astigmatism. The beam waist radii between the flat mirrors of the enhancement cavity had a ratio of $w_t/w_s = 0.86$. Beam astigmatism within the enhancement cavity led to additional optical losses in matching of the fibre laser modes to those of the enhancement cavity.

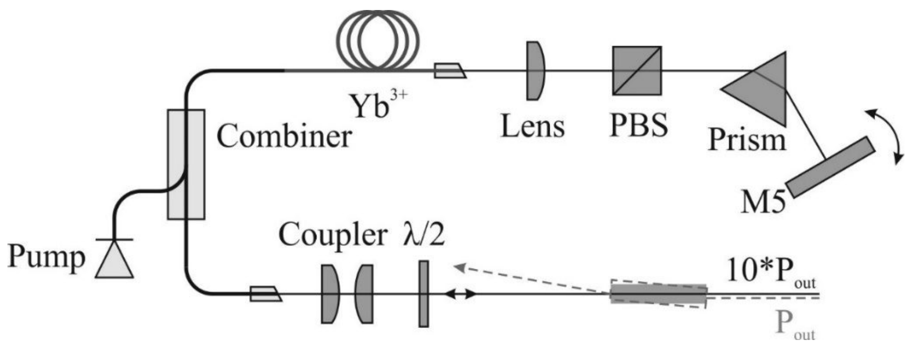

Fig. 5. Diagram of fibre laser resonator with 0.2% output mirror.

The radiation power within the enhancement cavity was measured at 30 W with a 6.2-W pump. The intra-cavity power was taken at the fundamental radiation wavelength of 1071.5 nm, transmittance of mirror M1 being 5% at this wavelength. Fig. 6 presents the dependence of the second harmonic radiation power upon the pump power. The inset shows the transverse intensity profile of the second harmonic beam.

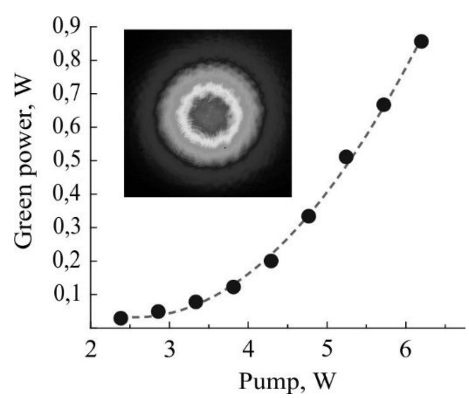

Fig. 6. Power of the second harmonic radiation as a function of the pump power (dots); dashed line is a parabolic approximation of the experimental data. The inset shows the transverse intensity distribution in the second harmonic (green) radiation beam.

4. WAVELENGTH TUNING OF THE SECOND HARMONIC RADIATION

The wavelength of the second harmonic radiation was tuned by synchronous adjustment of the fundamental radiation wavelength and the non-linear crystal temperature. The fundamental radiation wavelength could be modified within 1042–1090 nm by rotation of mirror M5. Throughout this range, the fundamental wavelength changed in 1-nm steps, thus indicating a certain degree of unwanted spectral selection, perhaps caused by polarisation effects. The dependence of the second harmonic power on the wavelength is given in Fig. 7.

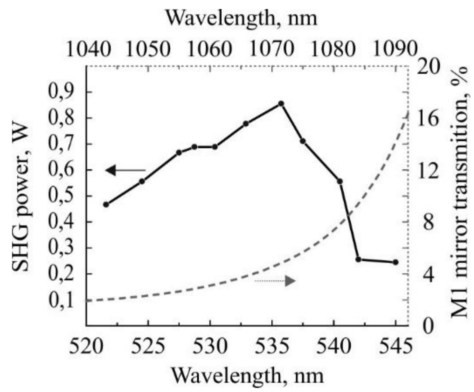

Fig.7. Power of the second harmonic (green) radiation at different wavelengths at the maximal fibre laser pump power (black line and bottom wavelength scale); reflectivity of mirror M1 in the infrared spectrum (dashed line and upper wavelength scale).

Towards the shorter wavelengths of the spectrum, the tuning range of the second harmonic was limited by the maximal temperature of 180 ºC possible in the thermostat used in our experiments. The dependence of the green radiation power on the wavelength was caused both by the corresponding dependence of the fundamental radiation power and by a considerable variation of mirror M1 reflectivity within the spectral tuning range.

5. SHG EFFICIENCY WITH AND WITHOUT THE ENHANCMENT CAVITY

Several recent publications [15–17] reported on relatively efficient second harmonic generation without an enhancement cavity. These studies are based on extra-cavity frequency doubling in powerful lasers (featuring CW output powers around 1 kW and higher) with a single pass through the non-linear crystal. It is of practical interest to find out, at least approximately, the level of fundamental radiation power, up to which enhancement cavities provide more efficient second harmonic generation, and above which they lose out to single-pass extra-cavity frequency doubling. The results of our numerical modelling are presented in Fig. 8. In our model, the transmittance of the enhancement cavity input mirror either was equal to the optical losses in the cavity, or remained constant. The optical losses were composed of those for second harmonic generation and additional losses (0.5%) originating from imperfect mode matching, &c. The generated results give us a qualitative estimation indicating that at CW radiation powers of 1 kW and higher, the single-pass frequency doubling efficiency reaches ~ 20% and more, making this simpler configuration competitive against enhancement cavities. Increasing the input power of the fundamental radiation further leads to single-pass conversion efficiency of 50% and more.

6. CONCLUSION

We have proposed and demonstrated a new configuration for frequency doubling in non-single-frequency infrared fibre lasers relying on a partially coupled enhancement cavity. The key feature of this configuration is the output coupler of the fibre laser located inside the enhancement cavity. Its role in our experiments was played by a normal to the beam anti-reflection-coated surface of the non-linear crystal placed inside the cavity. The proposed layout was used to achieve second harmonic generation efficiency of 14% relative to the fibre laser pump radiation power. Wavelength tuning was also demonstrated within the range of 521–545 nm with a maximum of 880 mW at 536 nm.

Efficiency of second harmonic generation in configurations with and without an enhancement cavity was analysed within a wide range of fundamental radiation input powers. We have demonstrated that at CW input power of around

1 kW or higher, the efficiency of extra-cavity frequency doubling in a single-pass configuration reaches tens of per cent, thus obviating the need of more complicated frequency doubling technique based on enhancement cavities.

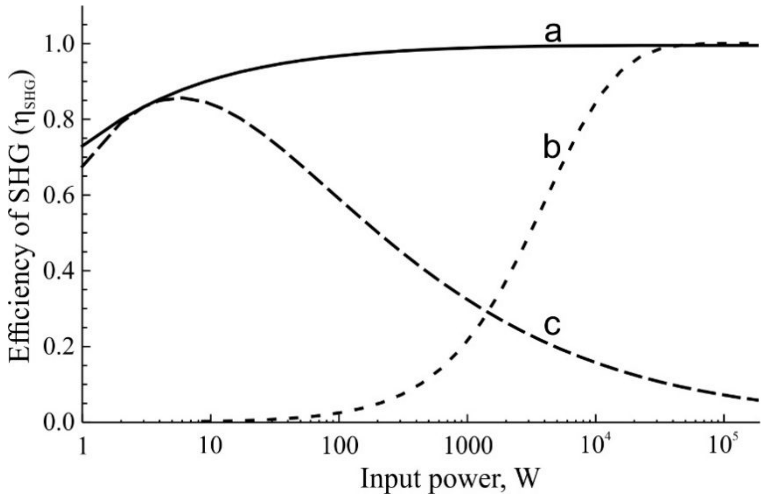

Fig. 8. Efficiency of second harmonic generation in an enhancement cavity configuration: (a) — at the input mirror transmittance optimal for each input power and (c) — at a fixed input mirror transmittance; (b) — in single-pass extra-cavity frequency doubling.

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