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Second-harmonic generation efficiency for multifrequency ytterbium-doped fibre laser radiation*

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Abstract. **The second-harmonic generation (SHG) efficiency for cw Yb-doped fibre laser radiation, which is characterised by many longitudinal modes with random phases, is compared with the SHG efficiency for amplified single-frequency Nd : YAG laser radiation in ppLN and KTP crystals, characterised by the type-I and type-IIphase matching, respectively. It is shown that the conversion efficiency into the second harmonic in the multifrequency regime for both crystals is higher by a factor of about 1.6, a value close to the calculated enhancement (2 for the Gaussian mode statistics). This difference is explained by possible deviation of the statistics of the Yb-doped fibre laser radiation from Gaussian, which is confirmed by measurements of the laser temporal dynamics.**

Keywords: *fibre laser, second-harmonic generation, crystal, KTP, ppLN, efficiency, multifrequency regime, single-frequency regime, Gaussian statistics.*

1. Introduction

Second-harmonic generation (SHG) has been used for many years to expand the spectral range of lasers of various types. The high SHG efficiency of pulsed lasers is determined by their high peak power and quadratic dependence of the second-harmonic power on the fundamental-frequency power. The SHG efficiency linearly increases with increasing fundamental-frequency power, until pump depletion becomes considerable.

Even in 1964 Ducuing and Bloembergen [1] considered how the SHG efficiency for multifrequency radiation (for example, for lasers with a large number of longitudinal modes) depends on the existence of phase correlations between cavity modes. In particular, it was shown that the conversion efficiency for multifrequency radiation containing modes with random phases (described by Gaussian statistics) can be increased by a factor of 2 in comparison with single-frequency radiation.

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However, it was noted in [2] that the increase in efficiency (statistical enhancement) is 2 for only low conversion coefficients of the field with a random complex amplitude and significantly changes when the radiation statistics deviates from Gaussian. The more slowly the probability distribution decreases at infinity, the larger the enhancement, and vice versa. Recently much attention has been paid to the generation of rogue waves in optics; a case where the probability of high-intensity events is relatively high (see, i. e., [3]). In this situation, the statistical enhancement in harmonic generation may be even higher.

In this study we investigated the statistical enhancement in SHG for multifrequency linearly polarised radiation of cw ytterbium-doped fibre laser. On the one hand, to exclude the decrease in the statistical enhancement due to the dispersion in a nonlinear crystal, the lasing spectral width (less than 10 pm) was much smaller than the spectral phase-matching width (above 0.4 nm). On the other hand, the effective number of longitudinal modes in the laser was sufficiently large ($N \sim 50$); therefore, the specific N value did not affect the statistical enhancement ($K = 2 - 1/N \approx 2$ [1]). For a small number of modes ($N < 8$) this dependence was experimentally confirmed in the case of SHG for He – Ne laser radiation in an RDP crystal with noncritical type-I phase matching [4]. Since He – Ne lasers are characterised by inhomogeneous gain saturation, the cavity length was chosen to be sufficiently small (such as to make the intermodal length exceed the homogeneous line width). This approach provided independence of gain saturation at all longitudinal modes and, as a result, their uncorrelatedness.

Ytterbium-doped fibre lasers are generally characterised by a relatively large cavity length ($L \sim 10$ m) [5]; small intermodal frequency ($c/(2Ln) \sim 10$ MHz); and a large number of generated longitudinal modes, excited when fibre Bragg gratings with a characteristic width of reflection spectrum from several gigahertz to several hundreds of gigahertz are used as cavity mirrors. The homogeneous gain bandwidth greatly exceeds the intermodal range, due to which mode phases can be correlated even in cw lasers. Therefore, the statistical enhancement for SHG in an ytterbium-doped fibre laser should be refined.

The progress in the development of physics and technique of ytterbium-doped fibre lasers and in the technology of efficient nonlinear crystals made it possible to use simple single-pass SHG schemes to convert radiation of these lasers into visible light (see, e.g., [6]). High nonlinearity in this wavelength range is observed in periodically poled crystals exhibiting quasi-phase-matching (e.g., ppLN [7]) and KTP crystals with type-II phase matching [8]. We performed experiments with crystals characterised by phase matching of these two types under different focusing conditions.

2. Experimental

To carry out the experiment, we designed a double-clad ytterbium-doped all-fibre laser (Fig. 1) with a cavity formed by two fibre Bragg gratings (FBGs). The active polarisation-maintaining double-clad fibre we used (Liekki Yb1200-6/125DC-PM) had a length of 3 m, a mode diameter of 6.3 μm, an internal cladding diameter of 125 μm, and nominal pump absorption of 2.6 dB m^{-1} at a wavelength of 976 nm. Pumping was performed by two 8-W multimode laser diodes (LDs) (Oclaro) through a pump combiner (PuC). The combiner of the $(2 + 1)\times 1$ type has two multimode ports and one single-mode port at the input and a double-clad fibre at the output.

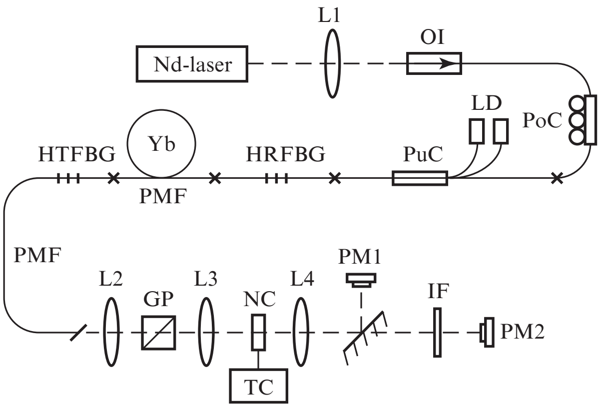

Figure 1. Schematics of the system.

A highly reflective FBG (HRFBG) was fusion spliced to the output port. This grating, with a reflection FWHM of 0.16 nm and reflectance above 95%, was written in a double-clad fibre and placed in a thermostat at a temperature of 25 °C. An output highly transmittive FBG (HTFBG), written in a polarisation-maintaining fibre (PMF) PM980-XP with two reflection peaks, corresponding to two polarisation states, spaced by 0.26 nm, was fusion spliced to the other side of the active fibre. The reflection FWHM was 0.07 nm; the reflectance amounted to ~25% for a given polarisation. The output FBG was placed in a thermostat. At a temperature of 80 °C the short-wavelength reflection peak of the output FBG had the same wavelength as the HRFBG reflection peak, and linearly polarised radiation with $\lambda = 1063.85$ nm was generated. With an increase in the output-FBG temperature to 100 °C the reflection peaks of these gratings ceased to be overlapped, and the ytterbium laser could be used as an amplifier. The fibre end face at the laser output was cleaved at an angle of ~8° to exclude coupling between the HRFBG and end face. The total laser cavity length L was 4 m, and the corresponding cavity round-trip time $t_{\rm rt} = 2Ln/c$ was 40 ns. The output radiation was collimated by an aspherical lens L2 with a focal length of 7.5 mm. A Glan prism (GP) was installed behind the collimator to increase the degree of polarisation and improve the long-term stability.

To compare the SHG efficiency for multifrequency and single-frequency radiations, we used additionally a single-frequency Nd:YAG laser with a wavelength of 1064.35 nm. Its radiation was amplified in an active optical fibre, into which it was coupled (using a lens L1) through a fibre optical isolator OI. The output isolator fibre was spliced to the single-mode input port of the pump combiner. Since the isolator, pump combiner, and HRFBG did not maintain polarisation, we used additionally a fibre polarisation controller (PoC) to match the polarisation states of the neodymium laser and ytterbium-doped fibre amplifier.

When increasing the pump laser diode current, we could increase the neodymium laser power to 0.5 W without lasing at the FBG reflection wavelength. The lasing spectrum was measured with an AQ6370 optical spectrum analyser (Yokogawa) and a scanning Fabry–Perot interferometer. The lasing spectral width of the ytterbium-doped laser did not exceed 2 GHz at a lasing power of 0.7 W. Thus, the effective number of modes involved in lasing was ~50. The experimental scheme we chose makes it possible to obtain identical geometric parameters of the multifrequency and single-frequency laser beams. The laser radiation was focused into the nonlinear crystal (NC) using a set of lenses L3. The beam position, waist diameter, and quality factor were measured with a BeamMaster BM-7 InGaAs profilometer (Coherent) placed on a longitudinal movable platform. The beam radius in the waist was 16, 26, and 55 μm for the L3 lenses with focal lengths of 3, 5, and 11 cm, respectively. The beam quality factor M^2 did not exceed 1.03.

Frequency was doubled in two KTP crystals with critical type-II phase matching in the XY plane. The crystal lengths l were 2.5 and 5 mm. The crystals were placed in a thermostat, governed by a temperature controller TC with a temperature variation range from 35 to 95 °C. To ensure equal powers of ordinary and extraordinary waves, the laser beam polarisation was set at an angle of 45° with respect to the Z axis of the crystal using a PAX5710IR2-T polarimeter (Thorlabs). The radiation transmitted through the crystal was collimated by a lens L4. Then the fundamental and second harmonics were separated by a mirror and measured by power meters PM1 and PM2, respectively. The interference filter IF was used for additional filtering of the second harmonic.

The position and tilt angle of crystals were optimised to obtain the maximum SHG power for single-frequency radiation at a temperature of 75 °C. Then we recorded the dependence of the total frequency-doubling effective nonlinear coefficient $\gamma = P_2/P_1^2$ on the crystal temperature for single-frequency and multifrequency beams. Both curves were approximated by the function $A\,{\rm sinc}^2[0.443\pi(T - T_0)/\Delta T]$ with independent parameters A, T_0, and ΔT, which were fitted by the least-squares method and normalised to unity in the maximum of the SHG effective nonlinear coefficient for single-frequency radiation. The measurement results for 2.5- and 5-mm-long KTP crystals are shown in Figs 2a and 2b. The difference in the positions of peaks of the effective nonlinear coefficient is related to the 0.5-nm difference in the wavelengths of multifrequency and single-frequency radiations. It can be seen in the plots that the statistical enhancement for multifrequency radiation depends weakly on focusing and lies in range of 1.5–1.65.

Similar experiments were performed with a lithium niobate periodically poled crystal doped with 5 mol % MgO (domain period 6.95 μm, crystal length 4.7 mm). In this case, polarisation was set along the Z axis of the crystal. The measurement

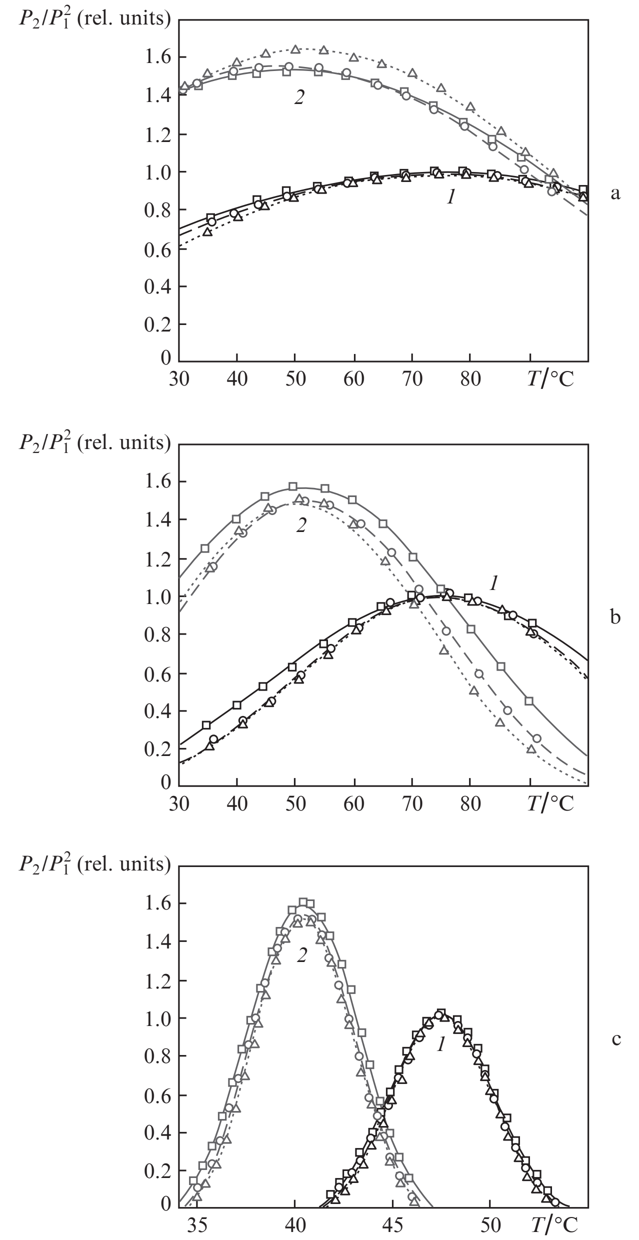

Figure 2. Normalised temperature dependences of the SHG effective nonlinear coefficient for KTP crystals with lengths of (a) 2.5 and (b) 5 mm and (c) MgO : ppLN crystal for (*1*) single-frequency and (*2*) multifrequency modes at beam waist radii of (□) 16, (○) 26, and (△) 55 μm.

results are shown in Fig. 2c. Comparison of Figs 2a – 2c shows that statistical enhancement depends weakly on not only focusing but also on the phase-matching type.

Information about the SHG statistical enhancement can also be obtained by analysing the temporal behaviour of the ytterbium-doped laser power during the cavity round-trip time. To this end, we used a LeCroy WavePro 725Zi-A oscilloscope with a transmission bandwidth of 2.5 GHz and a LeCroy OE455 photodetector with a bandwidth of 3.5 GHz. Since the lasing spectrum width (no more than 2 GHz) was below the transmission bandwidth, the obtained dependences for the power were not averaged during measurements. Figure 3a shows the time dependences of lasing power for single-frequency and multifrequency beams. The power noise of the single-frequency laser corresponds to the detector noise.

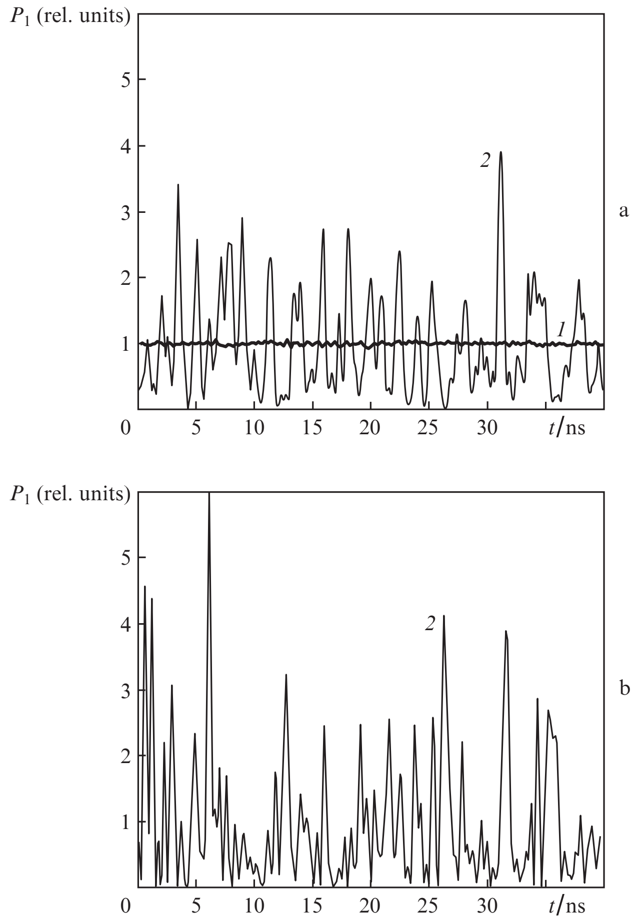

Figure 3. Time dependences of the power of (*1*) single-frequency and (*2*) multifrequency lasers, normalised to the mean: (a) experiment and (b) calculation for multifrequency radiation with Gaussian mode statistics and spectrum in the form of a hyperbolic secant.

3. Results and discussion

The data reported above indicate that, even at a relatively large ($N \sim 50$) effective number of modes involved in lasing of ytterbium-doped fibre laser, the statistical enhancement significantly differs from 2. This can be related to the presence of partial mode locking in the multifrequency cw laser, caused by the homogeneous saturation of the gain line on the lasing spectrum scale. As was noted in [2], the statistical enhancement depends also on the statistical properties of the field envelope. The lasing spectral width is much smaller than the phase-matching width in the crystals we used. In our case, the statistical enhancement can be determined using the quasi-static model in which the difference between the group velocities of the fundamental and second harmonics is neglected.

The temporal dynamics and statistical enhancement were calculated using the well-known model of a laser with noncorrelated modes (see, for example, [2]), in which phases of the modes are statistically independent and uniformly distributed over the interval $(-\pi, \pi)$. The profile of the lasing spectrum was chosen in the form of a hyperbolic secant, in accordance with the model of ytterbium laser spectrum broadening due to the self-phase modulation with dispersion neglected, which is experimentally confirmed for relatively narrow-band lasing [9]. Calculation was performed for 101 modes with intermodal spacing of 25.2 MHz and spectral FWHM of 2 GHz. The phase of each mode was chosen randomly on the interval $(-\pi, \pi)$. The time dependence of power $P_1(t)$ is periodic; the period is 39.7 ns (Fig. 3b). The multimode laser power averaged over the cavity round-trip time can be related to the single-frequency laser power. The SHG power is proportional to the squared fundamental harmonic power; therefore, the statistical enhancement under quasi-static conditions is the ratio of the mean of squared power to the squared mean power at the fundamental frequency: $\langle P_1(t)^2 \rangle / \langle P_1(t) \rangle^2$. It was found that the thus calculated increase in efficiency changes from realisation to realisation of randomly chosen phases but remains close to 2: 2 ± 0.15. A similar averaging procedure based on the experimentally measured time dependence of ytterbium laser power (Fig. 3a) yields 1.5, a value close to the experimentally observed enhancement in the SHG efficiency. Note that the larger enhancement in the case of Gaussian mode statistics is related to the presence of larger amplitude spikes on the time scale: up to six times with respect to the mean (Fig. 3b), whereas the magnitude of experimental spikes did not exceed 4 (Fig. 3a).

We should also note the experimental study of the SHG in a MgO : ppSLT crystal irradiated by a multifrequency ytterbium laser [10]. It was suggested that the SHG efficiency for multifrequency laser radiation exceeds that for single-frequency radiation by a factor of 2. The experiment was performed with only a multifrequency laser. At a phase-matching width of 0.16 nm and a laser spectral width of 0.07 nm the calculated increase in efficiency amounted to 1.5, a value close to our experimental result.

Thus, even the existence of a large number of modes does not guarantee doubled conversion efficiency. This must be taken into account when measuring nonlinear constants for crystals. However, Asaumi [11] used the formula $(2 - 1/N)$ for the statistical enhancement to correct the nonlinearity $d_{\rm eff}$ of a KTP crystal, which was measured with a multifrequency Nd:YAG laser. The neodymium laser gain is saturated homogeneously and may involve, as in the case of ytterbium-doped fibre laser, partial mode locking.

4. Conclusions

We investigated the statistical enhancement of SHG power for multifrequency ytterbium-doped fibre laser radiation in crystals with phase matching of types I and II. The measured statistical enhancement was found to be 1.5–1.65; i.e., noticeably smaller than the calculated coefficient 2 for laser radiation described by Gaussian statistics. It was shown that this difference can be explained by partial mode phase locking due to the homogeneous gain saturation by generated modes. Nevertheless, the significant increase in the SHG efficiency for multifrequency radiation in comparison with a single-frequency one in crystals of different types makes it possible to design an efficient visible-light source using fairly simple and reliable lasers based on active ytterbium-doped double-clad fibre, with pumping by multimode diodes and a linear cavity based on fibre Bragg gratings [5]. The use of an ytterbium-doped fibre laser with tunable FBGs for pumping (see, e.g., [8]) and a KTP crystal with vector type-II phase matching for frequency doubling allows one to convert smoothly visible light wavelength in a wide range, which is difficult to do in schemes based on periodically poled crystals and rather complex single-frequency fibre lasers supplemented with an amplifier (see, e.g., [6]).

References

1. Ducuing J., Bloembergen N. *Phys. Rev. A*, **133**, 1493 (1964).
2. Akhmanov S.A., D'yakov Yu.E., Chirkin F.S. *Vvedenie v statisticheskuyu radiofiziku i optiku* (Introduction to Statistical Radio Physics and Optics) (Moscow: Nauka, 1981).
3. Solli D.R., Ropers C., Koonath P., Jalali B. *Nature*, **450**, 1054 (2007).
4. Qu Y., Singh S. *Phys. Rev. A*, **47**, 3259 (1993).
5. Kurkov A., Dianov E. *Kvantovaya Elektron.*, **34**, 881 (2004). [*Quantum Electron.*, **34**, 881 (2004)].
6. Samanta G.K., Kumar S.C., Ebrahim-Zadeh M. *Opt. Lett.*, **34**, 1561 (2009).
7. Miller G.D., Batchko R.G., Tulloch W.M., Weise D.R., Fejer M.M., Byer R.L. *Opt. Lett.*, **22**, 1834 (1997).
8. Akulov V.A., Kablukov S.I., Babin S.A. *Kvantovaya Elektron.*, **42**, 120 (2012) [*Quantum Electron.*, **42**, 120 (2012)].
9. Kablukov S.I., Zlobina E.A., Podivilov E.V., Babin S.A. *Opt. Lett.*, **37**, 2508 (2012).
10. Tovstonog S.V., Kurimura S., Kitamura K. *Jpn. J. Appl. Phys.*, **45**, L907 (2006).
11. Asaumi K. *Appl. Phys. B: Lasers and Optics*, **54**, 265 (1992).