The study of second harmonic generation of the femtosecond laser pulses with a 950 nm central wavelength

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ABSTRACT

The paper presents the results of theoretical and experimental studies of the second harmonic generation process in the Ti:sapphire femtosecond complex, which includes a generator of the femtosecond pulse, stretcher, regenerative amplifier, two multi-pass amplifiers, compressor and second-harmonic generator. This complex provides the 50-fs pulses with energy of 20 mJ and it is used as a master oscillator in THL-100 hybrid laser system, which operates in the visible region at a wavelength of 475 nm. Experiments and calculations for various beam parameters of the fundamental harmonic, such as radiation intensity, spatial profile of the beam and the level of the noise component were performed. It is theoretically shown that in the absence of the noise component in the beam of the fundamental wave a good uniformity of the second harmonic should be observed. When making the amplitude heterogeneities in the first harmonic even greater heterogeneities in the second harmonic are appeared. It is experimentally shown that with increasing of energy beam the inhomogeneity of the second harmonic beam increases.

Keywords: femtosecond laser pulse, second harmonic generation, Gaussian beam, nonlinear crystal, homogeneity, intensity, heterogeneity

1. INTRODUCTION

Currently, the solid-state lasers with an optical or laser pumping are used for the formation of superpower femtosecond laser beams. The medium of neodymium-doped crystals or Ti:sapphire are most commonly used as the active medium in it. All these power solid-state laser systems operate in the near infrared (IR) spectrum. However, many applications require the powerful beams in the visible region of the spectrum. Production of laser beams in the visible range is solved by second harmonic generation (SHG) with infrared beams and well-mastered for nanosecond pulses [1]. These beams are widely used for pumping solid-state amplifiers in high power laser systems [2-3]. However, the production of laser beams in the visible range with femtosecond pulse duration quite poorly was studied. Currently the maximum power was realized at a wavelength of 400 nm and achieved 4 TW [4]. Further increase in capacity is limited by the size of the nonlinear crystals used for SHG. A characteristic feature of all the work on the SHG of femtosecond pulses is a great heterogeneity of the laser beam at the second harmonic [5-7]. In [5] it is shown that in cubic nonlinear medium small-scale amplitude and phase spatial heterogeneity (noise) that is always available in the beam can be amplified in the presence of a powerful wave. This noise in SHG should not exceed a definite value of the peak power of the input beam [6]. Otherwise it will lead to the collapse of the beam into separate parts, i.e., to small-scale self-focusing. Also highly efficient second-harmonic generation of femtosecond radiation in a nonlinear crystal KDP of 1 mm thick with a central emission wavelength of 910 nm in the first harmonic has been received [7]. Besides the importance of obtaining a laser beam in the visible region caused by the fact that it allows increasing the peak power of the focused laser beam by reducing the beam diameter at the waist approximately in two times.

In IHCE SB RAS the THL-100 laser system was developed. It operates in the visible spectrum (475 nm) and does not have the traditional limitations on the power of the output beam [8-9]. For its creation, the accumulated experience in the development of the high-power gas lasers was used [10-12]. To date the power of 14 TW was realized on it [13-15] and it is planned to increase the power up to 50-100 TW. In this laser system the second harmonic of a Ti:sapphire start complex is amplified in the gas amplifier on XeF(C-A) molecules. It is clear that the requirements for the beam quality of the start complex with femtosecond pulse duration are enough high. However, the experiments have shown that the

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second harmonic beam has the numerous local heterogeneities, which lead to beam filamentation, and impedes its further transport and gain. In connection with the above, to date, it is an important the more detailed study of SHG of femtosecond duration in order to find the conditions for obtaining a beam with a good homogeneity.

In this paper, the results of experimental and theoretical study of the SHG of femtosecond laser pulse at the central wavelength of 950 nm are presented. The purpose of research is to determine the causes of heterogeneities in the second harmonic radiation and the search conditions to minimize them.

2. THE EQUIPMENT AND METHODS

For experimental study of SHG the femtosecond Ti:sapphire start complex which is master oscillator for multiterawatt laser system was used. Its radiation is amplified in the gas amplifier on XeF(C-A) molecules [16]. The start complex consists of a master oscillator, a stretcher, a regenerative and two multi-pass amplifiers, a grating compressor and a second harmonic generator (2 mm KDP). The complex provides 50-fs laser pulses at a wavelength of 475 nm with energy up to 20 mJ. In the experiments we used a Gaussian beam of the fundamental wave with the energy of 2-10 mJ and 0.94 cm in diameter by the intensity drop to e^2 times. Schematic diagram of the experiment is shown in Figure 1. Radiation after conversion in KDP is reflected from two spectrally selective mirrors. Then, using a telescope the beam was directed at the profilometer of SP620U (Spiricon) or on the energy meter of OPHIR.

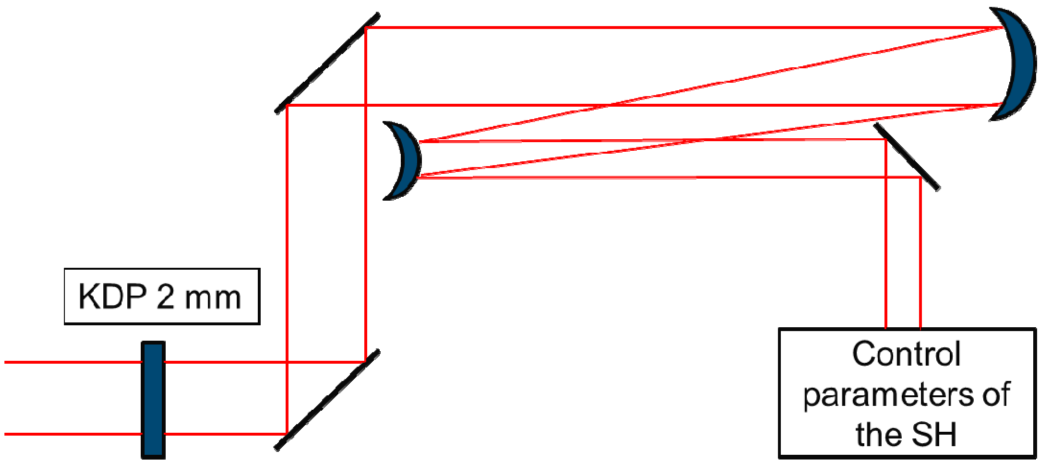


Figure 1. Block diagram of the experiment.

For the numerical simulation of second harmonic generation process of femtosecond pulses the algorithm with a «split-step predict correct» is used in which the resolved related quasi-optical equations describing the process of the second harmonic generation are solved.

3. RESULTS AND DISCUSSION

In SHG experiments the two mode regimes of the start complex were used. In the first regime a laser beam of 250 ps duration at a wavelength of 950 nm after the first multi-pass amplifier is compressed in the grating compressor and is converted into the second harmonic in a KDP crystal. In the second - the beam was amplified in two multi-pass amplifiers, passed through a spatial filter, also it was compressed in the compressor and converted into the second harmonic. The energy of the laser beam of the second harmonic in both cases was about 1 mJ. During the experiments the homogeneity of the intensity of initial and the converted beams was investigated. In the first case, the Gaussian beam at the fundamental harmonic had the small-scale heterogeneities (Figure 2,a). After passing through KDP the heterogeneities significantly increased (Figure 2,b). With energy increasing of the fundamental harmonic beam the heterogeneity of the second harmonic also increased significantly.

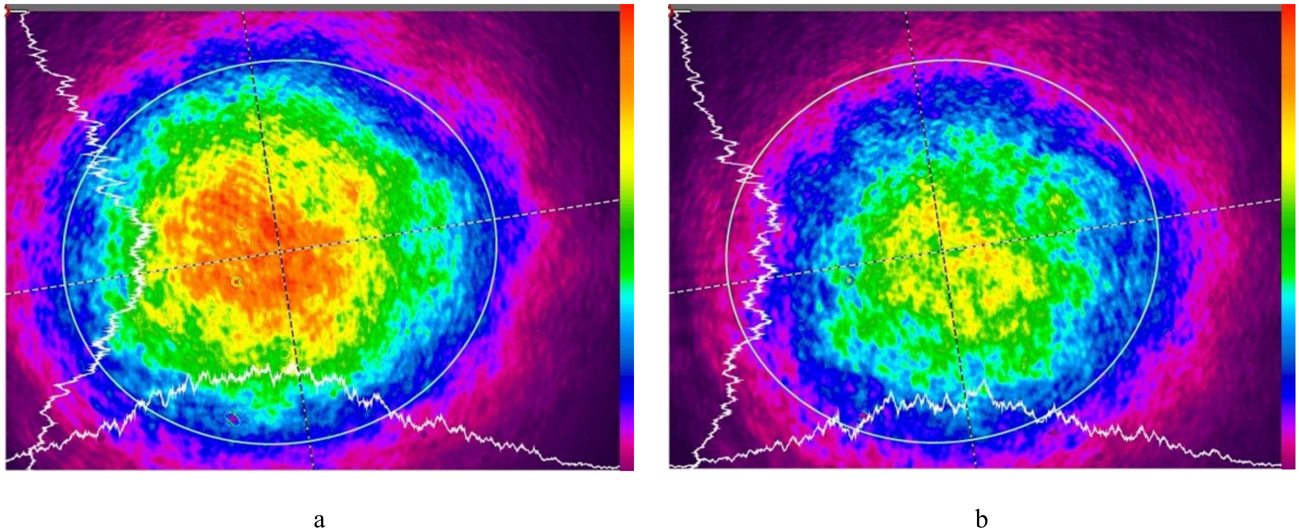


Figure 2. The distribution of the radiation intensity of the main beam (a) and beam converted into the second harmonic (b) in the first regime.

Another picture was observed in the second regime. With the help of the spatial filter the homogeneity of the fundamental harmonic beam was significantly improved. Gaussian beam with a diameter of 0.94 cm with a fairly good homogeneity was formed (Figure 3,a). The energy of the pump beam was 4.8 mJ. This significantly changed the situation for the converted beam to the second harmonic (Figure 3,b). The energy of the converted beam was 0.9 mJ, which corresponds to an efficiency of 18.75%. Small-scale heterogeneities significantly reduced, but the pinch of the beam began to appear due to the Kerr nonlinearity.

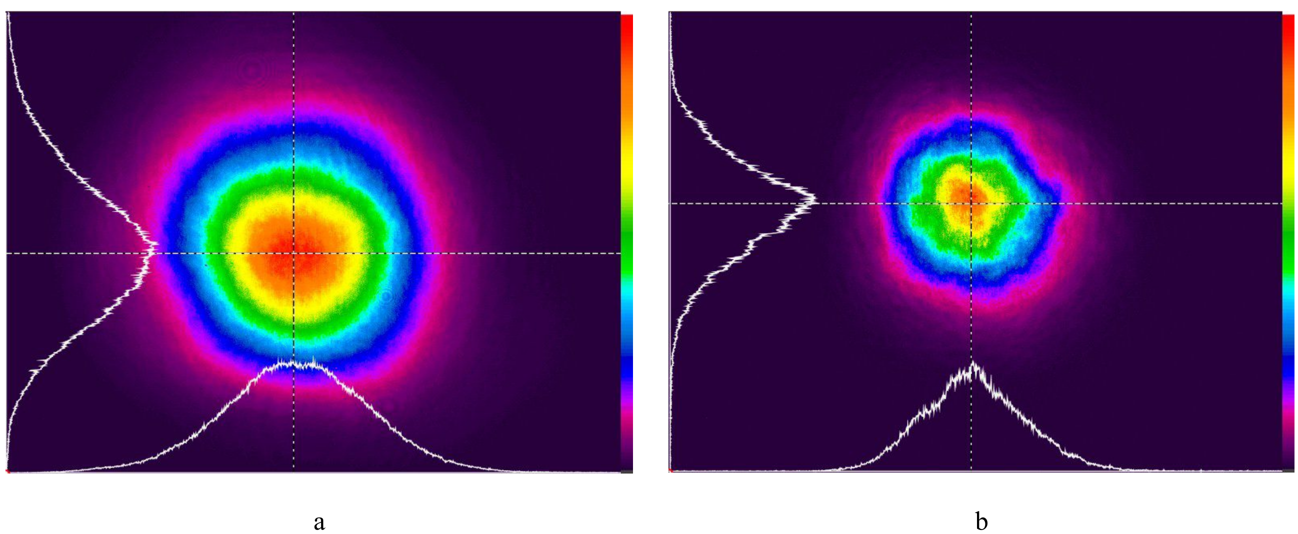
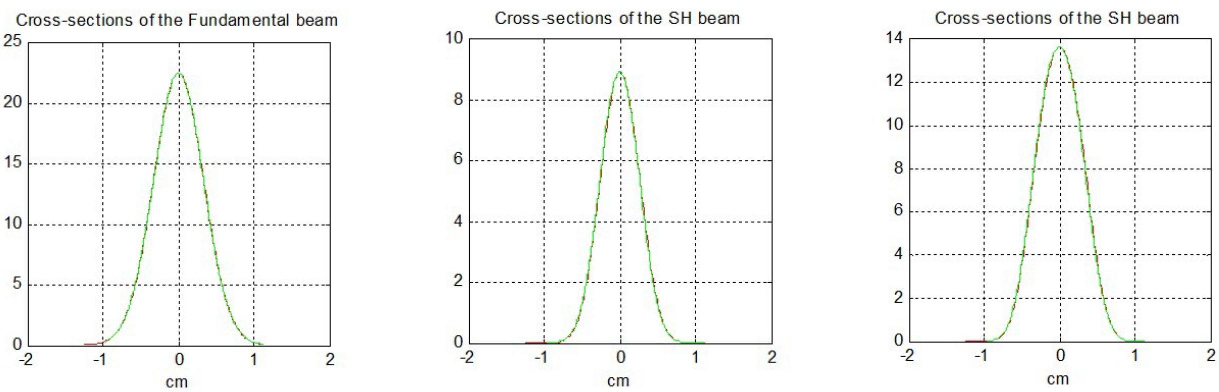


Figure 3. The distribution of the radiation intensity of the main beam (a) and beam converted into the second harmonic (b) in the second regime.

Also a theoretical analysis of the conditions of second harmonic generation was conducted. The calculation was performed for the KDP with 2 mm thickness, the pulse duration was taken 50 fs, central wavelength - 950 nm. The beam had a Gaussian shape with a diameter of 0.94 cm in e^2 intensity. The radiation intensity varied from 54 to 800 GW/cm^2. The output calculation parameters such as the transverse distribution of the intensity of the second harmonic and energy conversion efficiency of radiation are monitored.

Calculations have shown that the conversion of fundamental harmonic radiation (Figure 4,a) to the second harmonic (Figure 4,b) at an intensity of 54 GW/cm^2, which corresponds to 2 mJ energy, the profile of the beam at the second harmonic practically repeated the pumping beam. There were no small-scale heterogeneities. With increasing intensity up to 270 GW/cm^2 the picture has not changed (Figure 4,c). Model calculations have been carried out for large values of intensities. A significant impact on the intensity of the radiation beam structure was not identified.



a b c

Figure 4. The cross section of the first (a) order harmonic and the calculated cross section of the second harmonic at an energy of 2 (b) and 10 (c) mJ of incident radiation, respectively.

For the energy conversion efficiency of a femtosecond laser beam into KDP with 2 mm thickness was used numerical simulation. It was shown that it increases with increasing intensity of the fundamental harmonic beam (Figure 5) and reaches approximately 50% in operation (270 GW/cm^2). With further increase of the radiation intensity incident on the crystal the energy conversion efficiency tends to be a slight decrease, which goes into saturation. Reducing the efficiency is due to the appearance of the cubic nonlinearity in KDP. If we calculate the optimal thickness of the crystal, at which the maximum conversion of the infrared radiation into visible at high intensities (up to 800 GW/cm^2), it decreases and reaches 0.7 mm in energy efficiency of 64%.

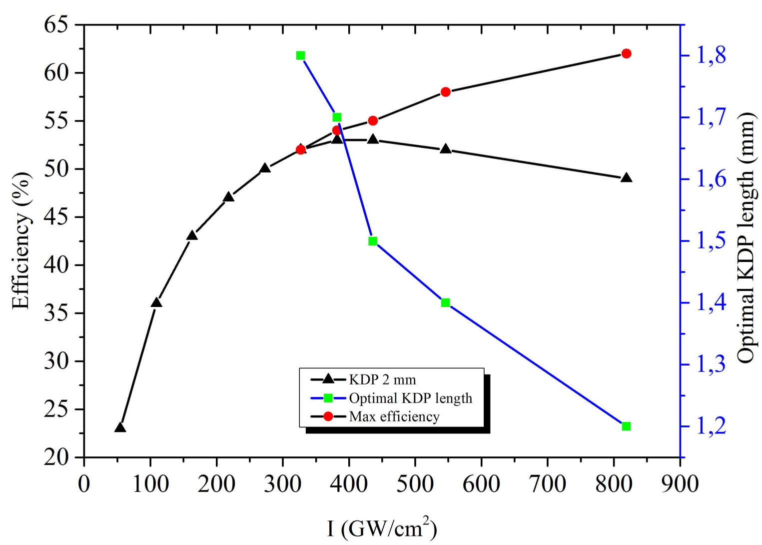


Figure 5. Theoretical dependence of the energy efficiency of SHG in KDP crystal 2 mm thick on the intensity of the first harmonic of the pulse at the entrance to the crystal (▲). The calculated optimum crystal thickness (■), necessary for high performance SHG (●).

As full harmonization of the calculations and the experiment with a beam diameter of 0.94 cm was not achieved, the model experiment with the best quality of the radiation in the smaller diameter of the pump beam at the second regime was carried out. For this purpose, the central part with a diameter of 2 mm was cut out from the entire beam of the fundamental harmonic, and at a distance of 2.4 m KDP crystal (2 mm) was installed. The energy part of the beam was 0.35 mJ at pulse duration of 50 fs. At the same time the beam profile was almost perfect Gaussian shape (Figure 6,a). Nevertheless the small-scale heterogeneities of radiation intensity in the second harmonic was observed (Figure 6,b). This suggests that a small fraction the beam pumping noise component is present, from which the completely unable to escape by filtration of a beam. This conversion efficiency was quite low, as the energy of the laser beam with a wavelength of 475 nm was 22 μJ.

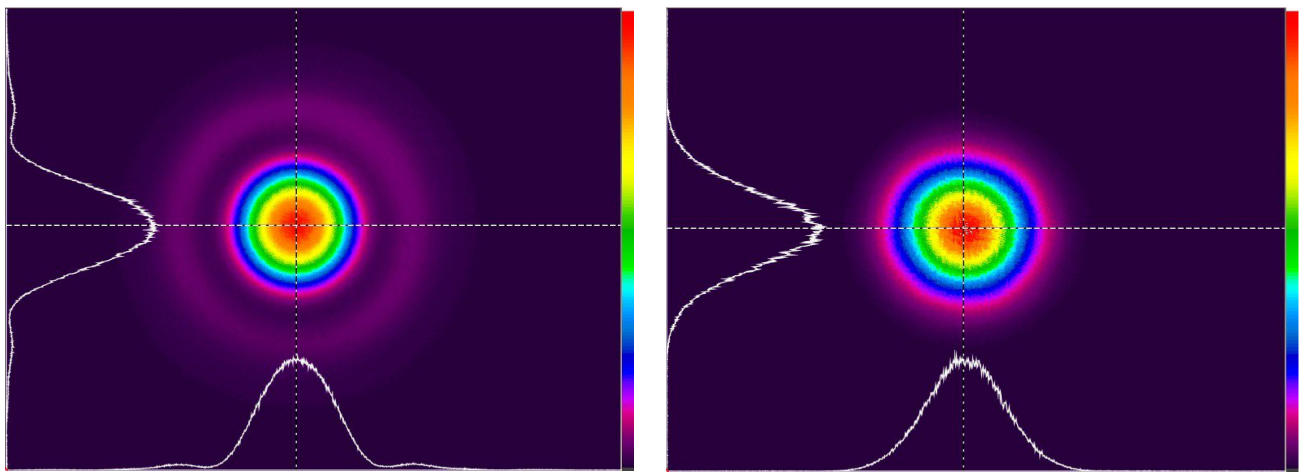


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Figure 6. The distribution of the radiation intensity of the main beam (a) and beam converted into the second harmonic (b) in model experiment with beam diameter of 2 mm.

For theoretical calculations of the model experiment the condition of calculations were specified, namely: phase was calculated using FRESNEL [17]. Previously models used the zero phase of beam, which in practice to achieve pretty hard. With an experimental beam profile and the calculated phase (Figure 7) it was possible to more accurately simulate the situation close to the experiment.

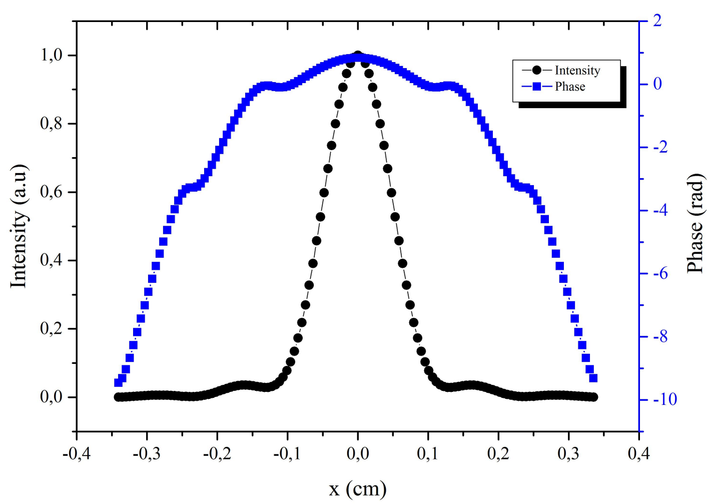

Figure 7. The intensity profile (●) and phase (■) laser beam calculated in the program FRESNEL.

As a result, the theoretical calculation of the data were obtained (Figure 8), in which converted to the second harmonic beam is virtually no local heterogeneity fluctuations, that observed in the experiment, and it again repeats the profile of the original beam.

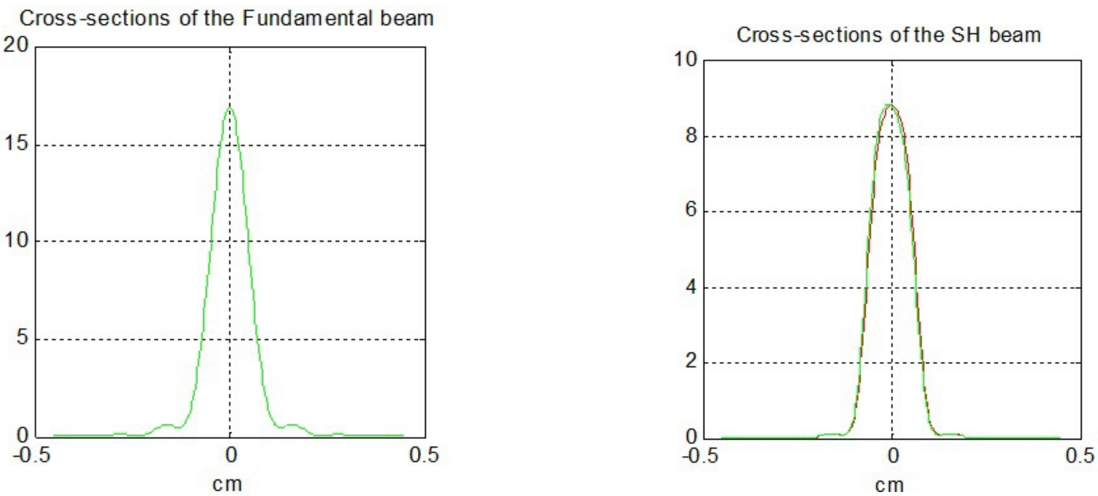

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Figure 8. The cross section of the first (a) order harmonic, cross section of the infrared radiation, passing through the KDP (red), and cross section of the second harmonic (green) (b).

At the same time entering into the calculation of the artificial distortion with the amplitude value of 10% gives a 18% of the heterogeneity of the second harmonic (Figure 9).

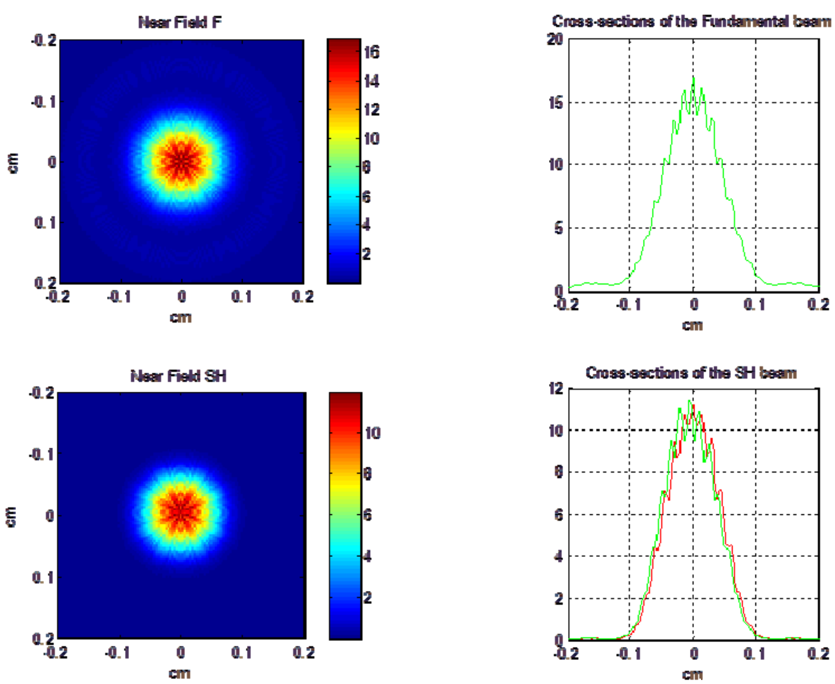

Figure 9. The intensity distribution of the initial of infrared radiation (top), infrared radiation, passing through the KDP (bottom, red) and radiation, converted to KDP (bottom, green).

4. CONCLUSION

Thus, the influence of radiation intensity spatial profile and level of the noise component of the first harmonic at a wavelength of 950 nm on the homogeneity of the second harmonic intensity was studied. The intensity of incident on the nonlinear crystal beam is changed in a 50-270 GW/cm^2 range. Theoretically and experimentally it has been shown that to obtain a good homogeneity in the second harmonic it is necessary to provide a high homogeneity of the radiation in the first harmonic and a minimum noise level in its composition. An experimental reduction of the noise components in the pump beam using spatial filter the small-scale heterogeneities in the second harmonic has significantly suppress. However, when the intensity of the first harmonic was 125 GW/cm^2 the preload of the beam begins to appear by the Kerr nonlinearity. It is shown that the presence of amplitude heterogeneities of the pump beam still more appears in the second harmonic. In the absence of heterogeneities (Gaussian beam) in the pump beam with an intensity of 125 GW/cm^2 in the calculation of the Gaussian beam is repeated, but the experiment shows the small-scale heterogeneities. This suggests either that some conditions in the theoretical model is not taken into account either in the pump beam a small fraction of the noise component beam is present on which is completely unable to escape by filtration. Perhaps for similar reasons the calculated efficiency was approximately two times higher than in a practice. It should be noted that in the experiments with increasing energy of the fundamental harmonic the increase of the heterogeneities at the second harmonic intensity is always observed.

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