Nonlinear conversion in optical waveguide filled with NaNO$_2$

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Abstract. This paper contains the first experimental results of nonlinear conversion in optical waveguide filled with solid nonlinear media. The experimental sample was made from SiO$_2$ fiber of the 1.6 cm length. During the pumping of the sample by the pulse laser, the generation of second harmonic radiation was observed at the whole length of the sample filled with NaNO$_2$. Despite the visibility of this effect, the detected signal was rather weak due to the scattering inside the fiber. Nevertheless, the successful experiment presented in this work may lead to the future development of new nonlinear devices using photonic crystal fiber filled with solid nonlinear medium.

1. Introduction
It is rather promising to fabricate microstructures filled with nonlinear media [1], [2], [3], [4], [5], [6], [7], [8], [9]. In such media as filled photonic crystals, microcells, photonic crystal fiber [10], [11], [12], [13], nonlinear conversion can be more efficient than in bulk material [4], [7], [8]. Thus, there is a huge interest to these structures, according to recent publications (see for example [14], [15], [16], [17], [18], [19]).

Turning the attention to the hollow core optical fiber, it is possible to find the results of filling it with nonlinear liquid [1], [2], [6] or gas [3], [5], [14]. For more information about such structures see [20]. But there a lot of difficulties, primarily technological, for fabricating structures filled with solid medium. On the other hand, structures filled with solids have no disadvantages of ones filled with liquid and gas: maintaining the particular pressure for gas, vacuum camera for beam input and output [5]. At least, such solid filled nonlinear fibers can be used for making an effective coherent two-wavelength source [1], photonic microcells [20], and nonlinear radiation converter [15].

2. Sample
We have chosen NaNO$_2$ because of its remarkable properties. At first, its melting temperature is 544 K, which is lower than softening temperature of SiO$_2$. Second, at room temperature NaNO$_2$ is a powder, so it is rather easy to work with it. Third, NaNO$_2$ is a well-known nonlinear material [21]. Also it has been already used successfully for filling the nanostructured materials [4], [9]. Anisotropy of NaNO$_2$ leads to different refractive indexes $n_x = 1.3395$, $n_y = 1.4036$, $n_z = 1.6365$ [22]. In case of SiO$_2$ optical tube, which has $n = 1.54$ refractive index, we have to use only $n_z$ refractive index of sodium nitrite in order to maintain the waveguide
condition \( n_{\text{core}} > n_{\text{tube}} \). Thus, it is required to obtain technologically the nonlinear crystal with particular orientation.

For our experiment we used the hollow core optical fiber of 10 cm length with internal diameter \( d = 80 \mu m \). The hollow fiber was filled with liquid \( \text{NaNO}_2 \) by means of using vacuum compressor. During this process, the nonlinear media filled some part of the fiber and crystallized inside. The length of the filled fiber was 1.6 cm.

3. Experiment

Figure 1 shows the generation of second harmonic generation in the sample, during pumping it with femtosecond laser pulses. Laser wavelength was \( \lambda = 1.03 \mu m \), so that the second harmonic wavelength corresponds to \( \lambda = 515 \text{ nm} \). The green light is well observed from figure 1, because the green filter was used for making picture, in order to cut off the laser radiation.

![Figure 1. Second harmonic generation in the sample of SiO\(_2\) fiber filled with NaNO\(_2\).](image)

We can observe the second harmonic generation along the whole sample. This approves the fact, that the sample became a waveguide and the required crystal grown in the core. But despite the visible result, a lot of radiation was scattered in the fiber cladding. The reason is in the inhomogeneity of the grown crystal. It should be mentioned that scattering in this sample is determined by the final structure of nonlinear crystal, and the impact of the structure factor in this case is significant (for example see [23]). Nevertheless, the appropriate technological cooling process can solve this problem in the future.

4. Results

The output power at the end of the sample was measured in order to estimate the quality of nonlinear process. From figure 2 this signal spectrum can be clearly divided into the incident radiation transmitted through the fiber and second harmonic radiation. This second harmonic’s peak was measured several times during changing of the pumping laser power (figure 3). The corresponding growth of the second harmonics generation is presented. The broadening of the 515 nm peak can be explained by the instability of the laser source and by the pulse broadening during the propagation through the sample.

Figure 4 shows the changes of the transmitted radiation power, when the laser pulse power was changed from 170 mW to 3.5W. It should be mentioned that the incident laser beam was focused in the core center at the top of the sample. \( P_{\text{out}} \) didn’t include the radiation scattered to other direction.

The initial part of the power dependence is well approximated by the equation \( P_{\text{out}} = 0.0665 \cdot P_{\text{in}}^2 \). This square-dependence equation is typical for second harmonic generation.
Nevertheless, losses in the crystalline sample core lead to the divergence between the experiment and approximation.

5. Conclusion
Second harmonic generation in the optical fiber filled with solid nonlinear media approves the possibility of the nonlinear conversion in photonic-crystal fiber where it is possible to obtain lower dispersion. Also the technological process of fiber filling with nonlinear media can be improved in order to make the nonlinear crystal in the sample core become more homogeneous. This is possible by temperature control during the crystallization process. All these means will be helpful in order to produce sample with higher effectiveness of nonlinear transformation by reducing the scattering and dispersion losses.
Figure 4. Transmitted power dependence on the incident laser power: experimental results and approximation equation.

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