Blue light generation in single-pass frequency doubling of femtosecond pulses in K\textsubscript{NbO\textsubscript{3}}

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Abstract

We study the generation of blue light in single-pass frequency doubling of femtosecond pulses in a thick K\textsubscript{NbO\textsubscript{3}} crystal. Depending on the input IR power, the maximum amount of generated blue light is a function of the position of the nonlinear crystal relative to the focusing lens. At certain focusing distance, the efficiency of blue light generation is substantially degraded. The issue of beam quality of the generated blue light is discussed. © 2000 Published by Elsevier Science B.V. All rights reserved.

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The generation of blue light has been the topic of interest to many researchers in the field of nonlinear optics from both fundamental and application points of view. With the development in blue light emitting diode lasers, the constructions of super-high density magneto-optic memories, CDROMs, and full color displays become feasible tasks. Yet, there are still many applications, where high power, short pulses, and wavelength tunability are required. The most direct and efficient way to generate a high intensity, frequency tunable blue light is through nonlinear optical processes, such as second-harmonic generation (SHG).

Over the years, the approach to the problem of nonlinear optical frequency conversion, including SHG, has expanded from considering nonlinear interactions of plane wave light fields [1] to investigating the nonlinear interactions of light pulses with the media [2]. With the decrease of pulse width, higher peak intensity of the field is achieved. Since the efficiency of SHG is dependent on the peak intensity of the pump field, then larger amount of second-harmonic field can be generated with shorter light pulses for the same average input power. Due to larger group velocity dispersion (GVD) of the shorter pulses, one would normally expect to have to decrease the thickness of the nonlinear crystal (NLC) in order to gain high conversion efficiencies. Also, the group velocity mismatch (GVM) of the pump and generated SH pulses becomes an important limiting factor when SHG is considered in a thick NLC.
However, it has been experimentally demonstrated that highly efficient SHG in thick KNbO$_3$ crystals can be achieved even under conditions of large GVD [3,4]. With a thick NLC (up to 10 mm long) and short pulses ($\sim 100$ fs) single-pass traveling-wave conversion efficiency up to 63% was experimentally achieved, which is comparable with SHG efficiency obtained in periodically poled nonlinear (PPNL) crystals [5]. Although, no complete theory exists, the high efficiency of SHG with a large GVD and GVM has been explained qualitatively as many thin slides of nonlinear material put together just like in a PPNL material [3]. Also, a numerical analysis shows that for given input pulse width, focusing, and input pump power, one can find an optimal crystal length for optical parametric down conversion process even with large GVD and GVM in a thick KTP crystal [6,7].

From practical point of view, one would be interested in developing ways of generating as much blue light as possible with a good beam quality if one can afford enough input pump power. For example, in lithography and data storage, one needs to maintain small beam size and good spatial beam shape for the generated second-harmonic light. In the plane-wave case, in order to generate intense blue light one has to build an optical cavity and use a strong pump beam. Although many techniques have been developed for keeping the stability of the cavity in order to generate blue light with a good beam quality, it is always desirable to find a more efficient and simpler way of doing it. Single-pass SHG with short pulses in a thick nonlinear medium seems to be one of those easier ways to generate plenty of blue light. Being a relatively new method for efficiently generating blue light, SHG process with fs pulses in a thick NLC is under investigation of using it as a source of not only coherent blue light, but also, squeezed light [4,9].

A single-pass SHG configuration consists of a nonlinear crystal and a lens used to focus the input laser beam inside the crystal. The efficiency of the generated second harmonic light is very sensitive to the spatial distribution of the pumping beam inside the crystal. Weiner et al. [3] studied this type of dependence in a 3 mm long KNbO$_3$ crystal. They used lenses of different focal lengths to focus the pump beam into the crystal. They studied the dependencies of both efficiency and spectrum of the generated blue light on the focal length of the lenses. The efficiency for the optimized focal length and position of the focal point inside the crystal is lower for higher pump powers than for the lower ones.

Recent experiments show that for a given low power beam of infrared (IR) light at the input of the NLC one can obtain a beam of blue light at the output with a conversion efficiency up to 63% [3,4]. With the increase of the pump power, however, the maximum achievable conversion efficiency can be lower than the efficiency achievable with a lower output power in certain range of input power. The spatial quality of the generated second harmonic beam becomes an important issue as the pump power is increased.

In this paper we investigate the conditions for generating considerable amounts of blue light with a good beam quality with femtosecond pulses in a thick NLC. We consider single-pass SHG in a thick KNbO$_3$ crystal for generating blue light. This work concentrates on the relationships between the SHG efficiency, focusing, and the beam quality of the blue light for different input IR powers. Our objective is to provide the best way to generate blue light with a high beam quality for applications. We define efficiency as the ratio of average generated SH power over average input pump power. Assuming that every input pulse generates respectively a SH output pulse, the efficiency can also be defined as the ratio of energies of the SH pulses to the energy of the pump pulses.

A set of measurements was taken in order to see the dependence of SHG efficiency on the input power for different values of distance $d$ between the middle of crystal and the focusing lens. The experiment was performed with a mode-locked Ti:Sapphire laser generating $\sim 130$ fs pulses at a repetition rate of 82 MHz at 858 nm. We used a 10-mm-long a-cut KNbO$_3$ NLC that was temperature tuned for noncritical type I phase matching for SHG at 429 nm. The crystal was placed on a motorized stage, which allowed us to change the distance between the crystal and the input lens with an accuracy of $10^{-6}$ m. The blue light was separated by using a filter from the IR beam and detected with a power meter.

Fig. 1 shows the obtained efficiency dependencies corresponding to three different values of $d$. Since
the position and the focal length of the lens were both fixed, then these distances correspond to different positions of the focal point inside the crystal. The dependencies in Fig. 1 are similar to the ones obtained by Weiner et al. [3] in their investigation of SHG efficiency as a function of the pump power for different values of focal length of the input lens. The similarity is due to the fact that the effective volume of harmonic generation is dependent in the same way on both the focal length and the distance between the lens and the crystal. However, when we look at the spatial structure of the generated blue beam as a function of the input power we see a dramatic change in the beam shape with the increase of the pump power. Fig. 2(a) shows the beam shapes that were obtained for three different values of input powers when the positions of both lens and crystal were fixed so that the focus would be approximately in the middle of the crystal. The pictures were taken when the generated light fell upon a black, partially absorbing screen so that one could judge the beam pattern with little regard to the actual intensity distribution across the beam. We used a lens with focal length equal to 3.8 cm. This resulted in more pronounced distortions of the output beam pattern and deep drop of efficiency as we scanned through the

The focal length of the lens we used to take this data was equal to 3.8 cm. This resulted in more pronounced distortions of the output beam pattern and deep drop of efficiency as we scanned through the

Fig. 3 plots the SH efficiency as a function of the focusing for three different values of input average IR power.
As one can see that, for low pump power, the efficiency increases and then decreases smoothly as the focusing is scanned across the crystal. However, when the input power sets higher, the SHG efficiency behaves strangely, with a big dip for certain focusing values. This dip is unexpected in simple SHG theory and is the main focus of this paper. We looked at the beam profile of the generated blue light for different input power and focusing values. Fig. 2(b) gives some typical examples of the changes in beam profile as we scan the focusing point of the input beam inside the crystal while the input pump power is fixed to a value of 150 mW. If the input power is set to a high value (in our case $P_0 > 100$ mW) the generated blue light beam profile changes from good to bad as the focus moves from front to the middle of the crystal (Fig. 2(b)), corresponding to the drop in efficiency from Fig. 3. As the SHG efficiency recovers when the focal point moves towards the back of the crystal, the beam profile also recovers to a good Gaussian shape. This indicates that the process causing the efficiency to drop is also the reason for the beam profile to change.

In Refs. [6,7], in which an optical parametric down conversion process in KTP was modeled, spatial and temporal walk-off were named as reasons for both spatial and temporal distortions of the generated pulses. Their results show that for high pump intensities and long propagation distances the effects of both temporal and spatial walk-off become very significant. The explanation for the spatial beam distortion in Ref. [6] was the closest situation to what we observed in SHG.

A visual observation of the scattered light on side of the crystal during the scanning of the focus through the crystal resulted in witnessing the generation of light at frequencies near IR but shifted from the ones of the pump laser. The strong scattering spot moves with the focal point of the pump beam as it scans through the crystal at high pump power. This new light becomes very noticeable as SHG efficiency drops in the middle of the distance scan. By feeding the output light into the spectrometer, we found that there is a new wavelength band near 850 nm. This new light at lower frequency side of the input IR spectrum could come from the down conversion process of the generated blue light with some energy loss mechanism. So far, we have not found existing literature to give us a satisfactory explanation to this phenomenon. In Ref. [8] optical parametric generation is experimentally proven, at some extent, to be the reason for generating new frequencies in BBO and LBO crystals.

In conclusion, we have expanded the studies done by Weiner et al. [3] on SHG of femtosecond pulses in a thick KNbO$_3$ crystal and obtained high efficiency ($> 60\%$). Our study emphasizes the conditions for generating as much as possible blue light with a good beam quality for potential applications in lithography and data storage. The efficiency drop for certain focusing conditions is very important and should be considered carefully when generating SH light with high intensity short pulses. More theoretical studies are needed to understand the nonlinear processes in this system and to explain the experimental observations presented in this paper. We hope that these experimental observations will stimulate more theoretical interests in this problem. A more complete numerical model that includes both temporal and spatial beam profiles with large GVD will be needed, which is a major theoretical task. This study is also very important in finding the mechanism that limits the squeezing generation in such system. Theory predicts a much higher degree of amplitude squeezing in the generated blue light, however, we only observed about 1.0 dB of squeezing [4]. With an improved degree of amplitude squeezing, we can greatly improve the sub-shot-noise detection of small signal and have practical application of squeezed light in laser radar [9].

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**References**
