Efficient frequency doubling of a femtosecond Yb:KGW laser in a BiB_3O_6 crystal

Arkady Major,[1,*] Daaf Sandkuijl[2] and Virginijus Barzda[2]

[1]*Department of Electrical and Computer Engineering, University of Manitoba, 75 Chancellors Circle, Winnipeg, MB, R3T 5V6, Canada*

[2]*Department of Chemical and Physical Sciences, Department of Physics and Institute for Optical Sciences, University of Toronto, 3359 Mississauga Rd. N., Mississauga, ON, L5L 1C6, Canada*

**major@cc.umanitoba.ca*

Abstract: Efficient frequency doubling of a high-power femtosecond Yb:KGW laser in a nonlinear BiBO crystal is demonstrated. Green second harmonic generation with more than 1.1 W of average power and 41% conversion efficiency was achieved using a single-pass configuration.

OCIS Codes: (190.2620) Harmonic generation and mixing; (190.7110) Ultrafast nonlinear optics; (140.3615) Lasers, Ytterbium

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1. Introduction

High power sources of visible ultrashort laser pulses are attractive for a large number of scientific and technical applications such as spectroscopy, laser projection displays or micromachining. Such pulses are usually produced by frequency doubling of ultrafast laser sources based on Nd^{3+}-ion or Yb^{3+}-ion doped gain media that oscillate in the near-IR range.

Recently, a new nonlinear material, the BiB_3O_6 (bismuth triborate, BiBO) crystal was introduced [1,2]. With a transparency range of 280-2500 nm it has excellent nonlinear optical properties for frequency conversion into the visible and ultraviolet wavelength ranges [3–5]. Its effective second-order nonlinearity was determined to be 3.2 pm/V at 1079 nm and is larger than that for the well-known BBO, LBO, KTP and $LiIO_3$ crystals [1]. This attractive combination of characteristics was already exploited to demonstrate the potential of BiBO for efficient blue second harmonic generation (SHG) using picosecond and femtosecond Ti:Sapphire lasers [6–9]. The phase-matching properties of BiBO for harmonics generation were also thoroughly studied [4,9,10].

In the green spectral range, however, efficient pulsed SHG was reported only with picosecond pulses [11]. Indeed, the conversion efficiency in the first attempt of femtosecond green SHG in BiBO was on the order of 1% [12]. In this paper we demonstrate generation of high power femtosecond green second harmonic with more than 1.1 W of average output power and 41% single-pass conversion efficiency.

2. Experimental setup

For the SHG experiments we used a previously described high-power femtosecond Yb:KGW laser [13]. It produced up to 2.7 W of average power in ~270 fs pulses at a repetition rate of 61 MHz. The mode locking threshold of this laser corresponded to 1.3 W of average output power. The spectrum of the laser output was centered at ~1033 nm and had a full width at half maximum bandwidth of 4.1 nm.

The second harmonic generation was carried out in a single-pass geometry in a BiBO crystal cut for type-I critical phase-matching (Θ = 167.7°, φ = 90°, *yz*-plane) [4,9,10]. It was antireflection coated for both the fundamental and generated harmonic wavelengths. The thickness of the crystal was 0.8 mm. Since the group velocity mismatch (GVM) between the pulses of the fundamental and second harmonic (SH) wavelengths in this case was calculated to be ~186 fs/mm, the temporal walk-off in the crystal was limited to 150 fs. Therefore, the duration of the generated SH pulses was kept in the femtosecond regime (<300 fs). The small thickness of the BiBO crystal also ensured its wide spectral (~12 nm) and angular (~15 mrad) acceptances at the laser wavelength [4,9,10], making it suitable for SHG using femtosecond pulses and tight focusing. The schematic of the SHG experiment is presented in Fig. 1.

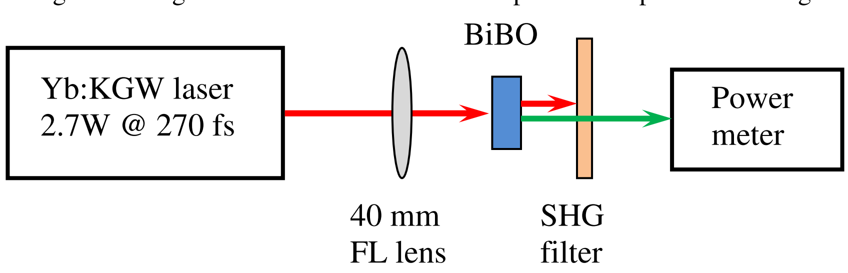

Fig. 1. Experimental SHG setup.

The output of the laser was focused into the crystal by a 40 mm focal length antireflection coated lens into a spot with ~30 µm diameter. Taking into account BiBO's refractive index of 1.79 at 1030 nm, this corresponds to a confocal parameter of 9.4 mm. Under these focusing conditions the spatial walk-off angle (~25 mrad) will cause the beam of the generated second

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harmonic to separate from the fundamental beam only after 2.5 mm of propagation inside the crystal [4,9,10]. The SHG experiments were performed at room temperature.

To filter out the fundamental wavelength, a standard HR mirror was used that provided 99.9% reflection of the fundamental wavelength and more than 90% transmission of the second harmonic output. The amount of incident radiation at the fundamental wavelength was varied by changing the pump power of the Yb:KGW laser.

3. Results and discussion

The dependence of SH output power versus the pump power was obtained in the following way. First, at the lowest pump level (~1.3 W), the position of the crystal was optimized with respect to the pump beam waist in order to get the highest SH output power. Next, the pump was gradually increased while recording the SH power. The position of the crystal was not changed during this measurement.

The experimental SHG results are summarized in Fig. 2. More than 1.1 W of green radiation was generated for 2.7 W of average fundamental power incident on the crystal, which corresponds to a conversion efficiency of 41%. The data in Fig. 2 were corrected for partial transmission of the SHG filter. The energy and peak power of the generated green pulses can be estimated to be 18 nJ and 67 kW, respectively. As can be seen from Fig. 2 at maximum input power there is a slight saturation in the SHG efficiency. This is most likely related to pump depletion during the SHG process.

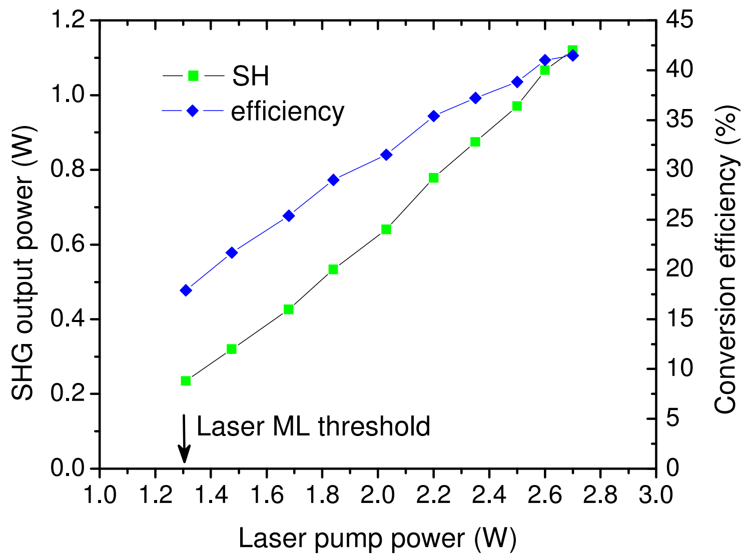

Fig. 2. Second harmonic output power vs incident pump power. ML – mode locking.

The spectrum of the femtosecond second harmonic laser output at ~516 nm is shown in Fig. 3. It has a full width at half maximum of 2 nm, confirming that the crystal had a broad spectral acceptance.

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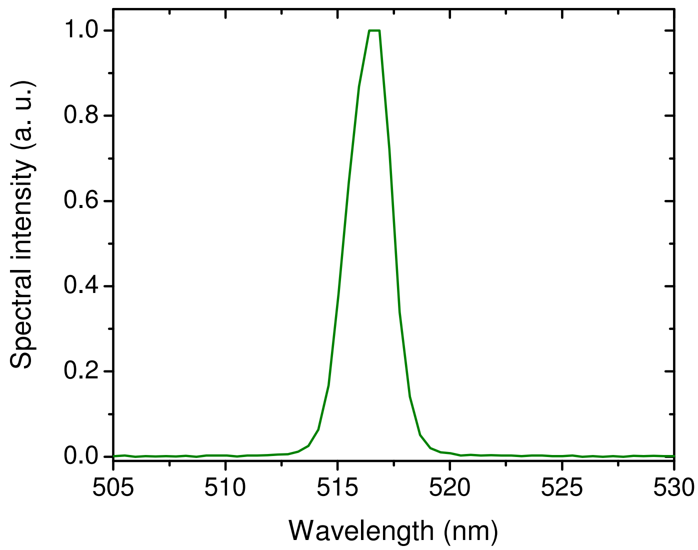

Fig. 3. Spectrum of second harmonic.

In another set of experiments we explored generation of second harmonic in BiBO with more energetic pulses. For this purpose an extended-cavity Yb:KGW laser was used that provided pulse energies in excess of 100 nJ [14]. For these measurements the same experimental setup was used and similar SHG conversion efficiency was obtained. The generated second harmonic pulse energy and peak power reached 43 nJ and 160 kW, respectively. In both SHG cases the spatial intensity distribution profile of the second harmonic closely resembled the TEM_{00} mode profile of the fundamental laser beam.

We expect that the SHG conversion efficiency can be increased to more than 50% by tighter focusing of the fundamental laser radiation or by using longer crystals. The latter approach was already successfully used with femtosecond pulses at 800 nm [7,9]. In this case the temporal walk-off between the fundamental and second harmonic pulses introduced by the GVM in the BiBO crystal was 4.6 times larger than the duration of fundamental pulse. This should be compared to only ~0.5 times in our case. The same technique was also recently used for efficient frequency doubling of femtosecond pulses in bulk $KNbO_3$ [15] and periodically poled $LiTaO_3$ [16] crystals.

4. Conclusions

In conclusion, we have demonstrated high power SHG of femtosecond pulses at 1033 nm in a BiBO crystal. The experiment generated more than 1.1 W of output power in the green spectral range with 41% conversion efficiency. Our results indicate that BiBO is very attractive for efficient green SHG with ultrashort pulses and has the potential to reach more than 50% conversion efficiency.

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