Communication

Green-Yellow-Orange-Red Spectral Range with Sum-frequency Generation Using BIBO Crystal Pumped with an Optical Parametric Amplifier

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Abstract: We show broadband sum-frequency generation (SFG) in the Green-Yellow-Orange-Red spectral range using bismuth triborate, BiB_3O_6 crystal (BIBO) as nonlinear material. We perform a noncollinear phase-matching configuration within BIBO crystal using the remaining light behind the second harmonic generation stage and the infrared idler of an optical parametric amplifier (OPA). The obtained mixing radiation of ultrafast light sources to generate femtosecond pulses across 520.5 to 742.5 nm region is observed. SFG spectrum from single-pass cross-correlation intensity over such visible range is showed. The SFG wavelengths as a function of tunable wavelength idler OPA agrees with the expectations of parametric conversion condition and open the door to practical multi-beam or multi-color sum-frequency generators.

Keywords: Sum frequency generation; femtosecond pulses; noncollinear phase matching

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1. Introduction

The growing field of ultrafast light sources still requires multi-beam or multi-colour systems motivated by scientific, medical and industrial applications[1-4]. Recently, wavelength tunability and intense pulse are needed for industrial manufacturing[5,6], scientific research of medical device fabrication[7], spectroscopy techniques to analyze surfaces and interfaces[8], biological imaging with multiphoton microscopy methodologies[9], time-resolved experiments[10] and many other fundamental applications of modern science. Multi-beam and access to the new spectral region of femtosecond pulses are possible with parametric frequency conversion, ergo ultrafast optical parametric oscillator (OPO)[11], optical parametric amplifiers(OPA)[12], second and third harmonic generators[13-15] or, as we show here, sum-frequency generators.

Novel ultrafast systems constitute powerful devices for generation of widely tunable coherent radiation with the help of nonlinear materials. Progress of birefringent crystals as nonlinear material enables frequency conversion for the generation in the new spectral region[16]. A nonlinear optical material like bismuth triborate, BiB_3O_6 (BIBO) shows exceptional nonlinear coefficients (d_{eff}=3.2 pm/V) for wavelength generation between 290 and more than 2500 nm[17]. Such BIBO crystal has demonstrated the efficient tunable parametric generation of femtosecond pulses compared with other birefringent materials[18,19]. With a single BIBO crystal, femtosecond optical parametric oscillator covers visible range across 480-710 nm at room temperature operation[20]. Sum-frequency generation delivering visible pulses from 412 to 500nm with noncollinear optical parametric oscillator (NOPO) was shown as interesting configuration operated with an output coupler with simultaneous emission of infrared (IR) and visible (VIS) light[21]. Amplified robust systems, like noncollinear and collinear optical parametric amplifiers, are useful as light sources for ultrafast spectroscopy and many other fundamental and real-word applications in modern science[22]. Operation of noncollinear optical parametric amplifiers (NOPA) systems in continuous tuning between 550 and 700nm and near-infrared is demonstrated[23]. In the case of collinear optical parametric amplifiers (OPA) systems, see, e.g. a second harmonic generator (SHG) of 520nm from femtosecond pulses of 1040nm output of Ytterbium-doped Potassium-Gadolinium Tungstate (Yb:KGW) laser (Spirit-8-OPA, Spectra Physics), the SHG stage is used as a pump of such OPA to generates in the infrared range signal (630-1020 nm) and idler (1040-2600nm). It is known that OPA systems require nonlinear conversion accessories to cover in the visible region and the remaining 1040nm light behind the SHG stage can be still used.

In this Letter, we experimentally expose BIBO crystal to generate the sum of the optical frequencies under two synchronously beams. One beam from the remaining 1040nm of SpiritOne-8 Spectra Physics laser and second, from an idler optical parametric amplifier. Such beams were leading to a parametric output with higher frequency in the visible range. This procedure allows nonlinear mixing radiation of ultrafast light sources to generate high-repetition-rate femtosecond pulses across the 520.5 to 742.5 nm region with noncollinear configuration. It is known that access to higher frequencies is possible with harmonic generators. Indeed, the collinear optical parametric amplifier systems require nonlinear optical harmonics to cover UV-visible range[24]. The nonlinear frequency conversion presented here offers several advantages as it achieved with the remaining fundamental 1040nm pump light, allowing single-pass noncollinear phase-matching condition on a broad spectrum, while at the same time providing a viable tool of tunable coherent light.

2. Materials and Methods

We perform a tunable visible light with noncollinear phase-matching configuration[25-27] that allows parametric frequency conversion with the help of BIBO as nonlinear material. BIBO crystal was mounted on a rotation stage (RS) for changing the phase-matching angle. The two beams that are coming from different arms overlap with a fixed angle of α=14° within a BIBO crystal. The remaining 1040nm and the IR idler beams are focused and crossed inside a BIBO crystal with orientation condition to the SFG with noncollinear phase-matching. In our case, both focused beam waist radiuses are close to 50 micrometres. Sum frequency generation of the pulses is achieved in a single pass of 500 μm crystal. The crystal is a type I interaction in the yz plane (ϕ=90º) at an internal angle of θ≈161º at normal incidence.

The set-up for the parametric frequency generation is shown in Figure 1. For our sum-frequency generation experiments, we used a SpiritOne-8 and SpiritOPA systems emitting a 20 kHz train of <400fs pulses.

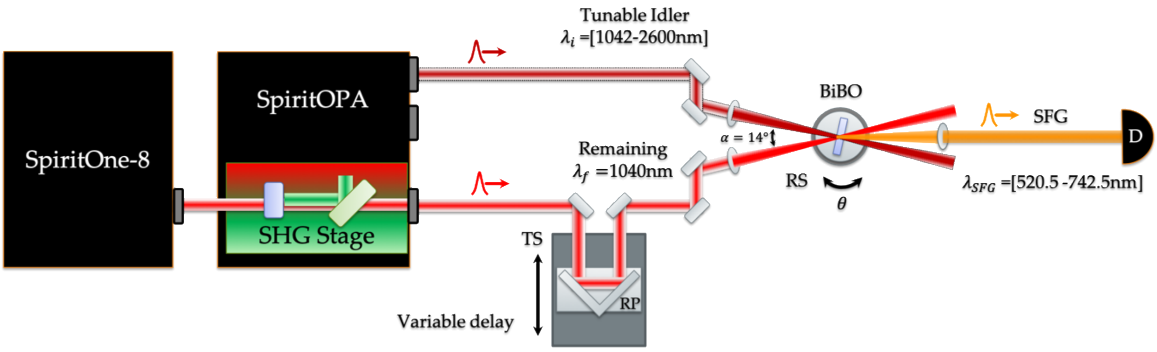

Figure 1. Schematic view of the experimental set-up used for measuring the sum-frequency generation (SFG) across 520.5 to 742.5nm region from two femtosecond pulses superimposed within a BIBO crystal. BIBO crystal is mounted on a rotation stage (RS) in a noncollinear phase-matching configuration with a fixed angle α=14°. The variable delay line is used to temporal overlap the remaining pulse (λ_f=1040nm) behind the second harmonic generation (SHG) stage of SpiritOne-8 laser and the λ_i pulse from the tunable range 1040-2600nm of the automated collinear optical parametric amplifier (SpiritOPA) with the help of a translation stage (TS) and a retroreflector prism (RP).

3. Results

The present study demonstrates the functionality of BIBO crystal in combination with an optical parametric amplifier (OPA) to generate high-repetition-rate femtosecond pulses across the 520.5 to 742.5 nm region. IR idler source is a computer controller tunable range 1040-2600nm from the automated collinear SpiritOPA. Such IR idler pulse of SpiritOPA is tuned to pump simultaneously with the remaining 1040nm pulse. Both pulses overlap in the crystal with different focal lenses to ensure maximum output power. Light emerged at the focal plane as sum-frequency generation that it is produced in the middle of the two beams. This shows that SFG will be separated from the IR light beams because the proper phase-matching and the intensity generation is measured(Figure 2). The focal plane of this sum frequency generated radiation is imaged in turn by a focal lens onto the input plane of a detector (D).

Figure 2 shows the sum frequency generation power measured at different wavelengths as a function of tunable idler OPA source, inset a) (wine line and intensity values), and the remaining 1040nm light, inset b) (red line and intensity values). The following expression gives typical SFG wavelength:

$$\lambda_{SFG} = \frac{1}{\frac{1}{\lambda_f} + \frac{1}{\lambda_i}} \tag{1}$$

where λ_f=1040nm and λ_i is the tunable IR idler. To acquire the power of maximum in a SFG using pulses with different values of λ_i, the crystal was rotated to change the internal angle of the crystal with the gyration of the crystal holder for noncollinear phase-matching. All the tunable internal angle range is from 120° to 152 °.

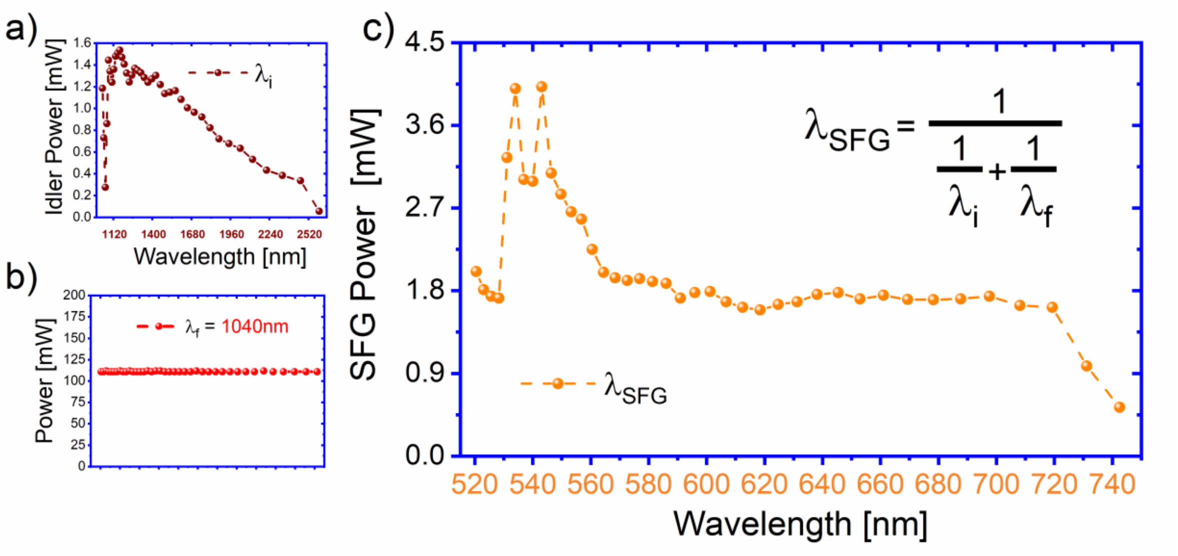

Figure 2. Tunable SFG power. SFG obtained on the noncollinear phase-matching configuration to different values of a) tunable range [λ_i =1040-2600nm] and b) the remaining 1040nm light behind the SHG stage of the amplified laser. c) Such SFG in the wavelength range of 520.5 to 742.5 nm. The orange dashed lines are only a guide for the eye.

Typical sum generation presented in this work for reproducibility, a motorized rotation is used for controlled rotation of the crystal. A second motorized translation stage and a mounted retroreflector prism are performed for a controlled path length of a variable delay line. Such a pump pulse with a variable delay line is used for improving the temporal pulse overlap superimposed in the crystal because of group-velocity matching. Adjustment of the optical delay line is needed because changes in the angle of phase-matching produce small changes in the length of the crystal. Here, we were able to achieve in the wavelength range of 520.5 to 742.5nm of such SFG from single-pass of maximum cross-correlation intensity as shown in the inset c) of Figure 2 (orange line and intensity values).

The normalized spectrum of SFG from single-pass cross-correlation intensity over such a visible range is showed in Figure 3. In this measurement, light emerged as a sum-frequency generation is coupled to a high-resolution spectrometer (HR4000) with an optical diffusor. As typical apparatus commonly used to measure the pulse duration, our generated light can be examined with the help of our adjustable optical delay. The average pulse-width of the idler OPA light beams were 330-fs measured with such 0.5 mm BIBO crystal, data not shown.

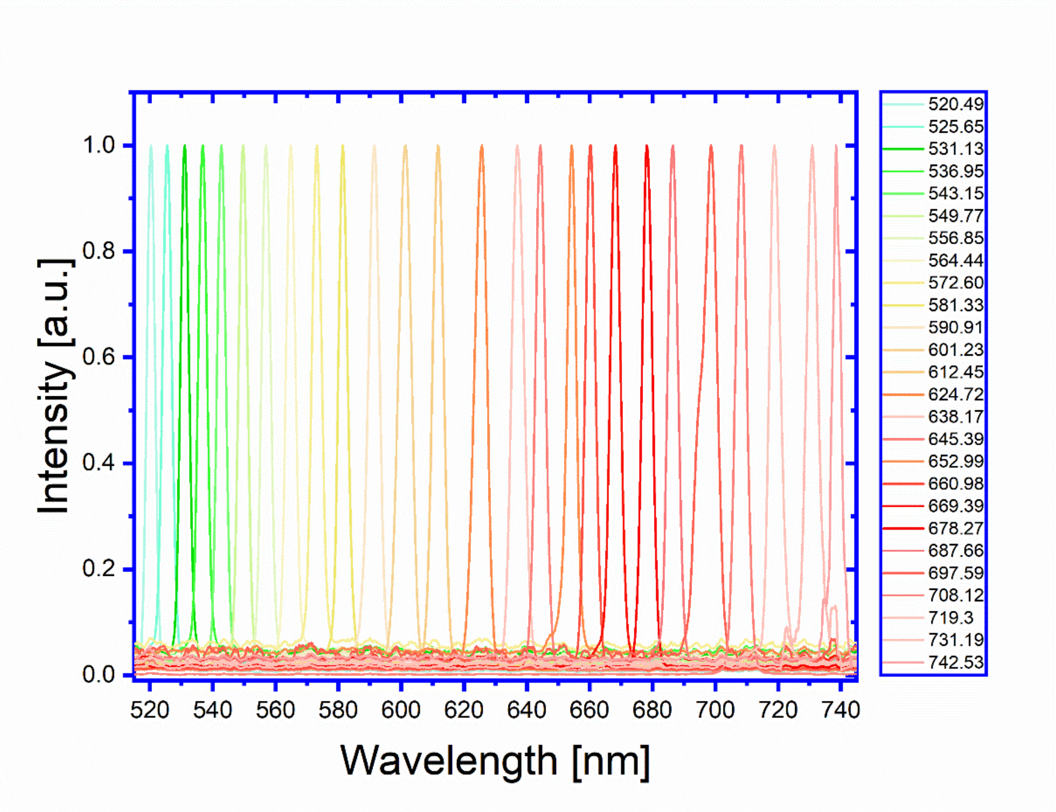

Figure 1. The resultant SFG spectrum. Spectrum showing the demonstrated tuning range of sum-frequency generation from 520.5 to 742.5 nm with normalized cross-correlation intensity measurements using a spectrometer HR4000 (Ocean Optics) as a detector.

4. Discussion

The nonlinear frequency conversion as sum-frequency generator presented here offers several advantages as it achieved with the remaining fundamental 1040nm pump light, allowing single-pass noncollinear phase-matching condition on a broad spectrum, while at the same time providing a viable tool of tunable coherent light. The obtained mixing radiation of ultrafast light sources to generate femtosecond pulses across 520.5 to 742.5 nm region is observed from Figure 2 with the help of BIBO as nonlinear material. The frequency conversion with noncollinear phase-matching an effective scheme that provide tuning coverage across the full transparency of the BIBO crystal and the corresponding magnitude of the significant nonlinear coefficient as a function of pumped wavelengths[28]. Green-Yellow-Orange-Red spectral range is generated and a tunable wavelength system may be implemented as a conversion accessory of optical parametric amplifier. It can be observed from Figure 3 that the changes in the bandwidth of such spectral range may be caused by a length detuning of the optimal phase matching of angle crystal and adjustment of path length to improve the sum-frequency generation of such overlap. Our nonlinear optical results open the door to high-resolution nonlinear spectro/microscopy applications, as it offers the possibility of selectively wavelength in a single-pass noncollinear configuration.

5. Conclusions

In conclusion, we have shown broadband sum-frequency generator using the remaining fundamental 1040nm light of a femtosecond laser source and IR idler from the optical parametric amplifier. Sum frequency generation into visible range is possible with noncollinear phase-matching in BIBO crystal. The obtained mixing radiation of ultrafast light sources to generate high-repetition-rate femtosecond pulses. We provide wide tuning across Green-Yellow-Orange-Red spectral range. The direct separation of three interacting waves is demonstrated with a simple cross-correlation configuration. Such configuration might be useful to perform practical multi-beam or multi-color experiments to scientific, medical and industrial applications.

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References

1. U. Keller, “Recent developments in compact ultrafast lasers”. Nature 424, 831–838 (2003).
2. J. Squier, "Ultrafast Optics," Opt. Photon. News 13(4), 42-46 (2002).
3. E. E. Hoover, J. A, Squier, “Advances in multiphoton microscopy technology”, Nature Photonics, 7, 2, 93-10, (2013).
4. K. Phillips, H. Gandhi, E. Mazur, and S. Sundaram, "Ultrafast laser processing of materials: a review," Adv. Opt. Photon. 7, 684-712 (2015).
5. E. Mottay, "Industrial ultrafast lasers for advanced manufacturing applications," in 2015 European Conference on Lasers and Electro-Optics - European Quantum Electronics Conference, paper TF_1_3, Optical Society of America, (2015).
6. N. Hodgson, M. Laha, T. S. Lee, H. Haloui, S. Heming, and A. Steinkopff, "Industrial Ultrafast Lasers – Systems, Processing Fundamentals, and Applications," in Conference on Lasers and Electro-Optics, OSA Technical Digest, paper JM3E.1, Optical Society of America, (2019).
7. R. R. Thomson, D. Choudhury, and C. Ross, "Ultrafast Laser Processes for Photonics," in Optical Fiber Communication Conference (OFC) 2019, OSA Technical Digest paper Th3D.1, Optical Society of America, (2019).
8. Y. Shen, “Surface properties probed by second-harmonic and sum-frequency generation”. Nature 337, 519–525 (1989).
9. J. Jonkman, C.M. Brown, G.D. Wright, et al. “Tutorial: guidance for quantitative confocal microscopy”. Nat Protoc 15, 1585–1611 (2020).
10. A. Erbe, S. Nayak, Y.-H. Chen, F. Niu, M. Pander, S. Tecklenburg, C. Toparli, “How to Probe Structure, Kinetics, and Dynamics at Complex Interfaces In Situ and Operando by Optical Spectroscopy”, Encyclopedia of Interfacial Chemistry, Elsevier, 199-219, (2018).
11. H. D. Malcolm, M. Ebrahim-Zadeh, “Parametric Generation of Tunable Light from Continuous-Wave to Femtosecond Pulses”, Science, 286, 5444, 1513- 1517, (1999).

12. I. Nikolov, A. Gaydardzhiev, I. Buchvarov, P. Tzankov, F. Noack, and V. Petrov, "Ultrabroadband continuum amplification in the near infrared using BiB3O6 nonlinear crystals pumped at 800 nm", Opt. Lett. 32, 3342-3344 (2007).

13. S. M. Giffin, I. T. McKinnie, and V. V. Ter-Mikirtychev, "Tunable visible solid-state lasers based on second-harmonic generation of LiF:F2- in potassium titanyl phosphate", Opt. Lett. 23, 192-194 (1998).

14. E. Nitiss, O. Yakar, A. Stroganov, and C. S. Brès, "Highly tunable second-harmonic generation in all-optically poled silicon nitride waveguides", Opt. Lett. 45, 1958-1961 (2020).

15. F. Cassouret, A. Kausas, V. Yahia, G. Aka, P. Loiseau, and T. Taira, "High peak-power near-MW laser pulses by third harmonic generation at 355 nm in Ca5(BO3)3F nonlinear single crystals", Opt. Express 28, 10524-10530 (2020).

16. M. Ebrahim-Zadeh, "Optical Parametric Oscillators: A New Generation," in Conference on Lasers and Electro-Optics 2010, OSA Technical Digest, paper CThP1, Optical Society of America, (2010).

17. H. Hellwig, J. Liebertz , L. Bohatý , "Linear optical properties of the monoclinic bismuth borate BiB3O6". Journal of Applied Physics, 88, 1, 240-244, (2000).

18. M. Ghotbi, M. Ebrahim-Zadeh, A. Majchrowski, E. Michalski, and I. V. Kityk, "High-average-power femtosecond pulse generation in the blue using BiB3O6", Opt. Lett. 29, 2530-2532 ,(2004).

19. M. Peltz, J. Bartschke, A. Borsutzky, et al. "Bismuth triborate (BiB3O6) optical parametric oscillators". Appl. Phys. B 80, 55–60 (2005).

20. M. Ghotbi, A. Esteban-Martin, and M. Ebrahim-Zadeh, "BiB_3O_6 femtosecond optical parametric oscillator," Opt. Lett. 31, 3128-3130 (2006).

21. T. Lang, T. Binhammer, S. Rausch, G. Palmer, M. Emons, M. Schultze, A. Harth, and U. Morgner, "High power ultra-widely tuneable femtosecond pulses from a non-collinear optical parametric oscillator (NOPO)", Opt. Express 20, 912-917 (2012).

22. C Manzoni and G Cerullo, "Design criteria for ultrafast optical parametric amplifiers", Journal of Optics, 18, 10, 103501, (2016).

23. Kobayashi, Takayoshi, Baltuska, Andrius, "Sub-5 fs pulse generation from a noncollinear optical parametric amplifier, " IOP Publishing, 13, 11, 1671-1682, (2002).

24. A. V. Mitrofanov, A. A. Voronin, S. I. Mitryukovskiy, D. A. Sidorov-Biryukov, A. Pugžlys, G. Andriukaitis, T. Flöry, E. A. Stepanov, A. B. Fedotov, A. Baltuška, and A. M. Zheltikov, "Mid-infrared-to-mid-ultraviolet supercontinuum enhanced by third-to-fifteenth odd harmonics", Opt. Lett. 40, 2068-2071 (2015).

25. T. R. Zhang, Heung Ro Choo, and Michael C. Downer, "Phase and group velocity matching for second harmonic generation of femtosecond pulses," Appl. Opt. 29, 3927-3933 (1990).

26. O. Gobert, G. Mennerat, R. Maksimenka, N. Fedorov, M. Perdrix, D. Guillaumet, C. Ramond, J. Habib, C. Prigent, D. Vernhet, T. Oksenhendler, and M. Comte, "Efficient broadband 400 nm noncollinear second-harmonic generation of chirped femtosecond laser pulses in BBO and LBO", Appl. Opt. 53, 2646-2655, (2014).

27. Carolina Romero, Javier R. Vázquez de Aldana, Cruz Méndez, and Luis Roso, "Non-collinear sum-frequency generation of femtosecond pulses in a micro-structured β-BaB2O4 crystal," Opt. Express 16, 18109-18117 (2008)

28. M. Ghotbi and M. Ebrahim-Zadeh, "Optical second harmonic generation properties of BiB3O6", Opt. Express 12, 6002-6019, (2004).