Wavelength Conversion Technology utilizing Linearly-Polarized Fiber Laser and its Applications

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In recent years the visible and ultraviolet high-power lasers utilizing wavelength conversion technologies have received considerable attention in display, biotechnology and medical fields. To achieve high wavelength conversion efficiency, the fiber lasers with high output power and high beam quality are well suited as fundamental wave sources. We have developed novel visible and ultraviolet high-power lasers utilizing linearly-polarized fiber lasers.

1. Introduction

Visible and ultraviolet lasers have been extending their applications from laser processing and marking to TV and projector display devices, bioinstrumentation such as flow cytometers, DNA sequencers or ophthalmologic and other medical instruments. For a wavelength range of 500-600 nm (green to orange), the expensive, large-sized dye lasers have been the first choice because these wavelengths have been difficult for laser diodes to oscillate directly. In response to this circumstance, technologies are now under active development to convert the wavelength of 1000-1200 nm of the fundamental wave produced by a solid-state laser to 500-600 nm employing second harmonic generation (SHG), one of the nonlinear optical effects [1).

Among nonlinear optical crystal devices used for wavelength conversion, the quasi-phase matching (QPM) devices utilizing periodically poled structure are extensively studied because of its simplicity [2). Typical examples include periodically poled lithium niobate (PPLN) and periodically poled lithium tantalate (PPLT).

Possible hurdles to overcome for practical high-power visible light lasers include the resistance to optical damage (photorefractive effect) occurring at high power levels [3), the efficiency of the system as a whole, and the size of the system. The resistance of PPLN and PPLT has greatly been improved by controlling the crystal composition by adding magnesium oxide (MgO), which allows simple module designs using QPM wavelength conversion elements for high-efficiency wavelength conversion.

The fundamental wave should have a high output power and high beam quality since high conversion efficiency in SHG requires high power density. It should also be a linearly-polarized wave since the QPM element is anisotropic.

Fujikura's fiber lasers, which provide high-power, high-quality linearly-polarized beam with excellent convergence, are suitable for a source for generating fundamental wave as the input of the QPM wavelength conversion element [4). The wide gain bandwidth of a fiber laser allows oscillation at a wavelength, which is difficult for solid-state lasers to generate. Other practical advantages of a fiber laser for the application are high power and space efficiency, high reliability, and low maintenance and beam deliverability larger,.

Fujikura paid much attention to the advantages of a fiber laser as a fundamental wave source for wavelength conversion and developed fiber lasers specialized for the application. Following these previous development efforts, we have designed a new practical wavelength conversion module, thus completing a high-power visible and UV CW laser light source based on wavelength conversion of a fundamental wave provided by a linearly-polarized fiber laser.

2. Linearly-polarized fiber laser for wavelength conversion

Figure 1 shows the basic configuration of a linearly-polarized fiber laser for wavelength conversion. The laser diodes for pumping are connected via the combiner to the resonator based on the polarization-maintaining fiber. The resonator consists of high- and low-reflection Fiber Bragg Gratings (FBGs) before and after the Yb-doped active fiber and the fiber-based po-

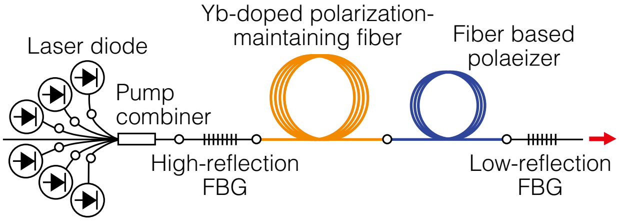

Fig. 1. Basic configuration of linearly-polarized fiber laser for wavelength conversion.

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Panel 1. Abbreviations, Acronyms, and Terms.

SHG—Second Harmonic Generation
SFG—Sum Frequency Generation
QPM—Quasi-Phase Matching
PPLN—Periodically Poled Lithium Niobate
PPLT—Periodically Poled Lithium Tantalate
FBG—Fiber Bragg Grating

larizer, respectively. The fiber-based polarizer is designed to give a greater bending loss difference between the two orthogonal polarized waves by employing a smaller distance between a core and stress rods than that of normal polarization-maintaining fibers. Optimal bending of such fiber allows oscillation of only one polarization component with a lower bending loss: a polarization extinction ratio higher than 20 dB has been attained [5]. The narrow bandwidth of spectrum of light reflected by the low-reflection FBG has led to a full width at half maximum less than 0.08 nm at the maximum output power. Furthermore, optimization of the reflectivity of the low-reflection FBG and the length of the Yb-doped fiber has resulted in a laser system with an output power over 40 W and a conversion efficiency of pump light to output light over 60%.

3. Wavelength conversion module

3.1 Basic configuration

The basic configuration of a wavelength conversion module is shown in Fig. 2. The module comprises a QPM wavelength conversion element, an optical system to focus the fundamental wave on the conversion element and couple the generated harmonics into the output fiber, and a wavelength-dividing filter to separate the harmonics from the fundamental wave.

The conversion efficiency depends on the power density of the fundamental wave in the wavelength conversion element. A large convergence angle of the fundamental wave from the fiber laser produces a high power density, but an excessive convergence angle would decrease the overall longitudinal conversion efficiency since the high power density at the beam waist is canceled by decrease of the power density on the input and output end surfaces of the wavelength conversion element. The convergence angle should therefore be optimized with respect to the length of the wavelength conversion element to obtain high conversion efficiency.

Phase matching is another prerequisite for a high conversion efficiency. Since the phase matching condition of the QPM wavelength conversion element depends on its temperature, a Peltier element is used to control the temperature of the element within the 0.01 °C level. It should be noted that more heat is generated by the wavelength conversion element due to light absorption at higher power level, which decreases the conversion efficiency by shifting the temperature from the optimum value for phase matching. The heat generation at high power level must therefore be taken into account on the temperature setting. Still another factor that reduces conversion efficiency is the intensity gradient of the harmonics in the axial direction of the wavelength conversion element producing a correspondent temperature gradient. To counter this, the position of the beam waist in the element is adjusted so as to limit the temperature gradient.

The light absorption by the wavelength conversion element not only reduces the conversion efficiency but also possibly damages the element itself. The light intensity resistance of the element is therefore a limiting factor to the power of the harmonics. The resistance sufficient for output levels of tens of watts has not been attained so far in spite of considerable effort for the purpose. The output power and conversion efficiency contradict each other: to attain a high output, the power density must be kept under the threshold of damage of the wavelength conversion element by adjusting the beam diameter in accordance with the power of the input fundamental wave.

The appearance of the prototype of a space-output type green laser light source is shown in Fig. 3. The green light source based on the basic configuration described earlier has attained a maximum spatial pow-

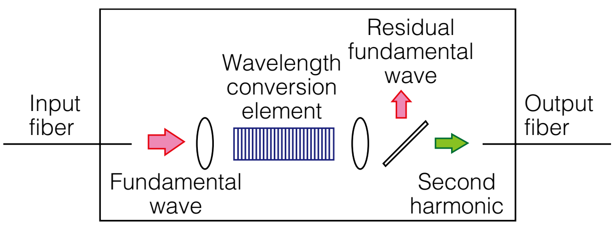


Fig. 2. Basic configuration of wavelength conversion module.

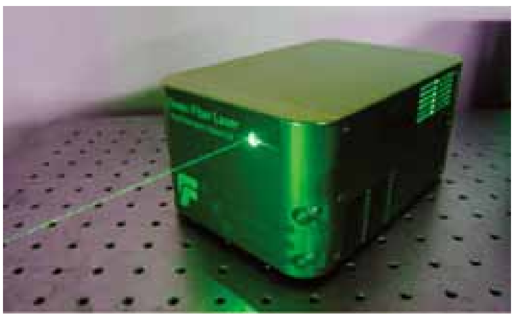


Fig. 3. Space-output green light source.

er of 8.5 W and a conversion efficiency over 25% when the 1064-nm fundamental wave is converted to the 532-nm harmonic by SHG.

3.2 Two-stage configuration

As a means to strike a balance between high output power and high conversion efficiency, a wavelength conversion module was developed in which two QPM wavelength conversion elements were connected in series as shown in Fig. 4. Desired performance was achieved by reinjecting the residual fundamental wave in the first stage by the conversion element into the second stage. The angle and position of convergence of the residual fundamental wave was optimized taking into account changes of the intensity distribution of the residual fundamental wave in the wavelength conversion module as the harmonic wave generated. The length of the wavelength conversion elements are so determined to obtain similar power densities from the respective wavelength conversion elements, thus equalizing the risk of element failure due to light absorption, which contributes to the improved output power of the system. Since the harmonics generated by the respective wavelength conversion elements are linearly-polarized, they can be coupled to a single-mode fiber by polarization beam combining.

4. Application examples of wavelength-converted laser light sources

4.1 Green light sources for displays

High-power green laser light sources with wavelengths of 530-540 nm has been attracting attention as display applications because of high luminance, high contrast, high color reproducibility and low power consumption. Particularly high-power projector light sources, used for 3-D digital movies or projection mapping, for example, are in great demand and laser light sources are expected to replace the traditional xenon lamps [6,7]. An important problem in this application is image quality limited by speckles due to the coherence of laser light [8].

Many studies on speckle reduction have been reported [9,10]. Reducing the coherence of laser beam by expanding the spectrum width of the laser [11] is one possibility. The spectrum width of the harmonic depends on the fundamental wave and thus may be expanded by expanding the spectrum width of the fundamental wave, but this is not practical because of resulting decrease in the oscillation efficiency of the fiber laser and the efficiency of the wavelength conversion. Our solution is a pseudo wideband light source using more than one harmonics with different wavelength, multi wavelengths, utilizing a wide gain bandwidth of a fiber laser.

Figure 5 shows a prototype of the multi-wavelength high-power green laser light source. Thirteen fiber lasers using FBGs with different reflecting wavelengths were combined to obtain a band of 1058-1082 nm, which was converted by SHG to 13 wavelengths at an interval of 1 nm between 529 to 541 nm. The output power and conversion efficiency characteristics are shown in Fig. 6 and the wavelength spectra are shown in Fig. 7. One wavelength conversion module of the

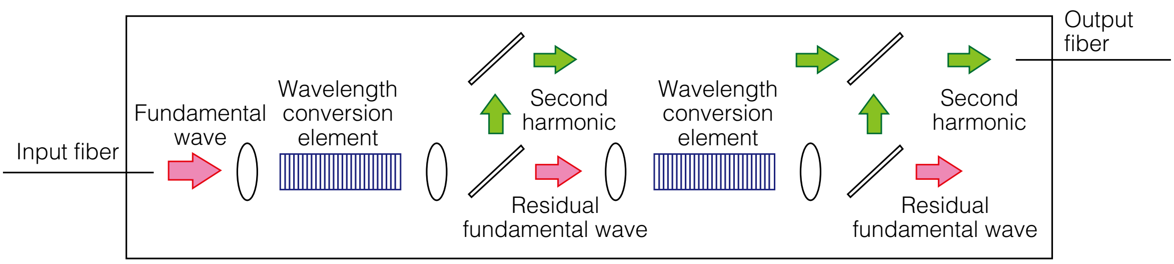


Fig. 4. Configuration of two-stage wavelength conversion module.

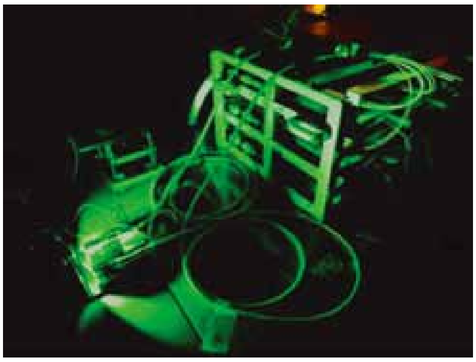


Fig. 5. Appearance of developed high-power green laser light source.

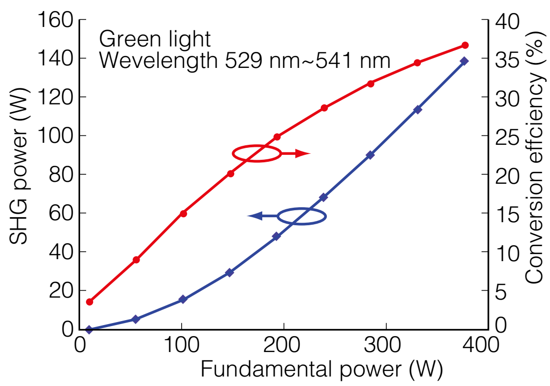


Fig. 6. Output property of developed high-power green laser light source.

two-stage configuration was used for conversion of each wavelength. The maximum fiber output is 10 W for each wavelength, i. e. 130 W for the entire system covering 13 wavelengths. The electricity-to-light conversion efficiency exceeded 10% at the maximum output, which was a sufficiently practical level.

The output fibers from individual wavelength conversion modules were bundled by a Fujikura's proprietary technique, and the output beam from the modules was launched through a single port. The speckle patterns from the 13 individual sources were thus superimposed and averaged, which resulted in a better speckle reduction effect.

4.2 UV laser light sources for bioinstrumentation

Bioinstrumentation such as flow cytometers, cell sorters or DNA sequencers irradiate the target (e.g. cells) with laser light and analyze the scattered light or fluorescence for the acquisition or separation of their information. A single unit of the instrument must have three to seven solid-state or gas laser units to cover a range from UV to visual light, which results in a large dimension. The alignment of the optical system to deliver the multiple laser beams is very difficult and readily disturbed by external perturbation. Frequent calibration is therefore needed. For these reasons, small and easy-to-deliver laser light sources are in great demand, as well as cost reduction of the expensive UV lasers [12].

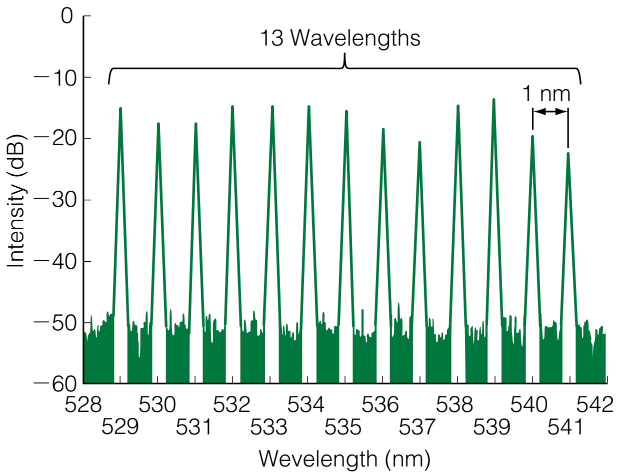


Fig. 7. Spectra of developed high-power green laser light source for display.

Fiber lasers provide high-quality beams and consequently high-quality harmonics, which can easily be coupled with fibers, and in turn transmitted via optical fibers. Another advantage of fiber lasers is higher efficiency than solid-state lasers, which means less heat generation and therefore easy cooling with a simpler cooling system, allowing simple, low-cost design. Our proprietary UV-resistant fiber overcomes the problem of transmittance reduced by defects formed in the fiber by an intense UV beam, allowing design of a high-reliability UV laser light source.

Figure 8 shows the configuration of a wavelength conversion module for the UV laser light source. In the two-stage configuration, the sum frequency generation (SFG) technique is used to obtain the UV light. The fundamental wave with a wavelength of 1064 nm enters the first wavelength conversion element, where 532-nm green light is produced by SHG, which in turn enters the second wavelength conversion element together with the residual 1064-nm wave. Finally, SFG in the second wavelength conversion element produces UV laser light with a wavelength of 354.6 nm, which is about 1/3 times that of the fundamental wave.

The appearance and output characteristics of the prototype UV laser light source are shown in Fig. 9 and Fig. 10, respectively. A coupling efficiency over 45% between the generated UV light and the output single-mode fiber and a fiber output over 20 mW were achieved by optimization of the convergence angle, beam waist position and element length.

4.3 Laser light source for medical instruments

Solid-state lasers with wavelengths of 570-600 nm (yellow to orange) are widely used in ophthalmology and other medical branches. In response to the need for laser light sources with higher output power and beam quality, we have developed a high-power yellow laser light source.

While the wide gain bandwidth of Yb-doped fiber lasers ranging from 1000 to 1200 nm does cover the range of 1140-1200 nm which can be converted by

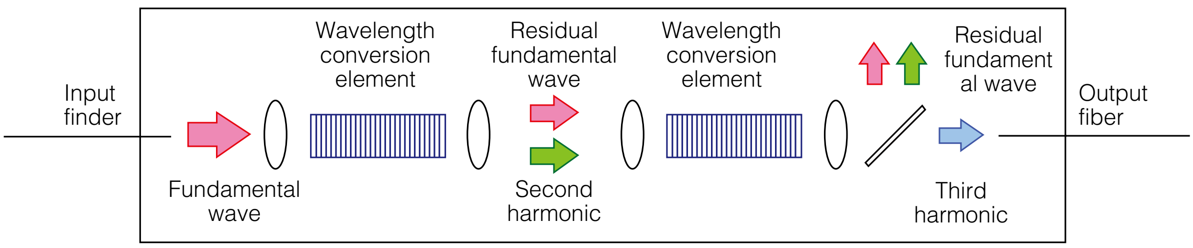


Fig. 8. Configuration of wavelength conversion module for ultraviolet laser light source.

SHG to yellow to orange color, oscillation in this range will induce parasitic oscillation in the 1030-1100 nm band, where the gain is higher, destabilizing the oscillation of the laser system. Although this is generally an important obstacle to output power increase, Fujikura had already been successful to suppress parasitic oscillation by utilizing the photonic band gap fiber to realize high-power oscillation in the range of 1160-1200 nm [13].

The present model of yellow laser light source is based on a linearly-polarized fiber laser for wavelength conversion in the basic configuration to facilitate commercialization. The reflectivity of the low-reflection FBG was increased to boost the gain in the resonator, which suppressed parasitic oscillation at the expense of oscillation efficiency. High-power oscillation in a wavelength range of 1140-1160 nm was confirmed. The output characteristics of this yellow laser light source are shown in Fig. 11. The 572-nm light was obtained as the harmonic of the 1144-nm fundamental wave. The spatial output over 4.5 W is sufficient for practical use of the laser light source.

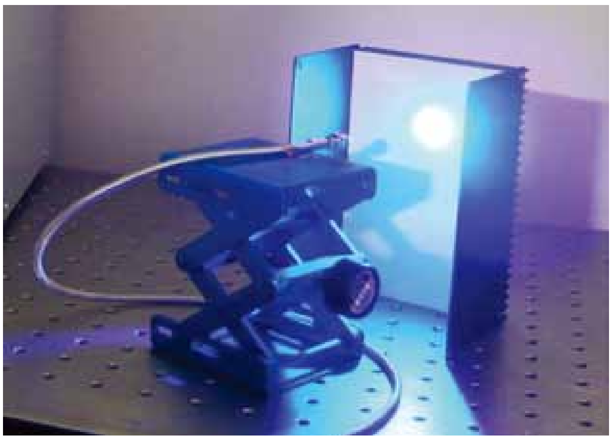
Oscillation of wavelength more than 1200 nm was also attempted utilizing stimulated Raman scattering [14]. A fiber laser with a wavelength of 1144 nm was used as a light source for pumping to configure a Raman resonator, which allowed oscillation at 1212 nm (a Raman shift of 68 nm), which realized a red (606 nm) laser light source by SHG.

5. Conclusion

The article has reported the development of laser light sources based on wavelength conversion of the fundamental wave provided by linearly-polarized fiber lasers of our proprietary design. The linearly-polarized fiber laser for wavelength conversion contains a number of our proprietary technologies such as polarization-maintaining fibers, fiber based polarizers or FBGs. It was shown that combination with the wavelength conversion module allows further development of value-added original products.

The authors will continue to pursue diversification of wavelengths of laser light sources and contribute to the development of novel applications.

(a) Appearance of ultraviolet laser light source.



(b) Ultraviolet light generation.

Fig. 9. Prototype of ultraviolet laser light source.

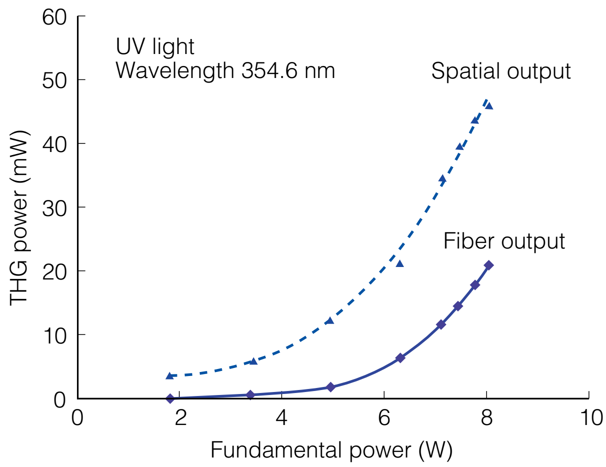


Fig. 10. Output property of ultraviolet laser light source.

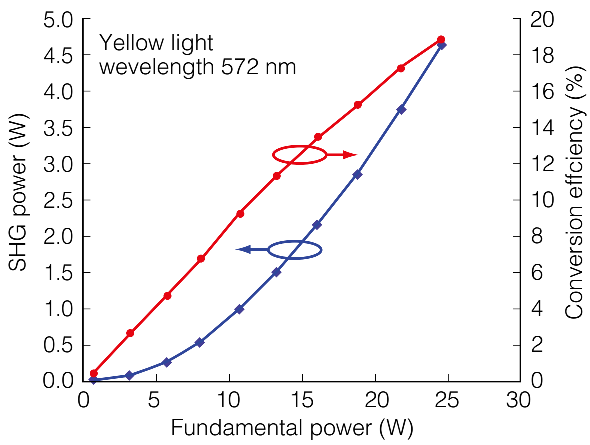


Fig. 11. Output property of developed high-power yellow laser light source.

Reference

1) S. V. Tovstonog, et al.: "Thermal effects in high-power CW second harmonic generation in Mg-doped stoichiometric lithium tantalate," Optics Express, Vol.16, No.15, 21 July 2008.
2) S. Miyazawa et al.: Basics and applications of polarization inversion devices (in Japanese), The Optronics Co., Ltd.
3) M. "Effect of non-congruency and impurities on the optical damage properties of LiNbO_3 and LiTaO_3 single crystals" (in Japanese), Nihon Kessho Seicho Gakkai Shi 20 (3), pp. 273-280, September 25, 1993.
4) G. K. Samanta, et al.: "Stable, 9.6W, continuous-wave, single-frequency, fiber-based green source at 532 nm," Optics Letters, Vol.34, No.10, May 15, 2009.
5) M. Kashiwagi et al.: "Highly efficient linearly-polarized fiber laser" (in Japanese), Fujikura Giho Vol. 2, No. 117, 2009.
6) I. Kawakami: "Digital cinema now! (64) 'more light!'" (in Japanese), Full Digital Innovation Vol. 154, pp. 44-46, July 2012.
7) K. Inoue: "Green light source now covers laser theaters" (in Japanese), Lase Focus World Japan, pp.44-46, September 2008.
8) S. Kubota: "Speckle measurement and its reduction device" (in Japanese), Kogaku Vol. 39, No. 3, pp. 149-158, March 2010.
9) Victor Yurlov, et al.: "Speckle suppression in scanning laser display," Applied Optics, Vol.47, Issue2, pp.179-187, 2008.
10) Zhaomin Tong, et al.: "Speckle reduction by angle diversity using a translucent spatial light modulator," Optica Applicata, Vol.42, No.3, pp.651-658, 2012.
11) Dmitri V. Kuksenkov, et al.: "Multiple-wavelength synthetic green laser source for speckle reduction," Proc. SPIE, Vol.7917, pp.79170B-1-79170B-12, 2011.
12) Kiminori Mizuuchi, et al.: "Efficient Second-Harmonic Generation of 340-nm Light in a 1.4-μm Periodically Poled Bulk MgO:LiNbO3," Jpn. J. Appl. Phys., Vol.42, pp. 90– 91, February 2003.
13) M. Kashiwagi et al.: "1180-nm Fiber laser employing polarization-maintaining photonic bandgap fiber" (in Japanese), *Fujikura* Giho Vol. 1, No. 120, 2011.
14) R. H. Stolen, et al.: "Raman response function of silica-core fibers," J. Opt. Soc. Am. B, Vol.6, Issue6, pp.1159-1166, 1989.