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ARTICLE

Tunable Harmonics Generation from Low Average Power Mode-Locked Er-Fiber Laser Using Periodic Poling Nonlinear Crystals

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Abstract: Sufficient second, third, and fourth harmonic generation of mode-locked Er-doped fiber laser (ML - EDFL) was experimentally demonstrated. This was achieved by using periodically poled $KTiOPO_4$ (PPKTP) and PP $LiNbO_3$ (PPLN) PPLN nonlinear crystals. Harmonic generation in both crystals depended on the direction of polarization. The highest conversion efficiency was obtained by using a half-wave plate to rotate the polarization before the crystals. When using the PPKTP nonlinear crystal, conversion efficiencies of 4.88%, 0.02%, and 0.002% were obtained for second, third, and fourth harmonics generation at wavelengths of 980, 520, and 390 nm, respectively. For the PPLN nonlinear crystal, temperature and polarization direction were optimized for each harmonic generation wavelength. As a result, conversion efficiencies of 8.6%, 0.1%, and 0.007% were obtained for second, third, and fourth harmonic generation at the same respective wavelengths. Tunable wavelength ranges and their SHGs, as well as the multi-wavelength output and their corresponding SHG wavelengths, were also reported.

Keywords: Er-fiber laser, Passive mode-locked fiber laser, Nonlinear polarization rotation, PPKTP, PPLN, SHG, THG, FHG.

PACS: Fiber lasers, 42.55.Wd, Mode locking, 42.60.Fc.

1. Introduction

Over the last decades, there has been a growing interest within the industry in compact systems that offer high brightness and high power efficiency [1, 2]. Recently, fiber lasers have garnered significant attention due to potential applications in the fields of industrial processing, bioinstrumentation, and display technologies. Compared with conventional solid-state lasers, doped fiber lasers have strong potential for the systems where air-cooling, long-term stability, and maintenance-free operation are required. It has been reported that fiber lasers and nonlinear crystals can be used to generate CW red and green light [3-5]. However, for some applications, such as laser display applications, high repetition rate pulse input is more attractive for second harmonic generation (SHG), third harmonic generation (THG), and fourth harmonic generation (FHG) processes. This is because the conversion efficiency is proportional to the square of input power, so the HG conversion efficiency of a pulsed input will be much higher than that of a CW input, with the same average input power due to the higher pulse peak power. Nevertheless, single-pass wavelength conversion by a nonlinear optical (NLO) crystal is one of the most attractive methods for generating coherent radiation in various spectral domains from ultraviolet to mid-infrared. Quasi-phase-matching (QPM) is a technique in some nonlinear optical crystals that allows a positive net flow of energy from the pump frequency to the signal and idler frequencies by creating a periodic structure in

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the nonlinear medium. This kind of structure ensures that there is positive energy flow from the pump frequency to signal and idler frequencies, even though all the frequencies involved are not phase-locked with each other. Energy always flows from pump to signal as long as the phase between the two optical waves is less than 180 degrees. Beyond 180 degrees, energy flows back from the signal to the pump. The coherence length is the length of the medium in which the phase of the pump and the sum of idler and signal frequencies are 180 degrees from each other. At each coherence length, the crystal axes are flipped, allowing the energy to continue its positive flow from the pump to the signal and idler frequencies. QPM was first proposed in the early days of nonlinear optics [6] and, nowadays, periodic poling technology that produces QPM has become commercially available. Compared with other phase matching methods, such as the birefringent phase matching (BPM) technique, the QPM technique allows to use the largest nonlinear coefficient over the whole transparent spectral range of the crystal without the walk-off effect. The most commonly used technique for creating quasi-phase-matched crystals is periodic poling. Periodically poled crystals consist of switched domain regions from ferroelectric crystals such as lithium niobate (LN) and potassium titanyl phosphate (KTP) and they can be wavelength-tailored for efficient second harmonic generation, sum frequency generation, and difference frequency generation [7]. However, in ferroelectric crystals, each unit cell has a small electric dipole moment. The orientation of the electric dipole in a unit cell is dependent on the positions of ions (the niobium and lithium ions, for example) in that unit cell. The application of an intense electric field can invert the crystal structure within a unit cell and, as a result, flip the orientation of the electric dipole. The interactions in these crystals are based upon quasi-phase-matching achieved by the switched domain regions (periodic poling region). Switched domain regions can be established by structuring a material with regularly spaced ferroelectric domains that have alternating orientations. These domains alternate between the + side and the − side direction, and the typical period for this alternation ranges from 5 to 35 μm. [8]. The poling period depends on the wavelengths of the light (input and generated) and the temperature of the crystal. The shorter periods of this range are used for second-harmonic generation, while the longer ones for optical parametric oscillation [9]. Controlled heating of some crystals such as in lithium niobate can be used to fine-tune phase matching in the medium due to slight variations of the dispersion that occur with changes in temperature. Periodic poling of crystals is a well-established technique used for SH and TH frequency conversions for pump wavelengths of 730 - 3500 nm. However, it is relatively uncommon to employ this method to achieve FHG. Nonetheless, it is possible to achieve FHG using periodically poled wide band gap inorganic crystals such as KTP or LN with efficient conversion rates. An example of this was demonstrated through fan-out poled MgO:LiNbO$_3$ [10]. Among all the periodically poled crystals, periodically poled KTP [11] and LN [12] have been the most attractive materials due to their large second-order nonlinear coefficient, wide transparency bandwidth covering UV to IR, and a well-established and low-cost fabrication process [9, 13, 14]. However, periodically poled lithium niobate (PPLN) suffers from a pointing instability at medium powers and permanent photorefractive damage at high power [7]. Thus, PPLN crystals have to be heated to a temperature of over a hundred degrees to reduce these effects. Alternatively, the adverse effects can be reduced by doping some magnesium oxide (MgO) into the crystal during growth. Compared to pure LiNbO$_3$ crystals, 4% - 5% MgO:c-PPLN crystals exhibit a hundred times higher resistance against optical damage, making them capable of handling high input and output power levels at room temperature [15]. Additionally, further enhancements in PPLN performance can be achieved by using nano-periodic surface structures [16]. In previous research, an Er-fiber laser-based femtosecond parametric generator in bulk PPLN was used for the second harmonic generation [17]. This laser was actively mode-locked using an AOM, and it achieved a conversion rate of 38 %. Another study involved frequency doubling of femtosecond pulses with periodically poled LiNbO$_3$, resulting in a 25% pulse-energy conversion efficiency. This achievement was made possible by using a low-power diode-pumped erbium-fiber soliton laser [18]. Moreover, the third and fourth harmonic generation were reported, with one harmonic generated from a two-branch femtosecond Er-YP fiber source [10]. The fiber oscillator was mode-locked via nonlinear polarization rotation using three quarter-wave plates (QWP) and one half-wave plate (HWP). The quantum conversion efficiencies after the amplification for the SH, TH, and FH generation were 30%, 9.2%, and 5%, respectively. In contrast, CW operation, which achieved a 64% efficiency in quasi-phase-matched second-harmonic generation, was reported using a seeded fiber amplifier with a periodically poled KTP crystal [19].

In this study, an Er-doped fiber laser is passively mode-locked using a nonlinear polarization rotation (NPR) process produced by four-wave plates as an artificial saturable absorber (SA). The study showcased harmonic generation in the low output of the fiber laser passively ML by four-wave plates, marking the first such demonstration, to the best of our knowledge. The laser system allowed for tunable harmonic wavelengths within narrow bands and even produced harmonics at multiple wavelengths. This rich dynamical behavior was contingent on the rotation angle of polarization, which was determined by the orientation of the half-wave plates.

2. Experiments

The experimental setup is schematically shown in Fig. 1. First of all, a mode-locked Er-doped fiber laser (ML-EDFL) is constructed. This laser cavity is pumped using a 980 nm laser diode and relies on nonlinear polarization rotation (NPR). The NPR technique is implemented through the use of four wave plates: two half-wave plates (HWP) and two quarter-wave plates (QWP). The polarization is adjusted to give a clean ML train pulse at either wavelengths 1540 nm 1553 nm or 1560 nm. The ML output beam of the laser is then passed through the M_1 mirror which is HR at 980 nm and HT at 1.5 μm. The mirror reflects the pump beam and lets the fundamental one transmit through. Since only the transverse-magnetic (TM) - polarization can satisfy the quasi-phase-matching (QPM) condition, a half-wave plate (HWP_3) is used to make the fundamental light's polarization parallel with the Z-direction of the nonlinear crystals (PPKTP or PPLN). Both crystals were standard three-dimensional commercial crystals, manufactured by Stratophase. However, there were some differences in their specifications. The PPKTP measured 1.5 mm in length and with a period of 25.2 μm, while the PPLLN measured 1 mm in length, with a period ranging from 18.2 to 19 μm.

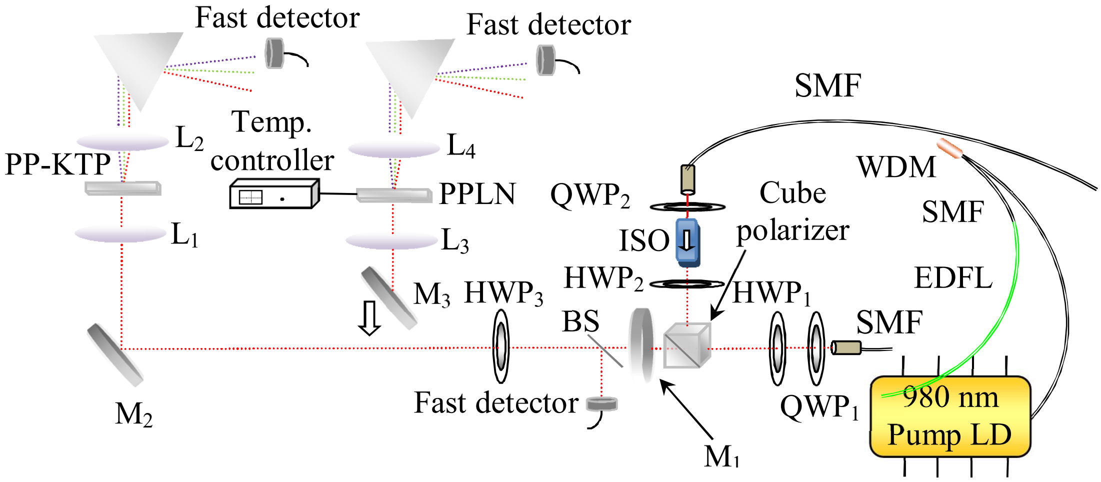

FIG. 1. Experimental arrangement for harmonic generation of ML Er-fiber laser using PPKTP or PPLN.

For the PPKTP experiment, the transmitted fundamental light beam from the ML Er-fiber laser is reflected by M_2 (a 45° reflection mirror at 1550 nm) to a 15 mm focal length lens (L_1). The lens focuses the beam on the PPKTP and then the output is collimated by 40 mm lenses. The fundamental beam is blocked by a band-pass filter placed beyond lens L_2. Passing harmonic wavelengths generated by the nonlinear crystal are separated by a special coated prism and the temporal profile of the signal is measured by a fast silicon (Si) detector from E. O. Tech. The wavelength and the power are also measured by a frequency analyzer (AQ6315E optical spectrum analyzer ranged from 350nm up to 1700 nm) and a suitable power meter from Newport, respectively. The PPLN experiment utilizes a similar setup, where a 45˚ HR at 1560 nm dielectric mirror (M_3) is inserted into the beam path after the M_1 mirror to reflect the fundamental beam into the telescope system consisting of two lenses L_3 and L_4. Both lenses have the same focal length of 15 mm but have a different coating. L_3 is coated to be HT at 1550 nm, whereas L_4 is coated to be HT at 800 nm. These two lenses can adjust the beam diameter to satisfy the optimum confocal condition for PPLAN crystal, which is about 15 mm, so the beam is focused to about 50 µm spot radius in the center of the crystal. The crystal is mounted in a temperature-controlled oven, which can be heated up to 80 ºC, and the temperature is varied to optimize the QPM condition of the PPLN for each harmonic wavelength. A Si fast detector from E. O. Tech. is used to measure the pulse trains for the harmonic generations after their separation by a suitably coated prism and a band-pass filter is used after lens L_4 to block the fundamental light. However, in both described experiments, a small part of fundamental light is separated by a beam splitter, located after M_1, and directed onto a fast InGaAs detector (Et 3500 from E. O. Tech.) to monitor the temporal profile of the fundamental beam. The two fast detectors that are used in this setup are connected to a digital oscilloscope (Tektronics 1GHz oscilloscope). This oscilloscope is used for recording pulse trains generated by the detectors. In this way, the fundamental pulses and SHG pulses can be recorded synchronously in order to be compared accurately.

3. Results and Discussion

First of all, SHG, THG, and FHG were created using a PPKTP crystal. Figure 2 shows fundamental, second, and third ML pulse trains with a pulse duration of 12.4 fs the trip time inside the fiber cavity. The fourth harmonic signal is too small and not detectable by a Si fast detector.

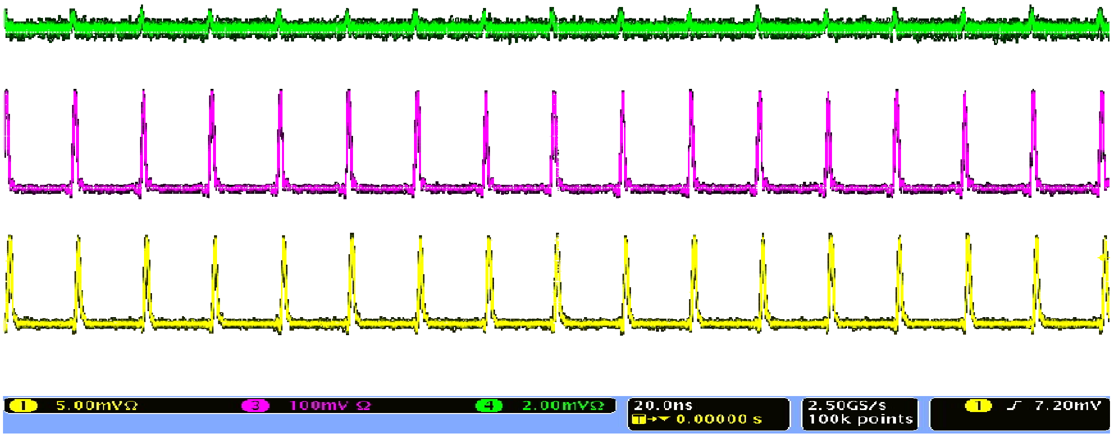

FIG. 2. Fundamental, SHG, and THG pulse train for PPKTP experiment.

The spectrum of the harmonic generation is shown in Fig. 3, where the fundamental beam wavelength is at 1560 nm while the SHG, THG, and FHG beams are at 780, 520, and 390 nm, respectively.

The FWHM of spectra were 12.10, 3.33, 1.54, and 0.92 nm for the fundamental, SHG, THG, and FHG beams, respectively. The pulse width (t_p) is found to be (where $t_p = k/\Delta\nu = k\lambda^2/c\ \Delta\lambda$ and $k = 0.315$ assuming sech^2 pulse shape): 211, 192, 184, and 178 fs for the fundamental, SHG, THG, and FHG beams, respectively.

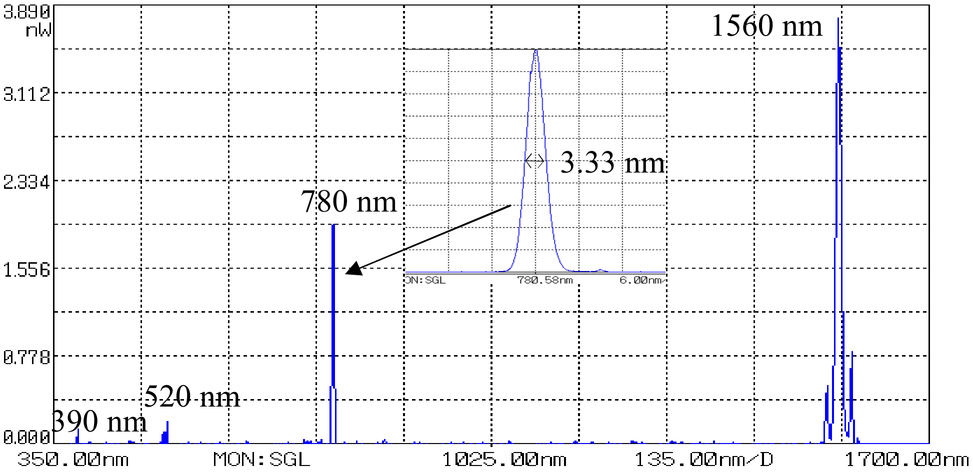

FIG. 3. Full spectrum of the fundamental beam of mode-locked fiber laser, SHG, THG, and FHG harmonic generation using a PPKTP crystal.

The harmonic output of ML-EDFL was optimized for each wavelength separately by adjusting the HWP_3 wave plate as shown in Fig. 4.

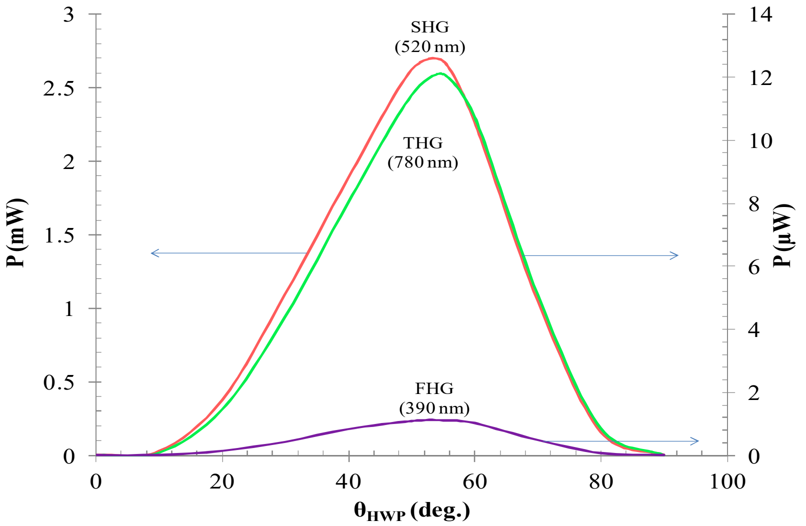

FIG. 4. Output power optimization of SHG, THG, and FHG generated by a PPKTP crystal.

Maximum powers of 2.7 mW, 12.1 μW, and 1.1 μW were then obtained for SHG, THG, and FHG, respectively, while the fundamental output beam launched to the crystal was 55 mW. Consequently, the optimum conversion efficiencies (i.e. P_{out}/P_{in}) of this crystal were 4.88%, 0.02%, and 0.002% for SHG, THG, and FHG, respectively. Further improvement of the conversion efficiency to produce higher harmonic generations output power was possible by replacing PPKTP crystal with PPLN crystal. In this case, the output depends on the crystal temperature and the polarization orientation angle of the fundamental beam. Figure 5 shows the optimized temperature to obtain the highest output power values for SHG, THG, and FHG beams are between 38 °C and 65 °C.

The harmonic output of ML-EDFL was also optimized for each harmonic wavelength separately by adjusting the HWP_3 wave plate, as shown in Fig. 6.

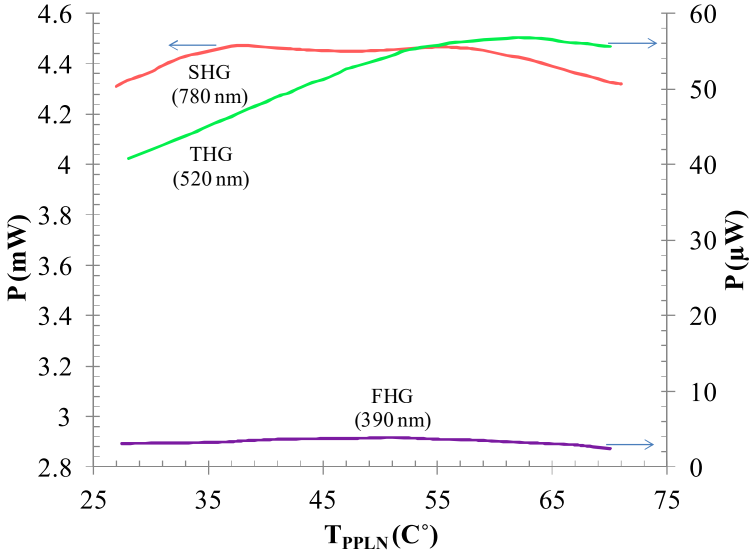

FIG. 5. Output power optimization of SHG, THG, and FHG harmonic generation using a PPLN crystal by adjusting the temperature of the crystal.

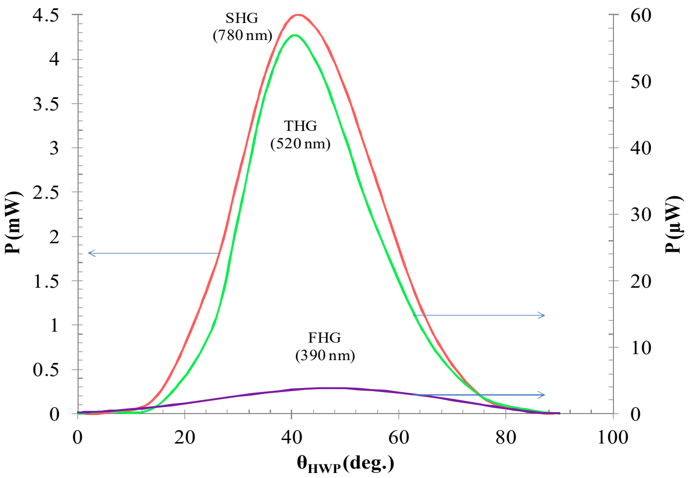

FIG. 6. Output power optimization of SHG, THG, and FHG using a PPLN crystal by adjusting the polarization direction of the fundamental beam.

Maximum of the optimum output powers for SHG, THG, and FHG beams were increased to 4.5 mW, 56.8 μW, and 3.8 μW, respectively. The output power of the fundamental beam that launched to the crystal was the same as the last experiment (i.e. 55 mW) and the conversion efficiencies of the crystal, in this case, were 8.6%, 0.1%, and 0.007% for SHG, THG, and FHG beams, respectively.

The FWHM of wavelength spectra (Fig. 7) were 12.06, 3.96, 1.85, and 1.11 nm for the fundamental, SHG, THG, and FHG beams, respectively, and the pulse width (t_p) was found to be (where $t_p = k/\Delta\nu = k\,\lambda^2/c\,\Delta\lambda$ and k = 0.315 assuming sech^2 pulse shape): 212, 161, 153, and 145 fs for the fundamental, SHG, THG, and FHG beams, respectively.

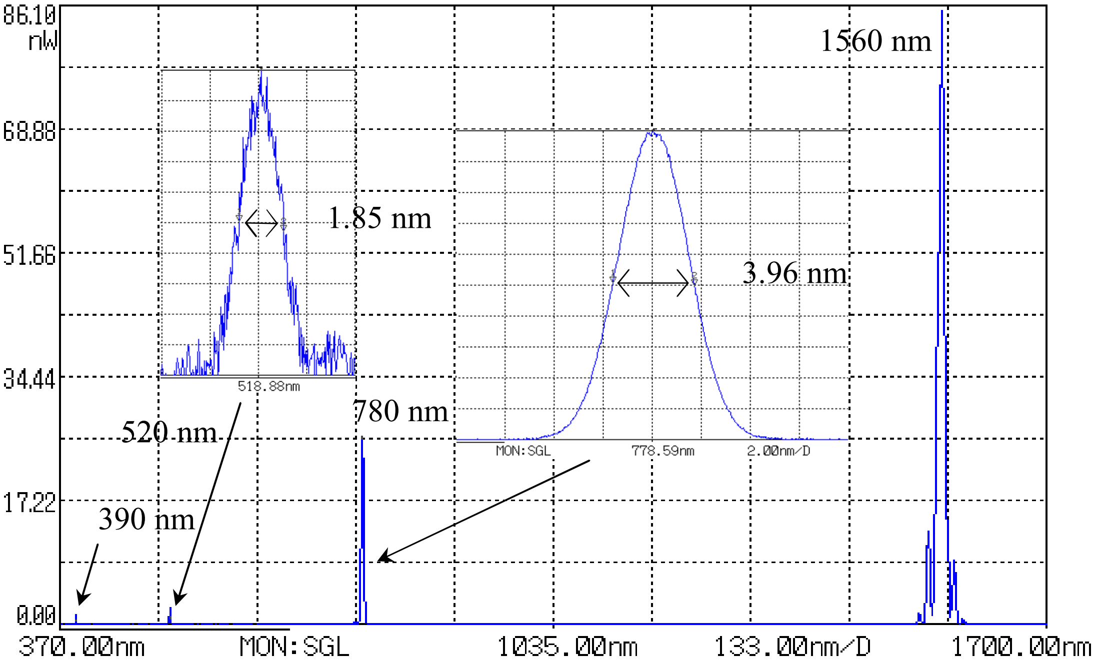

FIG. 7. Full spectrum of the fundamental beam of mode-locked fiber laser, SHG, THG, and FHG harmonic generation using a PPLN crystal.

Figure 8 shows a pulse train of the small segment of the fundamental beam (the transmitted part after an HR mirror at 1550 nm) and the SHG and THG after the prism. The peak powers of the pulse were calculated to be 3.25 MW, 344,43 kW, 4.60 kW, and 0.33 kW for the fundamental, SHG, THG, and FHG pulse trains, respectively. However, the ML fiber laser system based on NPR using four wave plates is found to be a tunable wavelength system and can produce other wavelengths rather than 1560 nm such as at 1540 and 1552 nm depending on the orientation of the half-wave plates (HWP).

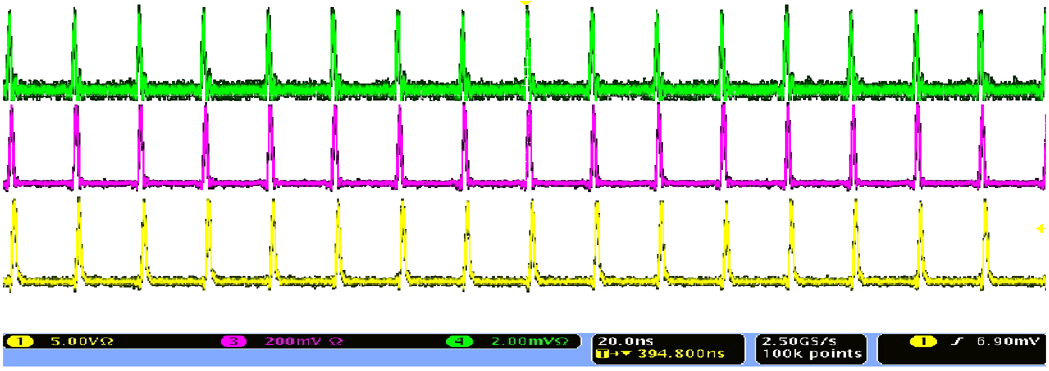

FIG. 8. From down up: fundamental, SHG, and THG harmonic generation pulse train for harmonic generation using a PPLN crystal.

Therefore, second harmonic generation (and other harmonic generations) can be generated for the mentioned wavelengths. However, Fig. 9 shows a second harmonic generation (SHG) for the fundamental beam at 1542.4 nm with a spectrum width of 13.2 nm. The SHG wavelength centered at 771.2 nm with spectrum width of 5.56 nm. This width shows that the fundamental and SHG pulse widths are now about 189 and 112 fs, respectively.

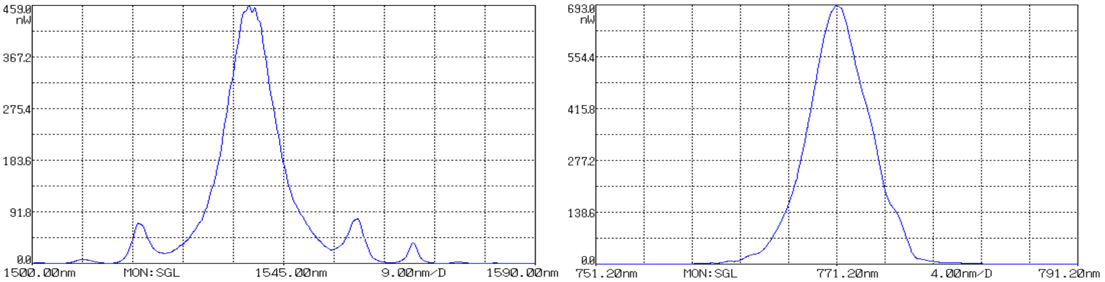

FIG. 9. Spectrum of the fundamental beam at 1542.4 nm and its SHG at 771.2 nm.

On the other hand, Fig. 10 shows an SHG for the fundamental beam at 1552 nm with a spectrum width of 11.3 nm. The SHG wavelength centered at 776 nm with a spectrum width of 4.2 nm. This width shows that the fundamental and SHG pulse width is now about 224 and 151 fs, respectively.

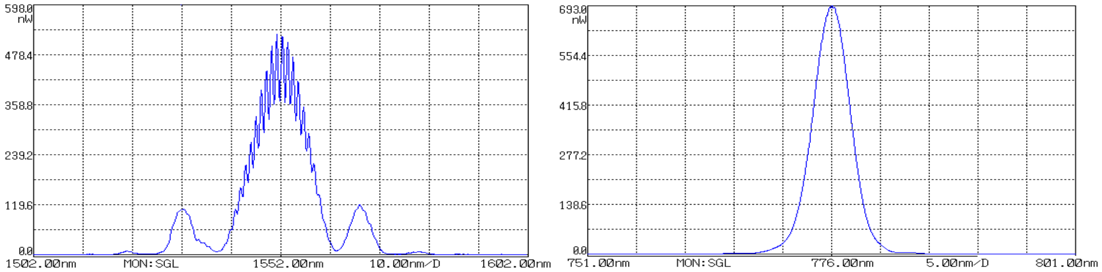

FIG. 10: The fundamental beam spectrum at 1552 nm and its SHG at 776 nm.

Multi-wavelength also can be generated from this laser by adjusting the polarization angle using the internals HWPs. Figure 11 shows many wavelengths covering a wide range of the spectrum centered at 1544 nm, resulting in generating a wide range of SHG centered at 772 nm.

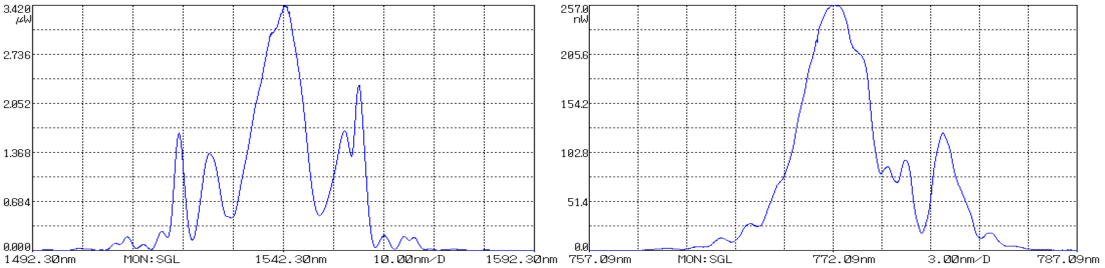

FIG. 11. multi wavelength of fundamental beam centered at 1552 nm resulting in a wide range of SHG centered at 772 nm.

Table 1 summarizes the tunable ranges of wavelength that can be obtained from this laser and its SHG, as well as the pulse width ranges to both fundamental and SHG wavelengths.

TABLE 1. Tuneable wavelengths and its SHG.

λ_{fund} (nm)	$\Delta\lambda_{fund}$ (nm)	$T_{p(f)}$ (fs)	λ_{SHG} (nm)	$\Delta\lambda_{SHG}$ (nm)	$T_{p(SHG)}$ (fs)
1536 - 1544	13.2-10.7	234 -188	768 - 772	5.5 - 4	157 - 112
1552 - 1554	11.3 - 10.2	248 - 224	776 - 777	4.2 - 4	159 - 151
1556 - 1560	13.7 - 8.4	304 -186	778 - 780	4.4 - 3.1	206 - 145

In contrast with other studies that utilized LN as conversion elements for pulse input [10, 17, 18], the conversion efficiencies for HG in this experimental work were relatively lower. This can be attributed to the use of lower input power and a high pulse rate, as well as the application of additional external amplification in some cases, which differs from previous studies [10]. On the other hand, using PPLN, which is temperature-controlled, gives better results and higher conversion rates compared to PPKTP. However, no reference paper was found for using periodically poled KTP crystal with fs pulse train output.

4. Conclusion

In this study, we demonstrated a setup to produce an ML fundamental beam with a wavelength of 1558 ± 2 nm using an EDFL and the NPR technique based on four HWPs. Subsequently, SHG, THG, and FHG beams at 779 ± 1, 520, and 390 nm, respectively, were generated by using PPKTP and PPLN wavelength conversion devices.

The output was optimized for both crystals by aligning the polarization of the input beam with the Z-direction of the nonlinear crystals. In the case of PPLN, additional optimization was achieved by controlling the crystal's temperature, which was maintained in the range from 38 °C to 65 °C to satisfy QPM conditions for SHG, THG, and FHG. Consequently, the conversion efficiencies for PPLN were more than twice as high as those for PPKTP, measuring at 8.6%, 0.1%, and 0.007% for SHG, THG, and FHG, respectively.

Other sets of SHG, THG, and FHG were generated by adjusting the polarization direction inside the laser cavity to yield fundamental wavelengths of 1540 ± 4 nm or 1553 ± 1 nm. Furthermore, multi-wavelength SHG pulse trains centered at 772 nm were obtained from multi-wavelength fundamental beams centered at 1552 nm by changing the NPR angle. These results highlight the laser's suitability for various applications, including communications and micromachining.

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