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# 97-μJ single frequency linearly polarized nanosecond pulsed laser at 775 nm using frequency doubling of a high-energy fiber laser system

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**Abstract.** We report a high-energy (~97 μJ), high-peak power (~20 kW), single-frequency, linearly polarized, near diffraction-limited ($M^2 < 1.2$) ~4.8-ns pulsed laser source at 775 nm with a 260-Hz repetition rate. This laser was achieved by frequency doubling of a high-energy linearly polarized all-fiber-based master oscillator–power amplifier, seeded by a single-frequency semiconductor distributed feedback laser diode at 1550 nm. The frequency doubling is implemented in a single-pass configuration using a periodically poled lithium niobate crystal, and a conversion efficiency of 51.3% was achieved.  [DOI: 10.1117/1.OE.56.8.086112]

Keywords: single frequency; frequency doubling; high-energy fiber laser.

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## 1 Introduction

Rare-earth-doped glass fiber lasers have seen progressive developments in the past two decades in various aspects, such as high power, high energy, ultrashort pulse width, narrow linewidth (single frequency), etc.[1,2] Fiber lasers can only operate in certain spectra range, such as 1,[3] 1.5,[4] 2,[5] or 2.8 μm,[6] due to the limit of the emission spectra for the rare-earth-elements doped in glasses. Due to the various nonlinear processes, including the Raman, frequency doubling, parametric processes, etc., fiber lasers have been utilized to generate a lot of very attractive coherent sources operating in ultraviolate,[7] visible,[8] midinfrared,[9] and even THz ranges.[10] Fiber-based construction of these laser systems enables robust, compact, and high performance operation.

The frequency doubling of narrow linewidth Er-doped fiber lasers can generate narrow linewidth laser sources around 780 nm, which can be utilized for optical atom cooling, quantum information storage, etc. Thompson et al.[11] demonstrated a single-frequency continuous wave (CW) 780-nm laser source with 900-mW laser power, generated from the frequency doubling of a fiber laser system using the cascaded periodically poled lithium niobate (PPLN) crystals. Vyatkin et al.[12] reported a single-frequency CW laser at 780 nm with 5-W average power by frequency doubling a single-frequency linearly polarized CW Er:Yb fiber laser. In this system, the frequency doubling was implemented by single passing one PPLN crystal. Another single-frequency CW laser at 780 nm with watt-level output power was built using the external-cavity-enhanced frequency doubling of an Er-doped fiber laser system.[13] Some other single-frequency lasers around 780 nm in the CW regime were also reported.[14–16] The pulsed single-frequency lasers of around 780 nm can find applications in remote sensing, optical metrology, etc. Chiow et al.[17] demonstrated the generation of 43 W of quasicontinuous 780-nm laser light by single-pass frequency doubling of a 1560-nm laser via the combination of two fiber amplifiers. Champert et al.[18] demonstrated a nanosecond pulsed laser at 772 nm by frequency doubling of a distributed feedback (DFB) laser diode seeded ytterbium–erbium fiber amplifier in a periodically poled KTP crystal. Dingjan et al.[19] reported the generation of a 4-ns pulsed laser of 780 nm by single-pass frequency doubling of an EDFA-boosted 1560-nm diode laser for excitation of a single trapped rubidium atom. Hu et al.[20] demonstrated a fiber-integrated laser source at 780 nm, producing 410-ps pulses at a repetition rate of 50 MHz and with 3.5-W average power. Some other pulsed lasers around 780 nm were also reported.[21,22] The pulse energy of these pulsed lasers is at the tens of nano-Joule to several micro-Joule level, and the peak power is below 1 kW due to the high repetition rate of these laser pulses.[18–22] Nanosecond laser pulses at 780 nm with tens of kilowatts peak power are demanded in a lot of applications, such as long-range remote sensing, materials processing, etc.

In this paper, we report a single-frequency, linearly polarized, near diffraction-limited, pulsed laser source at 775 nm by frequency doubling a single-frequency nanosecond pulsed all-fiber-based master oscillator–power amplifier (MOPA) and seeded by a fiber coupled semiconductor DFB laser diode at 1550 nm. This 775-nm laser can provide ~4.8-ns single-frequency laser pulses with a 260-Hz repetition rate, ~97-μJ pulse energy, and ~20-kW peak power.

## 2 Low Repetition Rate High-Energy Fiber Laser System

Figure 1 demonstrates the diagram of the high-energy, single-frequency, linearly polarized laser at 775 nm. It consists

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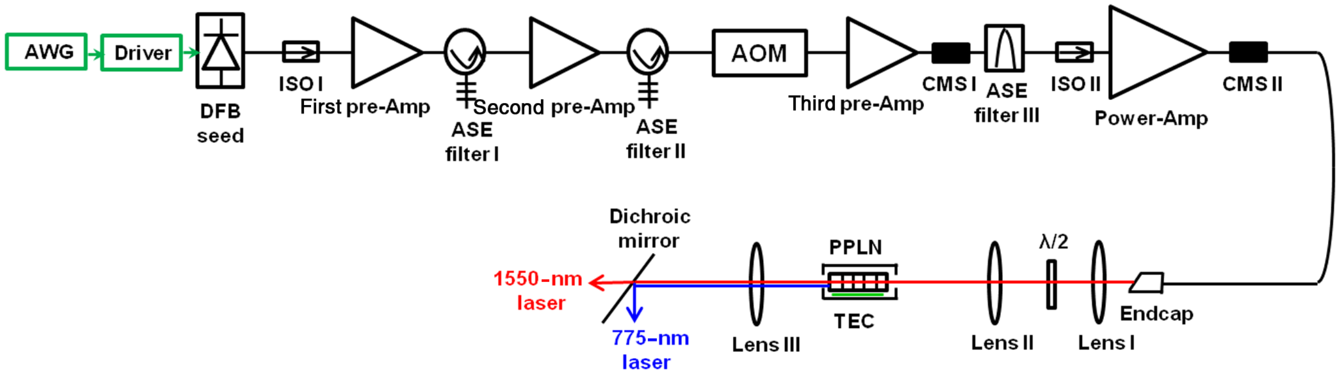


**Fig. 1** The diagram of the high-energy, single-frequency, linearly polarized laser at 775 nm.

of a high-energy monolithic MOPA seeded by a single-frequency fiber-coupled semiconductor DFB laser diode and a frequency doubling system in a single-pass configuration using a PPLN crystal as a nonlinear medium.

A butterfly laser driver, driven by an arbitrary waveform generator, was utilized to drive the single-frequency fiber coupled semiconductor laser diode with ~1-MHz linewidth to generate nanosecond laser pulses. The pulse shape, pulse duration, and repetition rate of the laser pulses can be easily adjusted by the arbitrary waveform generator. The generated shortest laser pulse is about 5 ns and is limited by the speed of the driver. The laser pulses with ~5-ns pulse durations and 240- to 260-Hz repetition rates was chosen as the seed for the MOPA to achieve the pulse energy and the peak power as high as possible. The pulse energy for the seed pulses is about 50 pJ. The MOPA consists of four stages of the fiber amplifier: two stages of a core-pumped fiber amplifier (first and second preamplifier), one double cladding (DC) fiber amplifier (third preamplifer), and one DC power amplifier. The gain fiber used in the two core-pumped amplifiers is ~1 m of commercial polarization-maintained (PM) Er-doped single-mode fiber (from Nufern Inc.) with a ~7-$\mu$m core. The spectral filter, consisting of one circulator and one high reflection fiber Bragg grating, was inserted after each core-pumped preamplifier to clear out the amplified spontaneous emissions (ASE). One acousto-optic modulator (AOM) was inserted after the second spectral filter to gate the pulses to increase the extinction ration. The gain fiber utilized in the DC fiber preamplifier was ~1 m of commercial PM Er/Yb-codoped fiber (from Nufern Inc.) with 12-/130-$\mu$m core/inner cladding. The cladding absorption coefficient at 976 nm is about 10 dB/m. One fiber coupled multimode semiconductor laser diode at 976 nm was utilized as the pump source for this amplifier. One homemade cladding mode stripper (CMS) was utilized to clear out the residual pump and some laser light propagating in the fiber cladding. One bandpass spectral filter centered at 1550 nm was inserted after the CMS to clear out the ASE. The active fiber utilized in the power amplifier was ~1 m of commercial PM Er/Yb-codoped fiber (from Nufern Inc.) with 25-/300-$\mu$m core/inner cladding. The cladding absorption coefficient at 976 nm is ~9 dB/m. Two fiber-coupled multimode laser diodes at 976 nm were utilized as the pump sources for the power amplifier. The other homemade CMS was utilized to strip out the light propagating in the fiber cladding. One fiber-based PM isolator was inserted between the two DC fiber amplifiers to prevent the backward propagation light. One commercial endcap (from Optizone Technology Inc.) was utilized as the output end of the whole fiber laser system to avoid any end-face reflection and to prevent the end-face burning from the large peak power density.

Considering the low repetition rate (240 to 260 Hz) of the seed pulses, the multistage synchronous pulse pumping technique was adopted in the four stages of fiber amplifiers to mitigate the ASE in the amplifiers.[23] The time sequence of the seed pulse, the AOM gate pulse, and the pump pulses are shown in Fig. 2. The pulse width for the seed pulse and the AOM gating pulse were fixed as ~5 and ~60 ns, respectively. The pump pulse widths in four stages of fiber amplifiers are optimized experimentally to achieve the maximum pulse energy and simultaneously to suppress the ASE as much as possible. As shown in Fig. 2, the optimized pump pulse width in the four stages of fiber amplifiers was ~1 ms, ~1 ms, ~300 $\mu$s, and ~500 $\mu$s, respectively. The peak power of the pump diodes for the three stages of the preamplifiers was optimized to 230 mW, 380 mW, and 2.5 W, respectively. The pulse energy after the three stages of preamplifiers was measured to be ~10 $\mu$J using an Ophir PE10-C pyroelectric energy sensor, which is insensitive to the ASE background and CW signal component. Therefore, the three stages of the preamplifiers produced ~53-dB gain for the seed pulses. Using the same energy sensor, the pulse energy of the laser pulses, which is the output from the power amplifier under different pump levels, was measured and is shown in Fig. 3. When the pump pulses, with ~21-W peak power and ~500-$\mu$s pulse width, were launched into the final power amplifier, the maximum

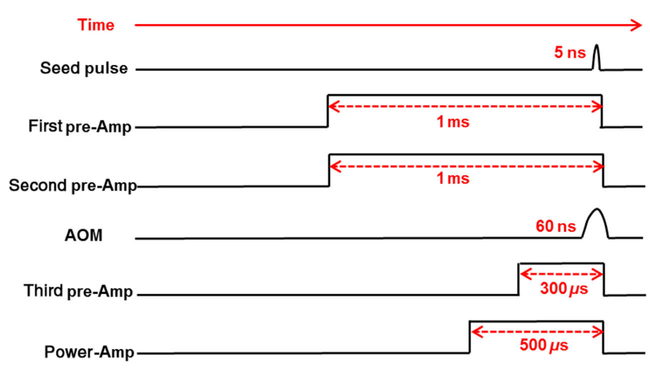


**Fig. 2** The time sequence of the seed pulse, the AOM gate pulse, and the pump pulses.

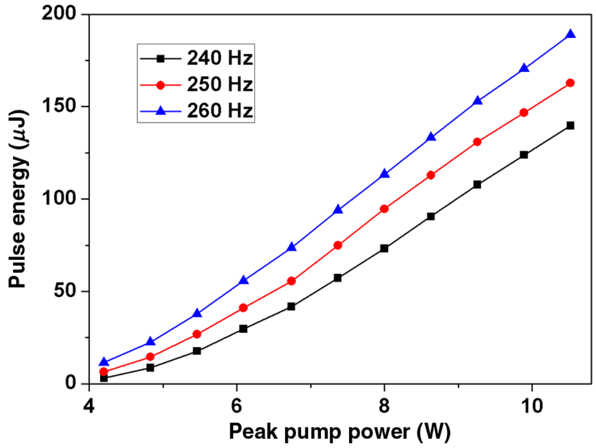


**Fig. 3** The output pulse energy for the 1550-nm linearly polarized single-frequency MOPA under different pump levels and with different repetition rates.

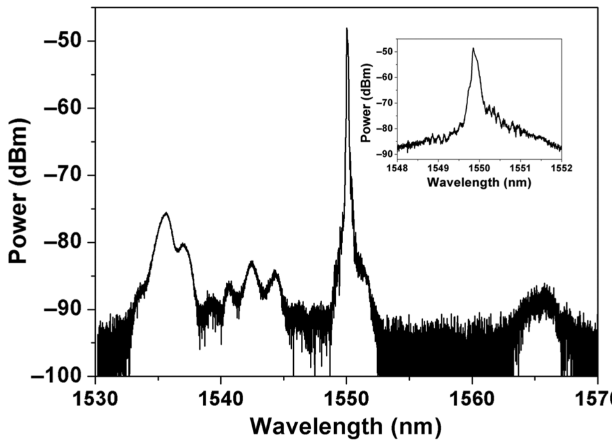


**Fig. 4** The output spectrum of the single-frequency laser with ~200-$\mu$J pulse energy. Inset: Zoomed-in spectrum of the laser.

pulse energy of ~200, ~172, and ~148 $\mu$J was achieved for laser pulses with 260-, 250-, and 240-Hz repetition rate, respectively.

The spectrum of the laser with ~200-$\mu$J pulse energy was measured using an optical spectrum analyzer (OSA) with 0.02-nm resolution. As shown in Fig. 4, the laser was centered at ~1550.02 nm. The signal-to-noise ratio (SNR) of >27.7 dB was achieved due to the pulse pumping technique adopted in the MOPA. The pulse duration was measured to be ~4.8 ns using a fast detector and an oscilloscope.

## 3 Generation of the High-Energy Single-Frequency Laser Pulses at 775 nm

The linear polarized 1550-nm laser pulses with ~200-$\mu$J pulse energy, ~4.8-ns pulse duration, and 260-Hz repetition rate were chosen to do the frequency doubling as shown in Fig. 1. The laser output from the endcap was collimated by an aspheric lens (lens I as shown in Fig. 1) with ~15.3-mm focal length and 1550-nm antireflection (AR) coating. The collimated laser beam diameter was ~2.6 mm. One half-wave plate was utilized to adjust the linear polarization of the laser. One plane-convex lens (lens II as shown in Fig. 1), with ~75-mm focal length and 1550-nm AR coating,

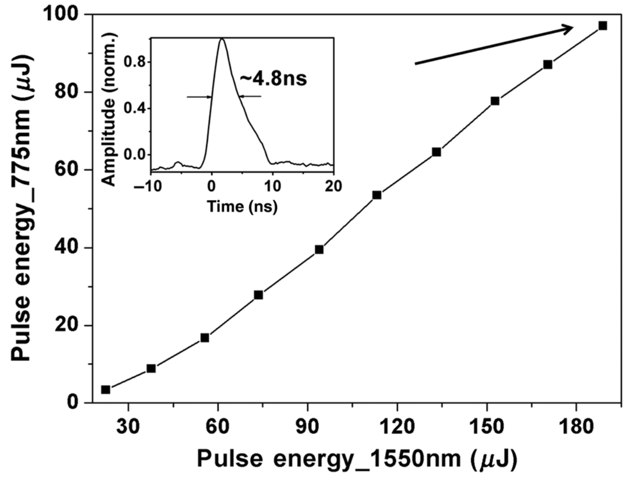


**Fig. 5** The output pulse energy of the 775-nm laser as a function of the pulse energy of the 1550-nm laser. Inset: the measured pulse shape of the ~97-$\mu$J laser pulses.

was used to focus the laser into the center of the PPLN crystal. The pulse energy of the 1550-nm laser pulses was measured to be ~189 $\mu$J after this lens due to the loss from these bulk optics. The diameter of the beam waist and the Rayleigh length were calculated to be ~103 $\mu$m and 5.32 mm, respectively. The PPLN crystal is 3-mm long, 1.4-mm wide, and 1-mm thick, with a 19.36-$\mu$m domain period chosen for quasiphase matching at 33°C. It was AR coated at both 1550 and 775 nm. One thermo electric cooler (TEC) was utilized to adjust the temperature of the crystal as shown in Fig. 1. The generated 775-nm laser was collimated by the other plane-convex lens (lens III as shown in Fig. 1) with ~30-mm focal length and the 775-nm AR coating. The residual 1550-nm laser (transmitted) and the collimated 775-nm laser (reflected) were split by a dichroic mirror. Note that we chose the above bulk optics, especially the lens I and II, based on the experimental optimization for the conversion efficiency of the frequency doubling.

The Ophir PE10-C pyroelectric energy sensor was utilized to measure the energy of the generated 775-nm laser pulses. Figure 5 shows the pulse energy of the 775-nm laser when the 1550-nm laser with different pulse energy was launched into the PPLN crystal. The maximum pulse energy of ~97 $\mu$J was achieved when the ~189-$\mu$J fundamental laser was launched. The corresponding conversion efficiency can be calculated to be 51.3%. Note that, in the experiment, the TEC was utilized to adjust the temperature of the PPLN to optimize the conversion efficiency. When the temperature was adjusted to ~33°C, the highest conversion efficiency was achieved. The conversion efficiency can be improved by cleaning the spectrum of the 1550-nm laser (see Fig. 4), using optimized PPLN crystal, etc. The pulse shape was measured using a fast detector and an oscilloscope with a 500-MHz bandwidth. As shown in the inset of Fig. 5, the pulse duration was about 4.8 ns, so the peak power of the generated 775-nm laser pulses reached ~20 kW. The polarization extinction ratio (PER) was also measured to be ~15 dB based on a half-wave plate and a Glan-laser polarizer. To the best of our knowledge, this is the first demonstration of a 100-$\mu$J level, tens of kilowatts peak power level single-frequency linearly polarized 775-nm laser based on the frequency doubling of the fiber lasers.

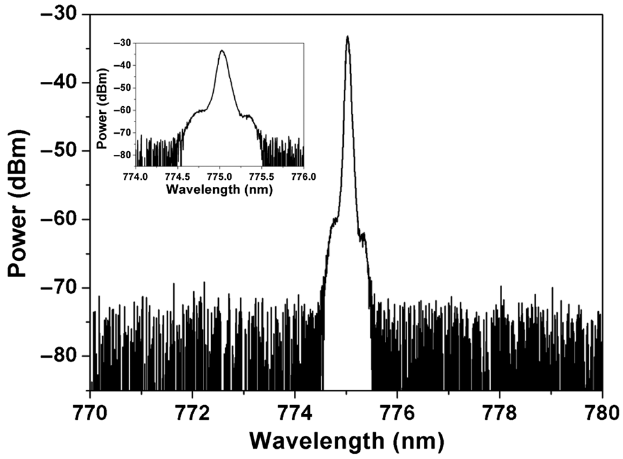


**Fig. 6** The measured spectrum of the 775-nm single-frequency linearly polarized laser with ~97-μJ pulse energy. Inset: Zoomed-in spectrum of the laser.

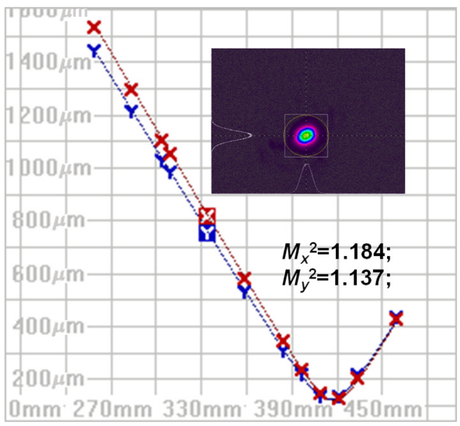


**Fig. 7** The measured beam quality factor ($M^2$) of the 775-nm single-frequency linearly polarized laser with ~97-μJ pulse energy.

The spectrum of the generated 775-nm laser with ~97-μJ pulse energy was measured using an OSA with 0.02-nm resolution and is shown in Fig. 6. The laser was centered at ~775 nm, and an SNR of greater than ~36 dB was achieved. Compared with the SNR of the fundamental laser (see Fig. 4), the SNR is much better due to the ASE filtering of the process of the double-frequency conversion.

The beam quality for the 775-nm laser with ~97-μJ pulse energy was evaluated with a beam quality factor ($M^2$) in two orthogonal transverse directions $x$ and $y$ using a commercial beam profile analyzer (M2-200S, Ophir Photonics Inc.). As shown in Fig. 7 the beam quality factor ($M^2$) was measured to be 1.184 and 1.137 in the $x$- and $y$-directions, respectively. Nearly diffraction limited beam quality was achieved.

## 4 Conclusion

We have successfully implemented a high-energy, single-frequency, linearly polarized, near-diffraction-limited ($M^2 < 1.2$), nanosecond, low repetition rate pulsed laser at 775 nm by frequency doubling of an all-fiber MOPA seeded by a single-frequency DFB laser diode. The 775-nm laser can produce ~97-μJ, ~4.8-ns laser pulses with 260-Hz repetition rate and ~15-dB PER. It is believed that the laser can be used for a lot of applications, including remote sensing, optical metrology, material processing, etc.


## Acknowledgments

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Biographies for the other authors are not available.