A high repetition rate (>MHz), high harmonic generation (HHG) based, vacuum ultraviolet (VUV) laser source is highly desirable for photoelectron spectroscopy to carry out a space-charge-free measurement by limiting the number of emitted electrons per pulse.\textsuperscript{1,2} This helps obtain higher signal-to-noise ratios and achieve a high energy resolution. Such conditions cannot be met with traditional Ti:sapphire laser systems, which typically have a repetition rate on the order of a few kilohertz. To ensure a peak intensity sufficiently high to drive the HHG process efficiently at high repetition rates, a femtosecond enhancement cavity (fsEC) was used to increase the peak intensity by coherently adding multiple pulses.\textsuperscript{3-6} In addition to long-term operation being rather laborious, enhancement cavities present technical challenges due to their sensitivity to environmental perturbations and ionization clamped intracavity power limitations.\textsuperscript{7,8} In contrast, single pass HHG configurations at high repetition rates are more robust and have been garnering increased attention recently,\textsuperscript{9,10} leading to the development of high power, femtosecond driving laser sources that are able to reconcile high repetition rates with high pulse energies. On top of being promising candidates for HHG-related applications, high power high repetition rate femtosecond lasers are also suitable for high precision laser material processing, ensuring rapid and cold processing.

Fiber, slab and disk laser amplifiers are leading the trend in the field of high power femtosecond lasers and all three are capable of \(\sim 1\ kW\) of average output power.\textsuperscript{11-13} Although they can find applications in laser processing, none of them are suitable for driving HHG due to the relatively low pulse energies being delivered (\(\sim 10\) \(\mu\)J for fiber lasers) and relatively long pulse durations (640 fs for fiber lasers, 615 fs for slab lasers, and 7.3 ps for disk lasers). Because short pulse durations are desirable for driving the HHG process, fiber lasers are the preferred choice due to the broader gain bandwidth they can support, compared to the commonly used Yb:YAG gain medium in slab and disk lasers. Actively doped fibers have the advantage of having a large surface-to-volume ratio, which results in excellent heat dissipation. However, due to the small core diameter of gain fibers, the peak powers reached inside the fiber are high and unwanted nonlinear effects, such as self-phase modulation, tend to occur. In order to avoid possible nonlinearities, the pulse duration of a seed laser needs to be stretched before it is amplified by a fiber amplifier, much like with fiber chirped pulse amplification (FCPA). In this way, high power operation with repetition rates ranging from 10 to 150 MHz have been reported,\textsuperscript{14-16} but the pulse energies (few microjoules) proved to be insufficient to carry out single pass HHG and an enhancement cavity was required to increase the peak powers. Single pass HHG experiments using FCPA have been demonstrated,\textsuperscript{17-19} however, this was for pulse repetition rates of 100 kHz, which when increased to 1 MHz would lead to lower energies and a less efficient HHG process. Therefore, upgrading the pulse energy to hundreds of microjoules at a repetition rate of 1 MHz for single pass HHG experiments could add to fsEC experiments carried out at tens of megahertz, and single pass experiments realized at tens of kilohertz.

In recent years, research in FCPA laser systems at a repetition rate of few megahertz has soared.\textsuperscript{20-24} In 2007, 90 W of output power at a 1 MHz repetition rate with a pulse duration of 500 fs was reported using an air-clad photonic crystal fiber,\textsuperscript{20} where the efficiency of the compressor was 70%. In 2011, an average power of 200 W at a repetition rate of 1 MHz with a pulse duration of 700 fs was realized using a large pitch photonic crystal fiber,\textsuperscript{21} where the efficiency of the compressor was 80%. In the same year, an average power of 212 W at a repetition rate of 2 MHz with a pulse duration of 470 fs was also achieved using a preferential gain photonic-crystal fiber\textsuperscript{22} and the efficiency of the compressor was 70%. In 2014, PolarOnyx reported 100 W of average power at 1 MHz repetition rate with a pulse duration of 700 fs\textsuperscript{23} and the efficiency of the compressor was 80%. The group of Morgner also demonstrated an average power of 80 W at 1 MHz repetition rate and a pulse duration of approximately 700 fs\textsuperscript{24} and the second harmonic was used to pump an optical parametric chirped pulse amplifier (OPCPA). Nonetheless, the pulse durations were limited around \(\sim 500\) fs, which was not ideal for driving HHG. To further reduce the pulse duration, nonlinear compression techniques and OPCPAs have been used, albeit at the expense of increasing the complexity and decreasing the efficiency of the overall system.
In addition to power scaling, another key device in chirped pulse amplification (CPA) technology is the compressor, which typically consists of two gratings and brings the pulse duration back in the femtosecond region after amplification. The typical reflection-type grating with a metal coating is not suitable because the beam quality of the high average power beam degrades due to thermal expansion, and the diffraction efficiency of a metal-coated grating gradually decreases over long-term use.\(^{25}\) The low damage threshold of metal-coated gratings is another obstacle in the realization of a high-power system. While the dielectric-coated grating is suitable for high-power operation, it has a small diffraction bandwidth. Recently, a new kind of large scale, high efficiency transmission grating at 1 \(\mu\)m was shown to adequately compress pulses.\(^{25}\)

In this contribution, we report on a FCPA laser system, which delivered 100 W of output power after pulse compression, at a repetition rate of 1 MHz, corresponding to a pulse energy of 100 \(\mu\)J. The compressor efficiency was as high as 85% resulting from the special large scale transmission gratings. The pulse duration was measured to be 270 fs using second harmonic generation frequency-resolved optical gating (SHG-FROG). To the best of our knowledge, this represents the shortest pulse duration achieved by a single amplifier.

Figure 1 shows the schematic diagram of the setup for the 1 MHz FCPA laser system. It consists of an oscillator, a pulse stretcher, a pulse picker, multiple stages of amplifiers, and a pulse compressor.

The oscillator was a typical nonlinear polarization evolution (NPE) based, mode-locked ytterbium (Yb)-doped fiber oscillator, which was designed to have a repetition rate of 64 MHz and delivered pulses with an average output power of 5 mW and a bandwidth of 30 nm. The output of this seed laser was directed to a conventional Martinez-type pulse stretcher, which consisted of a 180-mm-wide by 40-mm-high transmission grating with a groove density of 1250 lines/mm, a lens with a focal length of 1000 mm and a diameter of 150 mm, a high reflection rectangular mirror, and a roof mirror formed by two rectangular gold mirrors. The distance from the grating to the lens was 250 mm and the applied group delay dispersion (GDD) was 1.6 \(\times\) 10\(^7\) fs\(^2\). The grating had a thickness of 1 mm and an anti-reflection coating on the back surface. The diffraction efficiency was measured to be \(\sim 96\%\) at 40° incidence angle.\(^{25}\) A half-wave plate (HWP) was used to adjust the polarization state to maximize the diffraction efficiency. The stretched pulse duration was measured to be approximately 1 ns using a sampling oscilloscope and a 45-GHz-bandwidth photodiode. Due to losses from the diffraction gratings and multiple reflections on the mirrors, the average power decreased to \(\sim 2.5\) mW. A single-mode highly doped Yb fiber-based pre-amplifier, with a core diameter of 6 \(\mu\)m and a length of 25 cm, was placed after the stretcher to increase the power to \(\sim 100\) mW to compensate for losses incurred from an acousto-optic modulator (AOM) placed further down in the configuration. A 976 nm single-mode fiber (SMF) coupled, wavelength-stabilized laser diode was used as the pump source, and a forward pumping scheme was adopted to avoid possible damage to the pump source. In order to reduce the laser repetition rate from 64 to 1 MHz, a fiber coupled AOM was used. The driver of the AOM was electrically triggered by the signal from the oscillator and an average power of 0.5 mW at a repetition rate of 1 MHz was obtained at the output of the AOM. After the AOM, an amplifier stage consisting of a low-doping single-mode Yb fiber amplifier was used to increase the average power up to \(\sim 50\) mW. The pump source was also an SMF coupled, wavelength-stabilized laser diode at 976 nm. This amplifier stage was followed by another, which was comprised of a 2-m-long Yb-doped double-clad fiber (DCF) with a core diameter of 10 \(\mu\)m and a cladding diameter of 125 \(\mu\)m that was spliced to a combiner and pumped by a 100-\(\mu\)m-diameter multimode fiber coupled 10 W laser diode. After this third stage, the pulse energy was measured to be 100 mJ. The pulse from this amplifier was compressed using a Martinez-type pulse stretcher, which consisted of two gratings and brought the pulse duration back in the femtosecond region after amplification.
stage of amplification, the average pulse power was limited to 500 mW to avoid excessive gain narrowing, although several watts of average power could be obtained when the pump LD was set to its maximum.

To further increase the average power, fibers with a larger core diameter were used. A 1.5-m-long photonic crystal fiber (PCF) amplifier with a core diameter of 40 µm and cladding diameter of 200 µm was employed and pumped backwards by a 100-µm-diameter multimode fiber coupled 30 W laser diode with a 976 nm wavelength. An HWP was used to adjust the polarization state of the incident seed beam. The fiber was coiled with a coiling diameter of 40 cm to prevent bend loss and to obtain a good beam quality. When the pumping power was 25 W, an average power of 14 W was obtained after the isolator. The polarization extinction ratio (PER) was measured to be as high as 95%. The final stage of amplification was carried out by a straight 55-cm-long rod fiber, which featured a low numerical aperture (NA) of 0.02 for the signal, a mode field area of ~4500 µm², and a very high absorption coefficient of ~30 dB/m. To control the working temperature, the rod fiber was placed in a water cooled copper heat sink. The rod fiber was pumped backwards by a laser diode, centered at 976 nm, which provided up to 350 W of pumping power, coupled to a fiber with a core diameter of 400 µm and a NA of 0.22. Another HWP was used to adjust the polarization state of the incident seed beam. Figure 2 shows the power performance of the rod fiber laser. With an incident seed laser power of 13 W, more than 120 W average power was obtained from the rod fiber when it was backward pumped with ~200 W. The optical-to-optical efficiency was in excess of 60%. The PER was measured to be 99%, so the output was almost entirely linearly polarized, which can be attributed to the rectilinear placement and the polarization-maintaining characteristics of the fiber itself. To compress the laser pulse back down to femtosecond levels, the laser beam was directed to a pulse compressor. The compressor included a small-scale transmission grating (40 × 40 mm²), a large scale transmission grating (180 × 40 mm²), and a roof mirror. The distance between the two gratings was set around 1.5 m. More than 100 W of average power was obtained after the compressor, which corresponded to a compressor efficiency of ~85%. Figure 3 shows the optical spectra recorded after different amplification stages. Only minor gain narrowing effects are visible. This could be attributed to the distribution of the amplification gain over multiple stages of amplifiers. The gain was approximately 10 for each stage. The spectrum bandwidth was approximately 10 nm after the rod fiber amplifier. The fine structures visible in the spectrum were attributed to nonlinearities occurring in the amplifiers. The pulse duration was characterized by SHG-FROG. The results, as displayed in Fig. 4, indicate the pulse intensity and phase as a function of time. From the intensity spectrum, at full-width half-maximum (FWHM), the pulse duration was ~270 fs. This corresponds to a peak power of 0.37 GW if a pulse energy of 100 µJ is considered. Supposing a focused beam radius of 20 µm was used, a peak intensity of 3 × 10^{13} W/cm² could be obtained, which is sufficiently high to drive the HHG process. The spectrum bandwidth of 10 nm could support pulse durations as short as ~150 fs and the discrepancy between this value and the measured one of 270 fs was ascribed to uncompensated third order dispersions. Shorter pulse durations could be expected by adjusting the incident angle of the beam onto the grating, however, this would come at the expense of the compressor efficiency.

When a VUV laser based on HHG is used in spectroscopy experiments, especially in angle-resolved photoemission spectroscopy (ARPES), long-term continuous operation is desirable, which in turn requires the driving laser to operate stably over extended periods of time. The long-term stability of the laser system was therefore characterized. Figure 5 shows the measured output power of the rod fiber amplifier over a period of two hours. The output power was maintained at 116 W over a 2 h period with a standard deviation of 0.3 W, representing a significantly low fluctuation level. The inset of Fig. 5 is the beam profile taken after two hours of operation. There was almost no change between this and the one.
acquired at the start of the experiment. The two stress rods of the rod fiber are visible in the beam profiles, as evidenced by the two light-colored regions.

The laser system was capable of producing even higher output powers. At 330 W of pump power, 200 W of output power was obtained, however, the beam profile was distorted due to the onset of the transverse mode instability, which could be attributed to the remaining population inversion at the edge of the fiber core when the pumping power is higher than the threshold for the instability mode. While this kind of phenomenon has been observed in both ordinary DCFs and PCFs, the threshold in fibers without a PCF structure was found to be higher than that of fibers with a PCF structure.\(^{11}\) Large pitch PCFs and preferential gain PCFs have been created to increase this threshold to 300 W.\(^{21,22}\) For the type of rod fiber used here, the threshold was measured to be approximately 160 W\(^{26}\) and an output power of up to 150 W was achieved while maintaining a single transverse mode of operation. To preserve the lifetime of the fiber, the system was operated so that the output power after the rod fiber was limited to 120 W.

In conclusion, a 100-W-level rod-fiber-based femtosecond CPA laser system with a repetition rate of 1 MHz, corresponding to a pulse energy of 100 µJ, was developed. Special large-scale transmission gratings were used for pulse compression and stretching, leading to an efficiency of 85% for the compression. The pulse duration was measured to be \(~270\) fs using SHG-FROG. We believe this laser system to be suitable for carrying out HHG experiments and obtaining VUV radiation, which could subsequently be used for photoelectron spectroscopy experiments.

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