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Author
Pham, Hoang Mai Diem

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Review of Efficient Generation of Ultra-intense Few-cycle Radially Polarized Laser Pulses

Hoang Mai Diem Pham, *UCLA Electrical Engineering Student.*

ABSTRACT

Ultra-intense few-cycle laser sources have been a widely studied topic because of their high applicability related to relativistic energies. The chirped pulse amplification is a well-known traditional technology that was used to generate intense laser pulses. However, the generated laser was linearly polarized and it has long output duration. The limitations of this model led to the introduction of improved models that could achieve higher efficiency for the generation of high-energy, few-cycle radially polarized laser sources. One of the advanced technologies presented in this review is a scheme using Ti:Sapphire laser as a source, letting this laser go through a pressure gradient hollow-waveguide compressor, then passing the output through the broadband polarization-state converter. The result of this experiment is excellent when peak power levels can reach over 85 GW with the shortest duration reported at that time.

I. INTRODUCTION

Currently, the radially polarized beam is used in many applications, such as materials processing, optical communication, micromachining, particle trapping and acceleration, nonlinear optics, optical data storage, super-resolution imaging applications. The radially polarized beam has axial symmetry. Since the electric fields at all positions are in phase, the electric fields point towards the center or point outward from the center of the optical beam. Compared to other forms of polarization such as linear polarization, ellipse polarization, or circular polarization, the beam with radial polarization has more advantages. The unique distribution property of radial polarization produces a smaller size of the focal spot. The transverse components of the electric field destructively interfere, and we can observe extremely intense longitudinal components. There are many ways to generate a radially polarized beam. We can simply use a laser, or optical interference, or propagation through a conical Brewster prism, or divided waveplates. Specifically, for the generation of few-cycle radially polarized pulses with high energy, some experiments have been demonstrated such as optical parametric CPA (OPCPA), thin-film compressors (TFC), femtosecond filamentation in noble gas, and the hollow core fiber (HCF) compressor filled with noble gas [1]. This paper reviews the method that produces pulses by spectral broadening, and conversion of polarization modes.

II. METHOD

The method of producing high-energy, few-cycle pulses can be divided into two phases. The scheme is shown in Fig.1.

In the first phase, the scheme consists of a pressure gradient hollow-waveguide and a compressor. As in many other successful experiments, the Ti:Sapphire laser is used to provide stable, short, and ultra-intense pulses. Pulses are linearly polarized with the energy of 1.5 mJ at a 3 kHz repetition rate. The bandwidth is 35 nm, and the wavelength is 800 nm. The dielectric hollow waveguide is 1 m long. Its inner diameter is 500 μm and its outer diameter is 2 mm. The Ar gas is injected at the end of the waveguide, and it moves slowly with the constant laminar flow. The Ar gas will travel backward along the waveguide to the start point of the waveguide and flow out here. The pressure of Ar at this part is 0.15 Torr. The input pulses propagate in the opposite direction of the Ar flow. The spectral broadening is done inside this hollow waveguide by the self-phase modulation and group-delay dispersion. The spectral broadening can be maximized because the core radius is relatively large to the laser wavelength, and the pressure is reduced. The pulses that exit the waveguide is in broadened fundamental mode. After that, the pulses will go through a compressor.

In the second phase, the polarization mode converter is used to transform a linear polarization into a radial polarization. To avoid some disadvantages, such as the requirement to have a sufficient large waveguide core radius, high propagation losses, low energy, low coupling efficiency, the experiment applies an eight segmented achromatic waveplate for the converter. The waveplate has different birefringence rotation axis at ±11.25°, ±37.75°, ±56.25°, and ±78.75° angles. After converting to radially polarized mode, the pulses are compressed again down to 8 fs.

III. RESULTS AND DISCUSSION

For the first phase, the experiment gets a good result. The measured efficiency of the broadened output is 60%, which is approximate to the maximum reported efficiency, 68%. There are some reasons that contribute to this loss. First, the loss perhaps comes from the waveguide attenuation. The power of pulses decreases along with the laser propagation because of the

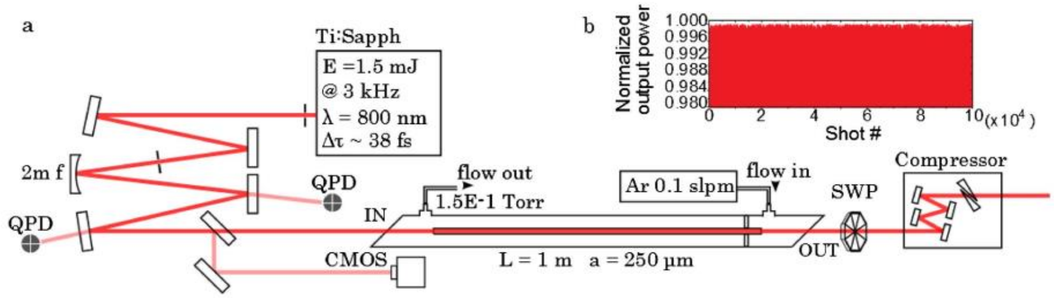

Fig. 1. a, schematic layout of the pressure gradient hollow-waveguide compressor setup and the polarization modeconverter. Ar gas is laminarly flown in the counterpropagating direction of the laser beam. b, short-term output intensity fluctuations over more than 3 s accounting for <0.5% over the average intensity value due to active pointing stabilization of the input beam. For optimum alignment, the fluctuations are comparable to the those inherent to the Ti:sapphire amplifier system [2].

waveguide material or design. The long waveguide has an exponential increase in power attenuation. Therefore, it is important to keep a short transmission. The second reason is the mode-coupling efficiency. This efficiency can be improved by considering some factors such as Gaussian intensity profile, normal incidence, beam waist diameter, or the light source should match with the characteristic of the waveguide. Third, we should maintain a high quality factor Q to increase the pulses' energy. Last, the mode EH_{11} has the lowest leakage and highly efficient coupling to a laser beam, so the energy in this fundamental mode relative to the total energy can affect the spectral broadening efficiency. The high efficiency in spectral broadening is an indicator of high intensity and spectral stability. The normalized output power of the hollow waveguide is shown in Fig.1 b. The stability is observed for both short term and long term. The inconstancy in short term is reported less than 0.5% rms of the output intensity. After being temporarily compressed, the pulses outputted from the compressor have a throughput of 86%.

For the second phase, the segmented achromatic waveplate is an interesting and feasible technique for the experiment but it was not explained in detail in the original paper. Therefore, it is difficult for readers to visualize its structure as well as the way it works. The segmented achromatic waveplate is a kind of simple and robust retarder that can be considered as a "continuous" device, so that it performs an excellent efficiency in the mode conversion and "does not require an additional mode cleaning Fabry–Perot interferometer"[3]. As mentioned in the method part, this experiment uses eight sectors $\lambda/2 \pm 2\%$ with eight different orientations of axis. When the broadened pulses pass through this segmented achromatic waveplate, in each segment, the polarization vector will turn to different angle. The polarization distribution at the output of this device has a form of radial polarization. The specific result of this step is that we can observe high spatial quality and high radial polarization purity (exceed 93%) at 0°, ±45°, and 90° axes.

On the whole, the final result we get from the experiment is radially polarized laser with a short duration (approximate 3 cycles), and the high peak and average power levels (85 GW and 2 W, respectively).

There is another thing that I want to comment on the original paper is the consistency of the value of the laser energy, which confuses the audience. The paper stated that "The drive laser (Coherent Legend Elite Duo USP) generates linearly polarized, up to 5 mJ pulses … centered at 800 nm wavelength [Fig. 1]." However, in the figure 1, it is shown that the energy is 1.5 mJ. In the next paragraph, the authors mentioned again about the value of energy, which is 1.5 mJ, so I think but not be sure, the actual value of energy used in the experiment is 1.5 mJ.

IV. CONCLUSION

In conclusion, the experiment was done based on a simple and effective method to successfully generate high-energy, few-cycle radially polarized pulses. In addition, the authors introduced the segmented achromatic waveplate technique to overcome the disadvantages of the linear-to-radial polarization mode converter. Although the article is limited in visualizing the segmented achromatic waveplate method, the authors attached a schematic layout as well as graphs and images of the outcomes to help readers have a better understanding. The excellent result of this research is the premise to work on radially polarized pulses with higher intensities and shorter duration. The technology used in this article can be applied to emerging applications such as vacuum electron acceleration to relativistic energies.

V. REFERENCES

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