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Optimizing the optical throughput of a neon-filled hollow-core fiber for ultra-broadband sub-5 fs pulses

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In this work, new optimization conditions to increasing the optical throughput of neon-filled hollow-core fiber for very broad optical bandwidth and reach extremely-short laser pulses are represented. In the used method, seed pulses from a Ti:sapphire mode locked laser of 18 fs pulses with energy 5 nJ/pulse were injected into a chirped pulse amplifier (CPA) to reach 2.6 mJ per pulse. By controlling the CPA compressor, the output pulses were tuned from 32 – 56 fs. These pulses were used to generate supercontinuum spectra through nonlinear interaction with neon gas filled hollow-fiber by self-phase modulation. The generated output pulses from the fiber were compressed using chirped mirrors to perform dispersion compensation. The observed results reveal that, the output of the fiber can be tuned from about 12 to 94 THz by varying the chirping of input pulses at different pressure of the neon gas. Under optimum conditions of broadband-width at 94 THz, the generated pulses reached the shortest possible time duration of 4.86 fs. The observed results can give an opportunity to control the progression of strong-electric-field interactions on the ultrafast time scale and can be applied to regenerate attosecond pulses in the deep ultraviolet range.

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1. Introduction

Recently a great progress has been announced in developing ultrafast laser systems for few optical cycle pulses in the near IR [1]. Nevertheless, for many novel applications, such as the study of ultrafast molecular dynamics in femtochemistry, ultrashort pulses in the UV-VIS optical range with high energies are needed [2]. Extending the spectral range of the ultrashort pulses to broadband is essential to investigate transient chemical processes where many molecular transition states have typical absorption bands [3]. In the past, high harmonics generated by frequency mixing near IR and VIS spectral range in nonlinear crystals was used to create ultrafast pulses in the UV[4]. Unfortunately, the observed pulses are often influenced by the seed pulse fluctuations. Furthermore, these laser schemes experience from difficulty of the tuning routine that is typical for application of two successive cascaded nonlinear procedures [5].

On the other hand, the complexity of time consideration itself includes the exact determination of the extremely short-time periods by means of frequency standards. So, the developments of femtosecond laser ensure remarkable attainments in the field of generation of laser frequency standards and the field of determinations of ultra-short time periods. It is important to notice that, further decreasing of pulse durations causes a huge increase in the laser peak power which can be applied for several ultrafast-phenomenon investigates [6]. These experiments comprise the generation of high harmonics [7], femtosecond-chemistry applications [8], and creation coherent UV sources in the attosecond regime[9]. Furthermore, the generation of these ultrashort pulses with extremely high intensities and spectral monochromasy of has enabled a new category of highly-resolved spectroscopic systems, which allows to investigate the detailed structures of complicated molecules [10].

Usually, the modern broadband laser systems include Ti:sapphire laser system [11] followed by a chirped-pulse amplification (CPA) technique [12]. Further, the introduction of broadband-chirped-multilayer mirrors in femtosecond lasers have allowed for ultrafast laser pulses with broadband dispersion control and exceptional high power levels [13]. The development of laser system to reach shortest possible pulse duration has started since the invention of laser four decades ago. One of the most reliable systems with ultrashort laser pulses has been introduced by Malcolm G. et al. in 1990, they used an additive-pulse mode locking of a diode-pumped Nd: YLF laser to attain short pulse duration of 0.5 picoseconds [14]. In 2007, Nurhuda M., et al. achieved sub-10 femtosecond laser pulses with high power levels by optimization of hollow fiber pulse compression using pressure gradients pulse compression [15]. Then Adachi S., et al. group tried to reach shorter durations by parametric chirped-pulse amplification system at 1 kHz to generate pulses as short as 6.4 fs at the 1.5 mJ at 1 kHz repetition rates[16]. In 2015, Hermance J. et al. group generated few-cycle duration of 6 fs with 0.6 mJ energy in a gas-filled hollow fiber [17]. In this scheme, the hollow fiber technique depends on self-phase modulation (SPM) that causes spectral broadening of the input pulses by supercontinuum generation [18]. Then, the output of the fiber is followed by dispersive elements for chirp compensation. Good spectral phases and high quality spectral profiles are needed to enable compression of the output pulses. They have observed output pulse energies limited to 600 mJ over a wide spectral range 650–950 nm [17].

In the current paper, experimental conditions to enhance the throughput optical bandwidth of the used optical fiber up to ~ 94 THz for the shorts possible pulse duration of 4.86 fs have been reported. Moreover, the applied method can be used to control the bandwidth and pulse duration by tuning the fiber-seeded pulses at different neon gas pressures.

2. Experimental setup

A diagram for the used setup to enhance the optical fiber throughput spectral bandwidth for ultrashort pluses is shown in Fig. 1. In this schematic, an 18 fs mode-locked Ti: sapphire of at 800 nm with average power of 400 mW at repetition rate 75 MHz was used to create a femtosecond seed beam. The construction of the seed laser system composed of a 4 W CW solid-state DPSS laser Opus (Laser Quantum) which is used to pump the Ti:Sapphire laser. It also contains two pump beam mirrors to direct the 532 nm beam into the Ti:Sapphire, a focusing lens to focus the pump light into the laser rod, a pair of concave spherical mirrors aligned with the Ti: sapphire laser rod, folded cavity mirrors, an output coupler, a pair prisms with a slit in between were used for dispersion compensation while by moving the slit up-down the output can be tuned from 780 - 820 nm. Then the seed beam was injected into an amplification stage using a chirped pulse amplification (CPA) at repetition rate one kilohertz. This amplifier produced a beam of 32 fs pulses at 800 nm and average power of 2.6 W. For preventing thermal destructive of the gain optics, a stretcher was used to expand out the seed pulses temporally and spectrally that decreases the pulse peak power level before that CPA amplification optics. The stretcher contains a highly dispersive optics composed of a couple of mirrors to direct the beam to a large diffraction grating and a telescope lenses to expand the beam followed by a spherical mirror and a flat mirror with broadband dielectric coatings. Then the that beam was injected into the CPA amplifier using a Faraday rotator which was used to separate input and output pulses. The CPA was pumped with a diode-pumped Nd:YLF Q-switched 527 nm green pulses of 170 ns with energy of 20 mJ at a repetition rate of 1 kHz (model DM20-527 , Photonics Industries). The regenerative amplifier CPA contains multiple passes gain medium with an optical switch for controlling the number of round trips inside the cavity which allows for a high gain. The optical switch composed of a quarter-wave plate, a Pockels cell, and a polarizer. The Faraday rotator is a passive optical device with a magneto-optic material for changing the beam polarization from horizontal to vertical in the forward direction by flipping the plane of the polarized light 45°. Then, the stretched beam was injected into a regenerative amplifier at proper synchronized times using Pockels cell as an optical switch. The energy of these pulses reach a maximum value of about 3 mJ after sufficient numbers of resonator round trips. Then a second Pockels cell was used as an optical switch to control the formed high energy pulses after the regenerative amplifier. A short bell-shaped high voltage electric pulses was used to synchronize the Pockels cell opening times. After the regenerative amplifier, the amplified pulses are then compressed back to femtosecond regime using a compressor composed of a "roof" mirror assembly, a diffraction grating, and an output flat-mirror. After the CPA stage, the amplified laser pulses of duration 32 fs reach energy of 2.6 mJ at 1 kHz.

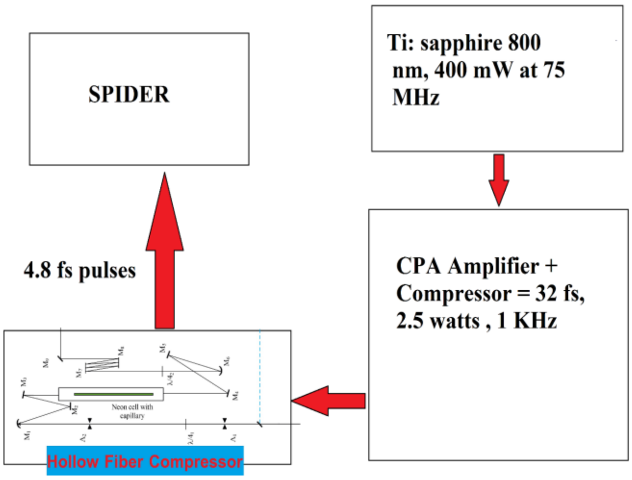

Fig. 1. Setup for the generator of 4.8 fs optical pluses.

In this setup, to reach extremely short pulse durations, the laser pulses are spectrally broadened in a neon gas contained within a long (1 meter, 250 µm inner diameter) hollow-fiber, which represents a dielectric waveguide for the light. The long fiber allows for considerably longer interaction lengths than conventional unguided interactions. While the intense femtosecond laser beam propagates through the neon gas in the fiber, it induces continuum generation due primarily to SPM which causes supercontinuum in the neon gas at different pressure values from 2.0 to 2.5 atm. To maximize energy throughput, it is important to well couple the beam into the fiber. This is attained by carefully matching the focal spot of the laser beam to the guided mode of the optical fiber. Finally, the output beam from the fiber is collimated using a concave mirror and then temporally compressed again with chirped-mirrors though six beam passes to achieve the shortest possible pulse duration, the output pulse energies were found to reach 600 mJ.

3. Results and discussion

To attain the shortest possible pulse duration with broad spectral bandwidth, both of the seeded and amplified pulses should be optimized. For the seeded beam, the pulses were optimized in mode-locked at 800 nm with pulse energy of 5nJ and duration of 18 fs. Fig. (2) demonstrates the CPA output beam bandwidth of about 18.95 THz fundamental-width at half maximum (FWHM) measured for a pulse which starts at 350 THz and ends at 400 THz. These measurements were done using spectral phase interferometry for direct electric field reconstruction (SPIDER) where S is the signal intensity in arbitrary unites. Meanwhile, the beam output from CPA can be chirped in the compressor stage by varying the separation distance between the diffraction gratings, the output pulses were tuned from 32 – 56 fs. The 2.6 mJ CPA amplified pulses have average power of 2.6 watts at repetition rate of 1 kHz as mentioned before. The restriction of pulse compression in this stage is because of the limitation of the bandwidth of the used laser gain at the CPA which found to be 18.95 THz. So that these femtosecond pulses were introduced into a hollow-fiber filled with neon gas to be expanded by self-phase modulation in a nonlinear gas medium to achieve more pulse compression in the few-cycle regime. The properties of the observed output ultrafast pulses are influenced by many factors include the nonlinear phase shift due to SPM in the neon gas, the pressure values of the neon gas, and the pulse width of the input pulse before the fiber. This is important specially in case of measuring the lower possible pulse duration for a given optical spectrum, which called the Fourier transform limit of a pulse or commonly “transform limited pulse” [19]. The condition of being at the transform limit is basically corresponding to the condition of a frequency-independent spectral phase, and essentially indicates that the time–bandwidth-product (TBP) is at its lowest value and that there is no chirp. So that, for an unchirped optical pulse, the transform limited and the bandwidth of that pulse are determined according to[20] $TBP = \Delta\upsilon\,\Delta$ where Δ is the full width at half maximum of the spectral bandwidth of the pulse and Δ is the full width at half maximum of the pulse duration. For Gaussian pulse profile, the TBP value should be ≈ 0.44 [20]

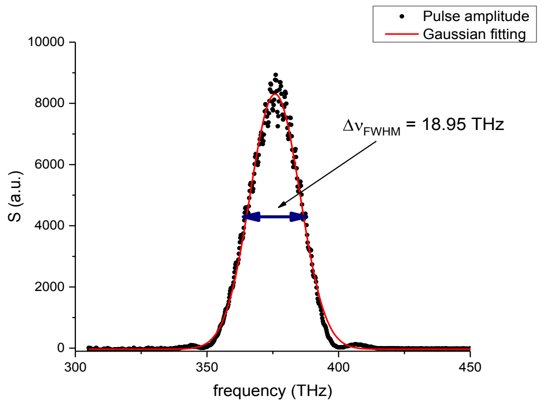

Fig.2 Spectral bandwidth of the CPA femtosecond laser beam.

Figs. 3-6, represent bandwidth broadening of the observed pulse and its corresponding pulse duration for different input pulse durations under different gas pressures. Fig. 3, reveals the output pulse spectral bandwidth broadening at the full-width-half-maximum with the corresponding pulse duration for the input pulse durations of 32 fs, 40 fs and 56 fs, respectively, using neon gas at pressure 1.8 atm. In this figure the bandwidth values are 12.12, 13.35 and 28.71 THz with pulse duration 9.64, 9.63, and 9.61 fs which are corresponding to TBP values of 0.116, 0.128 and 0.275 respectively. From the observed TBP values, it is implied that these conditions are far from the transform limit conditions so that the bandwidth values are very limited.

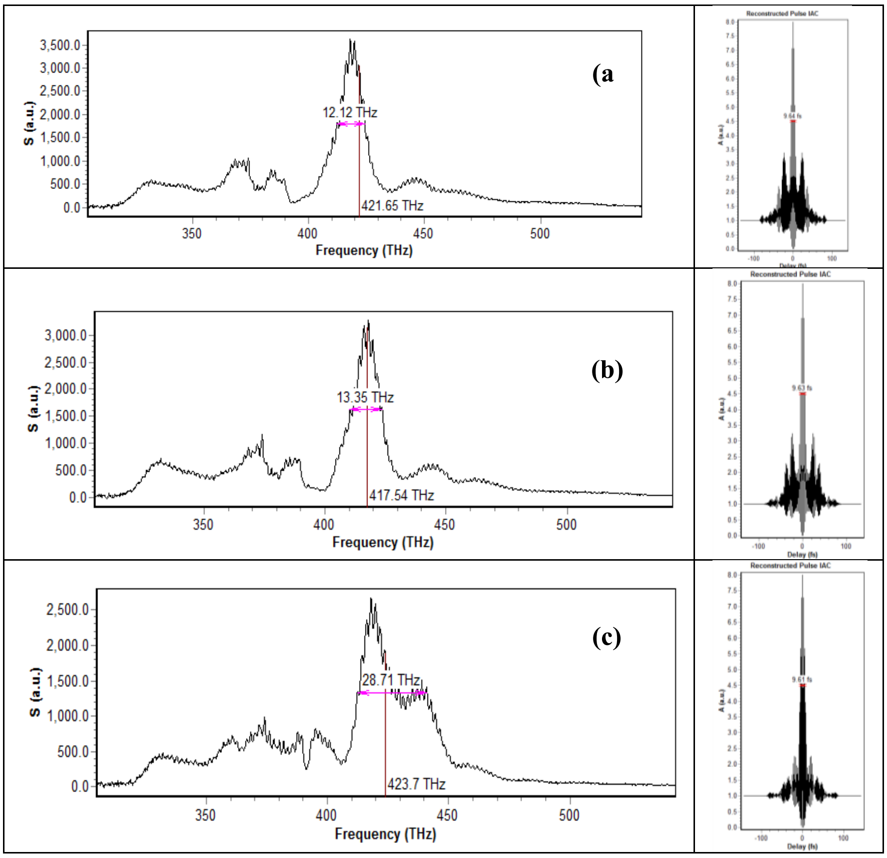

Fig 3. the output pulse spectral bandwidth broadening at the full-width-half-maximum (FWHM) (left) with the corresponding pulse duration (right) for the input pulse durations of (a) 32 fs; (b) 40 fs; (c) 56 fs using neon gas at pressure 1.8 atm.

Fig. 4, explores the output pulse spectral bandwidth broadening at the full-width-half-maximum with the corresponding pulse duration for the input pulse durations of 32 fs, 40 fs and 56 fs, respectively, using neon gas at pressure 2.0 atm. In this figure the bandwidth values are 41.25, 46.64 and 65.63 THz with pulse duration 9.87, 9.84, and 9.57 fs which are corresponding to TBP values of 0.407, 0.442 and 0.628 respectively. From the observed TBP values, it is inferred that these conditions are near to the transform limit conditions so that the bandwidth are wider than the previous case of 1.8 atm.

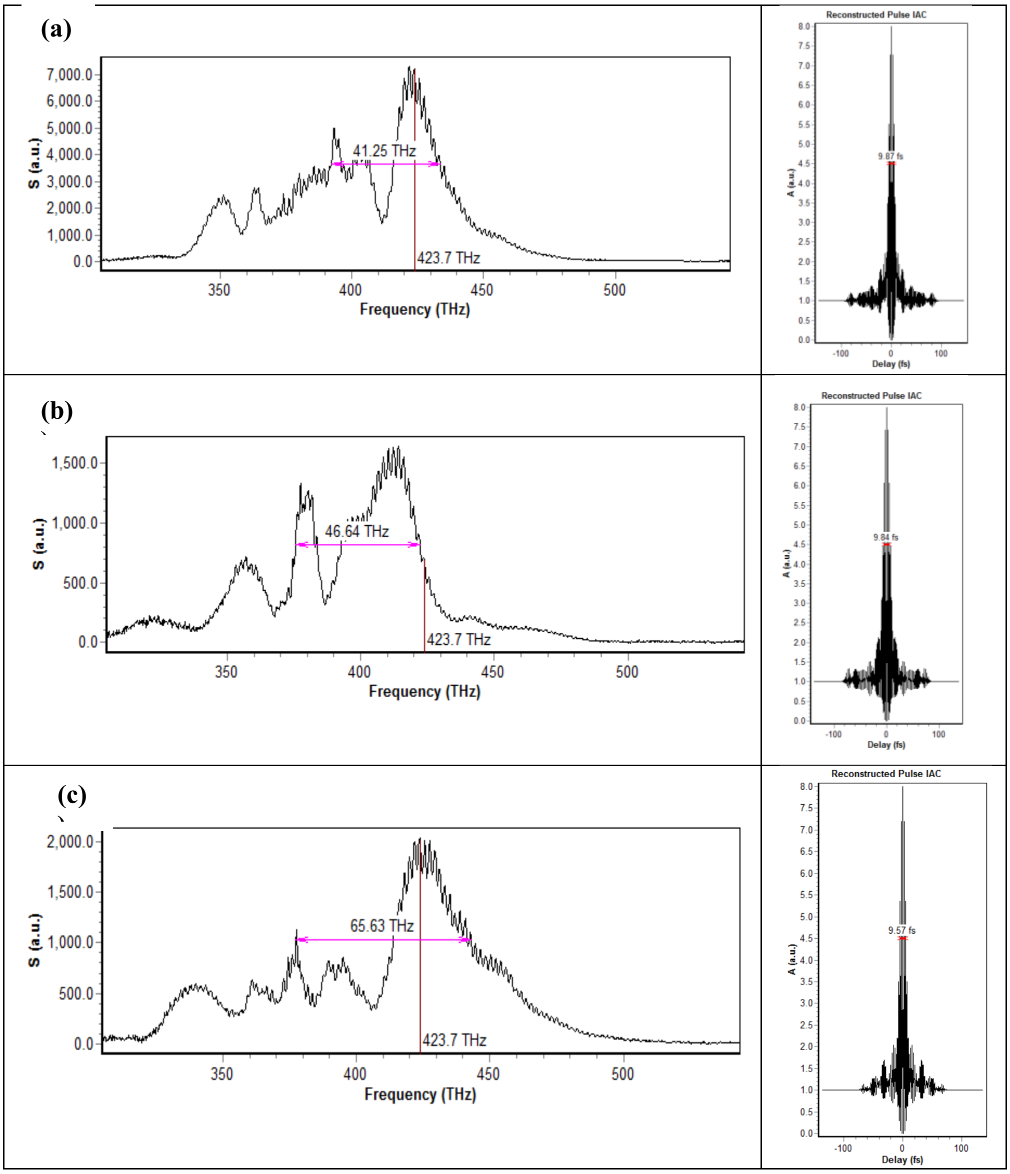

Fig 4. the output pulse spectral bandwidth broadening at the full-width-half-maximum (FWHM) (left) with the corresponding pulse duration (right) for the input pulse durations of (a) 32 fs; (b) 40 fs; (c) 56 fs using neon gas at pressure 2.0 atm.

Fig. 5, represents the output pulse spectral bandwidth broadening at the full-width-half-maximum with the corresponding pulse duration for the input pulse durations of 32 fs, 40 fs and 56 fs, respectively, using neon gas at pressure 2.25 atm. In this figure the bandwidth values are 92, 72.43 and 80.52 THz with pulse duration 10.39, 10.15, and 5.56 fs which are corresponding to TBP values of 0.955, 0.735 and 0.447 respectively. From the observed TBP values, it is concluded that these conditions are also near to the transform limit conditions, especially for the case of pulse duration 5.56 fs and bandwidth 80.52 THz. In the following step, the maximum possible neon pressure will be applied to find out more enhancement.

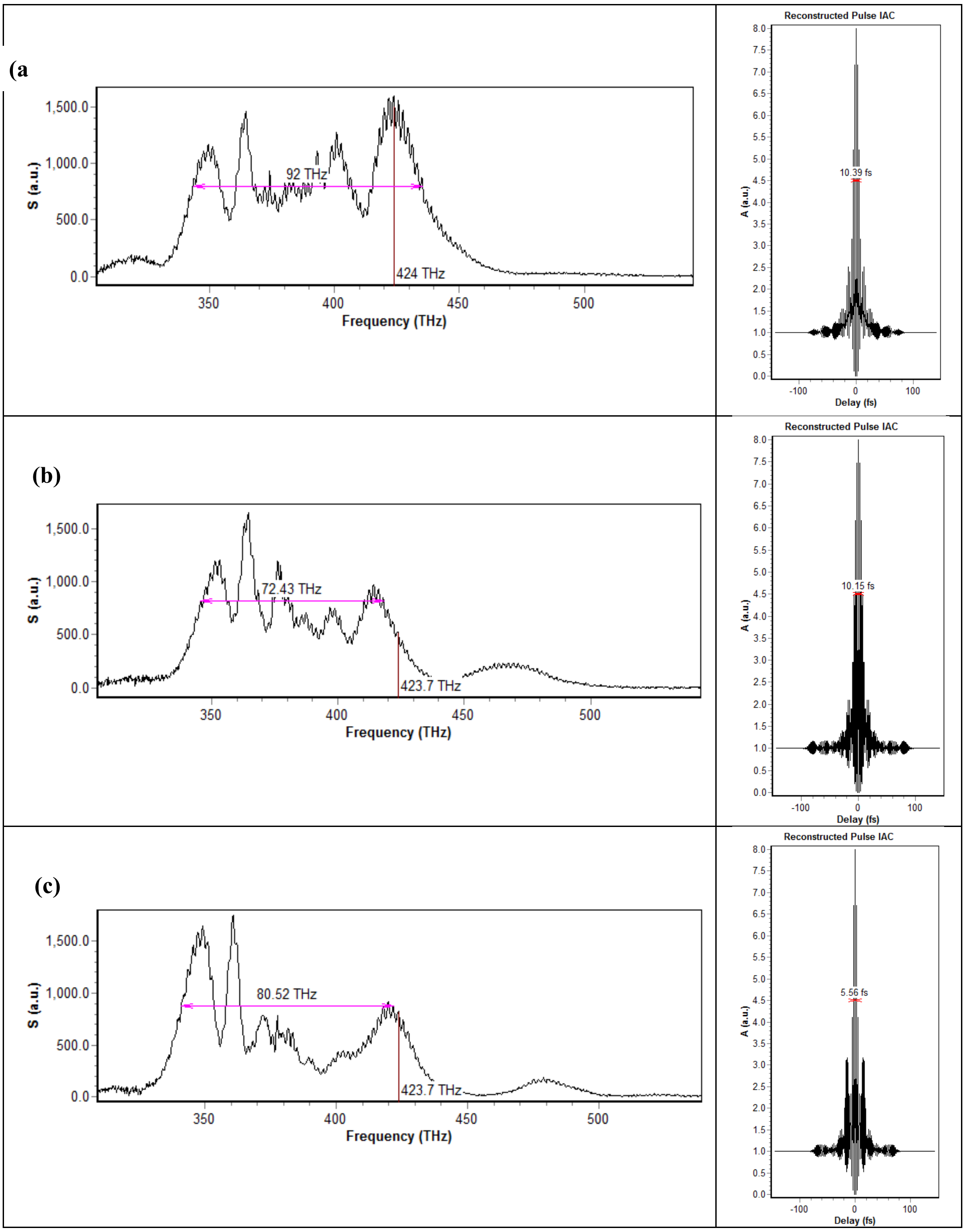

Fig 5. the output pulse spectral bandwidth broadening at the full-width-half-maximum (FWHM) (left) with the corresponding pulse duration (right) for the input pulse durations of (a) 32 fs; (b) 40 fs; (c) 56 fs using neon gas at pressure 2.25 atm.

Fig. 6, shows the output pulse spectral bandwidth broadening at the full-width-half-maximum with the corresponding pulse duration for the input pulse durations of 32 fs, 40 fs and 56 fs, respectively, using neon gas at pressure 2.5 atm. In this figure the bandwidth values are 99.34, 85.16 and 93.96 THz with pulse duration 9.43, 5.37, and 4.86 fs which are corresponding to TBP values of 0.936, 0.457 and 0.456 respectively. From the observed TBP values, it is concluded that these conditions are also near to the transform limit conditions, especially for the case of pulse duration 4.86 fs and bandwidth 93.96 THz. Under the applied conditions, the shorts possible pulse duration is reached and fulfilled the transform limited pulse conditions. The observed pulse duration values of 4.86 fs is shorter than previously observed value of 6 f for similar energy and spectral broadening [17]. The observed results show a noticeable development in the field of ultrashort pulses using a direct method to obtain wide broadband extremely short pulses in comparison with other more complicated recent approach [21].

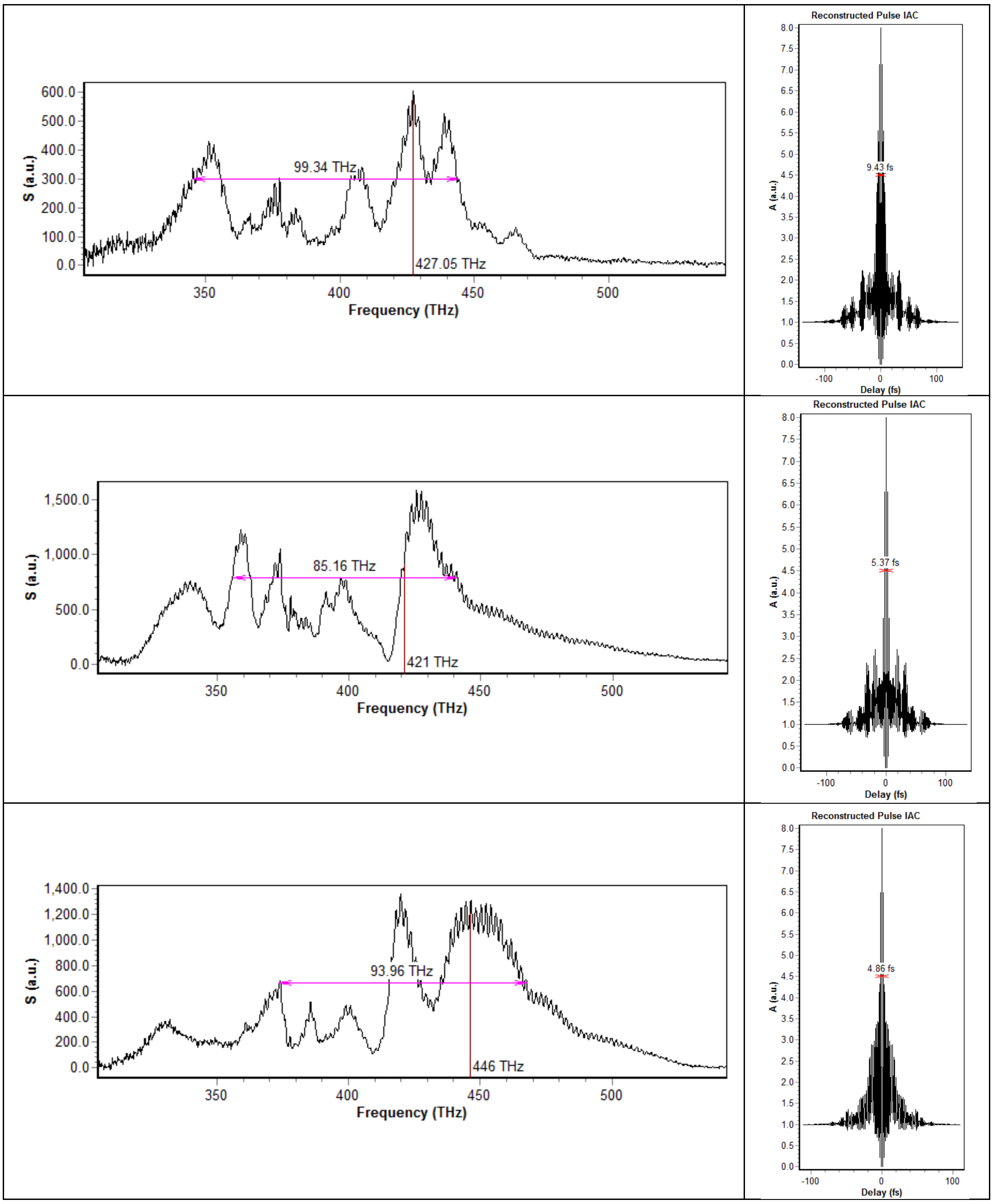

Fig 6. the output pulse spectral bandwidth broadening at the full-width-half-maximum (FWHM) (left) with the corresponding pulse duration (right) for the input pulse durations of (a) 32 fs; (b) 40 fs; (c) 56 fs using neon gas at pressure 2.5 atm.

4. Conclusion

In conclusion, by applying optimized experimental conditions the optical throughput of the hollow-fiber is improved. The applied method generates ultrafast pulses of 4.86 fs with bandwidth of about 94 THz. The injected pulses to the fiber input was 56 fs with bandwidth of about 18.95 THz. By comparing the input and the output bandwidths, it is concluded that the throughput enhancement reaches about five-octave-wide extending from 360 - 455 THz. This scheme represents a relatively simple and direct method to produce 4.86 fs which is short compare to recent complicated technique to observe 6 fs ultrafast pulses with similar bandwidth and pulse energies. The observed results are important to create attosecond pulses to investigate the dynamics of photo-transient complex processes in molecular biology.

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