Demonstration of All-Fiber Pulse Compression Using Hollow Core Photonic Crystal Fibers

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Abstract

Hollow-core photonic crystal fibers (HC-PCF) are used for high power beam delivery and can deliver ultra-short or compressed pulses at 1550 nm. This paper study the relation between the length of (9 &7) cell HC-PCFs and the full width at half maximum (FWHM) using laser source with centroid wavelength of 1546.7 nm, i.e. almost 1550nm, and FWHM of 286 pm or 10 ns in the time domain. The FWHM in the frequency domain was increased in both (19 &7) cell HC-PCFs as the length of Fabry-Perot interferometer increased till it reaches a specific length and then dramatically decreased to go to the almost same starting point.

Keywords: Hollow-Core Photonic Crystal Fiber, FWHM, Pulse compression, the compression factor

I. Introduction

Generation of ultra-short pulses (USPs) has attracted much interest amongst researchers owing to the fact that these pulses find potential applications in various fields of science, engineering and medicine [I–III]. Although semiconductor lasers can today provide pulses as short as a few femtoseconds, the ultimate stability of the pulse is guaranteed only by pulse compression techniques and, more precisely, by techniques that depend on nonlinear phenomena [I-III]. The interest of the scientific community has been focused on the development of new technologies of light sources and applications based almost entirely in such kind of fibers. Several research groups have made important advances both experimentally and theoretically in the understanding of soliton compression and soliton formation as well as its dynamics in HC-PBGFs [IV-VI].
There are many techniques interested and used to compress the optical pulse as the amplitude passive modulation, the mode-locking, the intra-cavity saturation absorption-amplification [VII, VIII], the stimulated Raman backward scattering in plasma [IX], etc. The operating principle of all mentioned techniques is based on the nonlinearity in the optical medium under the interaction of the intense laser beam [X, XI, XII, XIII]. For instance, S. O. Aruba et al. are reported an adequate model to describe the evolution of the nonlinear envelope pulses in the ultra-short pulse regime (from ps to sub-ps) [XIV], G’er’ome et al. also reported the existence of soliton compression. They achieved output pulses of 90 fs from 195 fs input pulses by using 8 m of tapered fiber [XV, XVI].

In this paper, we intend to investigate the relation between the length of (19, 7) cell HC-PCFs and the FWHM at 1550 nm in exponentially decreasing dispersion and exponentially increasing nonlinearity. The 1550nm wavelength is chosen to the best of results because of the low-absorption characteristics of the silica material used in fibers.

The pulse compression is quantified by the compression factor defined by the relation described in equation bellow [XVII]

\[
\text{Compression factor (Fc)} = \frac{T_{FWHM_{l/p}}}{T_{FWHM_{o/p}}}
\]

Where \(T_{FWHM_{l/p}}\) and \(T_{FWHM_{o/p}}\) are the FWHM of input pulse and the FWHM output compressed pulse, respectively.

II. Experimental Setup and Operation Principle

The experimental setup mainly consists of two parts, the first part will depict the experiments involves about (HC 19-1550) PCF, and then in the second part, will investigate (HC-1550-02) PCF. The operation principles are the same in both main experiments, as shown in Figure (1) which represent a lab image of the setup. This setup consists of pulse laser, Erbium-Doped fiber amplifier (EDFA), Fabry-Perot interferometer (FPI), Polarization controller (PC), Optical spectrum analyzer (OSA), and Digital storage oscilloscope (OSC).

In this experiment, the pulse laser source emits light with a central wavelength of 1546.7 nm, peak power of 1229.27 μw and FWHM is 286.292 pm. The output of the laser source is amplified by EDFA. Then the amplified light is passed through polarization controller PC to change an arbitrary polarization to linear one and this is done by the stress which induced birefringence produced by wrapping the fiber around three spools to generate independent wave plates that will alter the polarization of the passing light in a single-mode fiber. The fast axis of the fiber is in the plane of the spool, allowing an arbitrary input polarization state to be adjusted by rotating the paddles, after polarization enhancement step, the enhanced signal then pass through the Fabry-Perot interferometer FPI, where FPI consists in first experiment of (HC 19-1550)PCF and in second experiment of (HC-1550-02), both PCFs are in between two pieces of single-
mode fiber. Finally, an OSA and OSC were used to visualize the outcomes of the experiment.

![Experimental Setup Image]

**Fig. 1 experimental setup.**

| Symbol | Description                                      | Symbol | Description                                      |
|--------|--------------------------------------------------|--------|--------------------------------------------------|
| PC     | Polarization Controller (PC)                     | EDFA   | Erbium Doped Fiber Amplifier                    |
| LD     | Electronic chopping circuit and continuous laser diode (LD) | DCF    | Dispersion Compensation Fiber                   |
| PS     | Personal computer as a power source              | OSA    | Optical Spectrum Analyzer                       |
| FPI    | Interferometer                                   | PD     | Photo Detector                                  |
| Thermometer | Thermostat                                      | OSC    | Digital storage oscilloscope                    |

**Schematic Diagram for Pulse Compression Based on (HC 19-1550) PCF**

Figure 2 represents a schematic of the pulse compression achieved by 19 cell HC-PCF in frequency and time domain.
Fig. 2 A schematic diagram for spatially and temporal visualize of 19 cell HC-PCF FPI.

Schematic diagram for Pulse Compression setup of (HC-1550-02) PCF.

Figure 3 represents a schematic for the pulse compression obtained by 7 cell HC-PCF in frequency and time domain.

Fig. 3 A schematic diagram for spatially and temporally visualize of 7 cell HC-PCF FPI.
III. Results

Results that involve about pulse compression Based on HC 19-1550 PCF.

The experimental results of the pulse compression setup shown in Figure 2 are depicted in Figures 4(a-d). Figure 4 (a-a1) shows the compressed pulse using 7 cm long of HC 19-1550 PCF, the FWHM of a compressed pulse of 117.26 pm was obtained. The compressed pulse with FWHM of 149.511 pm was achieved using 12 cm of PCF, as displayed in Figure 4(b-b1). When 20 cm and 30 cm of PCF were used, 209.27 pm and 117.78 pm FWHM of the compressed pulse were obtained as shown in Figure 4 (c-c1) and (d-d1), respectively.

Fig.4 Visualizing pulse compression of the length 7 cm FBI, a) Spatial light visualize by OSA, a1) Temporally light visualizing by oscilloscope.

Fig.4 Visualizing pulse compression of the length 12 cm FBI, b) Spatial light visualize by OSA, b1) temporally light visualizing by oscilloscope.
The results presented in Figure 3 are summarized in Table 1, to explore the related compression factor. As can be observed the shortest length of PCF gives the highest value of the compression factor, when 7 cm PCF length is used, a compression factor of 2.43 was obtained.
Table 1 relation between HC 19-1550 PCF length, FWHM and compression factor.

| Length of HC 19-1550 PCF (cm) | FWHM of the Source (pm) | FWHM of the compressed optical pulse (pm) | FWHM of the electrical pulse (ns) | Compression Factor Fc |
|-------------------------------|-------------------------|-------------------------------------------|----------------------------------|----------------------|
| 7                             | 286                     | 117.26                                    | 20                               | 2.43                 |
| 12                            | 286                     | 149.511                                   | 12                               | 1.91                 |
| 20                            | 286                     | 209.27                                    | 6                                | 1.36                 |
| 30                            | 286                     | 117.78                                    | 20                               | 2.42                 |

To explore the influence of PCF length on the FWHM of the compressed pulse and the related compression factor, Figure 5 (a) and (b) are plotted. It can be seen that as the length of PCF increases the FWHM of the compressed pulse increased until decrease dramatically with the maximum length of PFC (30 cm), as shown in Figure 5 (a). From Figure 5 (b), the compression factor decreases as the PCF length increases and rapidly increased at the maximum length of PFC (30 cm).

Fig.5 a) shows the relation between FWHM and $L_{pcf}$, b) shows the relation between Compression factor and $L_{pcf}$.
Results that involve about pulse compression using HC-1550-02PCF.

The experimental results of the pulse compression setup shown in Figure 2 (a&b) are depicted in Figures 6(a-d). Figure 6 (a-a1) shows the compressed pulse using 7 cm long of HC-1550-02 PCF, the FWHM of the compressed pulse of 119.384 pm was obtained. The compressed pulse with FWHM of 148.76 pm was achieved using 12 cm of PCF, as displayed in Figure 6 (b-b1). When 20 cm and 30 cm of PCF were used, 161.622 pm and 119.583 pm FWHM of the compressed pulse were obtained as shown in Figure 6(c-c1) and (d-d1), respectively.

Fig.6 Visualizing pulse compression of the length 7 cm FBI, a) is Spatial light visualize by OSA, a1) temporally light visualizing by oscilloscope.

Fig.6 Visualizing pulse compression of the length 12 cm FBI, b) is Spatial light visualize by OSA, b1) temporally light visualizing by oscilloscope.
The compressed signals presented in Figure 6 are summarized in Table 2, and to investigate the related compression factor. As can be observed the shortest length of PCF gives the highest value of the compression factor, when 7 cm PCF length is used, a compression factor of 2.39 was obtained.
Table 2 Relation between HC-1550-02 PCF length, FWHM and compression factor.

| Length of HC-1550-02 PCF (cm) | FWHM of the Source (pm) | FWHM of the optical pulse (pm) | FWHM of the electrical pulse (ns) | Compression Factor |
|-------------------------------|--------------------------|-------------------------------|----------------------------------|--------------------|
| 7                             | 286                      | 119.384                       | 16                               | 2.39               |
| 12                            | 286                      | 148.76                        | 12                               | 1.92               |
| 20                            | 286                      | 161.622                       | 8                                | 1.769              |
| 30                            | 286                      | 119.583                       | 16                               | 2.391              |

To explore the influence of PCF length on the FWHM of the compressed pulse and the related compression factor, Figure 7 (a) and (b) are plotted. It can be seen that as the length of PCF increases the FWHM of the compressed pulsed increased until decrease dramatically with the maximum length of PFC (30 cm), as shown in Figure 7 (a). From Figure 7 (b), the compression factor decreases as the PCF length increases and rapidly increased at the maximum length of PFC (30 cm).

![Fig.7 a) relation between FWHM and Length of FPI, b)relation between Compression factor and length of FPI.](image)

IV. Conclusion

The 19 cell HC-PCF or 19-1550 PCF gives better compression factor than 7 cell HC-PCF or H-1550 PCF, because of the silica to air ratio which is a larger ratio in 7 cell PCF. As the FWHM decrease in the frequency domain as it is increasing in the timedomain that occurs because there is an inverse relationship between frequency and time. The maximum compression factor
achieved in both fibers was in length of 7 cm. The average power was decreased in the compressed signal due to excitation of multi modes in the gladding region while the fundamental mode still exists in the core region. There was a periodical relation in the compression factor and length of the interferometer because we gather the same result of compression factor with different lengths.

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