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PASSIVELY STABLE PULSED OPTICAL TIMING DISTRIBUTION AT 1030-NM WAVELENGTH USING HOLLOW CORE OPTICAL FIBERS

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Abstract

Here, we experimentally demonstrate passively stable timing distribution of femtosecond pulses at 1030-nm center wavelength using sealed hollow core fibers without vacuum components. We have achieved a timing precision of 0.3 fs RMS from 1 Hz to 1 MHz and < 250 fs peak-to-peak for 12 hours with a hollow core fiber length of 72 m without requiring any transmission delay stabilization.

INTRODUCTION

High precision timing and synchronization plays a fundamental role in enabling scientific discovery and advancing our understanding of atomic scale interactions. In particular, new generation photon-science facilities such as X-ray free electron lasers [1] and intense laser beamlines [2] now enable femtosecond-level time resolved experiments [3]. This capability is made possible by their recently developed pulsed optical timing distribution systems, which actively stabilize fiber optic paths with precision better than 1 fs RMS [4].

Compared to free-space optics, fiber optic delivery offers advantages in flexibility, laser safety, ease of deployment and superior output beam quality. However, standard fibers with silica glass cores used in conventional pulsed timing distribution systems mostly operate at telecom wavelengths (1300 nm – 1570 nm). These fibers face challenges such as high dispersion, nonlinear pulse shaping and environmental sensitivity, leading to excess timing jitter [5]. In addition, the need for active delay stabilization of standard fibers, due to their excess sensitivity to temperature, adds complexity and cost to pulsed timing systems. Moreover, the emergence of high-power laser systems based on Yb-doped gain media with high efficiency has made pulsed operation at the 1030-nm center wavelength particularly appealing. However, a simple, all fiber pulsed timing distribution at this wavelength has not been implemented yet due to the absence of dispersion compensating fiber at 1030 nm.

Therefore, alternative fiber optic mediums are investigated delivering passive thermal stability, high nonlinearity threshold and opposite dispersion sign at 1030 nm [6]. For example, emerging anti-resonant hollow core fibers (HCF) that guide light though a central hole have significantly lower environmental sensitivity [7], high nonlinearity threshold and low dispersion, while achieving attenuation similar if not better than glass-core fibers [8]. This makes them an improved medium for low-noise transmission of femtosecond pulses with high peak powers.

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In particular, the dispersion of the HCF (typically 2 to 3 ps/nm/km) exhibits the opposite sign compared to that of standard silica-core fibers at 1030 nm (typically around -45 ps/nm/km), making it ideal for timing distribution applications at 1030 nm.

Here, we present experimental results demonstrating passively stable pulsed optical timing distribution at a center wavelength of 1030 nm, utilizing sealed hollow core fibers without vacuum components. Our findings indicate that a 72-m HCF introduces only 0.3 fs RMS of added timing jitter for offset frequencies from 1 Hz to 1 MHz, compared with its input pulse train. Moreover, the HCF exhibits a timing drift of less than 250 fs peak-to-peak (or less than 60 fs RMS) over a 12-hour period without any fiber delay stabilization. Additionally, the HCF demonstrates excellent polarization stability at its output, with an average deviation of less than 0.07 %, ensuring the polarization stability necessary for pulsed optical detectors.

EXPERIMENTAL SETUP

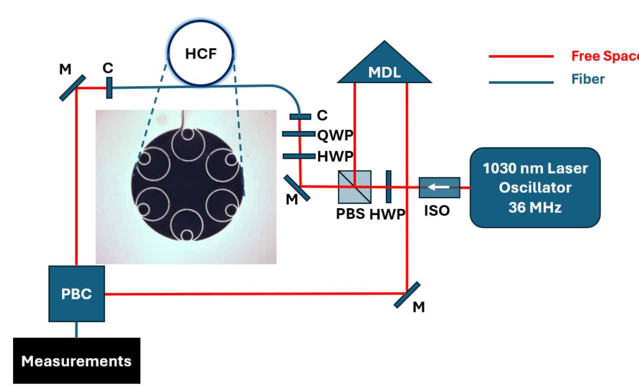

Figure 1: Block diagram of the experimental setup. ISO: isolator, HWP: half waveplate, QWP: quarter waveplate, PBS: polarizing beamsplitter, C: collimator, M: mirror; PBC: Polarization Beam Combiner, HCF: Hollow Core Fiber, MDL: motorized delay line. Inset: SEM image of the fiber microstructure.

The experimental setup is depicted in Figure 1. We used a mode-locked laser at 1030-nm center wavelength and ~36-MHz pulse repetition rate as the laser source for our experiments. An optical isolator was positioned following the Yb laser to mitigate parasitic backpropagations. The laser output was split into two arms: one short, free-space arm serving as “the reference arm”, and another long, fiber-coupled arm including a 72-m Nested Antiresonant

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Nodeless Hollow Core Fiber (NAN-HCF, Fig. 1 inset) serving as "the fiber distribution arm". Control over the power ratio between the reference and the fiber arms was achieved using a half waveplate (HWP) and a polarization beamsplitter cube.

In the reference arm, a motorized delay stage (MDL) allowed control over the relative time delay between the pulses. Subsequently, the light was directed to a polarization beam combiner (PBC) for recombination.

In the fiber distribution arm, an HWP and a quarter waveplate (QWP) were used to manage the input polarization of the fiber. The 72-m NAN-HCF had an attenuation of 0.55 dB/km at 1030 nm and a core size of 32 µm. It was spliced at both ends with a 2.5-m standard single mode fiber (SMF) having 2-dB splicing loss. This allowed easy interfacing with fiber-pigtailed collimators and also compensation for the first order dispersion. Following the propagation through the fiber, the pulses were recombined with the reference arm via the PBC.

In this way, the setup allowed polarization management, precise control over relative time-delay and dispersion compensation for accurate timing measurements.

EXPERIMENTAL RESULTS

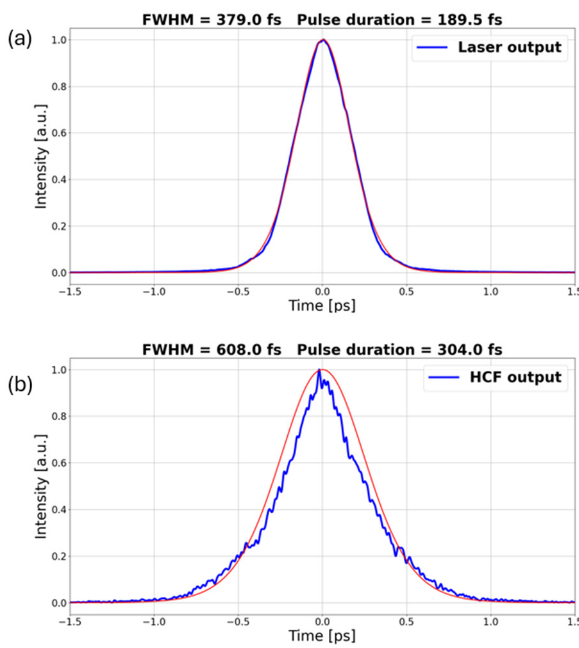

Figure 2: Autocorrelation traces of the 1030-nm laser beam at the input (a) and output (b) of the HCF.

Figure 2 illustrates the autocorrelation traces of the Yb laser before and after propagation through the fiber distribution arm. The input pulse duration into the HCF was ~190 fs, which was dispersed to ~300 fs duration at the output of the HCF.

Please note that our primary objective for splicing with the SMF was to facilitate a standard fiber connector interface to the fiber-coupled measurement devices, such as an autocorrelator, a balanced optical cross-correlator (BOC), or a fiber-coupled power meter. We did not aim for perfect compensation of fiber dispersion with an exact calculated and measured SMF length. The HCF output pulse duration was sufficiently short to provide an attosecond resolution timing jitter measurement using a BOC as shown in Figure 3. Here, the added timing jitter of the 72-m HCF was measured to be only 0.26 fs RMS integrated for [1 Hz - 1 MHz].

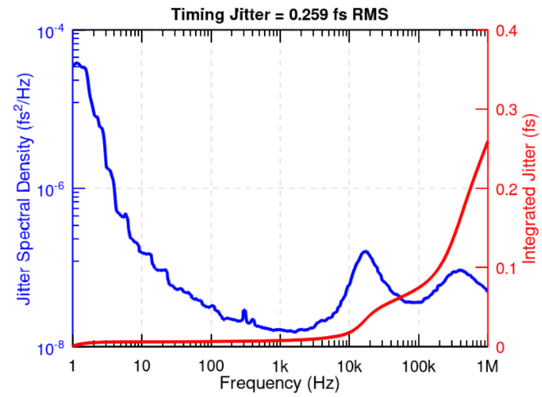

Figure 3: Measured timing jitter of the HCF above 1 Hz.

Then, the long-term passive timing stability of the HCF was measured simply by logging the BOC voltage output with a data acquisition card within its ~1 ps dynamic range. As can be seen in Figure 4(a), the long-term timing drift of the HCF was less than 250 fs peak-to-peak (or less than 60 fs RMS) over a 12-hour period. Figure 4(b) shows the spectral density of the drift data which indicates that the HCF timing drift was limited to only 10 fs RMS within ~1 h duration (i.e., ~300 µHz). It's important to reiterate that the BOC was used here as an out-of-loop measurement device for the assessment of HCF's passive stability in terms of fast timing jitter and slow timing drift (i.e., not for the fiber link stabilization).

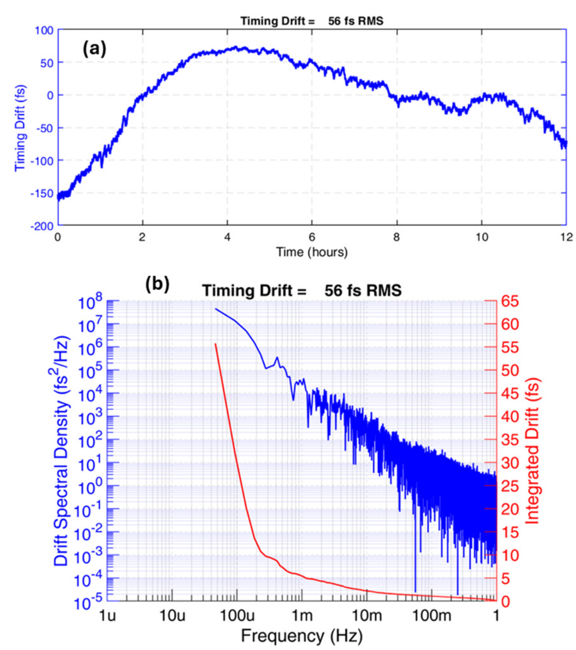

Figure 4: (a) Timing drift of the HCF measured for 12 h with 2-Hz sampling, (b) spectral density of the measured drift.

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Polarization stability of the HCF was also recorded over 12 hours. A PBS was placed after the HCF, and two powermeters were used to monitor the transmitted and reflected powers (see Figure 5). The HCF showed an excellent polarization stability where the average output power deviation between the two orthogonal polarization axes was measured to be only 0.07 %.

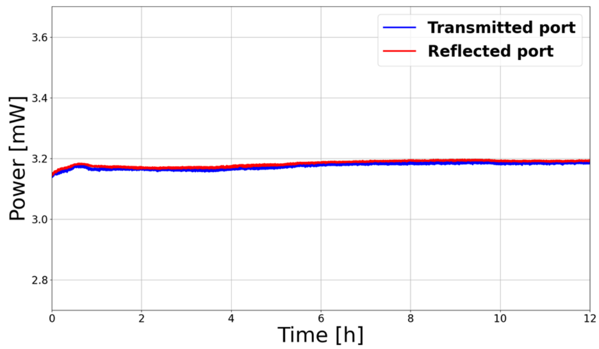

Figure 5: Measured output powers at two different polarization axes at the output of the HCF for 12 h.

DISCUSSION AND FUTURE DIRECTIONS

In addition to passive timing stability, further experiments were conducted to investigate the nonlinear limitations of the HCF. Here, the characteristic response curves of the BOC (i.e., the S-curves) were measured for different input power levels into the HCF. As shown in Figure 6, our findings reveal that the s-curves remain linear within their zero-cross range even under relatively high peak powers propagating through the HCF. This indicates that the pulses do not undergo significant nonlinear pulse distortions with increasing input power levels.

In this setup, the highest available peak power was limited by the Yb laser. Future experiments will explore the performance of the HCF timing distribution with different and more powerful laser sources. These investigations will provide valuable insights into the nonlinear behavior and power handling capabilities of the HCF, paving the way for advanced applications in ultrafast pulsed timing distribution systems.

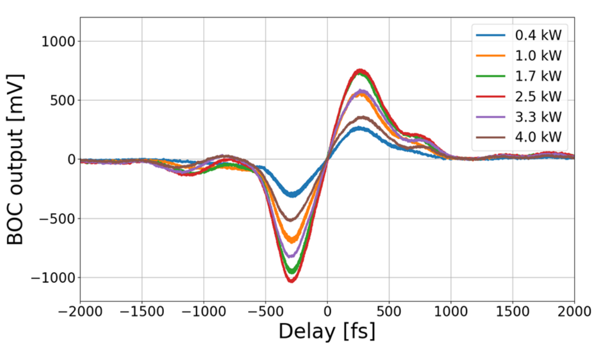

Figure 6: BOC characteristic curves obtained with varying peak power levels into the HCF, superimposed for comparison.

SUMMARY

In this paper, we have shown a passively stable pulsed optical timing distribution at 1030-nm center wavelength using a 72-m long hollow core fiber.

The HCF link was interfaced only with a few meters of standard silica fiber and did not require any additional fiber dispersion compensation which was confirmed by the autocorrelation measurements. The HCF delivered a superb short term timing stability of less than 1 fs RMS. In the long term, the passive HCF had a timing drift of < 250 fs peak-to-peak. In addition, The HCF also showed an excellent polarization stability at its output with less than 0.07% average deviation which ensures polarization stability required for pulsed optical detectors.

In summary, the HCF has the potential of opening up new possibilities for pulsed optical timing distribution systems by providing passive timing stability and low dispersion at a wavelength different than 1550-nm.

REFERENCES

[1] B. W. J. McNeil, and N. R. Thompson, "X-ray free-electron lasers", *Nature Photonics*, vol. 4, pp. 814–821, 2010. doi:10.1038/nphoton.2010.239

[2] G. Mourou, and T. Tajima, "More intense, shorter pulses", *Science,* vol. 331, pp. 41–42, 2011. doi:10.1126/science.1200292

[3] S. Pandey *et al.,* "Time-resolved serial femtosecond crystallography at the European XFEL", *Nat. Methods*, vol. 17, pp. 73–78, 2020. doi:10.1038/s41592-019-0628-z

[4] M. Xin *et al.,* "Attosecond precision multi-kilometer laser-microwave network", *Light Sci. Appl.,* vol. 6, e16187, 2017. doi:10.1038/lsa.2016.187

[5] M. Xin, K. Şafak, and F. X. Kärtner, "Ultra-precise timing and synchronization for large-scale scientific instruments", Optica, vol. 5, no. 12, pp. 1564-1578, 2018. doi:10.1364/OPTICA.5.001564

[6] H. Sakr *et al.*, "Hollow core optical fibres with comparable attenuation to silica fibres between 600 and 1100 nm," *Nature Communications,* vol. 11, 6030, 2020. doi:10.1038/s41467-020-19910-7

[7] R. Slavík *et al.,* "Ultralow thermal sensitivity of phase and propagation delay in hollow core optical fibres", *Sci. Rep.,* vol. 5, 15447, 2015. doi:10.1038/srep15447

[8] A. I. Adamu *et al.,* "10.9 km hollow core double nested antiresonant nodeless fiber (DNANF) with 0.33 dB/km loss at 850 nm", in Proc. OFC 2024, 2024.

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