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Ultrastable optical frequency transfer and attosecond timing in deployed multicore fiber

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The telecommunications industry's deployment of billions of kilometers of optical fiber has created a vast global network that can be exploited for additional applications such as environmental sensing, quantum networking, and international clock comparisons. However, for reasons such as the unidirectionality of long-haul fiber links, telecom fiber networks cannot always be adapted for important applications beyond data transmission. Fortunately, new multicore optical fibers create the opportunity for application coexistence with data traffic, creating multifunctional networks. Toward that end, we propose and demonstrate the faithful transfer of ultrastable optical signals through deployed multicore fiber in a way that is compatible with the unidirectionality of long-haul fiber optic systems, demonstrating fractional frequency instability of 3×10^{-19} at 10,000 s. By supporting state-of-the-art optical atomic clocks, subsea multicore fibers can break the distance barrier for ultrastable optical frequency transfer, opening the door to intercontinental optical clock comparisons at the highest level, with applications in fundamental physics, relativistic geodesy, and the redefinition of the second.

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1. INTRODUCTION

Fiber optic cables are the arteries of modern telecommunication networks, forming a dense web around the globe and interconnecting a data-hungry world. Amazingly, a single standard optical fiber is capable of transmitting hundreds of terabits of data every second [1], approaching its capacity limit. Even so, ever-increasing data traffic demands, driven by cloud computing and streaming services, are predicted to soon outpace fiber optic network capabilities [2,3].

In parallel to this growth in data traffic has been the growth in other applications that look to utilize the telecom industry's investments in deployed optical fiber systems. Some of these applications can directly utilize the telecom infrastructure, allowing for the simultaneous use of data-carrying optical fiber interconnects. Successful examples include environmental sensing and monitoring, where light launched through the fiber is used to measure strain and temperature changes to detect seismic events [4], analyze automobile traffic patterns [5], and aid in deep-ocean research [6,7]. Other applications of deployed optical fiber, on the other hand, do not easily mesh with network infrastructure. A notable example is the transmission of ultrastable signals from optical clocks and oscillators, of utmost importance for the redefinition of the SI second [8,9], tests of fundamental physics [10], and geodesy [11]. Consequently, long-distance optical clock transfer over fiber has required dedicated fibers and special equipment installations along the fiber path and therefore does not fully reside within the standard telecom network. Moreover, these restrictive infrastructure requirements are uneconomical in undersea interconnects, and comparisons of state-of-the-art optical atomic clocks over intercontinental baselines have been, unfortunately, precluded [12].

Here we show how advanced fiber technology, created to meet increased data traffic demands, can simultaneously offer compatibility with a range of other applications, creating a new opportunity for the formation of a vast multi-purpose network. Multicore fibers (MCF), where several light-guiding cores reside within a single fiber strand, can increase data-carrying capacity to Pb/s rates on a single fiber [13]. The prospect of MCF as the future long-haul telecom fiber has motivated the deployment of test beds in Italy [14] and China [15]. Moreover, MCF and associated technologies are sufficiently developed to enable commercial deployment of a subsea two-core MCF in the near future [16], and mass production of MCF has begun [17]. We add to the functionality of MCF by demonstrating state-of-the-art optical clock transfer and synchronization while operating each core unidirectionally, thus remaining compatible with standard telecom infrastructure. Over 25.2 km of deployed MCF, we transfer laser light with added fractional frequency instability of only 3×10^{-19} at 10^4 s. This added noise is low enough not to degrade the performance of the state-of-the-art optical atomic clocks and can be achieved while co-propagating with other broadband light (e.g., data traffic) within the same core. Moreover, we show the relative timing error between cores to be just tens of attoseconds across 6.3 km of fiber, supporting synchronization at the highest level. When considering the relevance of precision timing to other applications such as quantum networking [18–20], it is clear that the utility of MCF goes far beyond its original goal of increasing data capacity and provides a path toward networks that serve a multiplicity of scientific and technological applications (Fig. 1).

The exquisite frequency stability of state-of-the-art optical clocks and oscillators, orders of magnitude more stable than their microwave frequency counterparts, cannot be transferred any significant distance without being corrupted by the transfer medium. Whereas high-fidelity ~ 100 km scale transfer can take place over air [21], high-performance links at longer distances have all used optical fiber interconnects. In fiber, environmental changes couple directly into the phase and frequency of the transmitted light, either by temperature, humidity, and vibration inducing strain in the glass, or by the thermo-optic effect resulting in changes to the refractive index. This quality is advantageous for environmental sensing but detrimental to stable frequency transfer. However, by reflecting a small portion of the light back to the transmission source, the fiber's added instability can not only be measured but also compensated for [22].

Importantly, such bidirectional use of the fiber is not supported by long-haul telecom fiber networks. Standard telecom optical amplifiers, installed at roughly 80 km intervals to compensate for fiber losses, only allow unidirectional light travel in order to reduce data transmission errors from link back-reflections and cascading noise. Hence, while optical frequency transfer has crossed 1000 km distances, their need for carefully tailored bidirectional amplification has required additional hardware and signal routing that must be kept separate from the rest of the network [23–30].

The adoption of MCF in long-haul networks can provide a means to integrate frequency transfer at the highest level with telecom networks. With MCF, each core within the fiber strand can be used unidirectionally, but with separate cores operating with light propagating in opposite directions, including through multicore optical amplifiers [31]. That is, one core of the MCF can be used to transmit ultrastable clock light to the end-user, while a second core is used to return light to the source for fiber noise compensation. This noise compensation scheme works as long as light along the separate cores experiences the same environmentally driven phase and frequency shifts, which, as we show in more detail below, is indeed the case. Crucially, operation of MCF with different cores transmitting in different directions is not only fully compatible with telecom data transmission schemes but is the intended configuration to reduce cross-talk among the cores. Indeed, the longest data transmission distance over the MCF link to date—18,090 km of fiber transmitting 14.9 Tb/s per core—has been achieved with this design [32].

We demonstrate ultrastable optical frequency transfer over the world's first deployed MCF, located in the city of L'Aquila, Italy. Figure 2 shows the experimental setup. A 6.3 km MCF cable deployed in an underground tunnel network includes four strands of an uncoupled-core, four-core fiber that can be cascaded to form a 25.2 km link [14]. In addition to the MCF, there is a cable with eight strands of standard fiber (SMF-28) that runs in the same tunnel under the city, providing a benchmark for our MCF stabilization performance. Both the "transmission" and "receiver" ends of all the fibers are located in the same room, allowing for a full evaluation of the performance of the stabilized link. As a source of ultrastable light, we use a fiber laser with a wavelength of 1550 nm whose frequency is locked to a compact optical reference cavity [34]. Locking to the reference cavity provides laser fractional frequency stability at the 10^{-14} level, ensuring the link instability can be measured and compensated without corruption due to noise from the laser itself [35].

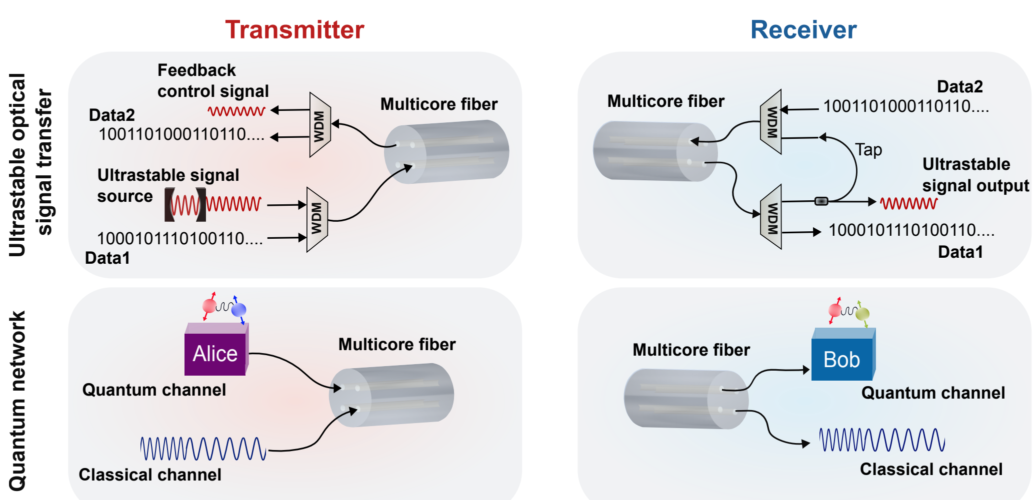

Fig. 1. The envisioned multifunctional multicore fiber (MCF) network. Functionalities enabled by the MCF include ultrastable optical signal transfer and coexistence of quantum and classical light in the same fiber.

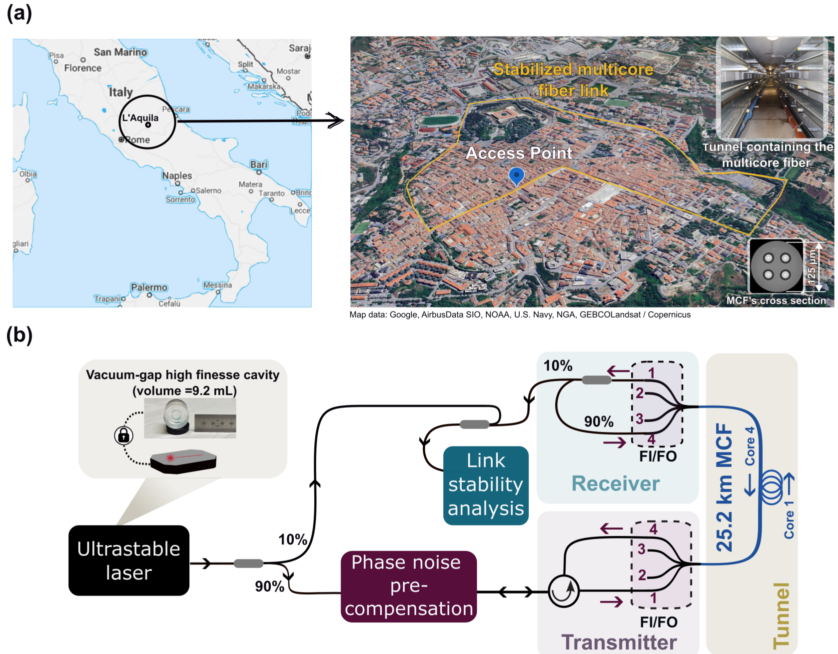

Fig. 2. Ultrastable frequency transfer over deployed MCF. a) Deployed MCF under the city of L'Aquila, Italy, as part of the INCIPICT project [33]. The four-core MCF runs in a tunnel under the city. b) Experimental setup of the noise-canceled deployed MCF. Four 6.3 km long strands of MCF are cascaded, forming a 25.2 km long link. All-fiber components are used in this setup. A fiber circulator acts as both a beam combiner and an isolator. Light is launched into either end of the MCF link with fan-in fan-out (FI/FO) devices.

For performance evaluation, we split the output of the ultra-stable laser, with 10% used as a reference for phase and frequency measurements of the light emanating from the remote end of the fiber. The remaining 90% of the laser light is used for transmission through the MCF and for fiber noise compensation. The fiber noise is measured by turning a round-trip path through the MCF into one arm of a laser-light interferometer, thereby converting phase and frequency fluctuations (relative to a short, free-space path in the phase noise pre-compensation section) into a fluctuating interference pattern on our photodetector. Corrections are applied to the laser frequency through an acousto-optic modulator [also housed within the phase noise pre-compensation section of Fig. 2(b)], pre-compensating the laser signal before transmission through MCF.

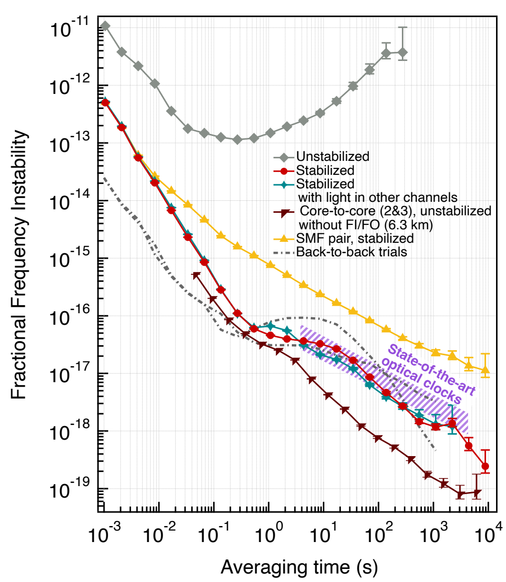

Fig. 3. Fractional frequency instability results with the MCF. The added instability of the stabilized and unstabilized MCF links (25.2 km), back-to-back trials (where the MCF fiber is excluded), and a stabilized pair of SMF fibers (25.2 km) are expressed in terms of the modified Allan deviation. The stabilized MCF is capable of supporting the transfer of state-of-the-art optical atomic clocks, despite being limited by the uncorrelated fibers from FI/FO devices. Relative core-to-core instability of unstabilized 6.3 km of MCF link without FI/FO is also shown. Error bars represent 1σ confidence intervals.

Using a fan-in fan-out (FI/FO) device [36], we launch about 2.5 mW of ultra-stable laser light into one of the cores of the four-core MCF. At the end of 25.2 km, another FI/FO couples the light out of the MCF and into a ~ 2 m long strand of SMF-28 fiber. We use 10% of this light for the performance evaluation, while the rest is coupled back into a separate core of the MCF for the interferometric detection of fiber noise. Photodetected signals, both for performance evaluation and noise compensation, are digitally sampled, providing measurements of the frequency fluctuations and phase noise added by the MCF fiber link, as well as a digital feedback control signal, respectively.

Link performance was characterized in terms of fractional frequency instability [37], shown in Fig. 3. Without active stabilization, the added fractional frequency instability from the link is 10^{-13} at 1 s of averaging, about three orders of magnitude above what is needed to support the transfer of state-of-the-art optical atomic clocks. Stabilization of the link reduces this instability to below 10^{-16} at 1 s. Even greater improvements to the link stability are realized at longer times, reaching 3×10^{-19} at our longest averaging time of 10^4 s. At this level, the stability of state-of-the-art optical clocks can be transferred with extremely high fidelity.

Importantly, the stabilized link performance for timescales longer than 1 s is not limited by the MCF itself but rather by the standard fibers at both the transmission and receiver ends of the link, such as those that are part of the FI/FOs. We confirmed this by repeated measurements of the fractional frequency instability of the systems, excluding the 25.2 km long MCF. In these so-called "back-to-back" measurements, we connected the FI/FO devices directly to each other, leaving the rest of the system unchanged. In this case, there remained a few spatially separated fibers where the light travels one-way, and any environmentally induced noise was much less strongly correlated among these fibers as compared to the cores of the MCF. The results for two representative back-to-back trials, shown as the dashed lines in Fig. 3, are comparable to the results for the full 25.2 km MCF link. Thus, while the 25.2 km link is shown to support optical clock transfer, further improvements appear attainable by, for example, simply reducing the length of the meter-long fibers used at either end of the link. Lastly, we also contrast this performance with that of a 24.4 km long pair of standard fibers from the co-deployed SMF cable, whose performance is approximately an order of magnitude worse than a pair of cores of the MCF. This result is typical of frequency transfer over paired fibers, where each fiber is operated unidirectionally [12,38]; even though the separate fibers are bundled together, their noise and instability are not sufficiently correlated to transfer signals from optical atomic clocks.

In all the measurements described above, the only light in the fiber was the ultrastable signal. Creating a multifunctional network requires compatibility with other signals within the same fiber, even within the same core. As a first step toward proving such multifunctionality, we repeated the stabilized frequency transfer over the MCF link but with simulated data traffic filling the telecom C-band, from 1530 to 1565 nm, with the ultrastable light multiplexed in its own channel at 1550 nm. Data traffic was simulated with spectrally shaped broadband incoherent light co-propagating with the ultrastable laser signal, both to the remote end of the fiber and in the return path. Using spectrally shaped amplified spontaneous emission is a proven and well-studied method to study nonlinear interference effects in fiber optic communication [39]. We see no degradation in the performance of the stabilized light transfer, and we are again limited by the uncorrelated standard fibers at either end of the MCF. More details on this measurement are given in the Supplement 1.

2. OPERATING AT THE STABILITY LIMIT OF FIBER

Corrections to the laser frequency are applied to the light as it travels a full round-trip through the fiber. This necessarily imposes a limit on the level of fiber noise cancellation due to signal propagation delay and is common to every actively stabilized fiber link. This limit is best viewed in terms of the noise power spectral density (PSD), where the fiber noise is separated into its various frequency components. In the ideal case, where the noise between the outgoing and return signals is perfectly correlated and there is full noise cancellation on the round-trip light, the resulting phase noise PSD at the remote end of the fiber may be expressed as [40]

$$S_D(f) \approx a(2\pi f\tau)^2 S_{\text{fiber}}(f), \tag{1}$$

where $a = 1/3$ for uniform spatial distribution of the noise, τ is the one-way transit time over fiber, and S_{fiber} is the unstabilized phase noise PSD of the link (more details on this expression may be found in the Supplement 1). As shown in Fig. 4, the calculated noise limit closely follows the measured MCF stabilized link for noise offset frequencies above 1 Hz. This indicates that the link performance

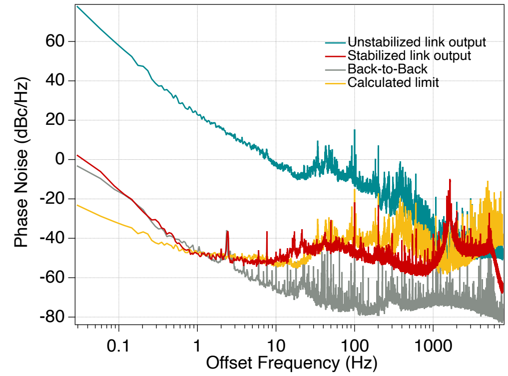

Fig. 4. Phase noise power spectrum. Measured phase noise of the link output and the calculated phase noise limit of the stabilized link. The measurement follows the calculated limit above 1 Hz offset frequency. Below 1 Hz, the noise is limited by the uncorrelated fiber noise in the lab, which is validated by the back-to-back measurement.

is as good as the best bidirectional SMF links at this length. Below 1 Hz, the predicted and measured noise curves deviate from each other due to the uncorrelated noise of the fiber pigtails. This is validated by the phase noise of an FI/FO back-to-back trial, also shown in Fig. 4, and further confirms the stability limit imposed by these fibers.

3. ATTOSECOND RELATIVE TIMING STABILITY

Whereas these ultrastable frequency transfer results rely on the high degree of noise correlation between cores of the MCF [41], more direct measurements on the core-to-core stability highlight the synchronization capabilities of this fiber. By launching a laser signal into all four cores simultaneously, we tracked the relative timing shifts between cores across 6.3 km of deployed MCF, the results of which are shown in Fig. 5(a). In this case, we did not stabilize the fiber link. To eliminate excess noise from the FI/FO pigtails, we used free-space optics to couple light into and out of the MCF and extracted the relative phase shifts among the cores using digital holography [42]. Details of the measurement setup may be found in Supplement 1. Variation in the relative delay between the cores is less than 10 fs (less than two optical cycles) over more than 7 h of continuous measurement. This relative time delay variation corresponds to a fractional length difference of less than 4×10^{-10}, or a 2.5 µm relative path length change over the duration of the measurement. With only femtosecond-level timing deviations over several hours, we cannot discount the possibility that the measurement setup itself contributes. We therefore consider this to be an upper limit on core-to-core instability.

A statistical measure of the core-to-core timing instability is given by the time deviation, shown in Fig. 5(b). At 1 s of averaging, the core-to-core time deviation ranges from 8 to 15 as, corresponding to only a few thousandths of an optical cycle and remains below 100 as for averaging times beyond 1000 s. For comparison, we calculated the time deviation of the unstabilized 25.2 km long MCF used for our frequency transfer experiments, also shown in Fig. 5(b). These results indicate that the relative core-to-core path length changes can be four orders of magnitude lower than the absolute path length change along the fiber. Such extraordinarily high relative timing stability can prove valuable in, for example, quantum networking applications, such as quantum key distribution and distributed entanglement [20,43,44]. In this

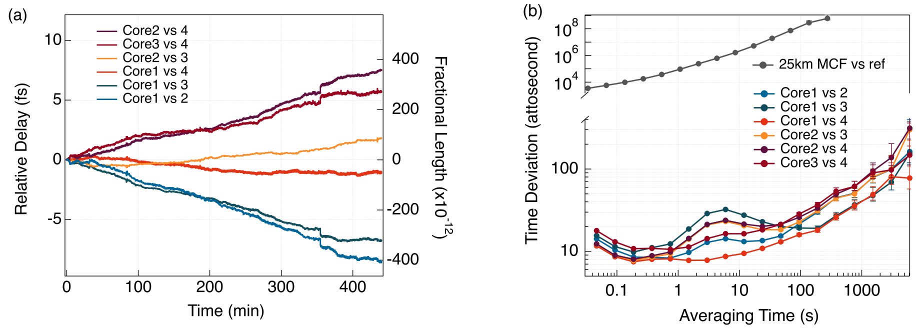

Fig. 5. Relative timing stability among cores of the MCF. a) Core-to-core relative delay and fractional length changes of the unstabilized 6.3 km deployed MCF (no FI/FO) over >7 h. The time delay between cores stays below 10 fs, equivalent to < 0.4 part per billion fractional length change over the experiment duration. The first 80 min of data affected by human activity near the measurement setup is removed. See Supplement 1 for the complete dataset. b) Time deviation (TDEV) between cores of the unstabilized 6.3 km long deployed MCF. TDEV of one core of the 25 km long unstabilized MCF relative to a reference laser is included for comparison.

case, classical light signals can reside in a separate core from the quantum channel, providing a means for extremely tight classical-quantum synchronization without the high-power classical light overwhelming the weak quantum signal.

4. CONCLUSION

Multicore optical fibers are well-positioned to be the future of long-haul fiber optic networks. We show ultrastable frequency transfer through a 25.2 km long deployed MCF with fractional instability reaching 3×10^{-19}, obtained while co-propagating with other optical signals and without bidirectional use of any one core. This demonstration shows the compatibility of in-network MCF for optical clock comparisons, expanding the application space of these optical fibers beyond data transfer. Longer transfer distances will require the integration of multicore optical amplifiers [45], with the ultimate goal of intercontinental clock comparisons with precision that is otherwise unattainable. Importantly, MCF optical amplifier testbed demonstrations have already established the capability of low-noise, high-fidelity data transfer over thousands of kilometers [31]. Of course, extending the length from the 25.2 km used here to continental and intercontinental scales will introduce more noise and reduced feedback bandwidth due to the long delay through the fiber. For extended fiber links on land, the installation of laser repeater stations, similar to current implementations on standard single-mode fiber systems [29], can be used to overcome the bandwidth limitation due to the delay. Undersea fiber links, stretching thousands of kilometers, represent a more formidable challenge. By taking advantage of a loop-back architecture, similar to what is currently installed with undersea optical repeaters spaced by ~ 80 km [4,46], the near-shore noise can be measured and compensated with reasonable feedback bandwidth. The noise from repeaters that span farther from shore will have a lower feedback bandwidth, but presumably will have lower noise as well. Ultimately, the viability of such an approach will depend on further experimental investigation.

In addition to frequency transfer, the exquisite relative timing stability between cores can enable quantum networking modalities with the highest synchronization requirements. With the wide-scale deployment of MCF on the horizon, a vast network serving a multiplicity of scientific and technological applications is within reach.

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Data availability. The data from the main text and supplementary materials are available from the NIST Public Data Repository. This is a contribution of the National Institute of Standards and Technology, not subject to U.S. copyright.

Supplemental document. See Supplement 1 for supporting content.

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