Stable radio-frequency transfer over optical fiber by phase-conjugate frequency mixing

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Abstract: We demonstrate long-distance (≥100-km) synchronization of the phase of a radio-frequency reference over an optical-fiber network without needing to actively stabilize the optical path length. Frequency mixing is used to achieve passive phase-conjugate cancellation of fiber-length fluctuations, ensuring that the phase difference between the reference and synchronized oscillators is independent of the link length. The fractional radio-frequency-transfer stability through a 100-km "real-world" urban optical-fiber network is 6×10^{-17} with an averaging time of 10^4 s. Our compensation technique is robust, providing long-term stability superior to that of a hydrogen maser. By combining our technique with the short-term stability provided by a remote, high-quality quartz oscillator, this system is potentially applicable to transcontinental optical-fiber time and frequency dissemination where the optical round-trip propagation time is significant.

OCIS codes: (060.0060) Fiber optics and optical communications; (060.5625) Radio frequency photonics; (120.3930) Metrological instrumentation; (120.5050) Phase measurement.

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1. Introduction

It has been shown that optical-fiber networks have the potential to disseminate highly stable time and frequency standards over very long distances [1,2]. This same technology also provides a means for remote comparison between highly accurate time and optical-frequency standards. Recent examples include experiments that transfer the repetition rate of highly stable mode-locked laser pulses [3], or optical-clock comparisons enabled over a dedicated 920-km fiber link [4] and over a 540-km public fiber-optic network carrying internet traffic [5,6]. Continuous frequency transfer with an accuracy of 5×10^{-19} / day over an 80-km fiber-optic link has also recently been reported [7].

In this paper, we are concerned with highly stable transfer of a radio-frequency (RF) reference over long distances *via* optical fiber. Many scientific applications can benefit from low-noise transfer of RF reference signals. These include geodesy, gravitational-wave

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detectors, high-energy accelerators, and radio astronomy using very long baseline interferometry. For instance, in the recently-announced Square Kilometre Array (SKA) project, fiber-optic RF transfer would avoid installing a local synchronization reference (*e.g.*, a relatively costly hydrogen maser) at each SKA radio-telescope receiver cluster. Our research points the way to cost-effective technological solutions of this type.

Many groups [1,8–17], have achieved RF-frequency transfer over fiber-optic distances of at least 50 km, using amplitude modulation to encode a RF signal onto the optical carrier; the transfer stability and precision attained are better than those of the best conventional methods based on the GPS satellite system (*i.e.*, a fractional frequency stability of ~10^{-15} with an averaging time of 10^4 s [18]) or on dedicated satellite transfer.

In order to attain the highest-possible stability, there is a need to address the effect of fluctuations in the optical-fiber path length (*e.g.*, due to temperature changes or mechanical vibrations). The most commonly used remedy is to measure the round-trip phase and then to suppress the effect of phase fluctuations by *either* actively altering the fiber length [1,8–10,13–15] *or* indirectly by electronically pre-compensating the outgoing signal phase/frequency [1,8,9,11,12,16,17,19,20]. In the latter case, the principle of phase conjugation is sometimes used to adjust the outgoing signal phase [1,8,11,17,21,22]. In this paper, we introduce a particularly simple frequency-mixing process to achieve phase conjugation in order to passively compensate the effect of optical-fiber fluctuations in RF-over-fiber frequency transfer.

However, irrespective of the technique employed, the compensation bandwidth is limited to frequencies less than the inverse optical-propagation round-trip time (RTT) of the fiber-optic link [1]. For example, the RTT for a 10,000-km link is ~0.1 s, which limits the compensation bandwidth to frequencies less than ~10Hz. One way to mitigate this limitation is to use an oscillator with high short-term stability at the remote site.

Here we combine a high-quality quartz oscillator, for short-term stability during the RTT (<1 s), with the phase-conjugate frequency-mixing technique to compensate longer-term (>1 s) phase fluctuations. A key outcome of our work is to demonstrate phase synchronization (or RF-frequency syntonization) with better stability than that of a hydrogen maser.

2. Our technique

Our fiber-optical RF-transfer system is depicted schematically in Fig. 1. It comprises two RF-amplitude-modulated distributed-feedback diode lasers (Eblana EP1550-NLW-B) operating at different wavelengths in the 1550-nm optical-fiber communication band (*e.g.*, in the channels centered at 1550.92-nm and 1543.73-nm); one is at a local ('Master', M) site and the other is at a remote ('Slave', S) site. Amplitude modulation is achieved by varying the drive current of each laser diode. The diode-laser temperatures are stabilized thermoelectrically to ~1 mK, corresponding to central wavelength and frequency stabilities of ~9×10^{-5} nm and ~11 MHz, respectively. The Master radio frequency RF_M at ~80 MHz is derived from a hydrogen maser; this RF frequency was chosen because it is the lowest common multiple of 10 MHz and 16 MHz, frequencies that are regularly used in Australian radio telescopes – a target application of our system. The Slave frequency RF_S at ~80 MHz is generated by a stable, low-noise 5-MHz quartz oscillator (Oscilloquartz, model 8607) with fine electronic tunability and a frequency-multiplier chain; it has good passive stability below 1 s. This good short-term stability of the high-quality quartz oscillator frequency RF_S enables our technique to maintain synchronization at the remote location over time scales that exceed any trans-continental RTT), while using passive phase conjugation based on frequency mixing to compensate for fiber-length fluctuations over longer times.

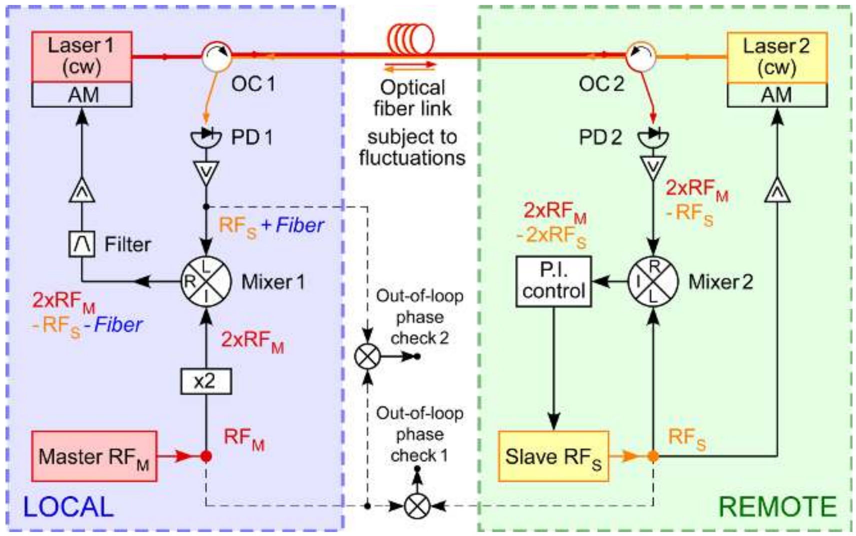

Fig. 1. Schematic for RF transfer over an optical-fiber link using passive phase conjugation based on frequency mixing. Relevant frequencies are labeled. AM: amplitude modulator; OC: optical circulator; × 2: frequency doubler; P.I. control: proportional-integral servo. Other symbols are conventional.

The two laser beams counter-propagate through an optical-fiber link and are then detected at each end. Propagation through the optical fiber introduces phase- or frequency-noise due to mechanical and/or thermal sources. Our scheme eliminates this noise *via* a simple frequency-mixing process to generate a phase-conjugate signal [1,21,22].

Our passive noise-cancellation scheme can be understood simply as follows. Commencing at the local site, as in Fig. 1, the Master oscillator output with frequency RF_M is frequency doubled and mixed down with the photodetector signal of frequency (RF_S + *Fiber*) which contains both the Slave oscillator frequency RF_S and the above-mentioned fiber noise contribution denoted by *Fiber*. The resulting Mixer 1 output signal (frequency 2 RF_M – RF_S – *Fiber*) is then used to modulate the drive current of Laser 1, from which the output light is sent through the optical fiber and detected at the remote site. Subsequently, the frequency of the detected signal at the remote site is thus (2 RF_M – RF_S), since the returning noise term *Fiber* algebraically cancels the phase-conjugate fiber-optic noise term. This noise-free signal is then mixed with the Slave oscillator output RF_S *via* Mixer 2 to yield a phase-error signal to lock the Slave oscillator, with the proportional-integral (P.I.) control minimizing the difference between oscillator frequencies 2 (RF_M – RF_S).

The corresponding algebraic formulation is presented in detail in the Appendix, which addresses the possibility that the above *Fiber* noise contribution might not actually be independent of the direction of propagation and so might not be exactly cancelled out. By considering the phase contributions at each step of the RF signal propagation process, the mechanistic analysis shows that the RF-over-fiber transfer is affected by two sources of residual phase noise: (a) the phase difference between the Master RF_M and Slave RF_S waves accumulated during the last round trip – this corresponds to their short-term passive stability; (b) the phase difference associated with the possibly different transit times for propagation in opposite directions (*e.g.*, as may result from birefrigence in an optical fiber). In general, minimization of these two sources of residual phase noise is required to enable stable phase transfer from Master RF_M to Slave RF_S.

A key advantage of our method is that, to first order, fluctuations in the optical-path length do not contribute appreciably to the phase-error signal so that no active optical-path length compensation is necessary. Furthermore, because of the short-term stability of the remote high-quality quartz oscillator, only slow drifts (over >1 s) in RF_S need to be corrected by

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phase-locking to RF_M. This enables transfer of absolute RF_M phase without further processing (*e.g.*, without rapid phase measurements or use of fast phase-locked loops, either of which can introduce additional noise [1]). This also enables compensation over a much greater range of fiber optical path-length changes compared to other methods, such as using a fiber stretcher. Consequently, our phase-conjugate RF-over-fiber transfer system is well suited to very long optical-fiber links. While the RTT (~10 ms per 1000 km) sets an upper frequency limit of a few Hz on the feedback compensation bandwidth, our high-quality quartz local oscillator can readily maintain sufficient stability on this time scale. Moreover, the link can tolerate brief interruption (*e.g.*, a few minutes) without having RF_S slip by a full phase cycle; in timing applications, therefore, short-term synchronization of RF_S is assured by the passive stability of the remote quartz oscillator.

Readily available analog electronic and photonic components are employed throughout our RF-over-fiber frequency-transfer system. Separate out-of-loop measurement components are used to check the phase-transfer quality of the remote Slave oscillator and the fiber-link noise, identified respectively as "phase check 1" and "phase check 2" in Figs. 1 and 2. These phase comparisons are undertaken by means of a high-precision digital RF phasemeter [23].

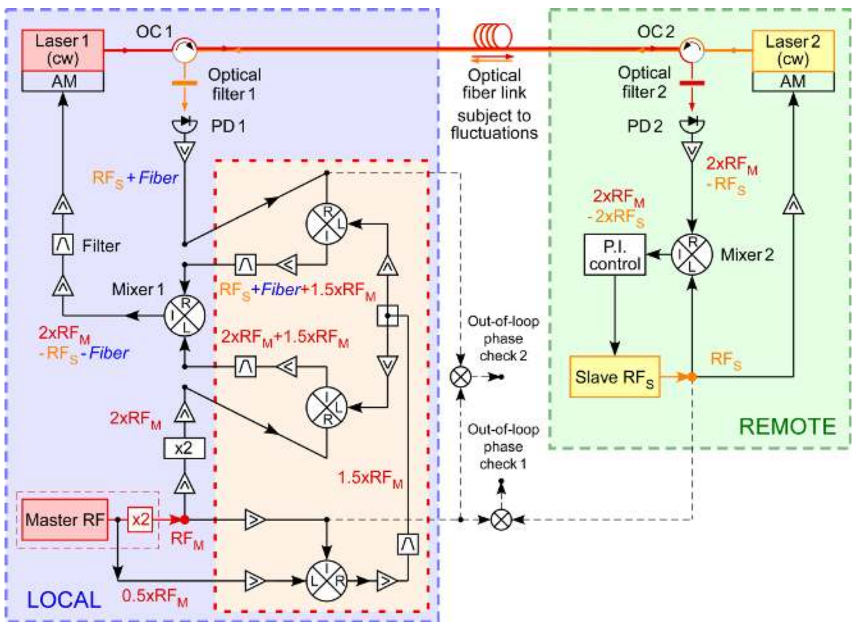

Fig. 2. More detailed schematic of an improved phase-conjugate RF transfer system that eliminates mixer crosstalk. Two common-frequency shifters of $1.5 \times RF_M$ (indicated within the dotted box containing three mixers) help to isolate the resulting signal of Mixer 1 at ~RF_M from interferences with shifted input frequency components at ~$3.5 \times RF_M$ and ~$2.5 \times RF_M$.

Our RF-dissemination method relies on accurate generation of the desired phase-conjugate signal *via* Mixer 1, as shown in Fig. 1; the isolation between the ports of this analog double-balanced mixer is typically ~40 dB or less. RF leakage is expected to degrade the performance if the desired product frequency of the mixer is similar to that of the inputs.

We have therefore introduced two additional common-frequency shifters (by an amount of $1.5 \times RF_M$ in this case), as shown within the dotted box with three mixers in Fig. 2. The output component of Mixer 1 can then be isolated from its input frequency components. Various RF bandpass filters are used to select relevant RF components. Two sets of optical bandpass filters (each with passwidth ~1.3 nm FWHM and suppression ratio >60 dB) allow the detectors to receive light only from opposite lasers operating at different wavelengths.

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3. Experimental tests of our technique

To demonstrate that the phase-error signal detected is immune to fiber-length fluctuations, a free-space delay line was inserted temporarily into the fiber-optic link. The length of the delay line could be adjusted over 40 cm to generate a significant (~1/5 of a period after a round trip) phase change to the 80-MHz RF signal. In this measurement, a signal taken from the Master RF oscillator was used as the Slave RF_S signal, with the quartz oscillator itself deactivated. As expected, the phase-error signal of Mixer 2 remained unchanged while the delay line was scanned, whereas the delay-line contribution (as measured by the out-of-loop phase check 2 mixer) varied correspondingly.

In a series of fiber-based investigations under realistic experimental conditions, we have measured the quality of phase synchronization of the Slave oscillator against the phase of the Master RF oscillator. The fractional frequency stability $\sigma(\tau)$ of our RF frequency distribution system has then been analyzed and expressed in terms of the Allan deviation, as a function of averaging time τ. These measurements were made on phase-coherent 20-MHz RF signals available within both the Master and Slave RF frequency-multiplier chains; 20 MHz was a practical upper limit, constrained by the maximum input frequency of the digital RF phasemeter. In each case, the remote and local sites for these links were co-located, thereby facilitating out-of-loop phase checks.

In Experiment I, our phase-conjugate RF-dissemination system was tested by transmitting the RF-modulated light over 20 km of single-mode optical fiber on a spool in our laboratory. In Experiment II, the system was tested using a long-distance "real-world" urban optical-fiber network. This was carried out on the Intra-governmental Communications Network (ICON) in Canberra, Australia's capital city; it provides 100 km of dark single-mode fiber around the city in a loop accessible from the Australian National University (ANU) campus. Both of these experiments employed modern single-mode fiber with attenuation less than 0.3 dB/km.

We had previously performed preliminary phase-conjugate RF-over-fiber transfer experiments [24,25] in Sydney using a noisy, lossy 21-km loop of dark optical fiber linking the National Measurement Institute (NMI) to Macquarie University (MQU); these provided early real-world tests of the robustness of our RF-over-fiber transfer system. The NMI–MQU link included numerous SC/PC-type fiber-optical connectors, so that it exhibited a high total round-trip loss of ~13 dB. Nevertheless, the results obtained on this far-from-ideal network indicated that, for $\tau > 10^3$ s, the performance of our RF-over-fiber transfer system was still superior to that of a hydrogen maser.

3.1 Experiment I: frequency stability results for RF transmission over a 20-km fiber spool

Figure 3 presents Allan deviation plots for a number of baseline measurements in our laboratory. Trace (i) shows the phase-detection noise floor of the RF phasemeter [23] used to measure the RF transfer stability "out-of-loop" as indicated in Figs. 1 and 2. Traces (ii) and (iii) show the specified stability of the remote quartz oscillator and our measurement of two independent hydrogen masers (constructed at NMI), respectively. Trace (ii) indicates that the free-running quartz oscillator frequency RF_S has good short-term stability ($\tau < 1$ s) but that additional stabilization is required on longer time scales.

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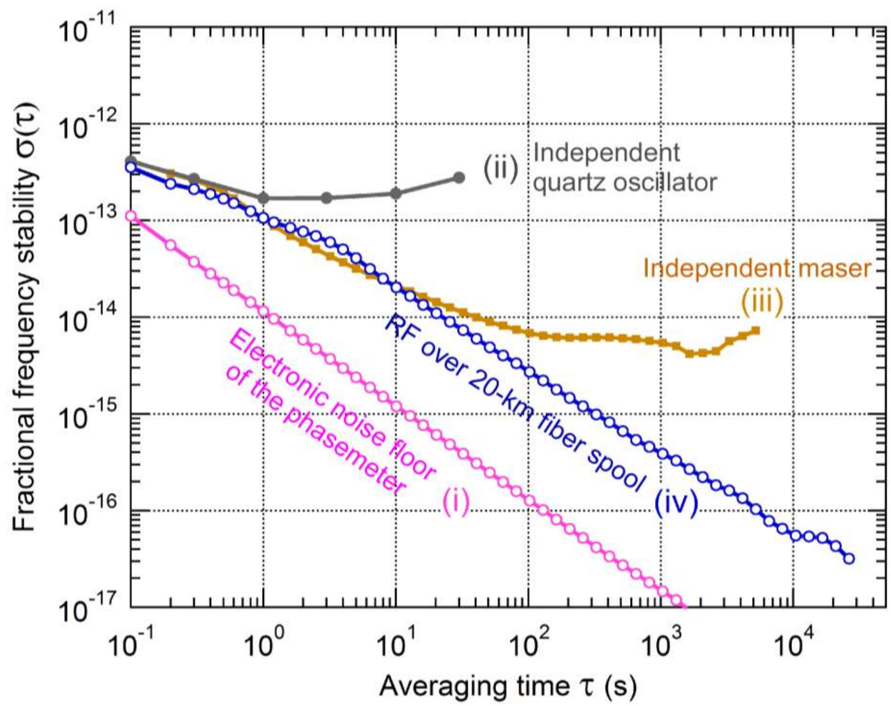

Fig. 3. Fractional frequency stability results, expressed as the Allan deviation σ(τ) for averaging time τ, comparing RF-transfer stability on a 20-km fiber spool with the stability of other system components.

The result for our passive phase-conjugate RF-stabilization technique using a 20-km single-mode optical fiber spool in the laboratory is shown in trace (iv). It indicates a frequency-transfer stability of 6×10^{-17} at an averaging time $\tau = 10^4$ s; this matches or is better than that of the hydrogen maser for integration times greater than 10 s.

3.2 Experiment II: results for RF transmission over the 100-km ICON urban fiber network

Allan deviation plots for our frequency-stabilization experiments on the 100-km ICON fiber network, are presented in Fig. 4, with various system configurations. Trace (i) again shows the noise floor of the RF phasemeter, while trace (ii) shows ICON's intrinsic fiber noise (measured by a digital technique [17,23,26]). Traces (iii) and (iv) were recorded using the phase-conjugate RF-transfer system, not only with the original 100-km length of the ICON network (trace (iii)) but also augmented by an additional 50-km fiber spool (trace (iv)). The fractional frequency stability for the 100-km ICON network is 6×10^{-17} (with an averaging time $\tau = 10^4$ s), the same as in the laboratory experiments on the 20-km fiber spool shown in Fig. 3(iv). This confirms that in-fiber path-length fluctuations have effectively been cancelled by using our passive phase-conjugate compensation scheme based on frequency mixing, as already suggested by the earlier free-space delay-line test. Finally, trace (v) of Fig. 4 shows the corresponding fractional frequency-transfer stability recorded with a relatively short (10-m) fiber cable; at an averaging time $\tau = 10^4$ s, it is ~2.5×10^{-17} – approximately half that recorded with the 100-km fiber link.

The results indicate that, for RF transfer on the real-world ICON fiber-optic network over distances up to ~150 km and with an averaging time τ of more than ~200 s, our phase-conjugate, frequency-mixing system can yield fractional stabilities that are better than those typically obtained with a hydrogen maser as in Fig. 3(iii). Likewise, fractional instabilities below 10^{-15} are maintained with averaging times τ above ~2×10^3 s (*i.e.*, ~0.5 h).

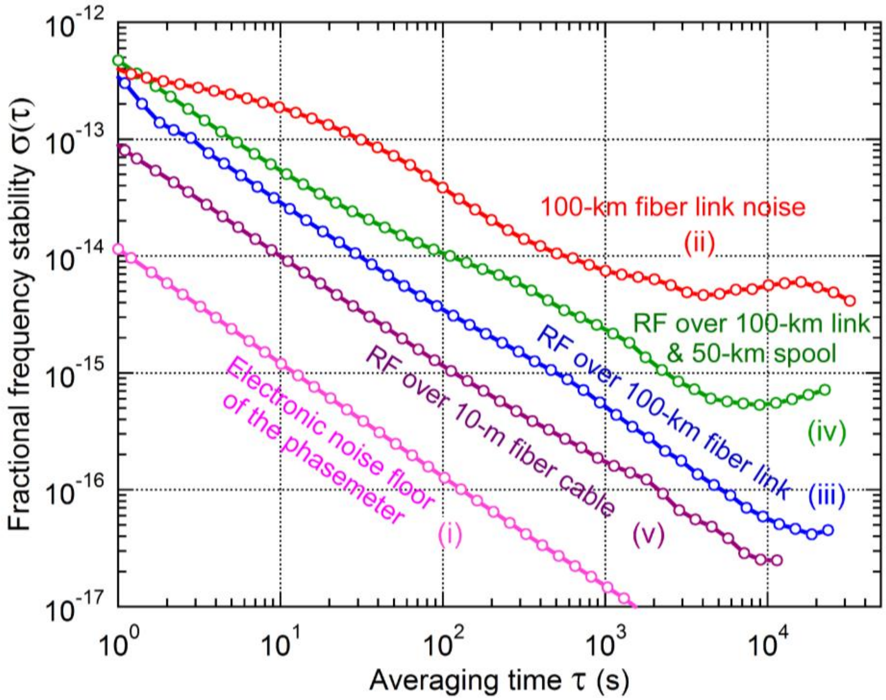

Fig. 4. Fractional frequency stability results, measured on the ICON urban network.

Traces (v), (iii) and (iv) of Fig. 4 demonstrate that the fractional frequency stability deteriorates as the length of the fiber link increases (presumably associated with attenuation of the optical signal [27]). In additional RF-over-fiber experiments with a total (link + spool) fiber length of 200 km (and a transmitted power ~5 nW), the drift of our phase-lock point was found to be comparable to the error signal of the RF phase – a limiting condition.

4. Conclusion

In summary, we have shown that RF-phase synchronization and RF-frequency syntonization can be achieved with high stability over fiber networks up to 150 km in length, and without optical amplification. This is achieved by means of a simple, relatively inexpensive system that combines the short-term stability of a remotely located high-quality quartz oscillator, with stabilization on longer time scales provided by a distinctive passive phase-conjugate approach based on frequency mixing.

Our 100-km performance trial of this RF transfer system over a real-world urban fiber-optic network yields a fractional frequency-transfer stability $\sigma(\tau) = 6 \times 10^{-17}$ for an averaging time $\tau = 10^4$ s. The long-term stability (above $\tau \approx 10^2$ s) of our frequency-mixing phase-conjugate RF-transfer system is superior to that of an independent hydrogen maser, obviating the need for such an expensive and maintenance-intensive reference source at each remote location.

In addition, the short-term stability of this system is potentially applicable to very long (>1000 km) fiber-optic networks where the round-trip time would otherwise limit the frequency stability over such time scales. This work is a first step towards developing techniques for time and frequency dissemination *via* optical fiber across the Australian continent (>3000 km). This includes applications such as the SKA project, for which our technique could be used to greatly reduce the number of relatively expensive hydrogen masers that would otherwise need to be located at SKA radio-telescope receivers.

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Appendix

In this Appendix, we present the algebraic framework for our approach to RF-over-fiber transfer, based on passive phase conjugation using frequency-mixing. The algebra and associated mechanistic details follow the system layout depicted in Fig. 1.

It should be noted that the RF signals appear in different manifestations during the various stages of the RF-over-fiber transfer process. For instance, electronic voltages at various radio frequencies are converted into amplitude modulation of optical carrier waves (from both Laser 1 and Laser 2) and then converted back (by photodetectors PD2 and PD1, respectively) into electronic signals. Although these RF and optical signals carry phase information, they are generated and observed as amplitudes, rather than *via* direct phase measurements.

Let us define the instantaneous frequencies for the Master RF_M and Slave RF_S oscillators at any time by t as $f_\Lambda(t)$, where $\Lambda = M$ and S, respectively. The corresponding phase $\phi_\Lambda(t)$ is related to its instantaneous frequency by $2\pi f_\Lambda(t) = d\phi_\Lambda(t)/dt$. Integration of $f_\Lambda(t')$ between the limits of t and t_0 leads directly to:

$$\phi_M(t) = \phi_M(t_0) + \delta\phi_M(t;t_0) = \phi_M(t_0) + 2\pi\int_{t_0}^{t} f_M(t')dt', \tag{1}$$

$$\phi_S(t) = \phi_S(t_0) + \delta\phi_S(t;t_0) = \phi_S(t_0) + 2\pi\int_{t_0}^{t} f_S(t')dt', \tag{2}$$

where $\delta\phi_\Lambda(t;\ t_0)$ is the accumulated phase change at time t, relative to time t_0, defined by:

$$\delta\phi_\Lambda(t;t_0) = 2\pi\int_{t_0}^{t} f_\Lambda(t')dt'. \tag{3}$$

To determine the details of the phase-error signal for the Mixer 2 output at a time t, we refer to Fig. 1 and consider signals starting one round-trip earlier at time $(t - \Delta t_{SM} - \Delta t_{MS})$. The laser radiation amplitude-modulated by Slave RF_S at that earlier time propagates *via* the optical-fiber link after an interval Δt_{SM} from the Remote site to the Local site, where it is mixed with the phase information of the harmonic of Master RF_M (*i.e.*, 2 × RF_M) at time $(t - \Delta t_{MS})$. The phase-difference information at Mixer 1 is given by:

$$\phi_{MIXER1}(t - \Delta t_{MS}) = 2\phi_M(t - \Delta t_{MS}) - \phi_S(t - \Delta t_{SM} - \Delta t_{MS}). \tag{4}$$

The light carrying this phase-difference information propagates back after an interval Δt_{MS} to the Remote site at time t, to be mixed at Mixer 2 with the instantaneous phase information from Slave RF_S. This generates the phase-difference output at Mixer 2 at time t, as follows:

$$\phi_{MIXER2}(t) = \phi_{MIXER1}(t - \Delta t_{MS}) - \phi_S(t). \tag{5}$$

By substituting Eq. (4) into Eq. (5), then manipulating and re-arranging the integrals that correspond to Eq. (5) *via* Eqs. (1)-(3), it can be shown that:

$$\begin{aligned}\phi_{MIXER2}(t) = {} & 2[\phi_M(t) - \phi_S(t)] - \\ & [\delta\phi_M(t;\ t - \Delta t_{SM} - \Delta t_{MS}) - \delta\phi_S(t;\ t - \Delta t_{SM} - \Delta t_{MS})] - \\ & [\delta\phi_M(t;\ t - \Delta t_{MS}) - \delta\phi_M(t - \Delta t_{MS};\ t - \Delta t_{SM} - \Delta t_{MS})].\end{aligned} \tag{6}$$

It should be noted that the three square-bracketed terms on the right-hand-side of Eq. (6), which result from re-arrangement of Eq. (5), do not represent three separate physical processes. They merely assist our understanding of the source of various noise contributions.

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In Eq. (6), the first square-bracketed term $[\phi_M(t)-\phi_S(t)]$ corresponds to the phase difference between the Master RF_M and Slave RF_S oscillators. This term dominates the other two square-bracketed terms (as will be further explained below). This leads to:

$$\phi_{MIXER2}(t)\approx 2[\phi_M(t)-\phi_S(t)]. \tag{7}$$

This is consistent with our description in Section 2, where the Mixer 2 output represents the phase difference between the Master RF_M and Slave RF_S oscillators; it can thus serve as an error signal for phase locking of the Slave RF_S oscillator to the Master RF_M oscillator.

Let us check now the residual contributions of the other two terms in Eq. (6). Under phase-locked conditions, $\phi_{MIXER2}(t)$ in Eq. (6) is reduced to zero by feedback control of the Slave RF_S oscillator. It follows that Eq. (6) can be re-arranged, which leads to:

$$\begin{aligned}2[\phi_M(t)-\phi_S(t)] = {} & [\delta\phi_M(t;\, t-\Delta t_{SM}-\Delta t_{MS})-\delta\phi_S(t;\, t-\Delta t_{SM}-\Delta t_{MS})]+ \\ & [\delta\phi_M(t;t-\Delta t_{MS})-\delta\phi_M(t-\Delta t_{MS};t-\Delta t_{SM}-\Delta t_{MS})] \quad .\end{aligned} \tag{8}$$

Therefore, the final quality of phase locking (in which the error signal $\phi_{MIXER2}(t)$ needs to be set to zero) is limited by the two residual terms on the right-hand-side of Eq. (8).

The first of the residual terms, $[\delta\phi_M(t;\, t-\Delta t_{SM}-\Delta t_{MS})-\delta\phi_S(t;\, t-\Delta t_{SM}-\Delta t_{MS})]$, corresponds to the phase difference between the Master RF_M and Slave RF_S waves that is accumulated during the last round trip; this is determined by the short-term passive stabilities of the Master RF_M and Slave RF_S oscillators themselves. Here, the propagation delay between Local and Remote sites sets a response limit for phase locking of a remote oscillator. For example, a 1000-km-long fiber-optic link will have a delay time of ~10 ms; a remote oscillator with high passive stability on this time scale is therefore required.

The second term, $[\delta\phi_M(t;\, t-\Delta t_{MS})-\delta\phi_M(t-\Delta t_{MS};\, t-\Delta t_{SM}-\Delta t_{MS})]$, corresponds to the phase difference acting on the Master RF_M signal that arises from the different propagation times for light travelling in opposite directions. The two terms $\delta\phi_M(t;t-\Delta t_{MS})$ and $\delta\phi_M(t-\Delta t_{MS};t-\Delta t_{SM}-\Delta t_{MS})$ correspond here to the fiber noise that was simply labeled as "*Fiber*" for either direction in the terse description of Section 2 and that therefore resulted in their cancellation. However, in this more general treatment, Δt_{SM} and Δt_{SM} now also include additional propagation times inside the Local and Remote electro-optical transfer units, which could create a phase offset between the Remote RF_S and Local RF_M waves. Furthermore, an imbalance in this term could be generated, for example, by rapid fluctuations or vibrations of optical-fiber length, by changes of stress-induced birefringence and polarization of the optical-carrier wave in the fiber-optical link, or by a wavelength change of the optical carrier in a dispersive fiber. Use of fast optical polarization scramblers could randomize and help average out the polarization effect. Likewise, a local flywheel (*e.g.*, a high-quality quartz oscillator, as employed in our experiments) can be used at the remote location to provide good short-term stability and overcome rapid fluctuations.

The two sources of residual phase noise identified on the right-hand side of Eq. (8) are common to many forms of fiber-optic frequency transfer. For RF-over-fiber transfer systems such as that presented in this paper, any minimization of fluctuations in these residual phase-shift contributions will enable satisfactory phase transfer of ϕ_M to ϕ_S, from Master RF_M to Slave RF_S.

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