Delivering the same optical frequency at two places: accurate cancellation of phase noise introduced by an optical fiber or other time-varying path

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Although a single-mode optical fiber is a convenient and efficient interface/connecting medium, it introduces phase-noise modulation, which corrupts high-precision frequency-based applications by broadening the spectrum toward the kilohertz domain. We describe a simple double-pass fiber noise measurement and control system, which is demonstrated to provide millihertz accuracy of noise cancellation.

High-resolution applications have stimulated the continuing progress in laser frequency stabilization.[1] So far, stable optical frequency reference systems tend to represent an entire optical tableful of equipment, rather than being integrated into a single module or chip. Thus one wishes to transfer the frequency-stable light from one optical table to another or between laboratories in the same or even a nearby building. A polarization-maintaining single-mode optical fiber represents a nearly ideal transmission medium for such optical signals, providing mechanical flexibility and low attenuation.

However, some problems arise from such signal transmission in an optical fiber; for example the fiber's optical insertion phase is extremely sensitive to environmental perturbations. Although these pressure, temperature, and bending sensitivities of the fiber are useful for sensor applications, they form a serious obstacle to the transfer of low-phase-noise signals: in traveling 25 m in our jacketed fiber, the laser's original spectral delta function was broadened to a 300-Hz Gaussian linewidth. Acoustic pressure variations associated with normal speech can write several radians of phase noise onto an optical beam in a nearby fiber, leading to single-pass frequency noise of ~1 kHz.[2] This Letter describes a simple and effective technique for accurate cancellation of such induced phase noise and thus permits fiber-based optical signal transmission in demanding applications, such as optical frequency standards and quantum optics, in which phase noise is critical. Our technique bears some similarity to the Doppler-cancellation techniques used in some coherence-sensitive aerospace experiments, such as the rocketborne hydrogen maser experiment of Vessot *et al.*,[3] to the optical work of Bergquist *et al.*[4] with an open path, and to clock synchronization work at the Jet Propulsion Laboratory.[5]

The physical concept underlying our phase-noise-cancellation principle is the fact that a corrupting signal-carrying path, such as an optical fiber or an open-air path, ordinarily possesses a negligible degree of nonlinearity and nonreciprocity. Basically, two counterrunning signals can propagate independently and experience the same phase perturbations, independent of direction. Thus a light signal, spectrally corrupted by its propagation, can be coded in an appropriate way at the far end and retransmitted back to the original source. The outward-plus-return path generates twice the corrupting phase modulation of a single transit. At the original source end we can isolate the signal returning from the far end, based on the special coding imparted there. The returned signal can then be phase compared with the original signal to yield a measurement of twice the phase variations produced by a single transit. This information may be usefully recovered if the coding at the remote end consists of a frequency shift of the carrier by some rf frequency, 2Δ. This offset could be produced by an acousto-optic modulator (AOM1, Fig. 1) located at the remote end. In the heterodyne beat of outgoing and returned optical signals one will find an rf photocurrent at frequency 2Δ. The returned optical field and hence this rf beat wave also contain twice the one-way phase noise. Dividing this frequency (and phase) digitally by 2 will provide at the source end a knowledge of what phase noise will be introduced by the fiber and so permits precise cancellation of its effects. Thus we have produced signals available in both the source and remote work areas that contain precisely the same optical phase, in spite of the phase noise introduced by the transmission medium.[5]

A nice option is to premodulate the phase of the input light beam to the fiber with the negative of the fiber noise so the beam can emerge from the far end basically noise-free relative to the laser source. This topology is demonstrated in Fig. 1; an additional AOM (AOM2) is used for this noise-compensating modulation. Note that AOM2 can provide an unbounded phase-correction range, obtained by an appropriate (small) frequency offset from AOM1.

An important additional concept is the use of a phase-locked loop to regenerate the rf photobeat wave containing the phase-noise information about

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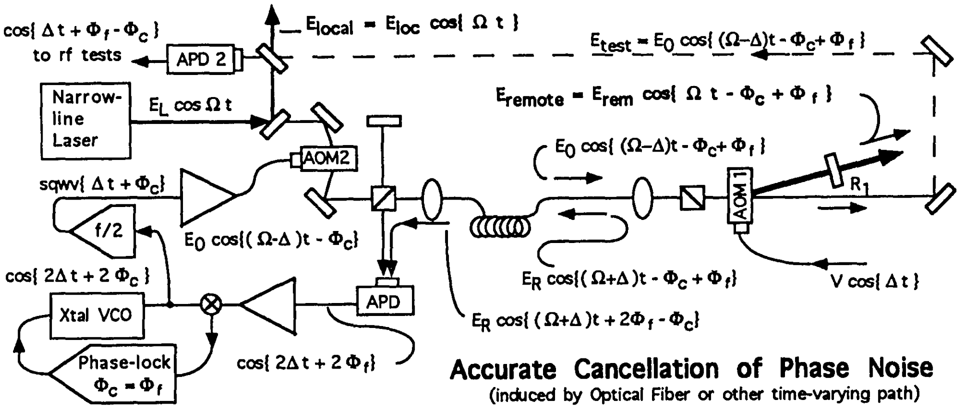

Fig. 1. Frequency shifter AOM1 at a remote site is double passed, so the frequency of the returned optical beam is offset by 2Δ. In this fiber-based example, one-way momentary phase induced by the fiber is Φ_f, becoming $2\Phi_f$ when the beam returns to the source end. The regenerated beat signal is $\cos\{2\Delta t + 2\Phi_c\}$, which is frequency/phase divided by 2 and filtered to become the driving source for phase-noise compensator AOM2. With ideal phase locking, the correction phase Φ_c closely matches Φ_f, so noise cancellation is nearly perfect. Xtal VCO, voltage-controlled crystal oscillator.

the fiber propagation. This phase-locked loop effectively prevents contamination of the fiber-noise measurement by eliminating high-frequency phase noise associated with photodetecting the beat. One chooses the phase-locked-loop bandwidth to be sufficient to track accurately the phase noise introduced by the transmission path. In our experiments this control-loop bandwidth is $\approx$10 kHz, as contrasted with the detected beat frequency of 150 MHz: This drastic reduction of the bandwidth in which photodetection noise is accepted means that interesting fiber phase-noise-cancellation results can be obtained even with submicrowatt returned fiber signals.

To explore this noise-cancellation concept experimentally, we use the setup shown in Fig. 1. The 532-nm laser source is a frequency-doubled Nd:YAG nonplanar ring oscillator. A modulator-transfer lock[6] to iodine provides a stability of $\sim$100 Hz for a 1-s averaging time. To show the fiber contribution to the noise in a realistic context, we have used a fiber of 25-m length. This is short enough compared with the laser's phase-diffusion rate [propagation time 120 ns, versus phase-diffusion rate $\approx 1\ \text{rad}/(100\ \mu\text{s})^2$] that the laser's own phase noise can be suppressed by comparing all optical phases with the laser's output. This jacketed fiber is designed to be polarization holding, while still achieving a substantially round TEM_{00}-appearing output beam. The 75-MHz AOM1 is double passed with retroreflecting beam splitter R_1 at the remote end. Thus (twice) the fiber phase information appears as phase shifts on the 150-MHz beat note detected by the avalanche photodiode (APD) at the source end. This rf signal, shown as $\cos\{2\Delta t + 2\Phi_f\}$ in Fig. 1, is used as the reference for a precision phase-lock circuit that controls the phase of a voltage-controlled crystal oscillator. The free-running FM noise of this rf oscillator is very small, and the loop has high gain below $\sim$6 kHz, so its output phase $2\Phi_c$ is accurately[7] equal to the fiber noise reference phase $2\Phi_f$ (to within 2 mrad rms). This oscillator's output (the AM-free, regenerated beat signal) is discriminated and digitally divided by 2. As shown in Fig. 1, the resulting 75-MHz square wave is bandpass filtered, amplified, and sent off to the corrector AOM, AOM2, working at the source end in line with the fiber input beam. By using here the opposite sign of first-order Bragg shift relative to the double-passed AOM1 at the far end of the fiber, we can expect the beam from AOM2 to precancel accurately the phase to be written on the light transmitted by the fiber. The several signals and phases are indicated in Fig. 1.

To test the noise-free character of the light beam leaving the far end of the fiber, we put the two ends of the fiber near each other and set up an auxiliary test measurement circuit (dashed light path in Fig. 1). For these phase-comparison tests we use the zero-order (unshifted) beam from AOM1 as our version of the fiber-transmitted signal, which yields a relative frequency offset of $\Delta = (2\pi)$ 75 MHz.

To facilitate precise rf measurements, we mixed the 75-MHz rf beat from APD 2 in a balanced mixer with a $\sim$75.003-MHz output from a low-noise[8] frequency synthesizer, thus producing a $\sim$3-kHz wave for analysis: this approach permits a high-resolution fast-Fourier-transform analysis of the optical spectrum. An essential point is that any 1-rad shift of the optical phase produced by the fiber will be conserved by this dual heterodyne approach to appear as the same 1-rad shift at the 3-kHz analysis frequency. Amplitude noise contributes negligibly.

Figure 2 shows the optical field spectral density of the beat between the two sources, measured with a fast-Fourier-transform analyzer. Curve (a) of Fig. 2 shows the optical spectrum when our compensator is off. Note that in 25 m of travel in our jacketed fiber the input laser field has been broadened to $\sim$1.2 kHz by the acoustic noise produced by a laboratory source.[9] The measured acoustic spectrum compared with the rms fiber phase shift yields a pressure sensitivity of 1 rad/m per 20-μbar acoustic pressure (+100 dB relative to $0\ dB_A \equiv 2 \times 10^{-4}\ \mu$bars). Fiber-induced noise was reported previously by Pang *et al.*[2] in terms of $\text{Hz}/\sqrt{\text{Hz}}$ generated by a measured acoustic noise field. From their data we estimate for their fiber

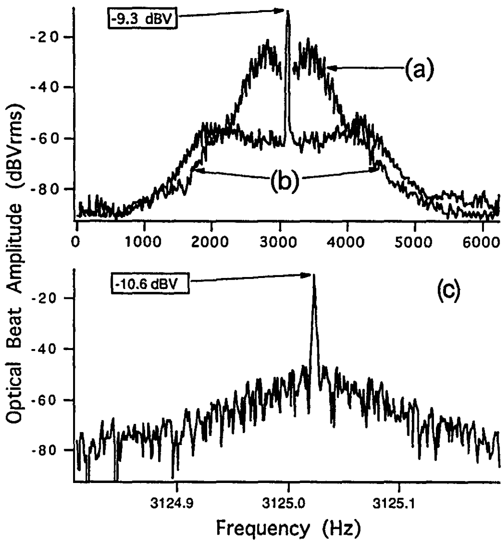

Fig. 2. Optical field spectrum at the output of a 25-m fiber. The input optical signal approximates a delta function. The signal arrives at the far end with a 1.2-kHz width, shown in (a). In (b) the phase-noise compensation system is operational, and one regains 99.6% of the power in the sharp spectral feature. The resolution bandwidth is 15.6 Hz. In (c) the resolution bandwidth is 0.95 mHz. The carrier is reduced by only 1.3 dB from (b) to (c) because of noise near the carrier.

an optical phase shift of 1 rad/m per 4 μbars (+83 dB_A). We estimate that 160 dB_A would be needed to produce 1 rad/m by volume compression alone, neglecting changes in the fiber light-guiding physics.

In Fig. 2 for curve (a) the compensator was off; for curve (b) it was active. The analysis bandwidth is 15.6 Hz. The spectral delta function of the laser has reappeared, with an apparent width equal to the analyzer resolution bandwidth. Curve (c) shows the results obtained with a 0.9-mHz analysis bandwidth. The noise has dropped by ~20 dB, rather than by the corresponding bandwidth ratio of 42 dB. This discrepancy arises because noise processes close to the carrier [see curve (c) of Fig. 2] were previously counted in the carrier. The apparent carrier has dropped only 1.3 dB as a result of this and all other noise processes. Figure 2 shows that our phase-noise compensator system can cancel phase noise so precisely that submillihertz accuracy of fiber-based transmission becomes possible. In fact, this apparent linewidth for the beat is again just the spectrum analyzer bandwidth for the time duration of the measurement.

Time-domain measurements of the beat phase showed some small variations over long times that arise from our optical phase-measurement setup: at the optical milliradian level, unbalanced air paths are important for the stability of the dc phase measured with the cancellation system. From measurements out to 1000 s, we find that the *optical* phase change is below 0.3 rad, again corresponding to submillihertz accuracy level for the cancellation.

The described method allows accurate dissemination of optical frequency within a metropolitan area served by a passive fiber-optic link. At present, time-delay effects would limit international frequency comparisons via undersea fiber links.

With the combination of precise rf phase locking and a simple demonstration setup, we have shown that the described system cancels the fiber-induced degradation of a clean input with millihertz accuracy. This fiber-induced degradation would otherwise cause hundreds-of-hertz additional bandwidth. The system also eliminates problems with differential Doppler effects in precision experiments.

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7. Tests of the phase-lock null point showed a maximum residual phase-noise density of $\sim 2 \times 10^{-5}$ rad/$\sqrt{Hz}$ at ~10 kHz, reducing at higher frequencies as a result of reduced phase noise from the fiber, and reducing also toward low frequencies because of the higher gain of the second-order phase-lock loop.
8. For the best resolution it is necessary to run both rf synthesizers from the same reference for these tests, but we emphasize that, in practice, only a single crystal oscillator is needed for the AOM1 source.
9. Approximately 0.2-μbar/$\sqrt{Hz}$ of pressure below 300 Hz was produced by a small heat gun (turned on cold) located 50 cm from the fiber and blowing away from it.