# Accurate cancellation (to milliHertz levels) of optical phase noise due to vibration or insertion phase in fiber transmitted light

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## Abstract

A single-mode optical fiber is a convenient and efficient transmission medium for optical signals. However, the optical insertion phase written on the light field by the fiber is very sensitive to the surrounding environment, such as temperature or acoustic pressure. This phase-noise modulation tends to corrupt the original delta-looking Hz-level optical spectrum by broadening it toward the kilohertz domain. Here we describe a simple and effective technique for accurate cancellation of such induced phase noise, thus allowing fiber-based optical signal transmission in very demanding high-precision frequency-based applications where optical phase noise is critical. The system is based on double-pass heterodyne measurement and digital phase division by two to obtain the correction signal for the phase-compensating AOM. The underlying physical principle is the fact that an optical fiber path ordinarily possesses an excellent degree of linearity and reciprocity, such that two counter-propagating signals can experience the same phase perturbations. Overall, the fiber's kiloHertz-level of broadening is reduced to sub-milliHertz domain by our correction.

## I. Introduction

The continuing progress in laser frequency stabilization has resulted in sub-Hertz laser linewidth.[1,2] This highly coherent optical radiation is useful in many high-resolution applications. However, stable optical frequency reference systems still tend to be bulky and unportable at present. A single-mode optical fiber becomes a natural choice to transfer the frequency-stable light from one place to another, providing mechanical flexibility, low attenuation and ease of use. A problematical side to such signal transmission in an optical fiber is the strong susceptibility of the optical insertion phase to environmental perturbations. Although these temperature, pressure, and bending sensitivities of the fiber are useful for sensor applications, they form a serious obstacle to the transmission of low-phase-noise signals. 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. [3]

While the fiber related optical amplitude and polarization noise problem has been well addressed in the past, the fiber phase insertion noise has not received the same amount of attention. Our work with ultra-stable lasers and their high resolution applications has necessitated our concern about the characteristics of the fiber induced phase noise and has motivated us to invent a new technique to accurately cancel the phase noise effect on our fiber transmitted signal.

In section II of this paper, we present our measurement results on fiber insertion phase noise. In section III, we describe in detail a simple and effective technique for cancellation of such induced phase noise to a level of milliHertz accuracy, thus allowing fiber-based optical signal transmission in very demanding high-precision frequency-based applications. 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.*[5], to the laser stabilization work of Bergquist *et al.*[6] involving transport over an open path, and to clock synchronization work at the Jet Propulsion Laboratory.[7]

## II. Measurement on Fiber Insertion Phase Noise

With a calibrated sound level meter and a pressure meter, we measured the acoustic noise intensity and associated air pressure around the fiber in which the induced optical phase noise information was obtained by a double-pass heterodyne measurement. The phase noise measurement set-up is shown in part (a) of Fig. 1. The light is sent through a fiber and retransmitted back to the source end after it has double passed an Acoustic-optic Modulator (AOM1, Fig. 1) located at the remote end. AOM1 is driven by rf frequency $\Delta$ and the returned phase-noise-carrying signal will have $2\Delta$ frequency offset relative to the original source. The two signals will produce a heterodyne beat (detected by an avalanche photodetector, APD) at frequency $2\Delta$, which also carries the information about the fiber round-trip insertion phase noise. By using a second heterodyne mixing process against a stable frequency synthesizer, this rf beat frequency can be further shifted down to a convenient audio frequency for high resolution analysis (Here we have used 3 kHz). The essential point of the heterodyne process is its ability to translate a signal along the frequency axis without distorting its spectral density distribution, thereby preserving the absolute phase noise information.

Fig. 1 (b) shows such a beat signal for our 25 m jacketed fiber[10] stretching across our laboratory. With only our usual lasers and other equipment operating, the laser's original spectral delta function has been broadened to a 350-Hz Gaussian linewidth. The fiber-induced phase noise modulation on the original light field has spread its sharp carrier into the neighboring noise spectrum. For a narrow receiver bandwidth, the noise-induced phase modulation is found to be small, and so the relative sideband amplitude at one Fourier frequency approximates the corresponding phase modulation index at that frequency. Therefore if we shift the center of the heterodyne beat signal to 0-Hz of Fourier frequency, then the one-sided sideband amplitude can be expected to represent the power spectral density of the acoustic noise field (differing only by a scale factor), assuming that acoustic modulation is the main contribution to the phase noise. Indeed the measured power spectral density of sound noise in our laboratory bears almost the exact same pattern. A quantitative calculation shows ~ 20-μbar acoustic pressure (+100 dB relative to $0dB_A = 2 \times 10^{-4}$ μbars) would produce 1 rad/m phase noise in our fiber. From the data in reference 3, we estimate for their fiber (from another vendor) an optical phase shift of 1 rad/m per 4 μbars (+83$dB_A$). Theoretically we estimate that 160 $dB_A$ would be needed to produce 1rad/m by volume compression alone, neglecting changes in the fiber light-guiding physics.

For additional tests, we placed a loudspeaker with a sine wave input near a section of our fiber. For the frequency range of 100-Hz to 2-kHz in which we have measured, the phase noise generation in the fiber shows almost a flat frequency response to the exciting acoustic power. In order to make repeatable measurements on our phase cancellation measurement system, we coiled our fiber into a small area and used a local laboratory sound noise source to dominate the possibly-variable background noise. This source was similar in its effect to normal laboratory sounds and produced the broadened spectrum with a 2.4-kHz width as shown in Fig. 3 (b). Its shape is determined by the spectral distribution of that particular acoustic field. When we switched to a loudspeaker with stochastic noise input, we were able to recover the Gaussian-shaped phase noise spectrum.

## III. Principle and Setup for Accurate Phase Noise Cancellation

So far we have measured the fiber induced phase noise after one round trip inside the fiber, yet our task is to cancel the phase noise on our optical signal arising from a single transit through the fiber. The physical concept underlying our phase-noise-cancellation principle is the fact that a phase-corrupting signal-carrying path, such as an optical fiber or an open-air path, ordinarily possesses a very low 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 our original signal to obtain a measurement of twice the phase variations produced by a single transit. This information may be recovered in a particularly useful way if the coding at the remote end consists of a frequency shift of the carrier by some rf frequency, $2\Delta$, as explained in section II. In the heterodyne beat of outgoing and returned optical signals one will find an rf photocurrent at frequency $2\Delta$. The returned optical field and hence this rf beat wave also contains 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 allows a very precise cancellation. Thus we have produced laser signals available in both the source and remote work areas which contain precisely the same optical phase, in spite of the phase noise introduced by the transmission medium.[7]

A nice option is to "pre-modulate" the phase of the input light beam to the fiber with the negative of the fiber phase noise so the beam can emerge from the fiber far end basically noise-free relative to the laser source. This is the topology demonstrated in Fig. 2, using an additional AOM (AOM2) 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 photo-beat wave containing the phase-noise information about the fiber propagation. This phase-locked loop effectively prevents contamination of the fiber-noise measurement by eliminating high-frequency phase noise associated with photo-detecting the beat. One chooses the phase-locked-loop bandwidth to be sufficient to accurately track the phase noise introduced by the transmission path. In our experiments, this control-loop bandwidth is $\approx$10kHz, 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. 2. The 532 nm laser source is a frequency-doubled Nd:YAG Non-Planar-Ring-Oscillator. A modulation-transfer lock[8] to Iodine provides a stability of ~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 which is short enough compared with the laser's phase diffusion rate (propagation time = 120 ns, vs. phase diffusion rate $\approx 1\ \mathrm{rad}/(100\mu\mathrm{s})^2$), so that the laser's own phase noise can be suppressed by comparing all optical phases to the laser's output. This jacketed fiber is designed to be polarization-holding, while still achieving a substantially round "$\mathrm{TEM}_{00}$ - appearing" output beam.[9] The 75 MHz AOM1 is double-passed with a retro-reflecting beamsplitter $R_1$ at the remote end. Thus twice the fiber phase information appears as phase shifts on the 150 MHz beat note detected by the avalanche photo-diode at the source end. This rf signal, shown as $\cos\{ 2\Delta t + 2\Phi_f \}$ in Fig. 2, 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 ~6 kHz, so its output phase $2\Phi_c$ is accurately equal to the fiber noise reference phase $2\Phi_f$ (to within 2 mrads rms). Tests of the phase-lock null point showed a maximum residual phase-noise density of ~ 2 x $10^{-5}\ \mathrm{rad}/\sqrt{Hz}$ 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. This oscillator's output (the AM-free, regenerated beat signal) is discriminated by an over-driven Emitter-Coupled-Logic line-receiver and digitally divided by 2. As shown in Fig. 2, the resulting 75 MHz squarewave is bandpass filtered, amplified, and sent off to the second 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 accurately "pre-cancel" the phase to be written on the light transmitted by the fiber. The several signals and phases are indicated in Fig. 2.

## IV. Fiber Phase Noise Cancellation Results

To verify the noise-free character of the light beam leaving the far end of the fiber, we have put the two ends of the fiber near each other and set up an auxiliary test measurement circuit (dotted light path in Fig. 2). 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, the 75 MHz rf beat from APD 2 was mixed in a balanced mixer with a ~75.003 MHz output from a low noise[10] frequency synthesizer, thus producing a ~3 kHz wave for analysis: this approach allows use of a high resolution FFT analysis of the optical spectrum. Various other rf signals at 75 MHz and 150 MHz are processed in the same fashion. Amplitude noise contributes negligibly.

In Fig. 3 we report measured spectral density of phase noise made via a FFT analyzer. Fig. 3 (a) shows the down-converted spectrum of the free-running crystal VCO; (b) is the actual 150 MHz optical beat signal received by the APD at the source end, which has, in its 2 x 25 m travel in the fiber, been broadened to ~ 2.4 kHz by the acoustic noise produced by a laboratory source.[4] This 150 MHz rf signal is used as the reference input for our phase-locked loop. Fig. 3 (c) shows that the phase-locked 150MHz crystal VCO faithfully duplicates twice the fiber phase information. Fig. 3 (d) is the divided-by-2 version of the crystal VCO power spectrum, which is identical to our optical beat spectrum at 75 MHz (detected by APD 2) when the compensator is off. After amplification to the ~1 W appropriate power level, this 75 MHz correction signal is fed into the phase-compensating AOM2. A negative sign for the effective feedback system is obtained by choosing the (-1) Bragg order for AOM1, while AOM2 is set to use the (+1) order. For curves (e) and (f) the compensator system is active. The curve (e) shows the optical field spectrum after traveling through the canceller AOM and through the 25 m fiber. The optical phase noise has been canceled so accurately that the spectral delta-function of the laser has re-appeared, with an apparent width equal to the analyzer resolution bandwidth, which is 15.6 Hz. Curve (f) shows the results obtained with a resolution magnification of 15,000, corresponding to a 0.9 *milli*-Hz 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 Fig. 3 (f)] were previously counted in the carrier. The apparent carrier has dropped only 1.3 dB as a result of this and all other noise modulation processes. To summarize, Fig. 3 shows that our phase-noise compensator system can cancel optical 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.

For time-domain measurements of the beat phase, we compared our 75 MHz phase-compensated beat signal against the low-noise[10] frequency synthesizer in a phase sensitive detector, such as a mixer. For the frequency-shifted-down (such as ~ 3 kHz) version of the beat signal, we also used a commercial lock-in amplifier as the phase detector. Another test was also performed by measuring the time interval between the beat signal and the reference via a frequency counter. All three measurements produced basically equivalent results, which are shown in Fig. 4 for both cases with the compensator on and off. We used an algorithm similar to that employed in frequency Allan Variance calculations to obtain these curves from time records of phase noise. With the compensator off, the beat signal shows a 1.6 Hz frequency error, determined by the asymptotic rising slope in curve (b) of Fig. 4, implying unbounded phase noise. This arises mainly from a drift of the fiber temperature during the rather long measurement. When the compensator was on, curve (a) of Fig. 4 shows the scale of the phase noise went down by a factor of $10^5$ compared with the previous case in curve (b). However, the data still showed some small variations over very long times. We believe these 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 sec, we find the *optical* phase change is below 0.3 rad, again corresponding to sub-milliHertz accuracy level for the cancellation.

## V. Possible Applications Relative to Frequency Standards

For frequency and time transfers within a metropolitan area served by a passive fiber-optic link, one could imagine propagating a modulated signal. In the JPL work on synchronizing maser clocks for the deep space network,[5] they showed that good time transfer can be obtained by stabilizing the phase of the double-passed modulation waveform. In contrast, our cancellation system holds the *optical* phase in the milliradian domain. Thus it seems likely that the *differences* of phase delay across the modulation spectrum could be very small indeed. We believe this would represent an improvement in precise clock synchronizing applications. It will be fascinating to see if we can obviate the need for an extremely good source at the remote end by using our optical approach to suppress the *absolute* phase noise of a modulated optical spectrum into the milliradian range. Decoding the modulation spectrum at the remote site might then enable us to deliver a radio frequency reference approaching H-maser quality but without the need for an expensive maser source at the remote site.

In thinking about potential future intercomparison of NIST and European *optical* standards via the transparent 1.5 μm undersea fiber cable (which includes a number of Erbium amplifier sections), one will have different channels for the two directions. We believe that a related noise cancellation method could still work if phase-stable optical sources were available at each site and if noise measurements were initiated from both ends of the trans-Atlantic span. We would assume the availability of an appropriate bi-directional additional datalink to communicate the digitized phase corrections at an adequate rate. Unfortunately, another limitation in principle seems to be operative: In our scheme, cancellation of phase noise introduced by the fiber is most effective when the fiber is short enough that all three transits will occur before the conditions have changed significantly. In practice this may be some distance on the order of some 10 km, corresponding to the ≈100 μsec phase stability time observed for the type of fiber employed in our tests. Considering the reduced vibration and slower temperature changes, it would be interesting to measure the phase-noise spectrum associated with the ocean-buried fiber-optic cable!

## VI. Conclusions

With the combination of precise rf phase-locking and a servo "actuator" - an AOM driven by an oscillator of controllable frequency, we have shown that it is possible to build an optical system which can deliver the *same* optical phase at two spatially separated measurement zones, even in the presence of phase noise being added by the transmission path. In a simple demonstration setup, we have shown that the described system cancels the fiber-induced degradation of an optical input with milliHertz accuracy. The fiber-induced degradation would otherwise cause hundreds of Hertz additional bandwidth. The system also eliminates problems with differential Doppler effects in precision experiments.

## VII. Acknowledgments

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## Figure Captions

1. (a) Fiber insertion phase noise measurement system. (b) Optical field spectrum after the original laser signal (with original spectrum approximating a delta function) has traveled back and forth in our 25 m jacketed fiber stretching across the laboratory. Gaussian fit shows a broadened linewidth ~ 350 Hz, arising from ambient laboratory noise ~ 65 $dB_A$.

2. Apparatus for accurate cancellation of phase noise. Frequency-shifter AOM1 at the remote site is double passed, so the frequency of the returned optical beam is offset by $2\Delta$. In this fiber-based example, one-way momentary phase induced by the fiber is $\Phi_f$, becoming $2\Phi_f$ when the beam returns to the source end. The regenerated beat signal is $\cos\{2\Delta + 2\Phi_C\}$ 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 $\Phi_C$ closely matches $\Phi_f$ , so the noise cancellation is nearly perfect. Xtal VCO, voltage-controlled crystal oscillator.

3. (a) Frequency spectrum of the free running Xtal VCO. (b) The returned optical field spectrum with a 2.4-kHz width after a round trip inside the fiber. In these relative measurements, the original optical signal may be regarded as a delta-function input to the 25 m fiber. (c) With our phase-locked loop operational, the crystal VCO exactly tracks (twice) the fiber phase noise, and so the spectrum (c) is the same as (b). (d) The optical signal arrives at the far end with a 1.2 kHz width, after a single fiber pass. This is identical to that of the Xtal VCO after it has been frequency/phase divided by 2. Therefore this represents the rf spectrum of the correction signal which is fed into AOM2. In (e) our phase-noise compensation system is on and one regains 99.6% of the power in the sharp spectral feature. The resolution bandwidth is 15.6 Hz. In (f) the resolution has been increased, corresponding to a 0.95 milliHertz resolution bandwidth. The carrier is reduced by only 1.3 dB from (e) to (f), most of that being noise near the carrier. This data shows that optical signals can be delivered via a fiber with **milliHertz** accuracy with our noise compensator and with **kiloHertz** precision without it.

4. Time-domain measurements of the beat phase. In (a) the phase-noise compensator is on, showing the optical phase change below 0.3 rad even for a 1000s measurement time, corresponding to submillihertz phase accuracy. In (b) the compensator is off, showing a 1.6 Hz frequency error, leading to unbounded phase noise.

## References:


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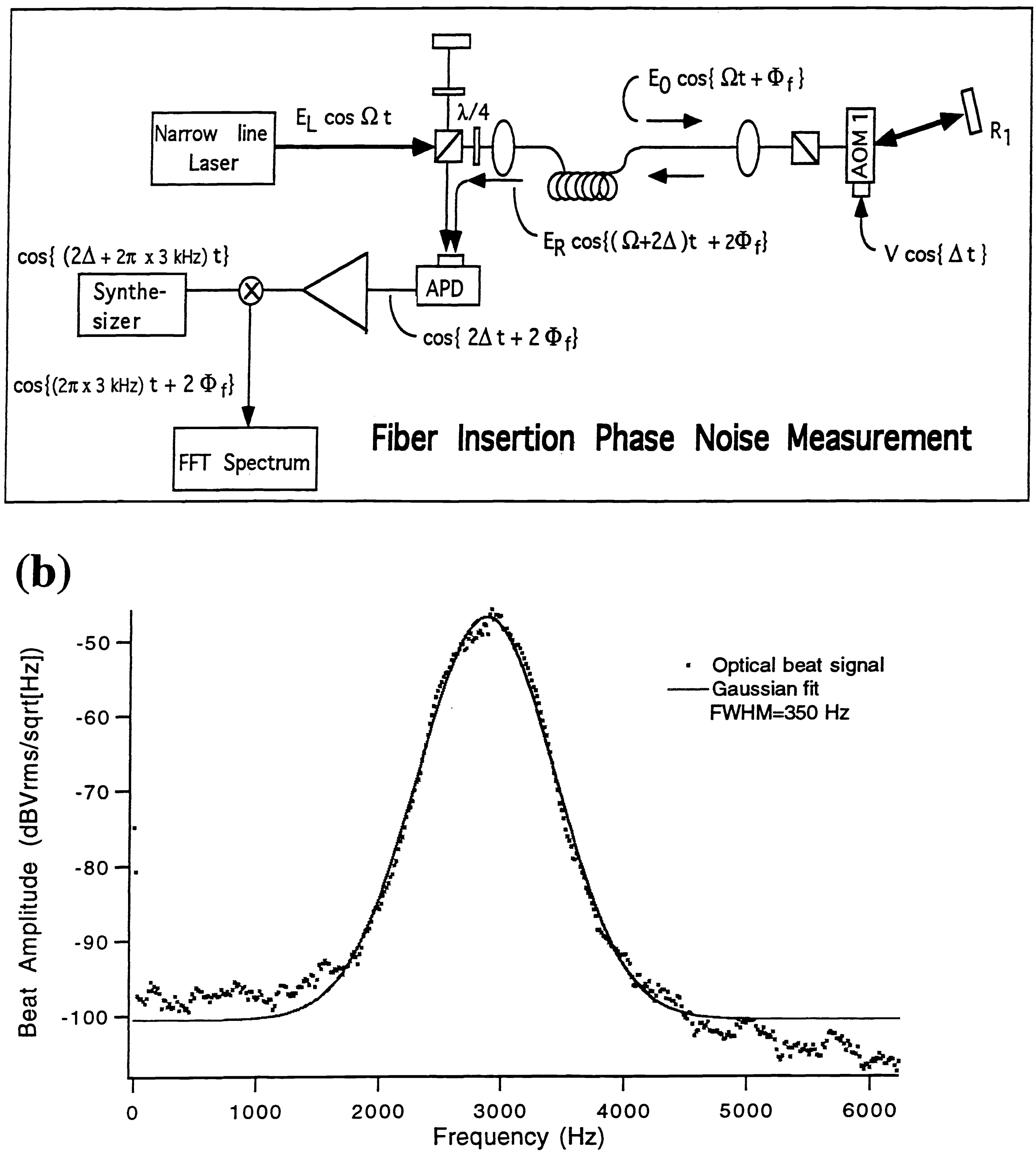
9. Round-beam, polarization-maintaining fiber produced by Alcoa-Fujikura (type 15T-4503-3) and fitted with optical collimators/connectors by Oz optics, Ltd. the mention of commercial names is for technical communication only.

10. 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.

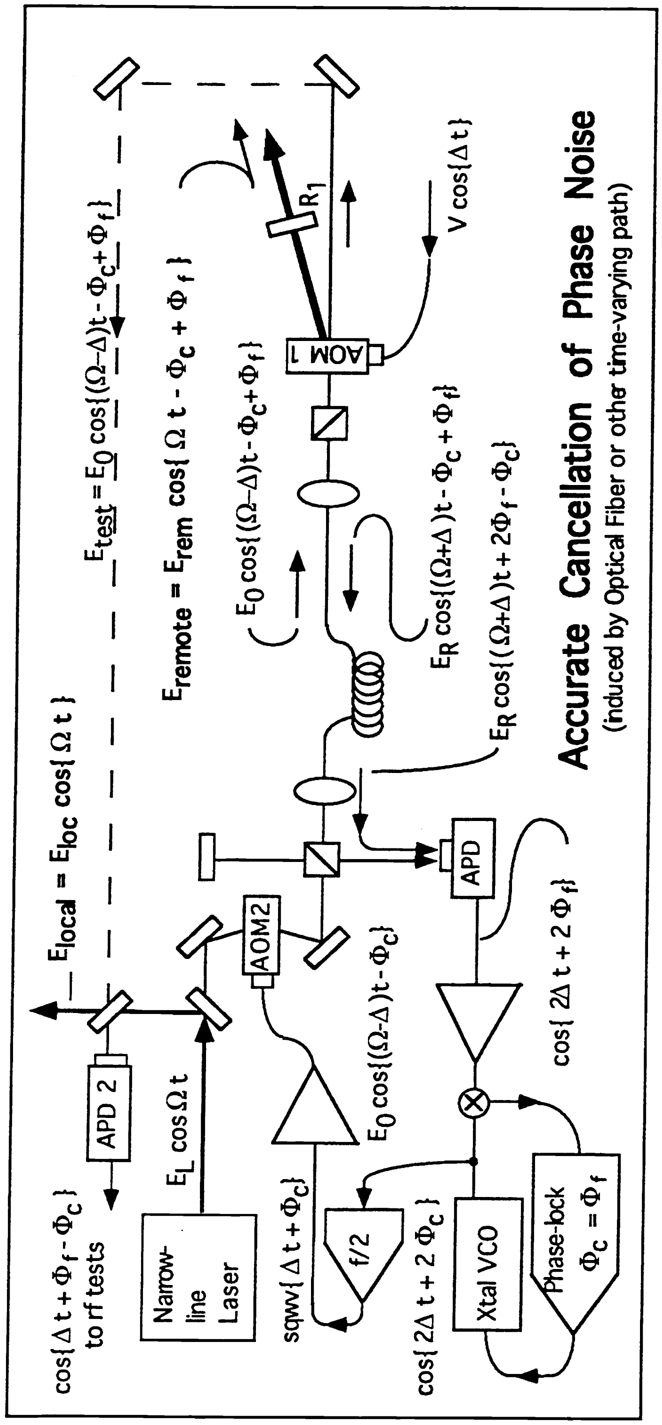
(a)

(b)



Narrow line Laser
$E_L \cos \Omega t$
λ/4
$E_0 \cos\{\Omega t + \Phi_f\}$
AOM 1
$R_1$
$E_R \cos\{(\Omega+2\Delta)t + 2\Phi_f\}$
$V \cos\{\Delta t\}$
$\cos\{(2\Delta + 2\pi \times 3 \text{ kHz})t\}$
Synthe-sizer
APD
$\cos\{2\Delta t + 2\Phi_f\}$
$\cos\{(2\pi \times 3 \text{ kHz})t + 2\Phi_f\}$
FFT Spectrum
Fiber Insertion Phase Noise Measurement
Optical beat signal
Gaussian fit
FWHM=350 Hz
Beat Amplitude (dBVrms/sqrt[Hz])
-50
-60
-70
-80
-90
-100
0
1000
2000
3000
4000
5000
6000
Frequency (Hz)


Figure 1



Accurate Cancellation of Phase Noise
(induced by Optical Fiber or other time-varying path)
Narrow-line Laser
APD 2
AOM2
AOM 1
APD
Xtal VCO
Phase-lock
f/2
to rf tests


Figure 2

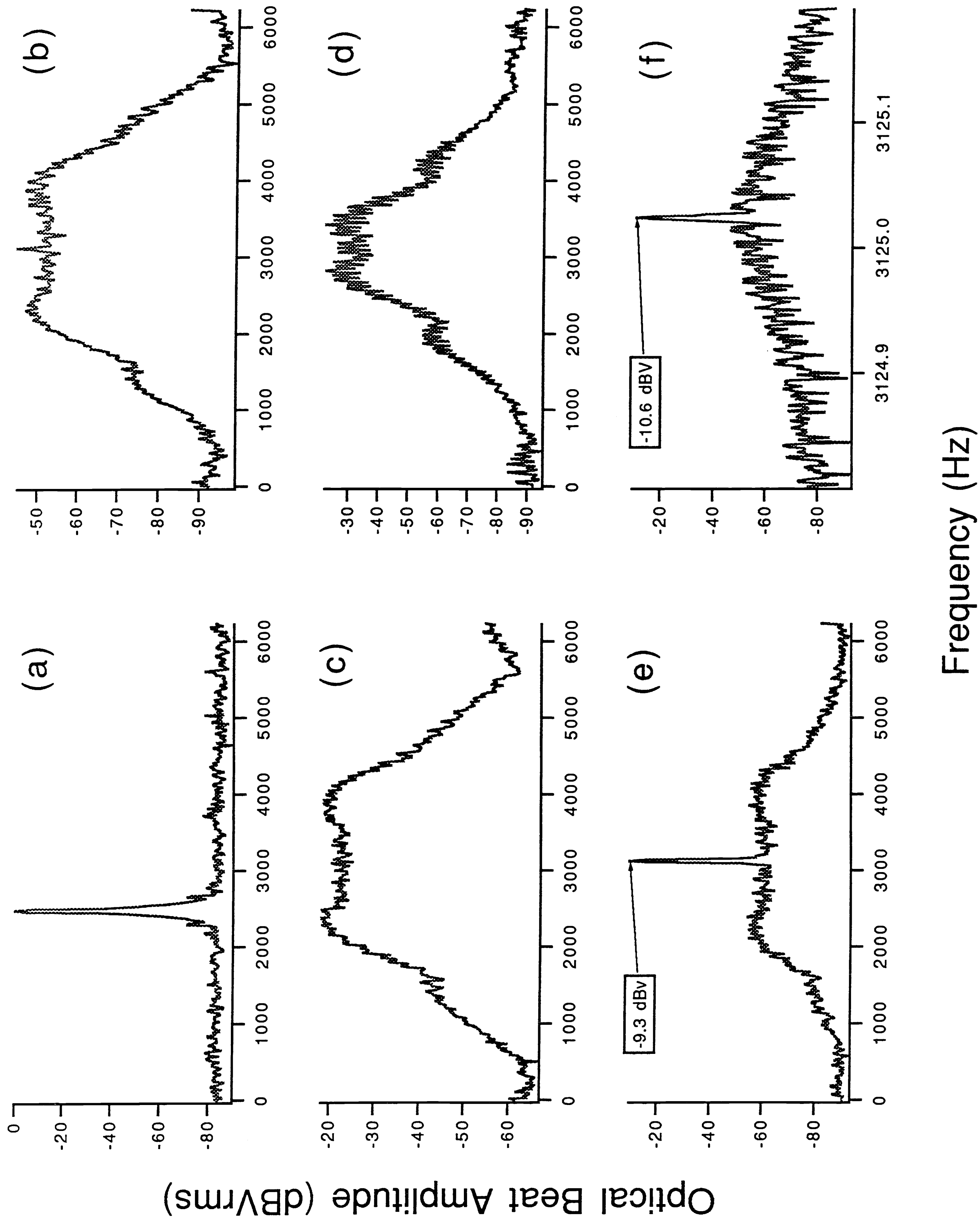

(a)
(b)
(c)
(d)
(e)
(f)
-9.3 dBv
-10.6 dBV
Optical Beat Amplitude (dBVrms)
Frequency (Hz)

Figure 3

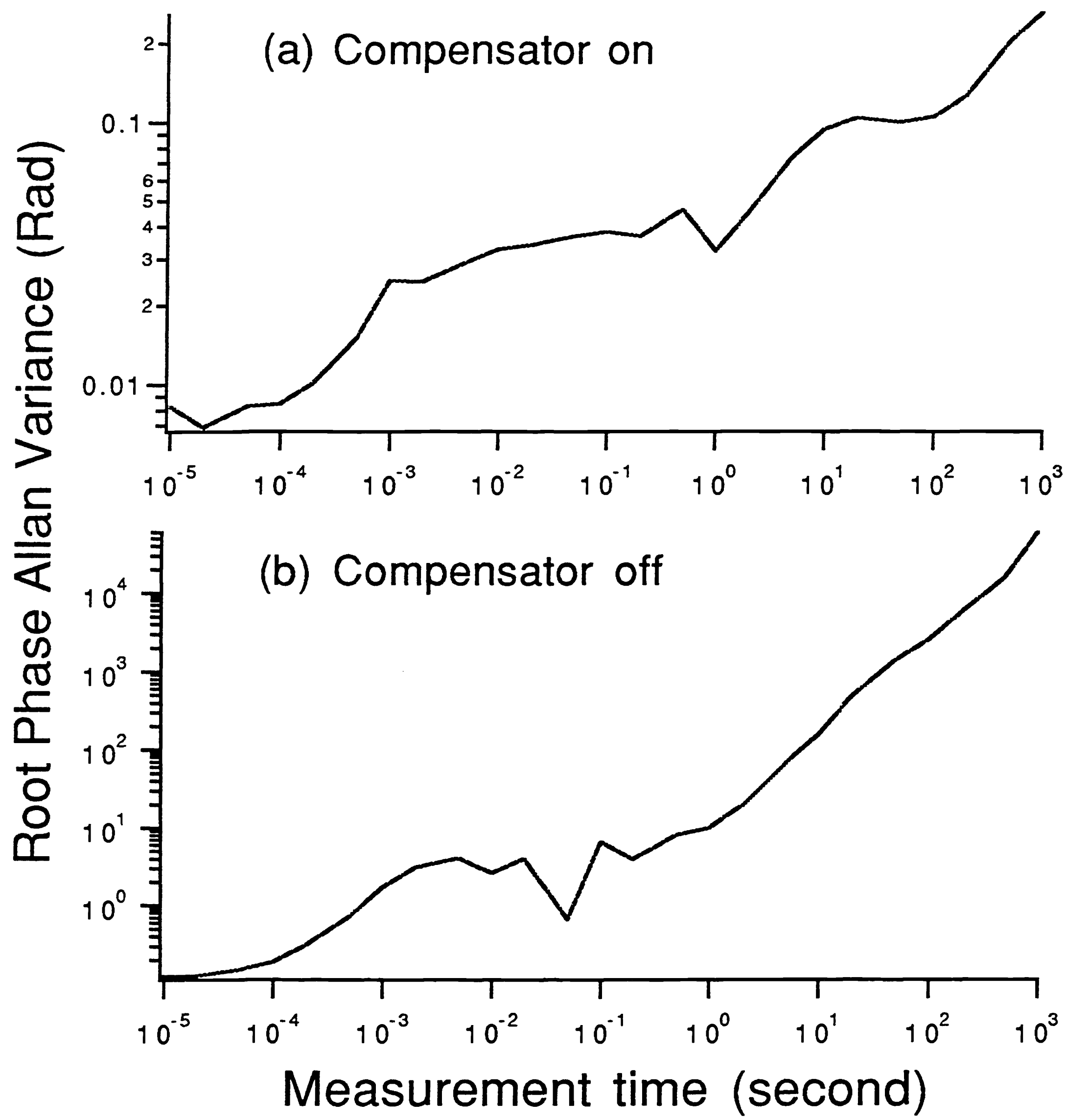

(a) Compensator on
2
0.1
6
5
4
3
2
0.01
1 0⁻⁵
1 0⁻⁴
1 0⁻³
1 0⁻²
1 0⁻¹
1 0⁰
1 0¹
1 0²
1 0³
(b) Compensator off
1 0⁴
1 0³
1 0²
1 0¹
1 0⁰
Root Phase Allan Variance (Rad)
Measurement time (second)

Figure 4