Multiheterodyne Measurement of Acoustically Induced Phase Noise in Fiber-optic Transfer of an Optical Frequency Comb

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Abstract: Optical frequency references under external single-tone acoustic perturbation are remotely delivered via an optical fiber. Multiheterodyne technique was used to measure the induced phase noise. Noise suppression was observed at frequencies below the perturbation frequencies.
Keywords: Multiheterodyne technique; Fiber optics; Excess phase noise; Optical frequency comb; Acoustic perturbation

1. INTRODUCTION

Recently there has been a growing interest in the remote delivery of optical frequency references from multifrequency sources such as femtosecond frequency combs for clock synchronization via fiber-optic networks. Such remote delivery finds applications in many fields such as telecommunications, navigation, grid deployment, remote sensing, precision measurement, and basic research [1-6]. When these fiber links span very long distances, even small perturbations affect the fidelity of the clock frequencies. It is generally believed that the main sources of the external perturbations are ambient temperature fluctuation and mechanical excitation [5,6]. Although theories for both processes are well established, little work has actually been done to systematically study their impact to the degradation of clock precision, especially in the context of fiber-optic transfer of optical frequency combs. An optical signal from a frequency comb carries highly-coherent frequency references as a series of discrete spectral lines, which for a complete characterization of excess phase noise, requires multiheterodyne technique. Multiheterodyne is a generalization of the optical heterodyne technique used for characterizing single-carrier clock distribution systems. It measures the coherent superposition of the optical heterodyne signals generated by multiple frequency components. When the refractive index fluctuation of the transfer medium is small enough so that its impact to all of the involved frequency components can be treated as approximately equal, the multiheterodyne signal becomes a close representation of the optical heterodyne signal produced by individual frequency components. A detailed theoretical analysis of multi-heterodyne phase noise detection has been given elsewhere [7,8]. In this paper we report the use of multiheterodyne technique to quantify the effects of external acoustic perturbations on the phase noise of optical clocks propagating in a fiber link. The work shares some similarities with the 1992 experiment by Pang et al. [9] but focuses on the contemporary topic of fiber-optic remote transfer of optical frequency combs.

2. EXPERIMENTAL SETUP

The optical frequency references are obtained from a commercial femtosecond-laser frequency comb operating at 1.56 μm, with a pulse repetition rate of 250MHz, shown in Fig. 1. The optical system is a Mach-Zehnder interferometer sandwiched between two fiber couplers. In the signal arm, an erbium-doped fiber amplifier (EDFA) and a variable optical attenuator (VOA) control the signal power going into the fiber link. The fiber link is a section of either single-mode fiber (SMF) or polarization maintaining fiber (PMF) wound loosely on a plastic spool. A loudspeaker is placed a few centimeters away on the side of the spool and is driven by a signal generator. A polarization controller (PC) is used to optimize the output signal. In the reference arm, an acousto-optic frequency shifter (AOFS) adds an 80-MHz offset to the frequencies of the reference signal. The two arms are then combined at a fiber coupler and connected to a photodetector (PD). The reference arm length is chosen so that pulses from both arms can temporally overlap on the detector. The beating between the two overlapped pulses generates an 80-MHz beat note on the photodetector. In order to minimize the impact of fiber dispersion to the heterodyne signal, a narrow band optical filter centered at 1559.79 nm with a pass band of 0.4 nm (i.e. about 100 GHz) is inserted at the output of the laser. The beat note is passed through a bandpass filter and an amplifier before it is mixed in quadrature with the 80-MHz driving signal from the AOFS driver. The resulting dc signal is then frequency analyzed by a fast Fourier transform (FFT) analyzer (SRS SR785) to reveal the noise spectrum.

3. EXPERIMENTAL RESULTS

Here we focus only on single-tone perturbations because in principle a broadband perturbation can be treated as the superposition of many single-tone perturbations. Fig. 2 shows the excess phase noise spectra with eight different

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perturbation frequencies. All the data are obtained with an 80-m transmission distance in SMF, and are measured within the span of about 1 hour in normal lab conditions. The driving power to the speaker remains the same for all eight figures. The acoustic power is estimated to be about 80 dB in decibel scale. It is evident from Fig. 2 that the single-tone perturbations cause an increase of phase noise power density within the spectral range of the perturbation frequency and its first few harmonics. Such a behavior agrees with the commonly accepted notion that external acoustic perturbations to optical fibers induce phase fluctuations in the light propagating through the fiber. What is interesting, according to our measured data, is the simultaneous reduction of the noise spectral density at frequencies below the perturbation frequency. Such an effect exists within the entire tested frequency span, but is especially pronounced between 100 Hz and 1 kHz. The same test is also done with an 800-m transmission distance in SMF and with an 80-m PMF replacing the SMF. Similar change of the phase noise spectral shape is observed in both cases. The decrease of phase noise at frequencies below the excitation frequency indicates that single-tone acoustic perturbation can effectively suppress low-frequency phase noise. The stronger effect within 100–1000 Hz is likely due to the greater acoustic efficiency of the speaker in this frequency range. On the other hand, we have also calculated the total phase noise power with and without the perturbation in all of these cases and found the noise power with perturbation to be consistently greater by 5-10% as shown in Table 1. In conclusion, we have used multiheterodyne technique to measure the excess phase noise spectra of a frequency comb as it passes through an optical fiber under external single-tone acoustic perturbations. Noise suppression is observed at frequencies below the perturbation frequencies, which is an interesting effect but requires further investigation.

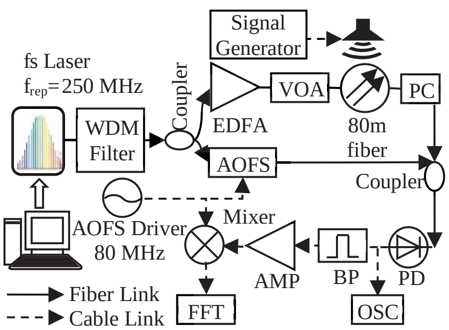

Fig.1. Experimental setup for multiheterodyne measurement. AMP, microwave amplifier; BP, Band Pass Filter; OSC, oscilloscope; PC, Polarization Controller; WDM, Wavelength Division Multiplexer.

Table 1. Total excess phase noise powers at different perturbation frequencies.

Acoustic noise Frequency	SMF			PMF		
	Total Noise Power	**Absolute Power Change**	**Percentage Power Change**	**Total Noise Power**	**Absolute Power change**	**Percentage Power Change**
No Perturbation	3.89E-02			3.63E-02		
100 Hz	4.33E-02	4.37E-03	11.21%	4.00E-02	3.76E-03	10.38%
200 Hz	4.28E-02	3.84E-03	9.87%	3.83E-02	2.06E-03	5.69%
500 Hz	3.92E-02	2.07E-04	0.53%	3.93E-02	3.02E-03	8.34%
1 kHz	4.38E-02	4.84E-03	12.42%	3.84E-02	2.11E-03	5.80%

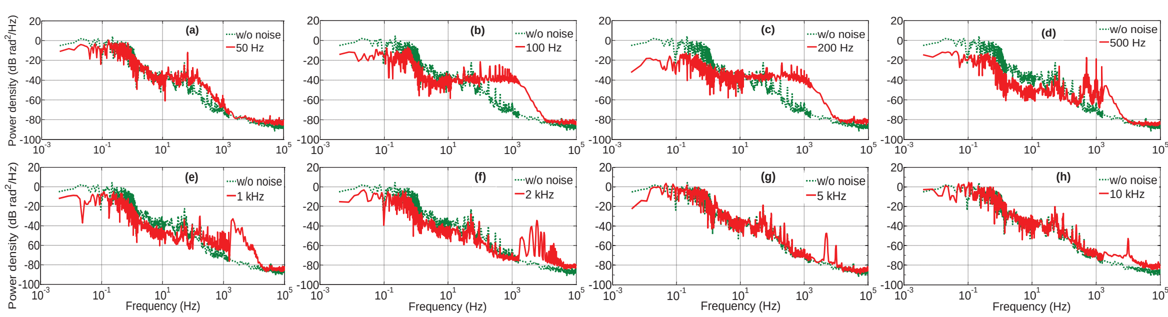

Fig.2. Excess phase noise spectra with (solid) and without (dashed) external acoustic perturbations. Measurement is done with 80-m SMF and 8 single-tone perturbation frequencies. The driving power is the same for all the frequencies.

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