# Phase Stable RF-over-Fiber Transmission Using Heterodyne Interferometry

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# Phase Stable RF-over-fiber Transmission using Heterodyne Interferometry

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**Abstract:** We demonstrate stable transmission of 3GHz over 300m of fiber with less than 0.017 degree (17fs) RMS phase error. An interferometer measures optical phase delay, providing information to a feed-forward correction of RF phase.

**OCIS codes:** (060.5625) Radio frequency photonics; (060.2360) Fiber optic links and subsystems

### 1. Introduction

New scientific applications require phase-stabilized RF distribution to multiple remote locations. These include phased-array radio telescopes [1] and short pulse free electron lasers [2]. RF modulated onto a CW optical carrier and transmitted via fiber is capable of low noise, but commercially available systems aren't long term stable enough for these applications. Typical requirements are for less than 50fs long term temporal stability between receivers, which is 0.05 degrees at 3GHz. Good results have been demonstrated for RF distribution schemes based on transmission of short pulses [3], but these require specialized free-space optics and high stability mechanical infrastructure. We report a method which uses only standard telecom optical and RF components, and achieves less than 20fs RMS error over 300m of standard single-mode fiber.

### 2. Principles of operation

The operation of our RF-over-fiber link is described in more detail in reference 4. Referring to figure 1, a frequency-stabilized optical wave from a 3GHz modulated CW laser is introduced into fiber 1 at A. After delay $t_1$, it reaches the receiver at B and is both received at photodiode $d_2$, and retroreflected after two passes through a frequency shifter, driven by $\omega_{fs}$ (50MHz). For each wave at $\omega_{fs}$ introduced into the frequency shifter, one optical wave is added to the output. The return optical signal is shifted by $2\omega_{fs}$, and goes back to A, where it is added to the unshifted wave from the reference arm. These two waves are passed through fiber 2 with delay $t_2$ to C, where photodiode $d_1$ detects the difference frequency $2\omega_{fs}$ (100MHz). The components mentioned so far form the heterodyne interferometer. Any variations in delay $t_1$ will add phase to the signal at $d_1$, as compared with the phase of $\omega_{fs}$ sent to the frequency shifter. Optical phase delay changes sensed by the interferometer are fed back to the frequency shifter, so that the optical phase at the receiver is stabilized. The amount of additional phase shift at $\omega_{fs}$ applied to the frequency shifter is fed forward to the 3GHz RF phase detection software, so that a correction can be applied to the 3GHz signal.

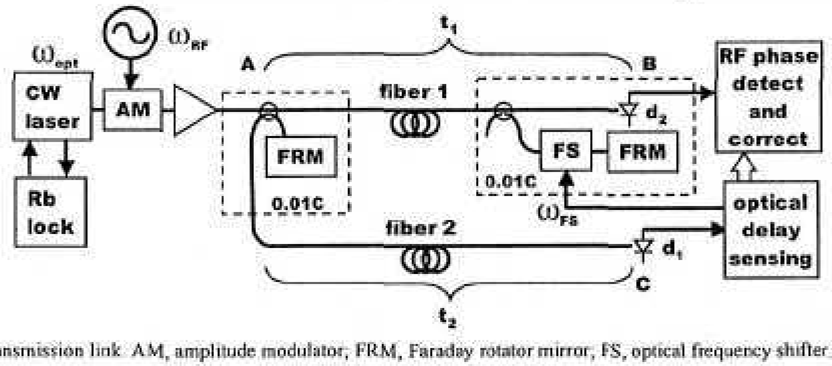


Figure 1. One RF transmission link. AM, amplitude modulator; FRM, Faraday rotator mirror; FS, optical frequency shifter. Dotted lines enclose temperature-controlled components.

Note that we detect optical phase delay, but correct delay for the modulated RF, which is group delay. Thus an additional factor of about 1% has to be added, to account for the difference between the thermal coefficients of phase and group delay, or equivalently the thermal coefficient of dispersion. The reasons for this can be understood by considering amplitude modulation of an optical carrier that results in two optical sidebands separated from the carrier by an RF frequency. Since there is dispersion in the fiber material, the carrier and each sideband propagates with a different phase velocity, with the result that the phase of the beat between them (the RF modulation) shifts with respect to the optical carrier phase. Thus there will be a difference between the optical phase and group indices given by

$$n_g = n + \omega \frac{dn}{d\omega}$$

where n is the phase index and ω is the optical radian frequency. If heating and cooling of the fiber changes the refractive index (by about 10^-5 per degree C, typically), and if this change was equal for the carrier and sidebands, *the carrier and modulation would shift together and we could simply shift the received RF in time by the same* amount as the optical carrier. In fact, dispersion is also changing with temperature, so that the thermal change in delay is different for the carrier and sidebands. Thus there will be a difference in the thermal coefficient of group and phase velocity in the fiber. Our measurements of this difference agree with similar measurements used to calculate the thermal coefficient of dispersion [5]. In practice, we measure this group/phase delay factor once for a particular installed fiber by adjusting the factor to minimize error in a measurement like that of figure 3. The receivers are then separated in two locations and that factor is used in operation.

The RF signal detected at photodiode d2 is digitized and phase corrected in software to remove variations in delay, and can then be output as a synthesized stable signal. Alternatively, it can be phase compared with an external RF signal to be controlled (e.g. via a voltage-controlled oscillator or phase shifter).

### 3. *Photodetector*

A potential issue with photodiode detection of RF is amplitude-to-phase conversion. If the average optical power varies, changes in carrier density can modulate the photodiode junction capacitance, resulting in a shift of RF phase. The magnitude of this phenomenon is dependent on the photodiode design and photocurrent. We have measured the amplitude-to-phase response of Discovery Semiconductor DSC50 photodiodes, and found that at high photocurrents there is a change in sign and a point of zero slope, as shown in figure 2. This zero-slope photocurrent—at about 5mW optical power—is where we operate the diode. Received photocurrent is sufficiently stable that no regulation of the input optical power is needed. Recently, improvements in photodiode design have further reduced this amplitude-to-phase effect (6).

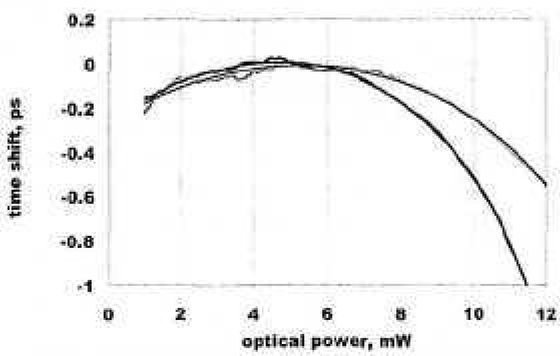


Figure 2. Photodetected phase (expressed as time) of 3GHz RF versus incident optical power, for two DSC50 diodes. Noise at low power is an *artifact of measurement. Different response between diodes may be due to variation in fiber-to-chip coupling*

### 4. Recent results

In a test at the Linac Coherent Light Source (LCLS) at SLAC, we controlled a VCO to match phase with a reference signal transmitted over 300m of installed fiber. The VCO phase was also measured by a second receiver, to provide an out-of-loop check. A block diagram of this experiment is shown in figure 3. An uncontrolled 1m long coax cable carries the VCO signal to the second receiver, and can introduce thermal drift. The room air temperature was controlled to about 1 degree C peak-to-peak.

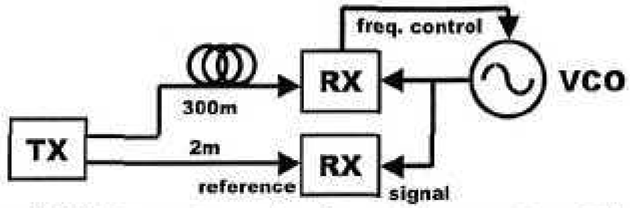


Figure 3. Two-channel measurement with VCO. The transmitter sends a reference signal to two receivers, which compare the reference with a signal to be measured.

If the cable delay coefficient is about 10^-5 per degree, we would expect 50fs long term drift, which is close to what is observed. The group/phase factor used in this experiment was measured previously, and not adjusted to minimize long term drift. As shown in figure 4, the RMS variation in the out-of-loop phase measurement over 11.5 hours is 17fs, while the short-term variation is 14fs. This number is larger than that reported in ref. 4 for a similar fiber length because in that case both receivers were in the same enclosure and shared components. The 300m fiber loop included several flat-polished connectors, which may contribute to short-term error by adding unwanted optical signals in phase with the main signal. Splices and APC polished connectors reduce this effect to an acceptable level.

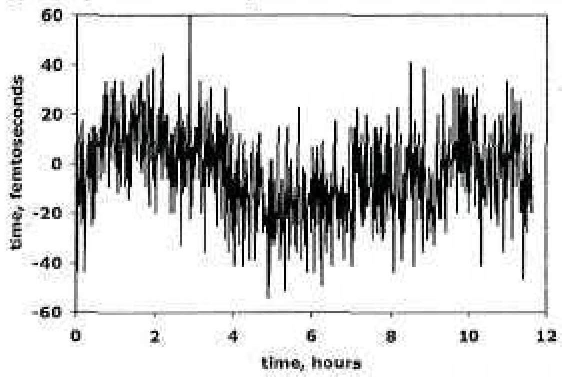


Figure 4. Out-of-loop results for installed 300m fiber loop, 2856MHz. 17fs RMS over 11.5 hours. Short term, 14fs RMS.

## Conclusion

We demonstrate a phase-stabilized RF distribution system capable of less than 20fs stability over hundreds of meters of fiber, for many hours. This system uses only standard telecom components and rackmount chassis. The number of channels can be expanded easily, since all active per-channel components are in the receiver, simplifying the transmitter. A four-channel version is being used in the LCLS free electron laser to synchronize lasers with RF detected from passage of the electron beam.

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