Passive Digital Algorithmic Stabilization of Optical Phase

J. Touch[1], M. Ziyadi[2], A. Abouzaid[2], M. Chitgarha[2], S. Khaleghi[2], A. Mohajerin-Ariaei[2], Y. Akasaka[3], J.-Y. Yang[3], M. Sekiya[3]
[1]*USC/ISI, 4676 Admiralty Way, Marina del Rey, CA 90292 USA*
[2]*Department of Electrical Engineering, University of Southern California, 3740 McClintock Ave, Los Angeles, CA 90089, USA*
[3]*Fujitsu Laboratories of America, 2801 Telecom Parkway, Richardson, TX 75082, USA*
touch@isi.edu

Abstract: The coherent signal processing of nonlinear wave mixing often creates interferometers that require feedback stabilization. A digital electronic optical phase stabilizer is described that avoids injecting pilot control signals and supports long-duration BER measurements.

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1. Introduction

Optical processing uses nonlinear elements to combine original and injected signals, selected and scaled using programmable filters. Such processing often creates unstable interferometers as a side-effect of isolating and coherently adding particular wave-mixing terms. These interferometers sometimes cannot be stabilized using conventional lock-in amplifiers, because such amplifiers inject pilot tones that can interfere with processing inside the interferometer. We developed a passive optical phase stabilizer using digital computer control, which can stabilize such interferometers sufficiently to support long timescale BER measurements.

Several teams, including ours, have been developing a phase-sensitive amplifier (PSA) based phase squeezer to reduce phase noise that accumulates in a phase encoded signal [1-3]. A key step in such systems involves adding a signal that is injection-locked to a weak component of the partially processed spectrum (step 3 in Fig. 1) [4]. Injection-locking typically locks onto the strongest signal, so the desired weak signal is separated using a programmable filter and locked on a separate path before being recombined with the rest of the signals. This creates an interferometer (solid, bold path, Fig. 1) whose optical path variations destroy the system signal phase alignment.

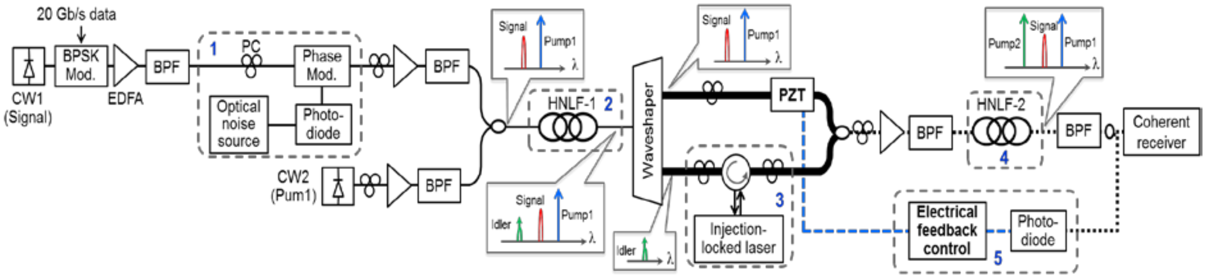

Fig. 1 PSA using injection locking of a weak signal, showing the resulting implicit interferometer (solid, bold black path)

Lock-in amplifiers would inject a pilot tone on both paths, including that of the weak signal, destroying the ability to lock to the weaker signal. Analog feedback systems can stabilize the signal, but the limited range of high-resolution phase shifters means that accumulated phase drift can exceed the shifter range in a short time, interfering with long-term BER measurements. Our solution is to implement the feedback system in digital electronics as a software algorithm (step 5 in Fig. 1), which avoids the need for a pilot tone and can be stable over several days.

2. Feedback overview

The feedback system measures optical power (Fig. 1, dotted black path) in relation to phase shift of one arm of the interferometer. Depending on the relative power of the signals on the interferometer arms, this power can vary in range and value, but can be normalized to the range [0..1]. Measured power (P) is related to the arm phase difference (δ) as $P = (1+\cos(\delta))/2$, which is equivalently $P = \cos^2(\delta/2)$. We measure power, thus phase is: $\delta = \pm 2*\mathrm{acos}(\mathrm{sqrt}(P))$.

Typically, a feedback system would correlate the measured power to the phase shift correction needed. A given power can be the result of one of two phase shifts – positive and negative – and so the system needs to validate each correction. For phase differences in the range [0.. $2\pi/3$], when the phase correction matches the phase difference (dotted blue region, Fig. 2 left, *e.g.*, A) the power will reach maximum (A’), but when the phase correction is the negative of the phase difference (solid red, *e.g.*, B) that same shift will result in reduced power (striped, *e.g.*, B’). The feedback system can sample the power after a correction is made, and when the power decreases it can reverse the shift to correct it. For differences in the range [$2\pi/3$..1] radians (Fig. 2, center), direct calculation always causes the power to increase, *e.g.*, matching differences (dotted blue) jump C to C’ but mismatching differences (solid red) jump D to D’ (striped), causing instability. Instead, we always jump by π radians (Fig. 2, right, green regions), so the phase difference is reduced (striped) regardless of whether the jump is correct (dotted blue) or not (solid red).

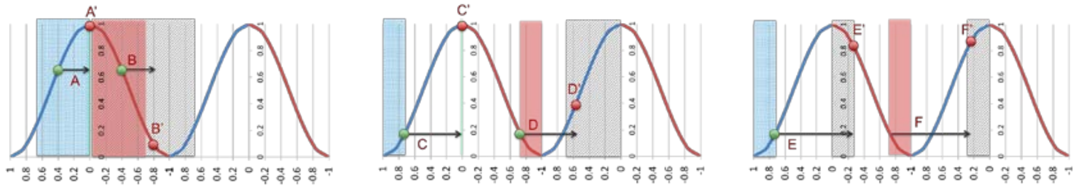

Fig. 2 Analysis of the impact of correct and incorrect phase difference calculation (X axis, units π radians) of based on normalized power (Y axis)

A number of additional optimizations were included to further stabilize the feedback system, including trend dampening and variance dampening. Trend dampening uses recent correct phase difference calculations to predict the next phase difference, *e.g.*, when the controlled arm is increasing in phase (requiring negative corrections), it tends to continue to have increases in phase. Variance dampening avoids overtuning the system, such that when the measured power is within some small fraction of the desired maximum, the system makes no corrective action.

4. Implementation details

We implement digital electronic feedback using an Arduino Due microcontroller. The Arduino analog inputs sample the combined optical signal power using an internal 12-bit 3.3V analog-to-digital converter (ADC) at 25 KHz. Its 84 MHz, 32-bit ARM processor configures the phase delay of a General Photonics Fiber Phase Shifter capable of up to 15π radians of shift at 20 KHz, using a 12-bit digital interface (Fig. 1, dashed blue path). The signal power is directly sampled from a photodiode whose (otherwise exponential) voltage output is translated to linear using an Analog Devices AD8304 logarithmic converter. In our configuration, the linear optical power is within the Due ADC range and can be measured to within 0.25%, thus requiring no additional amplification, which avoids introducing further instability.

The digital output is (coincidentally) also 12 bits and approximately linear, resulting in a resolution of π/270 radians per bit. The shifter was operated in the center of its range to reduce the impact of driver DAC nonlinearities.

Noise was measured as dominated at 0.1-10 Hz through the entire normalized photodiode response (1.1-1.4V). The control loop continuously measures and averages optical power, correcting phase every 30μs, and validating jumps of [0..2π/3] radians with a brief additional 1μs test. Other optical noise was minimized by physically isolating the testbed mechanically (active damper table) and thermally (enclosure to avoid human and environmental effects).

5. Results

The resulting system was capable of measuring system BER below 1E-5 in an ad-hoc configuration [4]. Current tests are being performed using an integrated, encapsulated configuration whose stability is expected to allow measurement of BERs less than 1E-8. Fig. 3 shows linear optical power (top), and shifter control signal (bottom) for three cases: unstabilized (left); stabilized, trending (middle); and stabilized jumping to stay within range (right). The device is useful for PSA phase noise reduction [4] and for all-optical multiplexing and demultiplexing. This work is partly supported by a grant from Fujitsu Laboratories of America and by NSF CIAN (CNS-0626788).

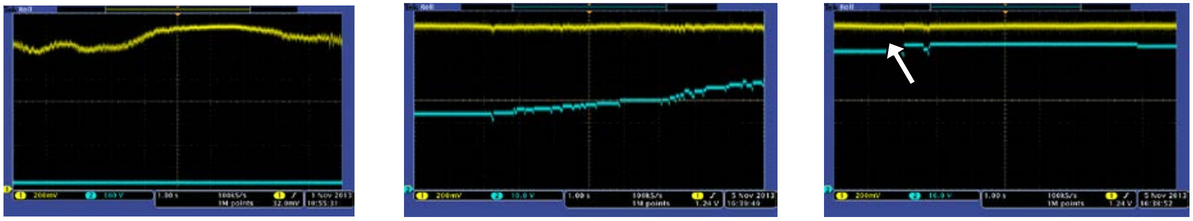

Fig. 3 Measured optical power (top, yellow) and shifter control (bottom, blue); unstablized, stable trending, stable with 2π jump (white arrow)

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