All-Optical Coherent Receiver with Feedback and Sampling

Hsu-Feng Chou, Leif Johansson, Darko Zibar, Anand Ramaswamy, Mark Rodwell, John Bowers

Department of Electrical and Computer Engineering, University of California,
Santa Barbara, CA 93106, USA. Hsu-Feng.Chou@ieee.org

***Abstract* — To obtain higher linearity in an analog photonic link, a novel coherent receiver design with feedback is proposed and demonstrated, where the linearity and signal-to-noise-ratio (SNR) tradeoff associated with a traditional phase demodulator can be eliminated. The local phase modulator in the feedback loop of the receiver tracks the phase change of the incoming signal and reduces the effective swing of the phase demodulator, leading to better linearity without reducing the strength of the transmitted signal. Thus, the SNR of the demodulated signal can be preserved while the linearity is improved. Up to 22.8 dB increase in spur free dynamic range (SFDR) is demonstrated. This novel receiver design is all-optical in the sense that no electrical loop amplifier is necessary. In order to operate the link at carrier frequencies beyond the loop bandwidth, an optical sampling technique is employed to downconvert the signal to the baseband. With feedback in the receiver, 14.1 dB of SFDR improvement is obtained experimentally in the sampled operation.**

***Index Terms* — microwave photonics, analog links, phase-modulation, sampling, demodulators, PLL**

I. INTRODUCTION

Analog photonic links have found a broad spectrum of applications ranging from residential CATV broadcasting to demanding military communications. By using intensity modulation, the performance of the link is mainly limited by the linearity of the optical intensity modulator [1]. Interferometer-based intensity modulators have a sinusoidal response while absorption-based ones have an exponential response. Tradeoffs usually occur between linearity and link gain. In general, the modulation depth must be restrained and the bias point properly tuned in order to obtain high performance [2]. On the other hand, optical phase modulators can have excellent linearity over a wide modulation range. The effective modulation depth is not limited by the optical power as in the intensity-modulated link but by the range in which the phase modulator is linear. This can result in an equivalent modulation depth much higher than 100%. However, the challenge is now moved to the receiver side of the link. A phase demodulator based on optical interference has a sinusoidal response and thus limits the linearity of a phase-modulated coherent link [3]. In other words, the same distortion problem stays in the link. To overcome this dilemma, we recently proposed a novel receiver with a feedback design that is capable of reducing the distortion while keeping all the advantages of using a phase modulator at the transmitter [4]. Up to 15 dB improvement in spur free dynamic range (SFDR) was demonstrated using the proposed receiver.

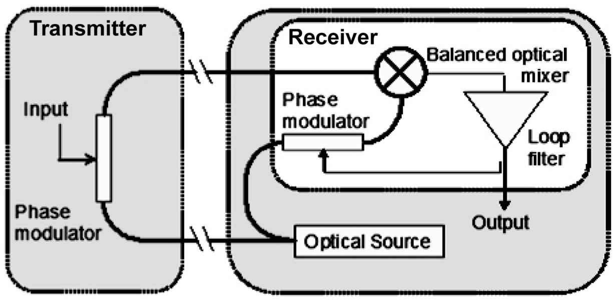

Fig. 1. Concept of the analog photonic link using a novel coherent receiver with feedback technique

The concept of this novel receiver is illustrated in Fig. 1. The output from the phase demodulator (a balanced optical mixer) is amplified and filtered by electronics and fed back to a local phase modulator. Within the loop bandwidth, the effect of the feedback is to reduce the difference in phase between the local optical wave and the incoming wave. Therefore, the effective swing across the phase demodulator is reduced, resulting in better linearity. This reduction could also be obtained by reducing the modulation depth at the transmitter, but the signal-to-noise ratio (SNR) is reduced as a consequence. In contrast, in the proposed receiver, both the signal and the noise swings are reduced by the same factor (loop gain), retaining the SNR while improving linearity.

In this paper, we further improved the receiver design so that the output of the balanced photodetector (part of the optical mixer) directly drives the local phase modulator to complete the feedback loop. The electrical load is properly designed to provide filtering for loop stability. This new approach reduces the extra delay, noise, as well as distortion associated with the loop amplifiers used in our previous demonstration [4]. More significantly, this simplified direct-drive architecture makes it easier to integrate the receiver on a single chip in order to minimize the loop delay for high bandwidth operation. In this work, the SFDR improvement from the traditional phase demodulator (no feedback) is increased to 23 dB with this “all-optical” (without electrical loop amplifier) receiver, 8 dB better than our previous “optoelectronic” approach (with electrical loop amplifiers) [4]. On the other hand, to port the link on a carrier frequency much higher than the loop bandwidth, the optical sampling technique is used. By replacing the continuous wave (CW) optical source with an optical pulse source operating at a sampling rate close to the carrier frequency (within the range of baseband bandwidth), the signal on the carrier frequency can be downconverted to the baseband. It is also demonstrated that the feedback technique is also able to improve the SFDR by 14 dB in the sampling scenario.

II. EXPERIMENTAL RESULTS

The experimental setup is schematically shown in Fig. 2. The baseband frequency of this particular setup is limited to less than a few MHz due to the loop delay caused by fiber patch cords of the optical components used in the coherent receiver. Specifically, 140 kHz and 160 kHz are chosen for the two-tone SFDR measurements in baseband operation. An integrated version of the receiver is under intensive investigation in order to increase the baseband bandwidth to the GHz range.

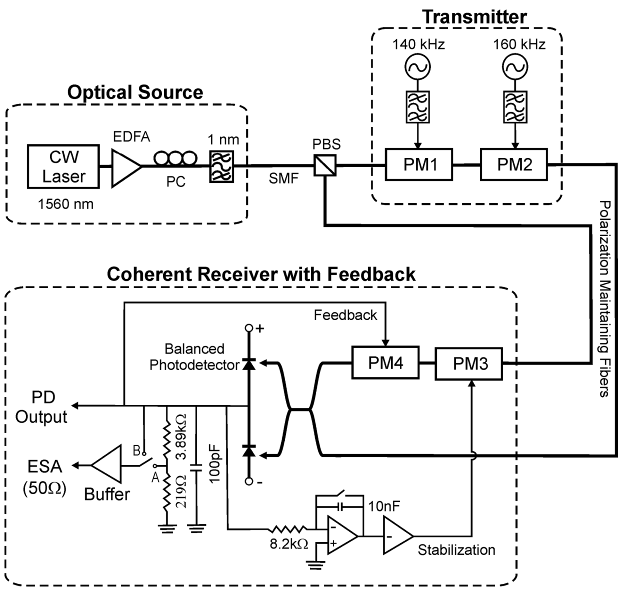

Fig. 2. Experimental setup of the coherent photonic link using the proposed receiver with feedback. PC: polarization controller; PBS: polarization beam splitter; PM#: phase modulator; SMF: single mode fiber; ESA: electrical spectrum analyzer; PD photodetector

An external cavity tunable semiconductor laser is used as the CW optical source at 1560 nm whose output is amplified by a high-power EDFA. For sampled operation, the CW laser is carved into optical pulses by an external $LiNbO_3$ modulator. The interferometer-based coherent link is constructed with polarization maintaining PANDA fibers and optical components for stability. The polarization controller after the EDFA can be used to adjust the power ratio between the two interferometer branches through the polarization beam splitter. The transmitter is composed of two sets of electrical synthesizer, bandpass filter, and $LiNbO_3$ modulator. This arrangement decouples the driving electronics at respective tones to ensure spectral purity. The harmonics distortions are suppressed to better than -80 dBc. The V_π of the phase modulators is around 4.4 V.

On the receiver side, two phase modulators, PM3 and PM4, are placed on the other branch of the interferometer. Both have open termination (very high impedance). The phase demodulator is composed of an optical coupler and a balanced photodetector with 0.9 A/W responsivity and biased at ± 10 V. PM3 is driven by a slow feedback loop to stabilize the interferometer against environmental drifts to the quadrature point of the phase demodulator, at which the output of the balanced photodetector is zero with no transmitted signal. PM4 is the local phase modulator that provides feedback at signal frequencies. The load of the balanced photodetector is 100 pF // 4.11kΩ // 8.2 kΩ. At 140 kHz, the impedance corresponds to 2.66 kΩ with an angle of – 13.5°. When the photocurrent from the balanced photodetector is large enough, say, a few mA, several volts of voltage swing can be obtained, which is sufficient to drive the local phase modulator and eliminates the need for electrical loop amplifiers. Therefore, this approach is termed "all-optical". Since the electrical spectrum analyzer has 50 Ω input impedance, an electrical buffer is used to match the impedance. A voltage divider is used at the input of the buffer to ensure that the buffer is operating at the most linear range (nominal 3rd harmonic distortion < – 103 dBc). The capacitance of the photodetector load determines how the loop transmission rolls off at high frequency. To prevent the feedback loop from oscillation, it is critical that unity gain is reached before the phase shifts by – 180°. At elevated frequencies, the load can contribute up to – 90° in phase while the loop delay (due to fiber patchcords and electrical wiring) adds extra phase monotonically with frequency (delay length * frequency / phase velocity * 360°) . Therefore, the loop delay is the main limitation on loop gain and baseband bandwidth: the shorter the delay, the higher frequency the loop can operate at without oscillation.

A. Baseband Operation

First, this all-optical coherent receiver is tested at baseband. To verify that the feedback loop does operate properly to reduce the swing across the phase demodulator, one tone at 140 kHz is transmitted and the receiver output (PD Output in Fig. 2) is measured on an oscilloscope. The theoretical open loop transmission of the local optical phase, T, can be determined by:

$$T = 2 \cdot \langle I_{PD} \rangle \cdot Z \cdot \frac{\pi}{V_\pi} \qquad (1)$$

where $\langle I_{PD} \rangle$ is the average photocurrent per photodiode, Z is the load impedance of the balanced photodetector. Note that T is defined for amplitude, not power. When 1) the loop transmission is large enough so that the phase difference between the signal phase and the local phase is small, and 2) the transmitter modulation depth is small so that the voltage-phase relationship of the phase demodulator is still linear, the voltage swing of the balanced photodetector output can be approximated as:

$$\frac{V_{closed}}{V_{open}} \cong \frac{\varphi_{signal} - \varphi_{local}}{\varphi_{signal}} \cong \frac{1}{1+T} \qquad (2)$$

Since the phase angle is small (–13.5°), T can be treated as a scalar for simplicity. Therefore, by measuring the ratio of the voltages, T can be obtained.

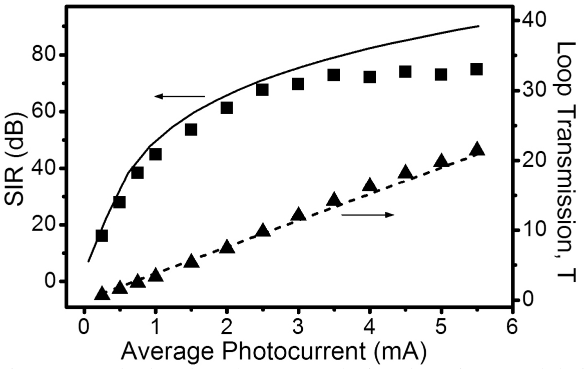

Fig. 3. Calculated and measured signal to intermodulation ration (SIR) at π rad peak-to-peak modulation and loop transmission, T, at 0.1 π rad peak-to-peak modulation, as a function of the average photocurrent per photodiode. (solid line: simulation; dashed line: theoretical)

The measured and theoretical values of T are shown in Fig. 3, where excellent agreement is obtained. This indicates that the all-optical approach does provide feedback gain as designed. For average photocurrents above 5.55 mA, the feedback loop starts to oscillate.

Next, two-tones at 140 kHz and 160 kHz are transmitted, both with a modulation depths of π rad peak-to-peak. The intermodulation distortion (IMD) at 120 kHz and 180 kHz are measured (almost equal strength) and the signal to intermodulation ratio (SIR) is plotted in Fig. 3. A theoretical curve calculated from the time-domain numerical simulation [5] is also shown. Close agreement is obtained for average photocurrent values smaller than 2.5 mA while the experimental SIR value seems to be clamped at 75 dB. The most likely reason is the increase of higher order distortions from the balanced photodetector at higher photocurrent levels.

The SFDR's with and without the feedback are also measured. For the case without feedback, the electrical connection to PM4 is simply disconnected. The measurement results are shown in Fig. 4(a) and (b). The reduction in voltage due to the voltage divider before the buffer is calibrated in order to obtain the actual voltage across the load. The power is referenced to that voltage across a 50 Ω load. For measuring the noise floor, the input of the buffer is connected to point B in Fig. 1, without dividing the voltage. This enables measurement of high dynamic range. At 2.0 mA of average photocurrent per diode, where T = 7.6, the measured SFDR's are 92.6 dB·Hz$^{2/3}$ without feedback and 110.7 dB·Hz$^{2/3}$ with feedback, showing an improvement of 18.1 dB over the traditional phase demodulator using a receiver with feedback.

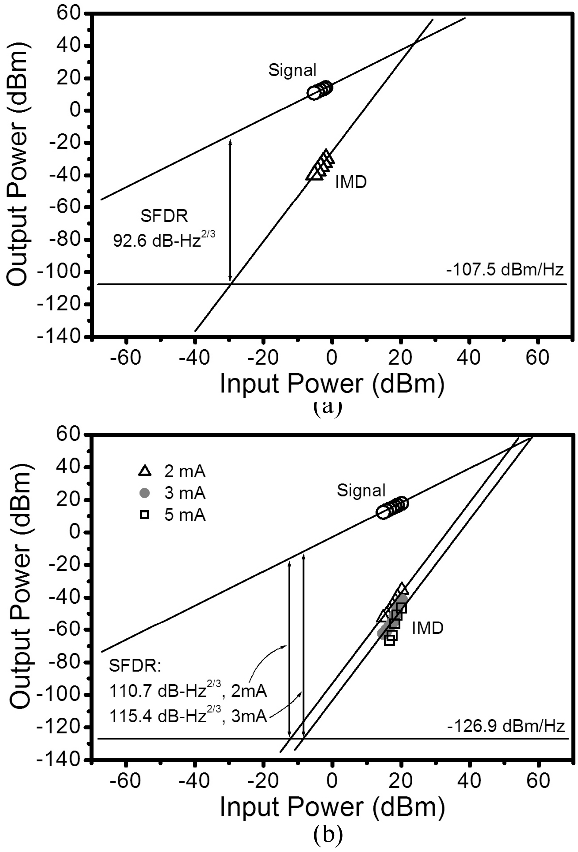

Fig. 4. SFDR measurements of baseband operation (a) whthout feedback, <I_{PD}> = 2.0 mA; (b) with feedback and three different <I_{PD}>. The signal frequencies are 140 kHz and 160 kHz, and the intermodulation frequencies are 120 kHz and 180 kHz.

It is worth noting that at the same input (transmitted) power, the output power of the link is reduced by approximately 20·log(1+T) dB with the feedback technique. However, the noise floor is also reduced by the same amount so that the SNR is preserved. The reward of the reduced output is much lower distortion. On the other hand, if the comparison is done at the same output power, using the feedback receiver can improve the SNR by 20·log(1+T) dB with a significantly reduced intermodulation distortion.

Ideally, even better SFDR can be obtained by increasing the loop transmission further through changing the variables on the right-hand side of (1). Fig. 4(b) also shows the measured IMD's when <I_{PD}> is increased to 3.0 mA and 5.0 mA. At 3.0 mA, the SFDR can be increased to 115.4 dB·Hz$^{2/3}$. However, the slope of the IMD curve starts to go above 3 beyond 18.2 dBm of input power (1.2 π rad peak-to-peak modulation depth). The slope change is even worse at 5.0 mA of average photocurrent. Referring to Fig. 3, 2.0 mA, 3.0 mA, 5.0 mA of average photocurrent correspond to the cases where the SIR is, respectively, not clamped, just clamped, and deeply clamped.

B. Sampled Operation

To transmit the baseband signal over an RF carrier frequency, an optical sampling technique can be used to downconvert the transmitted information back to the base band. The proposed receiver is also tested under sampled operation. The carrier frequency is set at 110.0 MHz and the transmitted tones are 110.140 MHz and 110.160 MHz. The CW laser source is first amplified by an added EDFA and carved by a push-pull type $LiNbO_3$ intensity modulator before boosted by the high-power EDFA. The FWHM pulsewidth is 1.08 ns, corresponding to a 12% duty cycle. The average photocurrent per diode is 2.0 mA, but the peak current can be 10 times higher. As shown in Fig. 5, the measured SFDR's are 85.9 dB·Hz$^{2/3}$ without feedback and 100.0 dB·Hz$^{2/3}$ with feedback, showing a 14.1 dB improvement. The noise floor of the no feedback receiver has been increased by 6.2 dB in the sampling operation, which could be caused by the added EDFA and led to a penalty in SFDR. A time-domain simulation for the sampled operation has been developed and reported separately [6].

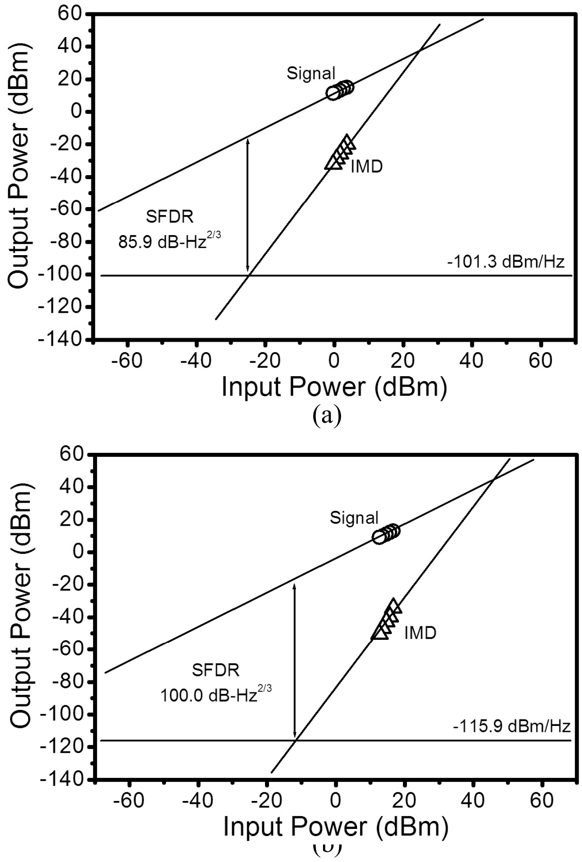

Fig. 5. SFDR measurements of sampled operation. (a) whthout feedback,; (b) with feedback. I_{PD} = 2.0 mA in both cases. The signal frequencies are 140kHz and 160kHz, and the intermodulation frequencies are 120 kHz and 180 kHz.

III. CONCLUSION

An all-optical coherent receiver with feedback has been proposed and demonstrated to increase the linearity of a coherent photonic link while maintaining the signal to noise ratio. The all-optical construction is simpler than our previous optoelectronic version and resulted in improved SFDR and stability. Nevertheless, the all-optical approach is more demanding on the photodiodes used in the receiver since they have to handle higher voltage swings. The first demonstration of optically sampled operation showed very promising potential of the proposed feedback receiver for wide applications. Monolithic and hybrid integration of this receiver concept are under intensive investigation to increase the baseband bandwidth.

ACKNOWLEDGEMENT

This work was supported by DARPA under the PHOR-FRONT program. The authors acknowledge useful conversations with Larry Coldren, Larry Lembo and Steve Pappert.

REFERENCES

[1] C. H. Cox III et. al,"Limits on the Performance of RF-Over-Fiber Links and Their Impact on Device Design," IEEE Trans. on Microwave Theory and Tech., Vol. 54, no. 2, pp: 906-920, Feb. 2006.

[2] B. Liu et. al, "Analog Characterization of Low-Voltage MQW Traveling-Wave Electroabsorption Modulators", Journal of Lightwave Technology, Volume 21, Issue 12, pp: 3011-3019, 2003.

[3] R. F. Kalman et. al, "Dynamic range of coherent analog fiber-optic links," Journal of Lightwave Technology, Volume 12, Issue 7, pp: 1263-1277, July 1994.

[4] H.-F. Chou, et. al, "SFDR Improvement of a Coherent Receiver Using Feedback", in Proc. of IEEE Conference on Coherent Optical Technologies and Applications (COTA), 2006, paper CFA3.

[5] D. Zibar et. al, "Time-Domain Analysis of a Novel Phase-Locked Optical Demodulator", in Proc. of IEEE Conference on Coherent Optical Technologies and Applications (COTA), 2006, JWB11

[6] D. Zibar et. al, "Theoretical Investigation of a Novel Optical Phase Demodulator Based on a Sampling Phase-Locked Loop", submitted to Microwave Photonics Conference 2006