Highly Linear Coherent Receiver With Feedback

Hsu-Feng Chou, *Member, IEEE*, Anand Ramaswamy, Darko Zibar, Leif A. Johansson, *Member, IEEE*,
John E. Bowers, *Fellow, IEEE*, Mark Rodwell, *Fellow, IEEE*, and Larry A. Coldren, *Fellow, IEEE*

***Abstract*—We propose and demonstrate a novel coherent receiver with feedback for high-linearity analog photonic links. In the proposed feedback receiver, a local phase modulator tracks the phase change of the signal and reduces the effective swing across the phase demodulator without reducing the transmitted signal. The signal-to-noise-ratio is thus maintained while linearity is improved. Up to 20-dB improvement in spur-free dynamic range (SFDR) is achieved experimentally. At 3.13 mA of average photocurrent per photodiode, the measured SFDR is 124.3 dB $\cdot$ Hz$^{2/3}$, which corresponds to an SFDR of 131.5 dB $\cdot$ Hz$^{2/3}$ when the link is shot-noise-limited.**

***Index Terms*—Analog links, coherent communication, feedback, microwave photonics, phase-modulation.**

I. INTRODUCTION

FROM residential CATV broadcasting to demanding military communications, analog photonic links have found a broad range of applications. In terms of linearity, the performance of an intensity-modulated analog link is mainly determined by the intensity modulator in the transmitter [1]. Interferometer-based intensity modulators have a sinusoidal response while absorption-based ones are typically exponential. In general, the modulation depth must be restrained and the bias point properly tuned to obtain a high degree of linearity [2]. On the other hand, electrooptic phase modulators can be quite linear compared to intensity modulators. The modulation depth is no longer hard-limited by the optical power to 100% as in an intensity-modulated link but by the range in which the phase modulator is linear. However, the challenge in constructing a high-linearity link is now moved to the receiver side. A traditional phase demodulator based on optical interference has a sinusoidal response and thus limits the linearity of a coherent link [3]. In other words, the same (sinusoidal) distortion remains in the link. Reducing the strength of the transmitted signal may reduce the distortion but the spur-free dynamic range (SFDR) remains unchanged.

To overcome this problem, we recently proposed a novel coherent receiver with a feedback design that is capable of reducing the distortion and improving the SFDR [4]. SFDR of 103.5 dB $\cdot$ Hz$^{2/3}$ was demonstrated, showing a 15-dB improvement from a traditional receiver. In this letter, we further improve the work in [4] using an all-optical construction and achieve SFDRs as high as 131.5 dB $\cdot$ Hz$^{2/3}$ in the shot-noise-limited scenario and a 20-dB improvement from a traditional receiver.

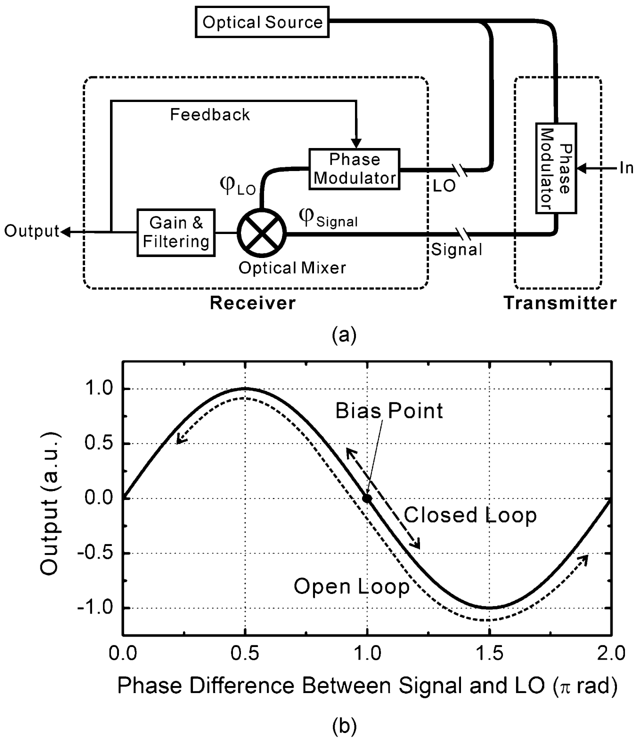

Fig. 1. (a) Concept of the proposed coherent receiver with feedback. Thick lines: optical link; thin lines: electrical link. (b) Transfer function of an interferometer-based phase demodulator (optical mixer). After closing the loop, the swing of the phase difference is reduced, resulting in a more linear output.

II. PRINCIPLE OF OPERATION

The proposed receiver in a coherent link is illustrated in Fig. 1(a). The optical source is first split into two branches: one goes directly to the "LO" input of the receiver while the other is phase modulated by the transmitter and then fed into the "signal" input of the receiver. The phase demodulator (an optical mixer) compares the phase of the two inputs and generates a differential signal. Fig. 1(b) shows the transfer function of an interferometer-based optical mixer, which possesses a sinusoidal response. The bias point is set to the quadrature point to eliminate the even-order distortions and obtain the highest slope efficiency. The modulation depth can be larger than π rad (equivalent to 100% in an intensity-modulated link) but the distortion in the demodulated signal increases with modulation depth. However, in the proposed feedback receiver, as shown in Fig. 1(a), the output from the optical mixer is fed back to a local phase modulator in the LO branch after amplification and filtering. The effect of such feedback is to reduce the difference

Manuscript received October 2, 2006; revised March 11, 2007. This material is based upon work supported by the Defense Advanced Research Projects Agency (DARPA) PHOR-FRONT Program under United States Air Force Contract FA8750-05-C-0265.

H.-F. Chou was with the Department of Electrical and Computer Engineering, University of California, Santa Barbara, CA 93106 USA. He is now with LuminentOIC, Inc., Chatsworth, CA 91311 USA (e-mail: Hsu-Feng.Chou@ieee.org).

A. Ramaswamy, D. Zibar, L. A. Johansson, J. E. Bowers, M. Rodwell, and L. A. Coldren are with the Department of Electrical and Computer Engineering, University of California, Santa Barbara, CA 93106 USA.

Digital Object Identifier 10.1109/LPT.2007.898811

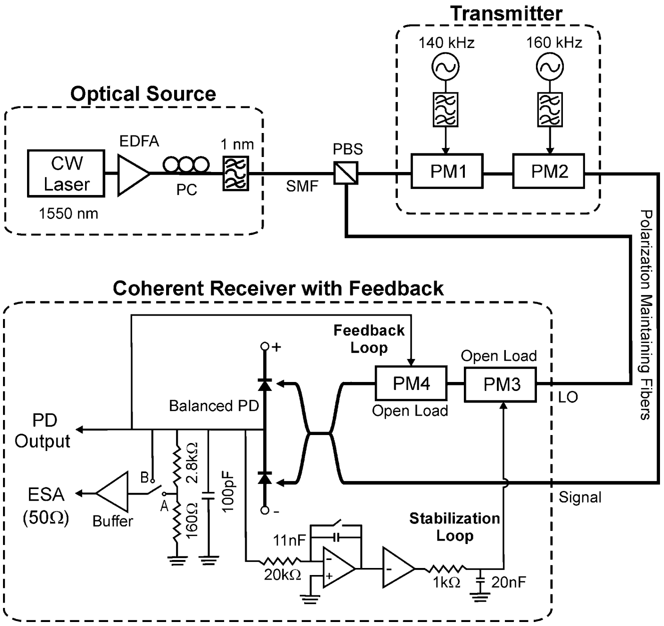

Fig. 2. Experimental setup. In order to handle the high dynamic range of the receiver, the buffer amplifier is connected to A for measuring signal and to B for measuring noise. PC: polarization controller. SMF: single-mode fiber. PBS: polarization-beam splitter. PM#: phase modulator. ESA: electrical spectrum analyzer.

in phase between the LO and the signal branches. The effective swing across the phase demodulator is thus reduced, leading to a more linear output [Fig. 1(b)]. Note that this reduction in swing is not achieved by decreasing the strength of the transmitted signal and the signal-to-noise ratio (SNR) of the transmitter remains the same. On the receiver end, the SNR of the output signal is also preserved after closing the loop since both the signal and the noise are reduced by the same factor. The benefit of such reduction in swing is the improvement in receiver linearity without decreasing the transmitted power and degrading the SNR, which leads to an effective improvement in SFDR.

III. EXPERIMENT

The experimental setup is schematically shown in Fig. 2. The bandwidth of this particular setup is limited to a few megahertz due to the loop delay caused by fiber patch cords of the discrete components used in the receiver. Therefore, 140 and 160 kHz are chosen for the two-tone SFDR measurements. The delay of an integrated receiver should be three orders of magnitude smaller. An external cavity tunable semiconductor laser is used as the CW optical source at 1550 nm whose output is amplified by a high-power erbium-doped fiber amplifier (EDFA). This interferometer-like coherent link is constructed with polarization-maintaining fibers and components for polarization management and stability. The lengths of the two interferometer branches are matched with an optical delay line to minimize the impact of laser noise. The polarization controller after the EDFA is used to adjust the power ratio between the two branches through the polarization beam splitter. The transmitter is composed of two sets of electrical synthesizer, bandpass filter, and $LiNbO_3$ phase modulator. This arrangement decouples the driving electronics at respective tones to ensure spectral purity. The harmonic distortions are suppressed to better than -80 dBc. The nominal $V\pi$ of the phase modulators is 4.4 V.

On the receiver side, two phase modulators, PM3 and PM4, are placed on the LO branch. Both have open termination (very high impedance). The optical mixer is composed of a single-polarization optical coupler and a balanced photodetector with 0.9-A/W responsivity and biased at ±12 V. The saturation power of the photodetector is over 12 dBm. Not shown in Fig. 2 are two 10-μF polypropylene capacitors that bypass the RF signal from the power supplies to the ground. In contrast to our previous work in [4], the feedback loop does not contain active amplifiers to provide loop gain. Instead, the passive load of the balanced photodetector is designed to provide gain and filtering. The balanced photodetector is thus directly driving the local phase modulator without using electrical amplifiers. This "all-optical" construction reduces the extra delay, noise, as well as distortion associated with the electrical amplifiers. More significantly, this direct-drive architecture makes it easier to integrate the feedback receiver monolithically on a single chip [5] in order to minimize the loop delay for higher operation speed, without resorting to hybrid packaging.

PM4 is the local phase modulator that provides feedback. The load of the balanced photodetector is 100 pF // 2.96 kΩ // 20 kΩ. Since the electrical spectrum analyzer has 50-Ω input impedance, an electrical buffer (LMH6703, nominal third-harmonic distortion < -103 dBc) is used to match the impedance. To prevent the feedback loop from oscillation, it is critical that unity gain of the loop is reached before the phase shifts by $-180°$. The capacitance of the load governs the roll-off of the loop gain and inevitably consumes $-90°$ of phase margin. As a result, the loop delay is the main bottleneck that limits the bandwidth. The shorter the delay, the higher frequency the receiver can operate at without oscillation. The loop delay in the current setup is approximately 3 m. PM3 is driven by a slow feedback loop to stabilize the interferometer against environmental drifts and maintains the bias of the phase demodulator to the quadrature point. A first-order *RC* filter is added to the output stage to suppress the noise that is generated by the stabilization electronics from entering the signal loop. The DC drift from the quadrature point is less than $\pm 0.04\%$.

The open loop transmission of the LO phase T is defined as the open-loop round-trip gain in the feedback path. It can be expressed as

$$T = 2 \cdot < I_{\mathrm{PD}} > \cdot Z \cdot \pi / V_{\pi} \tag{1}$$

where $< I_{\mathrm{PD}} >$ is the average photocurrent per photodiode and Z is the load impedance. Fig. 3 shows the SFDR measurements at $< I_{\mathrm{PD}} >= 3.13$ mA $(T = 11.24)$, where the LO optical power is 3.5 mW. By equating the optical phase of the feedback loop, it can be derived that the effective swing across the phase demodulator can be suppressed by a factor of $1/(1+T)$ from its original strength after closing the loop. In the case of $T = 11.24$, the effective swing is suppressed to 8%. As a result, SFDR is improved from 104.5 dB $\cdot$ $\mathrm{Hz}^{2/3}$ to 124.3 dB $\cdot$ $\mathrm{Hz}^{2/3}$, showing a 19.8-dB improvement by using the feedback receiver. The noise levels are measured by switching the buffer input to point B in Fig. 2.

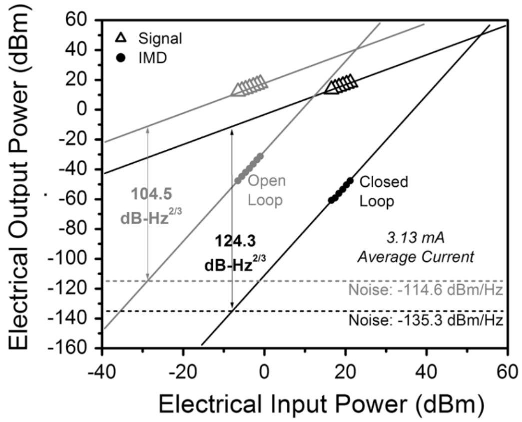

Fig. 3. SFDR measurements at 3.13 mA of average photocurrent. The powers are referring to a 50-Ω load. The noise level is normalized and measured with 300 Hz of resolution bandwidth. Gray lines: open loop. Black lines: closed loop. IMD: third-order intermodulation distortion.

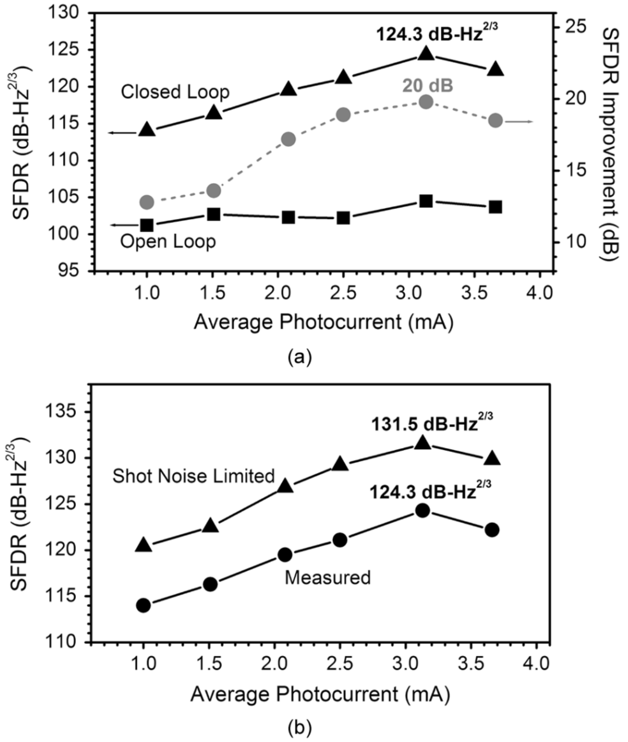

Fig. 4. (a) SFDR of the open and the closed loops. (b) SFDR with measured and shot-noise-limited noise levels for the closed loop case.

Theoretically, the RF gain of the link is given by $[T/(1+T)]^2$, which approaches unity when T is high. The SNR is dominated by the shot-noise in the receiver and the phase noise of the laser. It is preserved after closing the loop as can be observed in Fig. 3. On the other hand, the intermodulation distortion is suppressed at the same output level after closing the loop, resulting in the increase of linearity. The SFDR can be improved by $(1+T)^2$ compared to a traditional receiver but is subject to the linearity of all the components used in the receiver.

Fig. 4(a) shows the dependence of SFDR on the average photocurrent per photodiode for the open loop and the closed loop cases. For the open loop (a traditional receiver), increased photocurrent does change the maximum swing of the phase demodulator but it cannot improve linearity. Therefore, the measured SFDR shows little dependence on average photocurrent. On the other hand, for the closed loop, the loop transmission increases with average photocurrent [as expressed in (1)], which leads to a smaller effective swing across the phase demodulator and thus better linearity and SFDR. Nevertheless, the SFDR starts to roll off beyond 3.13 mA of average photocurrent and becomes unstable (even before the loop oscillates). This is believed to be caused by the degradation of photodetector linearity at high photocurrent levels.

The currently measured noise levels are approximately 10 dB above the theoretical shot noise level, leading to about 6.7-dB penalty in SFDR, as indicated in Fig. 4(b). At several milliamperes of photocurrent, shot-noise dominates over thermal noise, representing the theoretical limit of noise level. If the shot noise limit can be achieved, up to 131.5 $\mathrm{dB}\cdot\mathrm{Hz}^{2/3}$ of SFDR can be obtained. The excess noise is believed to be caused by the finite linewidth of the laser source (50 kHz) [3] and the noise from the high-power EDFA.

Ideally, the achievable SFDR of the proposed feedback receiver does not have fundamental limitations as long as the loop delay is short enough to sustain a desirable amount of loop gain at the bandwidth of interest. The practical challenge for extreme linearity lies on the linearity of the components in the link (phase modulators, photodetectors, and loop amplifiers if utilized). To scale the bandwidth to the gigahertz range, hybrid or monolithic integration of the receiver is necessary to keep the loop delay down to $\sim$10-ps level.

IV. CONCLUSION

A novel all-optical receiver with feedback is proposed and experimentally demonstrated to improve the SFDR of a coherent analog photonic link. The feedback design is successful in reducing the distortion due to the sinusoidal response of a traditional phase demodulator without degrading the SNR. SFDR improvement of 20 dB is demonstrated at the highest measured SFDR of 124.3 $\mathrm{dB}\cdot\mathrm{Hz}^{2/3}$, which corresponds to a shot-noise-limited SFDR of 131.5 $\mathrm{dB}\cdot\mathrm{Hz}^{2/3}$.

ACKNOWLEDGMENT

The authors would like to thank L. Lembo, P. Ly, S. Pappert, and J. Hunter for helpful discussions.

REFERENCES

[1] C. H. Cox III, E. I. Ackerman, G. E. Betts, and J. L. Prince, "Limits on the performance of RF-over-fiber links and their impact on device design," *IEEE Trans. Microw. Theory Tech.*, vol. 54, no. 2, pp. 906–920, Feb. 2007.

[2] B. Liu, J. Shim, Y.-J. Chiu, A. Keating, J. Piprek, and J. E. Bowers, "Analog characterization of low-voltage MQW traveling-wave electroabsorption modulators," *J. Lightw. Technol.*, vol. 21, no. 12, pp. 3011–3019, Dec. 2003.

[3] R. F. Kalman, J. C. Fan, and L. G. Kazovsky, "Dynamic range of coherent analog fiber-optic links," *J. Lightw. Technol.*, vol. 12, no. 7, pp. 1263–1277, Jul. 1994.

[4] H.-F. Chou, A. Ramaswamy, D. Zibar, L. A. Johansson, J. E. Bowers, M. Rodwell, and L. Coldren, "SFDR improvement of a coherent receiver using feedback," in *Proc. IEEE Conf. Coherent Optical Technologies and Applications (COTA)*, Whistler, BC, Canada, Jun. 25–30, 2006, Paper CFA3.

[5] M. N. Sysak, J. W. Raring, J. S. Barton, M. Dummer, A. Tauke-Pedretti, H. N. Poulsen, D. J. Blumenthal, and L. A. Coldren, "Single-chip, widely-tunable 10 Gbit/s photocurrent-driven wavelength converter incorporating a monolithically integrated laser transmitter and optical receiver," *Electron. Lett.*, vol. 42, no. 11, pp. 657–658, May 2007.