A Simple High-Speed High-Output Voltage Digital Receiver

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Abstract—We present measurements of a simple photoreceiver capable of generating 2.0 V at 15-Gb/s nonreturn-to-zero (NRZ), and 2.0 and 3.0 V at 24 and 10-Gb/s return-to-zero (RZ), respectively, directly from a p-i-n photodiode. Thus, this photoreceiver generates signal levels compatible with high-speed logic, clock recovery, and/or modulation with low-V, LiNbO$_3$ modulators without the need for electrical postdetection amplification. The bit-error ratio (BER) is not compromised with this approach since this receiver generates clean eye diagrams with a BER of $10^{-20}$ with $-30$-dBm input at 10 Gb/s.

Index Terms—Optical communication, optical fiber amplifiers, optical fiber communication, optical receivers, photodetectors, photodiodes, receivers, signal detection.

As data rates increase above 10 Gb/s, a bottleneck in photoreceiver design continues to be the design of electrical postdetection amplifiers which have a low-frequency cutoff below 30 kHz, high gain, automatic gain control, ±2-dB gain flatness and bandwidths above 10 GHz. In addition, for nonoptically preamplified detection, the fundamental limitations of receiver sensitivity using p-i-n photodiodes is the input thermal noise to the electrical postdetection amplifier, while with an avalanche photodiodes (APD) detector, limited gain-bandwidth and excess noise factor limit sensitivity. Therefore, as the system bandwidth increases, so must the input optical signal levels. It is well known that optical preamplifiers [1]–[3] can be used to increase photoreceiver sensitivity, however, postdetection electrical amplifiers still limit the bit rate in practical systems. Here, we demonstrate a simple optical receiver which overcomes the bit rate limits due to postdetection amplification with the use of a high current p-i-n photodiode and an erbium-doped fiber amplifier (EDFA) to yield over 3.0-V peak-to-peak ($V_{pp}$) output directly from the photodetector, in contrast to a 150-mV output previously reported [4]. High-output voltage is necessary for clock recovery, decision circuits, and/or direct remodulation with LiNbO$_3$ modulators. The basic components of this receiver (Fig. 1) are a two-stage (45-dB gain, 30-mW saturated output @ 1550 nm) EDFA, a 3-nm optical filter (selected for return-to-zero (RZ) operation with 1-ps optical pulses), and a high-current p-i-n photodiode. Since the incident light to the photodiode can be leveled, primarily by gain saturation with secondary pump level control, the dc (average) electrical signal out of the photodiode can be constant and independent of the incident light level. It is intended that the output power from the EDFA will be large such that, after the conversion to an electrical signal by the photodetector, a peak photodetector output voltage of greater than 1.0 V is generated. From an unmatched photodetector (no parallel output resistor), this equates to 20 mA p-p. To generate 20-mA p-p photocurrent without significant distortion and with duty cycles approaching 50%, photodetectors must have a small-signal 1-dB compression current ($I_{1dB}$) [5] of greater than 20 mA, since it is the peak current (for slowly varying signals) which causes photodetector compression [6]. This system includes all the necessary photoreceiver features: very broad electrical bandwidth, high sensitivity, automatic gain-control, very flat amplitude response, and tolerance for long pseudorandom bit streams due to the kilohertz low-frequency cutoff in the EDFA and the possibility of a dc coupled photodetector.

In digital systems, a flat amplitude and phase response is required to minimize pulse distortion. Since the EDFA preamplifier can be very flat over hundreds of gigahertz, only the photodetector package needs to be engineered to have flat response. Fig. 2 shows the frequency response of a high-current p-i-n photodiode. The device is a 0.5-µm-long intrinsic region photodiode similar to [7] having a responsivity of 0.36 A/W at 1550 nm and biased through a 20 kHz–30 GHz bias tee. The 3-dB bandwidth is 27 GHz and the small dips in the response above 17 GHz are packaging resonances. The phase response deviated less than ±10° from linear from 0.05 to 15 GHz. The photodetector output is not impedance matched, so all the ac photocurrent flows through the 50-Ω load impedance.

Measurements of $I_{1dB}$ at 1550 nm for this photodetector are plotted in Fig. 3 for test frequencies of 10 and 20 GHz. It is measured by illuminating the device with a small component of RF-modulated light and adding a component of unmodulated light separated in frequency sufficiently far to
Fig. 2. Measured frequency response of the high current photodetector at 5-V bias voltage, 100% modulation depth and 1-mA average photocurrent.

Fig. 3. Measured 1-dB small-signal compression current. The test frequencies are 10 (round) and 20 (square) GHz and the illumination wavelength is 1550 nm.

Fig. 4. Measured BER and photodetector output voltage versus input optical power to the EDFA preamplifier. The circles and squares correspond to NRZ and RZ modulation formats at 10 Gb/s, respectively. The photodetector bias voltages are 8 V (RZ) and 5 V (NRZ). The pattern length is $2^{231}-1$.

prohibit generation of detectable (beat-note) electrical signals but close enough (1–10 nm is sufficient) to achieve good overlap of the optical fields. The RF photoresponse decreases at high average (dc) illumination levels due to a buildup of carriers in the depletion region, accompanied by a partial collapse of the intrinsic region electric field [6]. As observed, the measurement is a slight function of RF frequency. The lower compression current at higher frequencies is the result of the higher ratio between the increased transit time and the period ($1/f$) for a given depressed electric field (constant current). Since the failure mechanisms at high photocurrents for this photodetector have not been investigated in detail, the bias voltage was kept just above that what was required for uncompressed (low distortion) operation to minimize the power dissipation in the junction.

To test the sensitivity of the high-current receiver, an externally modulated mode-locked laser [8] which generates 1.3-ps pulses was used to form RZ data streams and an externally modulated external-cavity laser diode was used to form the NRZ data streams. The receiver sensitivity and photodetector output voltage is plotted in Fig. 4 for RZ and NRZ data formats. The measured back-to-back receiver sensitivities were $-32.5$ and $-30$ dBm for RZ and NRZ data formats, respectively, for a bit-error ratio (BER) of $10^{-9}$. 

Fig. 5. Measured eye diagrams for (a) RZ 10 Gb/s at 3.0 V, (b) RZ 24 Gb/s at 2.0 V, and (c) NRZ 15 Gb/s at 2.0 V. The pattern length in all cases is $2^{231}-1$, with a 1/2 mark ratio. The average input power to the EDFA was $-5$ dBm in all cases. The photodetector bias voltages and average photocurrents are (a) 8 V and 7.6 mA, (b) 8 V and 8.0 mA, and (c) 6 V and 23.6 mA.
Note that the output voltage for the NRZ data at $-30$ dBm input power is just above the error detector threshold for $10^{-9}$ BER. Although this sensitivity is slightly below that which is possible [1]–[3] for optically preamplified receivers, it is intended to show that the high current receiver by itself does not degrade BER performance since no increase in BER was observed for output signal levels from 200 mV to 2.0 V. Note that at $-24$ dBm input power (EDFA $\sim 6$ dB in compression), the output voltage for the NRZ data format is over 0.5 $V_{pp}$. Thus, this 10 Gb/s receiver’s sensitivity is already comparable to that obtained in p-i-n-FET receivers [9], with the potential to increase it to below $-39$ dBm [3], [10]. Thus for high sensitivity systems, an additional 7–15-dB optical gain would be required to increase the sensitivity and to yield output voltages approaching 1 $V_{pp}$ for input power levels below $-30$ dBm. This would require an input EDFA (preamplifier) with a lower input compression point.

Photodetector output voltages of 3.0 and 1.0 $V_{pp}$ are obtained for the RZ and NRZ data formats, respectively. The higher output for RZ data is a consequence of a higher peak power on the photodetector, due to the lower (optical) duty cycle compared to NRZ for the same average photocurrent (only the average optical power is clamped with a saturated EDFA). To maintain a linear response, the photodetector bias voltage was increased for the RZ data format. This photodetector is capable of nearly 40 mA (peak) at 4-V bias (Fig. 3). Therefore, a bias voltage of 8 V was necessary for the RZ data format to maintain 5 V across the photodetector terminals while delivering 3 V (60 mA peak) to the 50-$\Omega$ load.

The eye diagrams for a 10- and 24-Gb/s RZ data stream are shown in Fig. 5(a) and (b), respectively, where a clean eye opening and low distortion are observed. Over 3.0 $V_{pp}$ and 2.0 $V_{pp}$ output is obtained for 10 and 24 Gb/s RZ data streams, respectively. Since the photocurrent is approximately the same, the difference is due to the lower duty cycle and hence a higher peak voltage for the 10-Gb/s RZ data format. The RZ eyes [Fig. 5(a) and (b)] reveal the inductive peaking in the frequency response (Fig. 2) as a slight undershoot in the pulse response. The undershoot limits the operation of this photodetector to RZ data rates below 25 Gb/s, as higher rates would move the undershoot into the decision-making region of the pulse. This reasserts the need for digital receivers to maintain flat, low-ripple frequency responses. For this receiver, that simply entails careful microwave packaging of the photodetector and the related passive biasing components.

To increase the output signal levels (not the input sensitivity) for NRZ data formats above 1.0 V, a high-power EDFA was inserted between the filter and the photodetector (Fig. 1). The eye diagram for a 15-Gb/s NRZ data stream is shown in Fig. 5(c) at 2.0 $V_{pp}$ output. Again note the clean eye opening as well as the low distortion. To ensure that the high signal levels did not degrade receiver performance, the BER was monitored while varying the optical power to the photodetector, thereby varying the output voltage from 0.2–1.9 V. Error-free operation (BER < $10^{-12}$) was obtained for all cases, with the threshold tolerance increasing in proportion to the signal voltage, as expected. The extension of this receiver to bit rates from 30 Gb/s to beyond 100 Gb/s is now practical with state of the art 20 mA, 25–80-GHz bandwidth detectors.

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