5.2dB Sensitivity Enhancement in 25Gbps APD-Based Optical Receiver Using Dynamic Biasing

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Abstract: First demonstration of dynamically biased 25Gbps avalanche photodiode-based receiver operating at 1.55 µm is reported. A 5.2dB improvement in receiver sensitivity and 10,000-fold reduction in bit-error-rate 25-Gbps are experimentally demonstrated using a commercially available InGaAs-InP APD.

OCIS codes: (040.1345) Avalanche photodiodes (APDs); (060.4510) Optical communications; (060.2330) Fiber optics communications; (040.5160) Photodetectors

1. Introduction

To meet the increasing demand for bandwidth, 25 Gbps solutions per channel are sought for 100 Gbps ethernet systems, passive optical networks (PONs) [1], as well as future 400 Gbps ethernet, which can utilize four-level pulse-amplitude modulation (PAM-4) [2]. While avalanche photodiodes (APDs) have traditionally been the photodetector of choice in high-speed direct-detection receivers, their commercial availability at speeds beyond 10Gbps has been a challenge. APDs offer high sensitivity and low-cost compared to receivers that employ PIN photodiodes with optical pre-amplification. An APD provides high internal gains through a stochastic cascade of impact ionizations effected by a strong reverse bias, a feature that is not present in the simpler PIN photodetectors. However, the APD's internal gain comes at the cost of the avalanche-buildup time, the time it takes for the chain of all impact ionizations to terminate every time a photon-generated carrier triggers an avalanche of impact ionizations. The buildup time often limits the APD's gain-bandwidth product (GBP) and can lead to inter-symbol interference (ISI) when the APD is operated at gains of interest (~10) in high-speed optical receivers. There have been numerous efforts in the past two decades to explore new materials, device concepts, and structures to overcome the buildup-time limitation of InP and InAlAs APDs for above-10 Gbps long/middle reach operation and for low-power applications [3]. Key examples are waveguide APDs [4,5], where a very thin absorption layer is used to reduce carrier-transit time. However, they suffer from the tradeoff between responsivity (which improves with the waveguide length) and speed (which decreases as the device capacitance increases with the waveguide length). In addition, they have very tight optical tolerance requirements due to the narrow waveguide [6]. Recently, Nada *et al.* [6] at NTT reported a vertical illumination InGaAs-InAlAs APD operating at 50Gbps with a GBP of 270 GHz; the operating gain at 35 GHz was achieved at low gain (~3) due to the buildup time, which translates to a sensitivity of -10.8 dBm. It has become clear that in order to break the GBP limit of APDs the buildup time must be substantially reduced. Toward that goal, Si-Ge APDs have been developed and shown promise [7]; however, low responsivity and high dark currents are still challenging problems. To the best of our knowledge, the only commercially available 25Gbps APD has been develop by Albis (http://www.albisopto.com).

In 2015, the authors reported the first demonstration of a dynamically biased APD that broke the traditional sensitivity-versus-speed limit by employing a data-synchronous sinusoidal reverse-bias [8]. This technique drastically suppresses the average avalanche-buildup time [9,10]. The dynamic biasing regulates the impact-ionization process, thereby limiting the buildup time to unprecedented low levels, regardless of the structure and material composition of any build-time limited APD [9]. The initial demonstration showed that compared with traditional DC biasing, the sensitivity of germanium APDs at 3Gbps is improved by 4.3 dB, which is equivalent to a 3,500-fold reduction in the bit-error rate (BER). In this paper, we present the first demonstration of BER and sensitivity enhancement due to dynamic biasing at transmission speeds of 25 Gbps operating at λ=1.55 µm. The dramatic improvement opens the door for extending the operability of APDs in present 100Gbps and future 400 Gbps systems.

2. Dynamic biasing of linear-mode APDs for NRZ detection

Previously, the authors proposed a sinusoidal biasing scheme that is frequency-matched and synchronous with the optical NRZ bit stream [9,11] as a method to improve receiver sensitivity. As in [9,11], we assume that the reverse bias applied to the APD has the form $V(t)=V_{DC}+V_{AC}\sin(2\pi f_c t+\phi)$, where f_c is set to be equal to the data transmission rate, R (bits per second). The quantities V_{DC}, V_{AC} and ϕ are selected to control the multiplication factor in each bit period, and more importantly to maximize the benefit of dynamic biasing in minimizing the buildup time and ISI. In practice, the synchronization between the sinusoidal bias and the data stream is established electronically by means of a clock/data recovery (CDR) and phase lock loop (PLL) circuits [12]. It was argued theoretically in [9] that the APD's pulse response under dynamic biasing is substantially shorter than that under traditional static biasing as a result of reduction in the build-up time, once the delay between the bias waveform and the bit stream is optimized. Specifically, it was predicted that dynamic biasing can yield a receiver performance equivalent to that when the GBP of the APD is elevated by a factor of 5 once the delay between the pulse and the dynamic biasing is set near the optimal value [9]. Figure 1 (from Ref. [10]) shows the calculated buildup-time limited eye-diagram when dynamic biasing is used for an InP APD having a multiplication-region width of 200 nm. The eye for conventional biasing is totally closed in this case (not shown). Since the instantaneous gain of the APD follows the dynamic bias within each bit, the shape of the eye is different from the conventional NRZ eye under static biasing of the APD [10]. The physics of the buildup-time reduction can be explained as follows: First, photons that arrive early in the optical pulse experience a period of high electric field in the multiplication region of the APD, where they can generate a strong avalanche current in the early phase of the optical-pulse interval. As a low electric field period follows within the same optical pulse, carriers in the multiplication region undergo a weakened impact ionization process, which leads to the termination of the avalanche pulse with a high probability. Second, photons that arrive late in the optical pulse period are still detected as the APD remains reverse biased throughout the bias period. However, the resulting avalanche gain is very low and the resulting avalanche pulses are very short. Overall a high gain is generated over the optical bit but with minimal ISI.

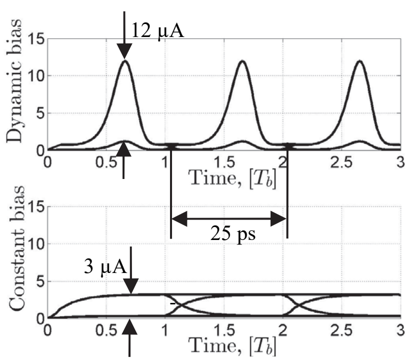

Fig. 1. From Ref. [10]. Calculated eye-diagram of an InP APD with a multiplication-region width of 200nm, at 40 Gbps NRZ, for dynamic (top) and static (bottom) biasing. A 10% non-extinction ratio is assumed.

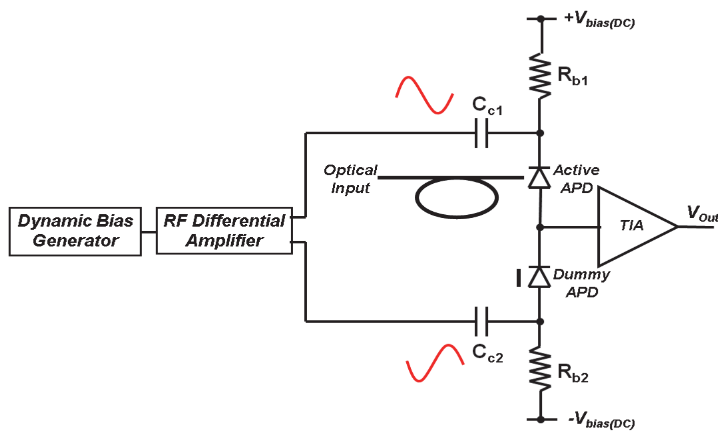

Fig. 2. Custom designed differentially balanced receiver circuit for dynamically biased APD.

3. Experimental results

An optical receiver with dynamic biasing was designed and implemented using commercially available components and a 25Gbps InGaAs-InP APD (Albis APD16L), as shown in the block diagram of Fig. 2. The tested APD has shown a breakdown voltage of about 21 V and the responsivity was estimated as 0.91A/W at 1.55 μm wavelength. To eliminate the dynamic-bias signal injection to the APD output, a matching "dummy" APD (shown as the bottom APD) was utilized in a fully differential configuration. The pattern generator from the bit-error-rate tester (BERT, Multi-Lane ML4009) was used to drive a Mach-Zehnder modulator, in conjunction with a 1.55 μm DFB laser source, producing a pseudo-random optical bit stream at a data rate of 25 Gbps. The optical signal was fed into the upper APD through an optical delay line that controls the phase between the optical bit stream and the AC bias signal. The 25GHz sinusoidal AC bias signal was generated by applying appropriate frequency division/multiplication and RF amplification to the clock provided by the pattern generator, which made it automatically synchronous with the bit sequence. For simplicity, an external RF amplifier; the gain of the external RF amplifier is 30dB. The APD's photocurrent goes through a matching 50 Ω resistor that acts as a photocurrent-to-voltage convertor. In practical receiver, the 50 Ω resistor and RF amplifier would be replaced by a trans-impedance amplifier (TIA), which may further boost the overall optical-receiver sensitivity due to an improved signal-to-noise ratio.

Figure 3 shows a comparison of the eye diagrams, when an AC bias of 2.7V peak-to-peak is applied (top) and when no AC biasing is applied (bottom). The optical input in both cases is -23 dBm with the data rate of 25 Gbps. The DC bias of -20.8 V, which corresponds to the APD gain of 8.5, is selected to maximize the eye opening in the static biasing case. For the dynamic biasing case, the AC bias is superimposed on the same DC bias, where its phase is tuned by using the optical delay line to maximize the eye opening. The dramatic 4x widening in the eye is clearly evident as a result of the application of the delay-optimized AC bias. Figure 4 shows the BER as a function of the optical power seen by the APD for both static- and dynamic-bias cases. The results show that the receiver sensitivity (when BER=10^{-3}, consistent with IEEE Standard for PON) at 25 Gbps transmission is improved by 5.2 dB. The results also demonstrate a significant improvement in the BER. For example, when the optical input is -20dBm, the improvement in the BER is by a factor of 10,000.

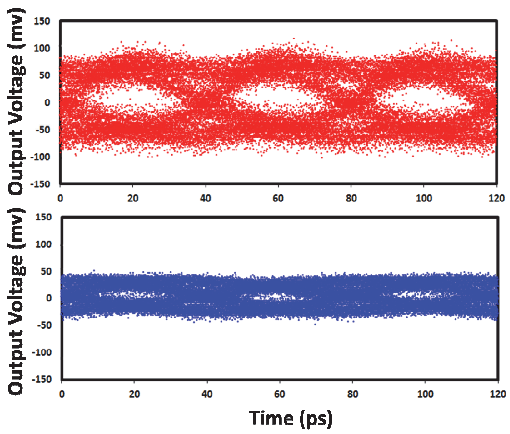

Fig. 3. Comparison of the eye diagrams for the dynamically biased APD (top) and the conventional statically biased APD

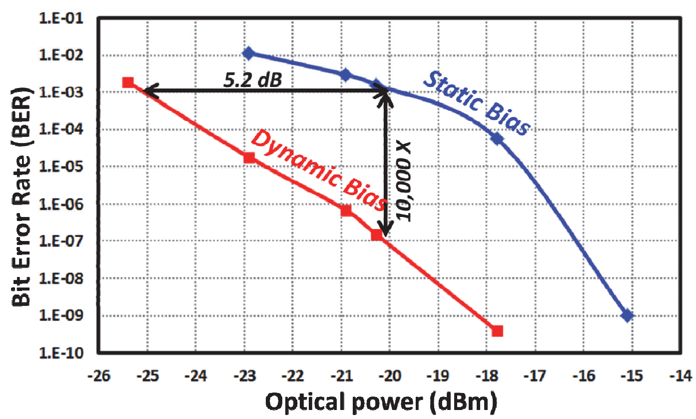

Fig. 4. Comparison of the BER for the dynamically biased APD (bottom) and the conventional statically biased APD (top).

4. Conclusions

We have shown that bit-synchronous dynamic biasing of an APD offers a 5.2 dB enhancement in the optical receiver sensitivity in 25Gbps NRZ signaling while employing a commercially available 25Gbps APD. This dramatic enhancement in performance is achieved by reducing the avalanche buildup time, thereby minimizing the ISI. The results are consistent with our earlier demonstration at a speed of 3 Gbps, while employing a germanium APD. The present demonstration confirms the validity of the dynamic-biasing technique for speed and sensitivity enhancement of APDs over a wide range of bit rates and APDs. Since the added cost in implementing dynamic biasing is small at high volumes, we anticipate this technique to be an enabler of high-performance 25 Gbps APD-based receivers and beyond for present and future high-speed systems.

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