First Demonstration of a 100 Gbit/s PAM-4 Linear Burst-Mode Transimpedance Amplifier for Upstream Flexible PON

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Abstract *We demonstrate operation of a linear burst-mode TIA integrated with a commercial lensed APD supporting 100-Gbit/s PAM-4 with OMA sensitivity of −15.8-dBm and 50-Gbit/s NRZ with OMA sensitivity of −23.7-dBm. Dynamic range exceeding 21.7-dB is achieved for NRZ and 15.4-dB for PAM-4 reception. ©2022 The Author(s)*

Introduction

Burst-mode (BM) transimpedance amplifiers (TIAs) are key component of upstream (US) passive optical network (PON) receivers, specific to PON technology. The ever-increasing demand in upstream rates towards 50 Gbit/s and even 100 Gbit/s demands for new electrically broadband and linear designs that can support digital equalisation and multi-level modulation formats. In PON, the upstream signal received at the optical line termination (OLT) receiver is a stream of consecutive individual bursts from different optical network units (ONUs), which may exhibit a large dynamic range of optical powers due to the differential path loss of the optical distribution network (ODN – up to 15 dB), as well as the variation in ONU transmitters launch powers (more than 5 dB expected for ITU-T 50G PON [1] US). BM TIAs are required to rapidly (within 150 ns) level this large power dynamics and suppress transients due to changing optical DC levels for different bursts. They optimally condition the signal for electrical post-detection using a slicer or an analog-to-digital converter (ADC). The wide range of required gains and the need for fast gain and offset adjustment renders the design of BM TIA circuits increasingly difficult at higher symbol rates.

Recent demonstrations of burst-mode reception included 25 Gbit/s with non-return-to-zero (NRZ) [2]-[5] or quaternary pulse amplitude modulation (PAM-4) [6]. 50 Gbit/s BM reception was shown either using an optical preamplifier without TIA [7]; in the context of data centres with limiting (nonlinear) TIA, without support for PON dynamic range [8]; or using PAM-4 linear BM TIAs up to 25 GBd [9]-[10]. However, the 50 Gbit/s upstream option of 50G PON, currently under definition in ITU-T, will employ 50 Gbit/s (50 GBd) NRZ requiring even more TIA bandwidth and enhanced linearity to support equalisation of chromatic dispersion, chirp and limited electro-optic bandwidth (as well as its variability at wide range of gains). The linearity is not only an enabler of equalisation, but also allows for PAM-4 as a potential future PON modulation format, allowing to double the bitrate to 100 Gbit/s PON to most [11] or all ONUs [12].

In this paper, using a novel linear BM TIA assembled with an off-the-shelf 25G-class APD, we demonstrate, to our knowledge, not only the first BM-TIA-assisted reception of BM 50 Gbit/s NRZ (50G) signals with PON-compatible dynamic range but also the first reception of BM 100 Gbit/s (100G) PAM-4. For 100G, an outer optical modulation amplitude (OMA) at 10^{-2} BER sensitivity of −15.8 dBm with a dynamic range of at least 15.4 dB was achieved, while for 50G an

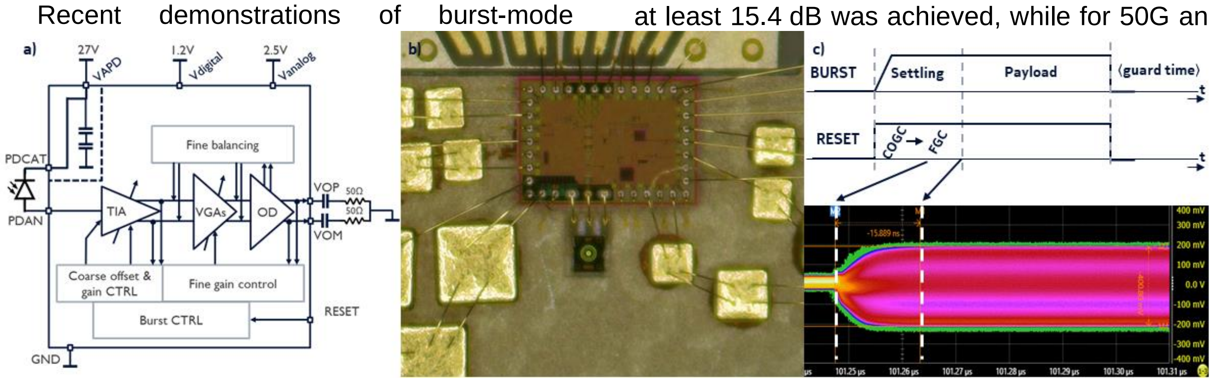

Fig. 1: (a) High-level circuit schematic of the TIA, (b) Photomicrograph of the assembly with the TIA chip and APD, (c) Burst timing diagram and explanation of the settling time of the fine gain control loop.

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OMA sensitivity of −23.7 dBm and a dynamic range beyond 21.7 dB is demonstrated.

100 Gbit/s Linear BM TIA

A linear BM TIA integrated circuit (IC) was fabricated in a 0.13 µm SiGe process whose heterojunction bipolar transistors have a fT of 350 GHz. It consumes 275 mW (on average) from a 2.5 V supply for the datapath, of which 69% is used for the RF signal path. The burst-mode control circuits run on 1.2 V supply. As shown in Fig. 1(a), the IC has a first transimpedance amplifier stage whose gain and DC offset can be adjusted coarsely according to the incoming burst strength using a coarse offset and gain control loop (COGC). It is followed by a series of variable gain amplifiers (VGAs), whose gains are set using a fine gain control (FGC) loop. Accurate removal of the remaining dc-offset from the signal is done using a so-called fine balancing loop. Lastly, an output driver (OD) is used to drive a differential 100 Ω load. The TIA achieves a total transimpedance gain ranging from 39 dBΩ to 80 dBΩ (electrical) to cope with a wide optical dynamic range, exceeding 20 dB (optical).

The burst-mode operation is illustrated in Fig 1(c). An external reset, provided by the OLT, signals the start of the preamble. The burst controller activates the COGC, which quickly adjusts the transimpedance gain to the incoming burst strength and subtracts the estimated DC component of the input photocurrent offset. Subsequently, the FGC loop is activated and adjusts the total data path gain to obtain a fixed output voltage swing with a fast settling time, irrespective of the input power. The fine balancing loop corrects residual errors in the coarse offset current cancellation and mismatch in the amplifiers. The total settling time of the BM TIA is well under 150 ns, meeting the typical PON target preamble time [1].

To allow digital equalisation at the receiver and PAM-4 modulation, Yin *et al.* [13] have demonstrated the linearity requirement expressed in total harmonic distortion (THD) to mitigate the power penalty in presence of limited bandwidth of opto-electronic components and chromatic dispersion. As a result, the BM TIA has been designed for linearity, achieving a THD <5% (for burst weaker than −6dBm peak-to-peak input).

The chip was wirebonded together with an off-the-shelf 25G-class avalanche photodiode (APD) on a test board. At ≥50 GBd rates, traditional APD/BM TIA assemblies are typically limited by the LC resonance present between the TIA and the APD, primarily caused by the internal capacitance of the APD, the parasitic inductance of the wirebond between the anode of the APD and the input of the TIA and by the cathode wirebond. Our design alleviates this bottleneck by decoupling the >20 V APD bias on-chip with capacitors isolated from the rest of the IC. This allows to connect the anode and the cathode of the APD directly to the TIA, through very short wirebonds, thereby reducing the impact of their inductance. The mutual inductance between the side-by-side wirebonds which are in proximity of each other further reduces the total parasitic inductance, pushing the resonance to even higher frequencies.

System Experiment

We evaluated the linear BM TIA in the experimental setup shown in Fig. 2(c,f). An electrical 50 GBd signal (NRZ or PAM-4) was generated and amplified to drive an MZM supplied with a 1308.7 nm laser source. For NRZ, the transmitter eye closure (TEC) evaluated in optical back-to-back as per ITU-T G.9804.3 was 2.4 dB, and the extinction ratio (ER) evaluated on a long run of consecutive identical digits was measured to be 10.6 dB. For PAM-4, the outer ER was 6.7 dB, Fig. 2(d,e). A burst-mode signal with large dynamics (>20 dB) was generated by carving the continuous signal coming from the MZM by means of a SOA. The optical signal-to-noise ratio at the SOA output at any burst power level was higher than 40 dB. The SOA burst carver generated 10-µs-long bursts with 100 ns guard time, following a staircase pattern (see Fig. 2(a)) or an interleaving loud-soft pattern (Fig. 2(b)), with loud bursts at a maximum power

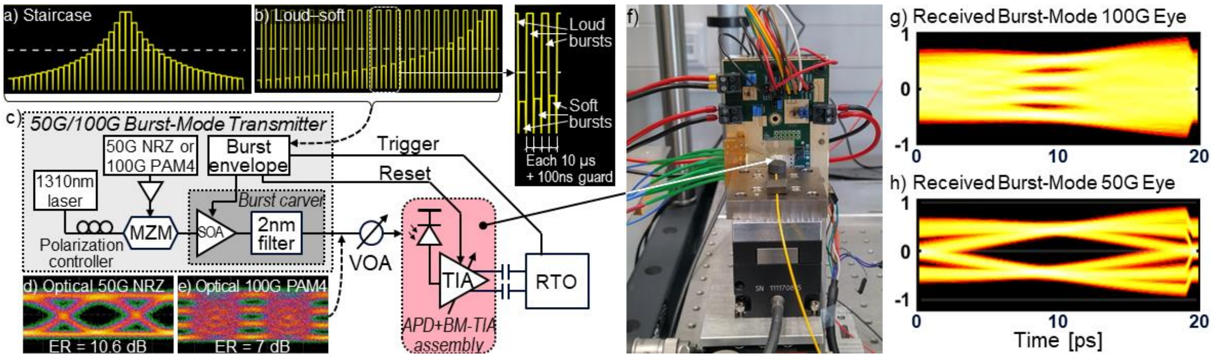

Fig. 2: Burst envelopes driving the burst carver: (a) staircase and (b) loud-soft showing a zoom with details. (c) Experimental setup used for the system test; MZM – Mach-Zehnder modulator, SOA – semiconductor optical amplifier, VOA – variable optical attenuator, RTO – real-time oscilloscope. Optical eye diagrams of (d) 50G NRZ and (e) 100G PAM-4. (f) Photograph of the experimental testbench. Burst-mode electrical eye diagrams after equalisation: (g) 50G NRZ and (h) 100G PAM-4.

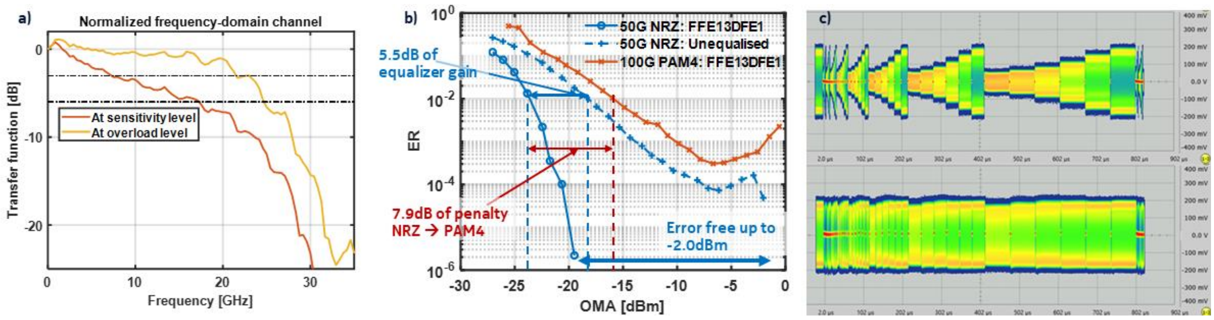

Fig. 3: (a) End-to-end bandwidth measurement of the entire system at high and low TIA gain. (b) Bit error ratio as a function of OMA for 100G PAM-4 and 50G NRZ signals. (c) Example of wide dynamic range TIA operation (leveling) at varying timescales; top: electrical signal with DC component removed, with gain control disabled; bottom: gain control enabled.

level (average power – AVP: −1.7 dBm) and soft bursts with varying power levels representing PON dynamics. A 2-nm-wide optical bandpass filter was used at the transmitter to suppress out-of-band amplified spontaneous emission noise from the carving SOA, and a VOA was used to adjust the power of the carved bursts to the target range. The optical signal was then coupled to the lensed APD assembled with the BM TIA. The APD bias was fixed at around 95% of the breakdown voltage (responsivity ≈3A/W). The electrical waveforms from the TIA were AC-coupled and sampled by an RTO. Acquired traces were processed offline using a Mueller-Müller clock recovery and equalised using a symbol-spaced 13-tap feedforward equaliser (FFE) with one tap decision feedback equaliser (DFE), leading to the eye diagrams shown in Fig 2(g,h). The number of taps was chosen as a trade-off between performance and a realistic complexity. The equaliser taps were trained on a preamble of 500 bits (10 ns) and fixed after, while BER was calculated over the whole equalised payload data.

Results and discussion

Based on the received signal, the transfer function were computed to estimate the frequency response of the entire system including the 25G-class APD and BM TIA assembly. The result is shown in Fig. 3(a). We achieve a normalized 6 dB bandwidth of 17.1 GHz at sensitivity level and 24.6 GHz at overload level. The TIA IC itself has a 3 dB bandwidth of 21 GHz and 44 GHz for high gain and low gain respectively (simulated post-layout extracted values).

To evaluate the TIA performance, BER measurements for BM 100G PAM4 and BM 50G NRZ were performed. The resulting BER curves as a function of OMA are shown in Fig. 3(b). For the 50G experiment, the measured sensitivity at a pre-FEC BER threshold of 10^{-2} [1], expressed in OMA, was −23.7 dBm (AVP: −25.9 dBm). The 10^{-2} BER can be lowered to $<10^{-12}$ using a rate-0.84 low-density parity check (LDPC) code [1]. The graph also shows 50 Gbit/s NRZ unequalised operation, illustrating a 5.5 dB improvement in sensitivity due to digital equalisation. The bursts remain error free (pre-FEC input BER$<10^{-6}$) at least up to an OMA of −2.0 dBm (the highest input power measured during the sweep, still with margin to the BER threshold), yielding a dynamic range of at least 21.7 dB. For 100G, an OMA sensitivity of −15.8 dBm (AVP: −17 dBm) was achieved at a BER of 10^{-2} and remained below target BER threshold up to −0.4 dBm OMA (dynamic range of 15.4 dB). The penalty between 100G PAM-4 and 50G NRZ was measured to be 7.9 dB in OMA at BER of 10^{-2}, similar to values reported in the context of flexible PON downstream based on PAM-4 and NRZ [11].

Fig. 3(c) shows that for varying optical input powers and varying burst lengths, the output swing of the BM TIA settles to a constant voltage swing (without compression of the eye diagram). This validates the linear BM operation of the TIA.

The sensitivity penalty for the loud-soft pattern using the 50G NRZ signal due to charging and discharging of the AC coupling after 150-ns-long preamble was found to be up to 0.9 dB over the first 17280 bits (346 ns) of the received signal when using a guard time of 100 ns. This penalty fades to 0.3 dB after 9 µs and can be mainly attributed to imperfect settling of the balancing loop, resulting in signal shifts due to the AC-coupling with the RTO.

Conclusions

In this paper we demonstrated the first linear BM TIA, suitable for reception of 100 Gbit/s PAM-4 and 50 Gbit/s NRZ. Assembled with an off-the-shelf 25G-class APD, we demonstrated PAM-4 OMA sensitivity of −15.8 dBm at BER 10^{-2} over at least 15.4 dB optical power dynamic range, and 50 Gbit/s NRZ with an OMA sensitivity of −23.7 dBm over 21.7 dB dynamic range.

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