Low-Complexity Balanced Quasi-Coherent Receiver with Integrated 2x2 MMI Balanced Photodiode and TIA for 50G PON

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Abstract *An integrated balanced quasi-coherent receiver front-end is designed, fabricated, and experimentally demonstrated for 50G Passive-Optical-Network. At 50 Gb/s NRZ, the measured OMA sensitivity (BER=1e-2) is -25.8 dBm B2B and -19.8 dBm after 5 km SSMF in C-band, without chromatic-dispersion compensation and equalization in DSP.*

Introduction

Due to the emergence of video/audio streaming, cloud computing, and the development of 5G networks with front, mid, and backhaul capabilities, there has been an exponential increase in demand for higher bandwidth and data rates across access networks. To satisfy these requirements in access networks, new Passive Optical Network (PON) standards with data rates exceeding 25 Gb/s have been proposed, such as 50G-EPON [1] and 50GPONpmd [2].

Coherent detection is regarded as a possible solution for satisfying data rate, reach and optical budget requirement for high-rate optical access networks [3]. However, high order modulation formats in coherent receiver are incompatible with existing NRZ modulation format in deployed PONs. Besides, complex Digital Signal Processing (DSP) in traditional coherent receiver makes the cost and power consumption unacceptable to upgrade existing PON components [4]. Alternatively, in Intensity Modulation Direct Detection (IMDD) schemes, Avalanche Photodiodes (APD) have been used to enhance sensitivity due to their higher responsivity than PIN photodiodes [5]. Semiconductor Optical Amplifier (SOA) provides further optical pre-amplification [5]. Another issue for high-rate PONs is serious signal degradation introduced by chromatic dispersion after long distance transmission in Standard Single Mode Fibre (SSMF) which needs to be compensated by complex DSP. In addition to the cost increase from using APD, dispersion-compensation DSP increases both the cost and power consumption. Though moving laser wavelength from C-band to O-band can partially alleviate the problem, thanks to lower chromatic dispersion in O-band, equalization for compensating chromatic dispersion is usually required as the data rate goes beyond 25 Gb/s. To break the bottleneck of traditional coherent and IMDD receivers, low-complex quasi/simplified-coherent detection schemes have been proposed in recent years [4,7,8]. These schemes not only improve the sensitivity but also require no complex DSP functions such as carrier phase estimation, chromatic dispersion compensation/equalization, and higher order symbol detection. To the best of the author's knowledge, no integrated system solution has been published that combines both a photonic IC (integrated optical couplers and photodiodes) and electrical IC (high-speed TIA) in quasi-coherent receivers with baud rates surpassing 25G for a single wavelength in either C- or O-band. Furthermore, previous demonstrations of quasi/simplified-coherent systems [4,7,8] have not effectively addressed the suppression of Relative Intensity Noise (RIN) originating from the Local Oscillator (LO).

This paper proposes an integrated balanced quasi-coherent receiver which contains a 2x2 MMI, a pair of balanced PIN photodiodes and a high bandwidth TIA. The received signal power can be optically amplified through beating with a LO, decreasing the impact of the TIAs electronic noise. In addition, the RIN caused by the LO is largely suppressed by employing balanced photodiodes [9] in the proposed quasi-coherent configuration. The sensitivity expressed in optical modulation amplitude (OMA) of -25.8 dBm (-27 dBm average power) and -19.8 dBm (-21 dBm average power) at BER 1e-2 for 50Gb/s NRZ in B2B and 5 km SSMF in C-band has been experimentally demonstrated. For 40Gb/s NRZ, the sensitivity (in OMA) of -27.8 dBm and -22 dBm at BER 1e-2 are achieved in B2B and 10 km SSMF in C-band. Additionally, we achieve sensitivity (in OMA) of -29.8 dBm and -21.8 dBm at BER 1e-2 for 25 Gb/s NRZ in B2B and 20 km SSMF in C-band respectively.

Principle of Balanced Quasi-Coherent Receiver

Fig. 1 shows the simplified block diagram of the proposed balanced quasi-coherent integrated

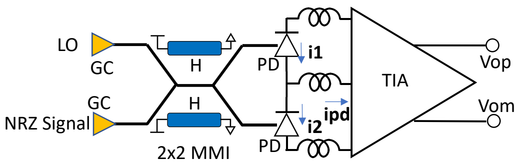

Fig. 1: Block diagram of balanced quasi-coherent receiver.

receiver. Signal and LO are coupled into the photonic IC (PIC) via a grating coupler (GC) with 3 dB insertion loss and mixed through 2X2 MMI. Then, two outputs from optical coupler are fed separately into two on-chip photodiodes. Based on the basic principle of 2x2 MMI, after the squaring and subtraction operation in the balanced photodiodes, common-mode components are eliminated but differential parts add up constructively. Eq. (1), Eq. (2) and Eq. (3) are currents flowing through two PDs (i1 and i2) and flowing into TIA (ipd), R is responsivity of PD. Thanks to the use of a strong LO, the AC signal components are amplified significantly. The RIN introduced by the LO is suppressed thanks to the balanced operation [9,10]. In order for the balanced receiver to operate optimally, it is important that each photodiode generates equal amounts of DC current. Due to manufacturing tolerances, the MMI will deviate slightly from the ideal splitting ratio, or the photodiode responsivity can differ slightly. To tune the splitting ratio, two waveguide heaters (H on Fig. 1) are placed next to the MMI. By applying a thermal gradient across the MMI, the optical power can be steered. This allows us to reduce the amount of unwanted DC current flowing into the TIA and to improve the RIN rejection. Therefore, there is no need for dedicated DC block capacitors in front of the TIA: such DC-coupled receivers architecture can be beneficial particularly for burst-mode signal detection in PON's upstream [6]. The balanced quasi-coherent PIC is fabricated in imec's iSiPP50G silicon photonic platform. The high-speed TIA is fabricated in ST 55nm Si-Ge BiCMOS process. The two chips are integrated together via wire bonding on a PCB.

$$\mathrm{i1} = \frac{1}{2}RP_{LO} + \frac{1}{2}RP_s + \sqrt{P_{LO}P_s}\cos(2\pi ft + \varphi) \quad (1)$$

$$\mathrm{i2} = \frac{1}{2}RP_{LO} + \frac{1}{2}RP_s - \sqrt{P_{LO}P_s}\cos(2\pi ft + \varphi) \quad (2)$$

$$\mathrm{ipd} = 2\sqrt{P_{LO}P_s}\cos(2\pi ft + \varphi) \quad (3)$$

Experiment Setup

The experiment setup is shown in Fig. 2. An arbitrary waveform generator (Keysight M8196A) with a sample rate of 92 GSample/s is used to generate 25/40/50 Gb/s pseudo random binary sequence (PRBS) data with a length of 2^15 -1. After the AWG a broadband RF amplifier drives a commercial Mach-Zehnder modulator (MZM) which is biased at its quadrature point. The distributed feedback laser (NKT KOHERAS BASIK) for operation in 1549.45~1550.59 nm wavelength range is used as laser source for the transmitter. After the MZM, the NRZ optical signal is further amplified by Erbium-doped fibre amplifier (EDFA). A programmable variable optical attenuator (VOA) is used to set signal power at different values. A same type of distributed feedback laser source is used as LO whose wavelength is offset to the transmitter laser. The LO power arrives before GC is 10.1 dBm. Finally, the PIC is fibre probed using two cleaved fibres. Different length of SSMF is inserted into the channel for evaluating the impact of chromatic dispersion to the receiver. Polarization controllers are used to adjust the polarization state of light because coupling efficiency of grating coupler is polarization state sensitive. The TIA outputs are wirebonded to the RF PCB and connected to RTO using an Ardent TR70 coaxial connector. The demodulation of the receiving NRZ signals have been performed offline in Matlab, including a simple square function and a low pass filter (f_{cutoff}=0.7Bitrate). These operations can also be realized by envelope detector [11] in analog domain. No extra equalization or chromatic dispersion compensation was used. The BER is calculated by bit error counting method.

Experiment results and discussion

Fig. 3 shows the results of sensitivity for our quasi-coherent receiver at 25/40/50 Gb/s NRZ

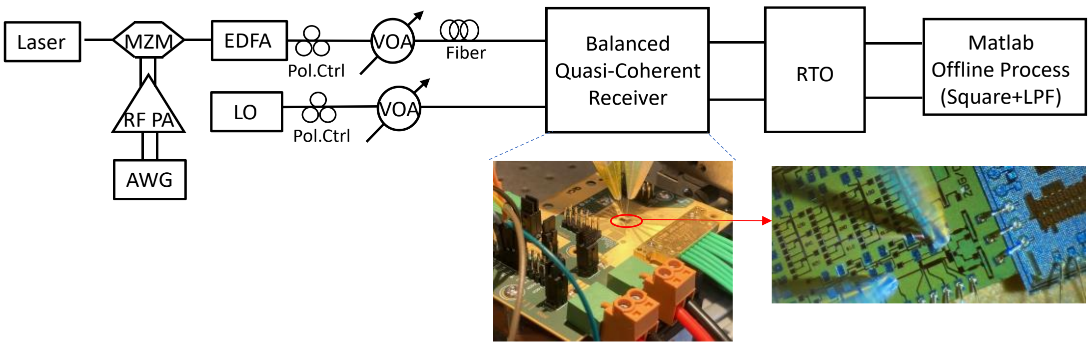

Fig. 2: Experiment setup.

with different transmission distance in SSMF. The sensitivity is received optical power arriving before GC. In B2B case with BER of 1e-2, the sensitivity in OMA is -25.8 dBm (-27 dBm in average), -27.8 dBm and -29.8 dBm for 50Gb/s, 40Gb/s and 25Gb/s NRZ respectively. After

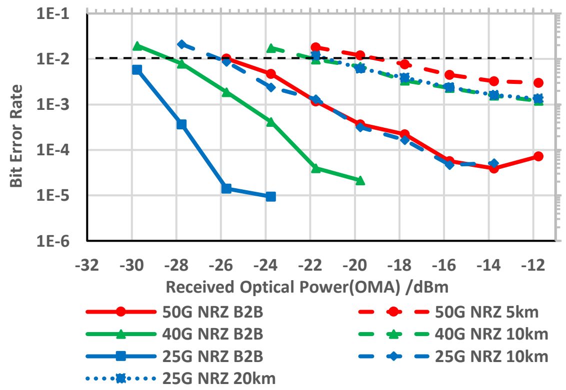

Fig. 3: Sensitivity of our quasi-coherent receiver at different data rate with different length of SSMF.

transmission in SSMF at C-band, targeting at BER 1e-2, the sensitivity (in OMA) is -19.8 dBm at 50 Gb/s NRZ with 5 km SSMF, -22 dBm at 40 Gb/s NRZ with 10 km SSMF and -21.8 dBm at 25 Gb/s with 20 km SSMF. The intermediate frequency is chosen to be close to the TIA 3dB bandwidth by tuning the frequency difference between the signal laser and LO [7]. As a result, the chromatic dispersion in the upper sideband can be suppressed. In Fig.4, the sensitivity (in OMA) dependence on carrier frequency of IF signal is shown. To obtain optimal sensitivity, carrier frequency should be chosen carefully for different data rates. As shown in Tab. 1, compared with others' work for 25/50G PON, we have demonstrated 50 Gb/s detection using a balanced quasi-coherent scheme via an integrated optoelectronic receiver. To compare the performance, we calculated the difference of the received average optical power as the previously published work [4,5,7] has no OMA

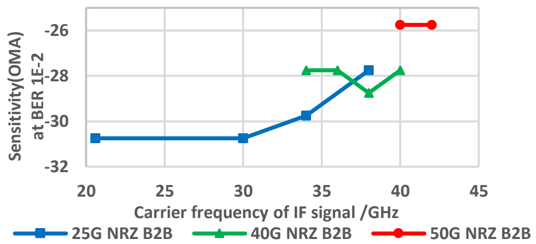

Fig. 4: Sensitivity dependence on carrier frequency of IF signal at BER 1e-2.

numbers. At 50 Gb/s NRZ, compared to EDB detection with SOA+PIN-TIA in [5], a sensitivity enhancement of 3 dB is achieved at BER threshold 1e-3. At 25 Gb/s NRZ, there is 7.2 dB improvement compared to EDB detection with APD in [5] of BER 1e-3. Besides, there is 6 dB improvement compared with [7] in a B2B situation of BER 1e-2, while operating at a reduced LO power of 10.1 dBm. Furthermore, the sensitivity remains at -19.8 dBm and -21.8 dBm after 5 km SSMF at 50Gb/s and 20 km SSMF at 25 Gb/s in C-band respectively. This has been achieved without digital chromatic dispersion compensation and equalization.

Conclusions

We have designed and fabricated a balanced quasi-coherent integrated receiver front-end, and measured its performance at 50 Gb/s, 40 Gb/s, and 25 Gb/s NRZ. The measured sensitivity expressed in OMA is -25.8 dBm and -19.8 dBm at BER 1e-2 for single wavelength 50 Gb/s NRZ in B2B and 5 km SSMF in C-band respectively without APDs (or optical preamplifiers) and any complex DSP. Measurement results suggest that a similar O-band implementation can reach extended transmission distances up to 20 km for 50 Gb/s NRZ, making this system a promising solution for cost-effective high-rate PONs.

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Tab. 1: Comparison with state of art (*B2B **5km SSMF ***20km SSMF)

	This work		[5]	[7]	[4]
Detection method	Balanced quasi-coherent		SOA or APD-based EDB Rx	Quasi-coherent	Simplified coherent 3x3 coupler
Sensitivity/dBm (50G NRZ)	At BER 1e-2 -25.8/-27*(OMA/AVP) -19.8/-21**(OMA/AVP)	At BER 1e-3 -23*(AVP)	At BER 1e-3 -20*(AVP)	N.A.	N.A.
Sensitivity/dBm (25G NRZ)	At BER 1e-2 -29.8/-31*(OMA/AVP) -21.8/-23***(OMA/AVP)	At BER 1e-3 -29.6*(AVP)	At BER 1e-3 -22.4*(AVP)	At BER 1e-2 -25*(AVP) -23***(AVP)	At BER 1e-2 -37*(AVP)
SOA	No		Yes (At 50G)	No	No
LO power/dBm	10.1		No LO	15	12
Wavelength range	C-band		O-band	C-band	C-band
Photodiode type	PIN		PIN/APD (50G / 25G)	PIN	PIN
Integration	MMI+PD+TIA		APD/PIN+TIA	PD+TIA+ED	NO

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