Highly-Linear Transimpedance Amplifier for Remote Antenna Units

G. Royo, C. Sánchez-Azqueta, C. Aldea, and S. Celma
Group of Electronic Design – (GDE-I3A)
Universidad de Zaragoza, Zaragoza, Spain
{royo, csanaz, caldea, scelma}@unizar.es

C. Gimeno
ICTEAM Institute, Université Catholique de Louvain
Louvain-la-Neuve, Belgium
cecilia.gimenogasca@uclouvain.be

***Abstract*— In this paper, a highly-linear low-noise transimpedance amplifier (TIA) for use in the downlink receiver of remote antenna units in distributed antenna systems is presented. It is intended for intermediate frequency over fiber (IFoF) communications at 500 MHz. With the implementation of a programmable transimpedance, IFoF transmission is achieved, showing a very low error vector magnitude over a large optical input dynamic range. The topology consists of a fully-differential shunt-shunt feedback TIA, which has been designed and fabricated in a 65-nm RF CMOS technology with a 1.2-V voltage supply. A driver based on a cascode configuration has been implemented for measurement purposes. The total power consumption is 19 mW, from which the TIA dissipates 6 mW, while it achieves a bandwidth of 700 MHz.**

Keywords*— Transimpedance amplifier; multi-mode fiber; radio over fiber; programmable gain.

I. INTRODUCTION

The demand of mobile and wireless devices has been continuously growing over the last years, driving the development of new wireless communication systems. These systems must provide high data capacity at high data transmission rates and good accessibility, which are main requirements of short-range wireless networks. Actual wireless communication systems must also increase their coverage and show higher immunity to interferences, which is an important issue in densely populated areas, where a large number of wireless networks concur, and it can be very challenging to achieve high data transmission rates.

In recent years, there is a growing interest in distributed antenna systems (DAS) fed by multi-mode fibers (MMF), especially for in-door applications. In a radio-over-fiber system, the RF signal is generated in a central station (CS), directly modulating a laser with a low optical modulation index (typically around 10%) and is then sent to several remote antenna units (RAU) through MMFs (see Fig 1a) These low-cost optical fibers present very low attenuation, wide bandwidth and immunity to electromagnetic interferences. Delivering the RF signal from the CS to several low-power RAUs, instead of a single high-power antenna offers a better distribution of the wireless signal, which results in very good coverage while reducing interferences with other networks [1]. To enhance the performance of a DAS, the RF signal is first down-converted to an intermediate frequency (IF), using an IF-over-fiber (IFoF) scheme, as shown in Fig. 1b.

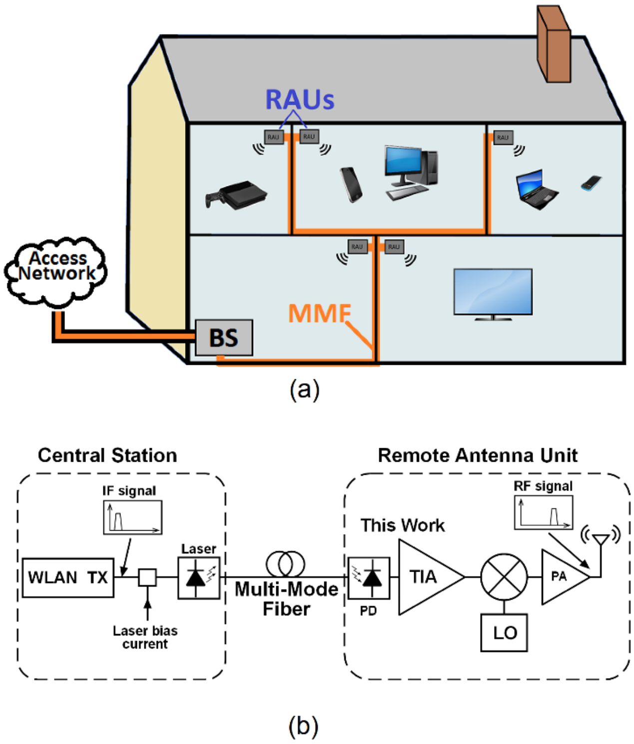


Fig. 1. a) Conceptual scheme of a distributed antenna system for indoor home networks; b) block diagram of an intermediate frequency-over-fiber downlink system.

To reduce the cost of installing a distributed antenna system, cost-effective fully-integrated RAUs must be designed, since a high number of RAUs is needed to ensure good coverage. The use of an IFoF system also reduces the cost of optical components while improving the sensitivity of the receiver. As shown in Fig. 1b, the design of the downlink consists of five main elements: (i) a photodiode (PD) that converts the light into current; (ii) a transimpedance amplifier (TIA) to generate a voltage signal; (iii) an up-converter to recover the original RF signal, (iv) a power amplifier (PA) and (v) the antenna. The main requirements for the RAU downlink are low noise and high linearity to properly process the IF signal. Consequently, an optical front-end must be available to bring these characteristics together.

In this work, we propose the design of a new fully-differential, low-noise transimpedance amplifier with highly linear performance aimed for use in a RAU downlink for short-range IFoF communications. It achieves a bandwidth up to 700 MHz and a controllable gain to increase the input dynamic range. The proposed TIA has been designed in a 65-nm RF CMOS technology.

The paper is organized as follows: Section II provides a detailed description of the proposed transimpedance amplifier; Section III presents the measurement results and Section IV presents the main conclusions of this work.

II. CIRCUIT DESCRIPTION

The transimpedance amplifier that converts the photocurrent to a voltage signal is typically the most critical block in an optical receiver. It is mandatory that the TIA present a very low noise level, as the equivalent input noise (EIN) of the TIA will determine the overall noise of the system and, therefore, the sensitivity of the receiver.

The overall bandwidth also depends greatly on the frequency response of the TIA, which must overcome the high intrinsic capacitance of the photodiode. In some recently published works, integrated avalanche photodiodes (APD) with very low junction capacitance are employed [2, 3]. However, these photodiodes show a worse linear performance than PIN photodiodes, while IFoF communication requires a good linearity to minimize the error vector magnitude (EVM). High linearity is also a requisite of the TIA, which also critically determines the linearity of the receiver.

In CMOS technology, open-loop TIA configurations based on the common gate stage, such as the regulated cascode, can offer high bandwidth and low noise, but they show a bad linear behaviour, so they are not recommendable for IFoF applications. Closed-loop TIAs show much better linearity and lower noise level, which increases the input dynamic range, while they can also achieve wide bandwidth [4].

In this work, a shunt-shunt feedback TIA topology has been chosen, as it shows the best performance for IFoF applications. A differential configuration has been used, reducing the effect of supply and substrate noise, and minimizing second order harmonics and intermodulation products, thus improving the overall linearity [5]. In this work, the authors propose a TIA based on an open-loop voltage amplifier implemented with three cascaded differential pairs and a negative resistive feedback loop (see Fig. 2). A programmable resistor has been included to control the transimpedance of the TIA, R_T, which can be approximated by a second order transfer function:

$$R_T \approx -\frac{2R_F}{1+\frac{2R_F C_{in}}{A}s+\frac{2R_F C_{in}}{A\omega_A}s^2} \tag{1}$$

where R_F is the feedback resistor, C_{in} the equivalent input capacitance, mainly determined by the photodiode capacitance, and A and ω_A the open-loop gain and the dominant pole frequency of the voltage amplifier, respectively.

By means of a programmable feedback resistor, R_F (see Fig. 3a), the input dynamic range can be extended, by reducing the transimpedance for larger input signals to avoid saturation and maintain a low non-linear distortion. However, it is well known that, as the transimpedance decreases, the quality factor, Q, increases [5]. This has a significant impact on the system stability, as it should be kept at low values; otherwise, the system becomes underdamped, high-frequency peaking appears and the system could start to oscillate. From (1), the Q factor can be approximated by:

$$Q \approx \sqrt{\frac{A}{2R_F C_{in}\omega_A}} \tag{2}$$

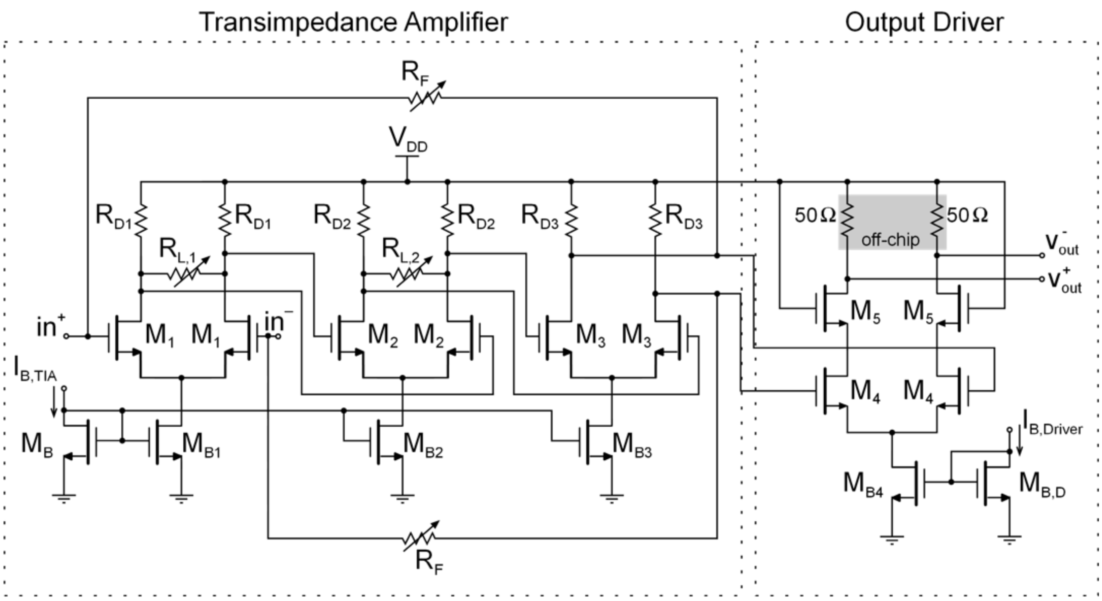
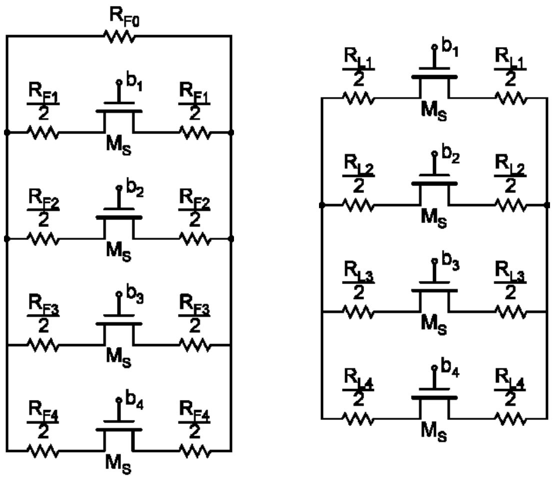


Fig. 2. Transistor-level topology of the proposed transimpedance amplifier with output driver for measurement purposes.



(a) (b)

Fig. 3. Implementation of the 4-bit programmable resistor arrays (a) feedback resistor, R_F and (b) load resistors, $R_{L,i}$.

In order to maintain constant Q against R_F changes, the first two differential pairs have been modified, implementing variable load resistors, $R_{L,1,2}$ (see Fig. 3b) to accordingly modify the dc open-loop gain, A, of the voltage amplifier. In this work, 4-bit thermometer-coded resistor arrays, R_F and $R_{L1,2}$, have been included to achieve, respectively, a simultaneous control of the transimpedance and the open-loop gain.

III. Results

The proposed TIA has been fabricated in a 65-nm RF CMOS technology with a single voltage supply of 1.2 V. The design has been optimized for an external high-bandwidth InGaAs PIN photodiode with a responsivity of 0.85 A/W at 1550 nm, a 0.45-pF junction capacitance and a bandwidth of 3 GHz under 50-Ω load, while the inherent parasitics of the wiring between the PD and the chip have been modeled with 5 nH inductances. An output driver based on a cascode architecture with open drains and external loads has been implemented to provide enough driving capability for the 50-Ω input measurement devices.

The power consumption of the TIA alone is 6 mW, and the total chip including the output driver, consumes 19 mW. The transimpedance can be programmed from 60 dBΩ up to 76 dBΩ with a 4-bit thermometer-coded resistor array, which has been adjusted to provide a linear-in-dB gain control, with 4-dB steps. As shown in Fig. 4, the simultaneously double control of the transimpedance and the open-loop gain avoids frequency response peaking at low-transimpedance.

The input-referred noise of the TIA has been simulated, to take into account only the circuit noise. At 500 MHz, the TIA exhibits an input-referred noise of 8 pA/$\sqrt{\text{Hz}}$.

To perform linearity measurements, we use the demodulation of 54-Mb/s 64 QAM data transmission at 500 MHz. Fig. 5 shows the measured EVM of the demodulated signal as a function of the input RF power level for the different transimpedance configurations.

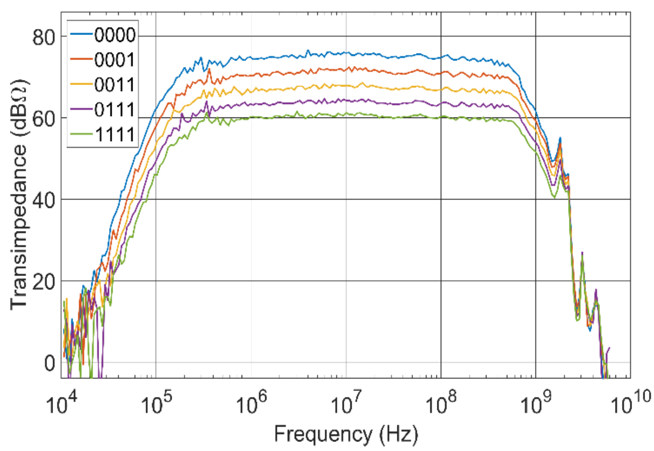


Fig. 4. Measured frequency response of the TIA with double control of transimpedance and open-loop gain.

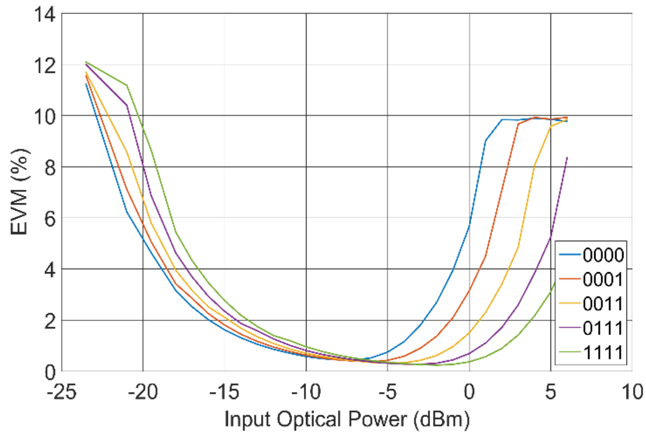


Fig. 5. Measured EVM as a function of the equivalent input optical power at different transimpedance configurations.

The electrical measurements have been performed using the M9381A PXIe vector signal generator and the M9391A PXIe vector signal analyzer using the experimental setup shown in Fig.6. The TIA exhibits an EVM of less than 2% for a wide input range from -60 dBm to -20 dBm RF power, which corresponds to an optical input dynamic range of -16 dBm to +4 dBm. This is the lowest EVM compared to the values reported in [2, 3, 6], and it is achieved for a wide input dynamic range of 20 dBm optical power, compared to the 3 dBm and 5 dBm ranges reported, respectively, in [2] and [3], respectively.

In Table I, the main parameters and measurement results for our proposal are summarized and compared to recently published TIAs for RoF applications. To compare the performance of the proposed TIA with recently published works, we define a Figure of Merit (FoM):

$$FoM = \frac{\text{Transimpedance } (\Omega) \cdot \text{BW (GHz)}}{\text{Power Consumption (mW)}} \tag{3}$$

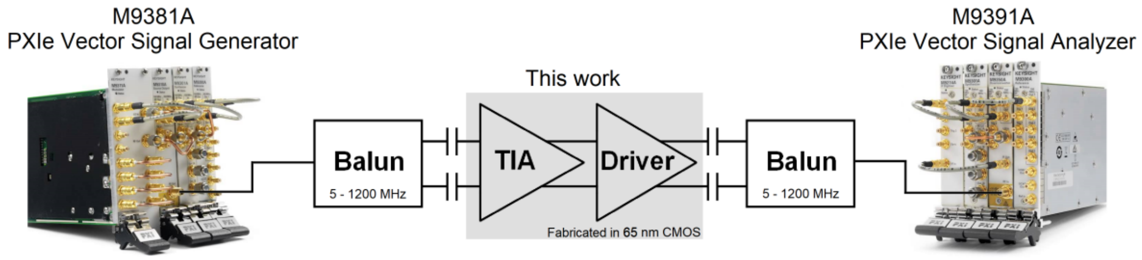


Fig. 6. Experimental setup for data transmission and EVM measurement.

TABLE I. SUMMARY OF THE MEASUREMENT RESULTS AND COMPARISON WITH OTHER RF TRANSIMPEDANCE AMPLIFIERS

Parameter	**[2]**	**[3]**	**[6]**	**This Work**
Technology	130-nm CMOS	180-nm CMOS	150-nm PHEMT	65-nm RF CMOS
Photodiode Technology	Integrated APD	Integrated APD	External PIN	External PIN
Supply Voltage	1.2 V	1.8 V	5 V	1.2 V
Transimpedance	54 dBΩ	62 dBΩ	46 dBΩ	60-76 dBΩ Linear-in-dB
Frequency of operation	2.5 GHz	5.2–5.8 GHz	12 GHz	700 MHz
Input Noise Current Density	-	7.3 pA/$\sqrt{\mathrm{Hz}}$	21 pA/$\sqrt{\mathrm{Hz}}$	8 pA/$\sqrt{\mathrm{Hz}}$
EVM	3.89%	2.5%	3%	2%
Total Power Consumption	18 mW*	156 mW	100 mW	19 mW
FoM ($\Omega \cdot GHz/mW$)	70	47	24	232

*Excluding output buffer

As shown in Table I, the proposed TIA achieves a much better FoM, thanks to the higher transimpedance and the low power consumption of 19 mW, including the output driver. It is also the only TIA with controllable transimpedance, extending the input dynamic range for which high linearity is achieved. Another advantage of this design is the compatibility with external PIN photodiodes, which present a much higher junction capacitance, of the order of 0.5 pF, compared to the extremely low 35-fF integrated photodiode presented in [3].

IV. CONCLUSION

A low-noise differential TIA for use in a downlink receiver in RAUs for IFoF communications has been presented in this paper. The TIA performs a 16-dB linear-in-dB gain range, with a 4-bit thermometer-coded resistor array to achieve a wide input dynamic range from -16 dBm up to +4 dBm optical power. The stability is ensured with an open-loop gain of the core amplifier using programmable load resistors, and the TIA overcomes the high intrinsic capacitance of an external PIN photodiode, achieving a 700-MHz bandwidth with a maximum transimpedance of 76 dBΩ. Designed in a 65-nm RF CMOS technology with a 1.2-V voltage supply and with a low power consumption of 6 mW, the proposed TIA presents a very high linearity, achieving a better EVM than recently published works, improving the overall performance of the RAU, which makes it a good candidate to be used in cost-effective distributed antenna systems using IFoF.

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