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A 100-Gb/s, 1-tap Feed-forward based Analog Equalizer for Optical Communication Applications

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Abstract—This paper reports the design and measurement results of a 1-tap feed-forward based analog equalizer, mainly designed with differential pair amplifier cells composed of Indium Phosphide (InP) heterojunction bipolar transistors. This analog equalizer exhibits a maximal peaking frequency and amplitude of 50 GHz and 12 dB respectively. Large signal measurements demonstrated an equalization at 100 Gb/s of a 3m-long 1.85-mm-connector coaxial cable, which represents a lossy channel of 20 dB at 50 GHz. To the authors' knowledge, this is the first analog equalizer reported with an equalization capability demonstrated at 100 Gb/s.

Index Terms—Analog electronics, feed-forward equalizer, InP DHBT, equalization.

I. INTRODUCTION

With the continuous growth of global IP traffic, new methods are constantly developed in order to increase optical communications channel capacity [1]. From a standard of 25 Gb/s a few years ago, we are progressively reaching data rates of 100 Gb/s with an OOK modulation format in one single wavelength, mainly for short reach applications. These high data rate transceivers become difficult to implement because of electro-optical components bandwidth limitation [2]. Forward error correction (FEC) is commonly used in order to overcome these limitations but it needs data rate overhead and it also requires important power consumption as well as complex algorithms [3].

Nowadays, many solutions have been tried to increase optical communication data rate while relaxing receiver complexity. One of the main low-cost solutions remains analog equalization. Indeed, this technique can increase the overall channel bandwidth in order to reduce intersymbol interference (ISI) thus getting a correct bit error rate at the reception.

Figure 1 illustrates the principle of this well-known technique. An analog equalizer is used to set a peaking at high frequency in its own frequency response. By cascading this analog equalizer with a limited bandwidth system, we increase the total bandwidth, thus allowing a data rate increase [4].

A lot of very high speed analog equalizers have been reported through last years, but no one have been addressed the 100-GHz class bandwidth which is considered here. In [5], authors reported a 90-Gb/s 2:1 multiplexer with a 1-tap feed-forward equalizer (FFE) in SiGe HBT technology, capable of

Fig. 1. Overall frequency response of a limited bandwidth system cascaded with an analog equalizer

equalizing a 90-Gb/s NRZ signal with a channel loss of 12 dB at 45 GHz. Here, we report a 1-tap FFE capable of equalizing a 100-Gb/s NRZ signal with a channel loss of 20 dB at 50 GHz.

This paper is organized as follows. In the first part, we present the design of our analog equalizer. The second part deals with the chip fabrication and the last part reports our S-parameters and large signal measurement results.

II. DESIGN

Our analog equalizer is a 1-tap FFE based architecture designed with InP double heterojunction bipolar transistors (DHBTs). This technology provides high f_T/f_{max} as well as a large breakdown voltage.

Figure 2 presents the schematic of our analog equalizer. It is composed of input and output buffers and a 1-tap FFE composed of a main stage which is biased by a DC supply V_α and a 1-tap stage composed of a delay and a variable gain amplifier whose gain is tunable with the DC supply V_β .

The input buffer is a differential pair amplifier cell degenerated by a resistor-capacity couple in order to enhance the bandwidth as well as the linearity. This input buffer is broadband impedance matched with the 50- Ω input emitter-follower. The main stage α follows the same architecture, but some passive components values differ because of adaptation impedances between stages.

Fig. 2. Schematic of the 1-tap feed-forward based analog equalizer

As for the 1-tap stage, it is composed of a large bandwidth differential pair amplifier cell acting as a delay while providing a large bandwidth and a high linearity (τ), and a variable gain amplifier which is also a differential pair amplifier cell but with very low degenerative resistor values, in order to tune the gain of this amplifier with an independent DC supply (V_β).

Finally, the output buffer is a large bandwidth tunable analog equalizer based on a differential pair amplifier cell. This architecture has already been reported in [6]. This output buffer can provide a boost with variable peaking frequencies thanks to the differential pair degeneration made by a couple resistor-varactor. The capacitive value of the varactor is tunable thanks to V_{CAPA} . It can be useful for our application because a 1-tap FFE can only have one peaking frequency [7]. The parallel 100- Ω collector resistors of the output buffer ensure the broadband output impedance matching.

III. FABRICATION

Our circuit has been fabricated thanks to InP DHBTs providing a f_T/f_{max} of 270/420 GHz and a breakdown voltage larger than 6 V [8]. The process also provides 3 levels of metalization, NiCr resistors and MiM capacitors. Figure 3 shows the fabricated chip whose size is 3.6 x 1.5 mm². The core of the circuit occupies an area of 0.43 mm². Its power consumption is around 660 mW, depending on the equalization settings. The value of V_{ee} is -3.5 V.

IV. MEASUREMENT RESULTS

A. S-parameters measurements

We performed S-parameters measurements with an Anritsu Vector Star from 100 MHz up to 110 GHz. The test bench is composed of bias-T, 1.85-mm-connector coaxial cables and

probes. Figure 4 presents the measurement results of the mixed mode differential gain S_{21} (S_{dd21}) [9] for different values of V_β and V_{CAPA} and the input and output reflection coefficients. Due to the differential aspect of our 1-tap FFE, there are two input and output reflection coefficients presented. These parameters do not show a variation with the different possible settings of the analog equalizer.

As mentioned in the abstract, we get a maximal differential peaking of 12 dB at 50 GHz by properly adjusting the tuning parameters. We have a minimal DC gain of -9 dB as well as a maximal peak gain of +5.5 dB. The input and output reflection coefficients are lower than -10 dB up to 70 GHz for both of them. The tuning parameters allows us to have a tunable peaking frequency between 30 and 50 GHz. The peaking amplitude can also be tuned between 0 and 12 dB.

B. Equalization performance

The first step of large signal measurement experiments consists of feeding our analog equalizer at one input with a 100-Gb/s NRZ signal provided by a SHF 50-Gb/s 2¹⁵-1 PRBS source followed by an in-house 2:1 selector. The eye amplitude

Fig. 3. Microphotograph of the fabricated chip. Chip size is 3.6 x 1.5 mm² and the core of the circuit occupies an area of 0.43 mm²

Fig. 4. S-parameters measurements results for $V_\alpha = -2.9$ V and for different values of V_β and V_{CAPA}

Fig. 5. Eye diagrams for the differential output of the analog equalizer at 100-Gb/s for $V_\alpha = -2.9$ V and for different values of V_β and V_{CAPA} . Visible overshoots are synonyms of pre-emphasis, which is a well-know equalization effect

is around 300 mV_{pp}. The other input is connected to a DC supply whose value is the mean value of the PRBS signal. Figure 5 illustrates different eye diagrams measured at the differential output of the analog equalizer for different values of V_β and V_{CAPA} . The equalization effect is well identified with the visible desired overshoots synonym of pre-emphasis.

In order to demonstrate the equalization performance of our analog equalizer, we filtered the 100-Gb/s PRBS signal with a 1.85-mm-connector coaxial cable. The synoptic of the measurement test bench is illustrated in figure 6. It is composed of the same $2^{16}-1$ PRBS source at 100-Gb/s but in this case filtered by a 3m-long 1.85-mm-connector coaxial cable, whose frequency response is presented in figure 7(a). This figure also presents the calculated frequency response of

Fig. 6. Synoptic of the transient measurement bench

(a) S-parameters measurements of 3m-long 1.85-mm-connector coaxial cable S_{21} and the calculated frequency response of the equalized channel

Fig. 7. Equalization performance at 100-Gb/s. (b) and (c) present 100-Gb/s input signal filtered by a 3m-long 1.85-mm-connector coaxial cable (top) and equalized output (bottom) eye diagrams and waveforms, respectively

the equalized channel composed of this coaxial cable and our analog equalizer with the appropriate settings. We get a 3-dB bandwidth of 35 GHz instead of almost 2 GHz thanks to our analog equalizer.

Figure 7(b) and 7(c) presents the results of this measurement. We obtained an opened 100-Gb/s eye diagram with a measured Q factor of 2.68 at the analog equalizer output. The associated waveforms illustrate this equalizing effect by clearly reshaping the signal.

Other measurements have been performed with different lower lengths of 1.85-mm-connector coaxial cable showing even better performances in terms of Q factor of the equalized eye diagram at the output of the analog equalizer. Figure 8 illustrates the results for a 2m-long 1.85-mm-connector coaxial cable with the same vertical scales than in figure 7. In that case, we measured a Q factor of 3.75 at the analog equalizer output.

TABLE I
CONTINUOUS TIME ANALOG EQUALIZERS STATE-OF-THE-ART

Parameter	Unit	[10]	[11]	[5]	[7]	[12]	This work
Maximal Equalization Data Rate	Gb/s	49	up to 70	90	40	78.6	100
Equalizer type	*	7-Tap FFE	Continuous Time Linear Equalizer	1-Tap FFE	7-Tap FFE	Continuous Time Linear Equalizer	1-Tap FFE
Frequency peaking tunability	*	YES	NO	YES	YES	YES	YES
Peaking frequency(ies)	GHz	*	52	*	*	5 up to 57	30 up to 50
Equalization	dB	9 @ 25 GHz ¹	31 @ 52 GHz	12 @ 45 GHz ¹	9 @ 20 GHz ¹	40 @ 57 GHz	12 @ 50 GHz
Power Supply	V	5	3.3	3.6	1	1.8	-3.5, V_{α} , V_{β} , V_{CAPA}
Max. Power Consumption	mW	750	336.6	1940	80	250	660
Chip area	mm ²	1 x 2	0.99 x 0.895	1.66 x 1.66	2 x 2	0.71 x 1.03	3.6 x 1.5
Process node	*	0.18 μ m	0.13 μ m	0.13 μ m	65 nm	0.13 μ m	0.7 μ m
Material	*	SiGe	SiGe	SiGe	Si	SiGe	InP
Transistor	*	BiCMOS	BiCMOS	HBT	CMOS	BiCMOS	DHBT
f_T	GHz	160	230	210	*	230	270
f_{max}	GHz	160	280	260	*	280	420

¹ Equalized cable loss reported by measurements at Nyquist frequency

Fig. 8. Equalization performance at 100-Gb/s. (b) and (c) present 100-Gb/s input signal filtered by a 2m-long 1.85-mm-connector coaxial cable (top) and equalized output (bottom) eye diagrams and waveforms, respectively

V. CONCLUSION

An analog equalizer with a 1-tap FFE architecture and designed with InP DHBTs is reported. We measured a tunable peaking from 0 to 12 dB in a frequency range between 30 and 50 GHz. Large signal measurement were conducted and we performed an equalization at 100-Gb/s for a 3m-long 1.85-mm-connector coaxial cable with a loss of 20 dB at 50 GHz. As demonstrated, the tunability of our analog equalizer makes it efficient to equalize various lengths of 1.85-mm-connector coaxial cable. The table I presents the different parameters and results of the best analog equalizers reported to date. Our 1-tap feed-forward based analog equalizer demonstrates a good peaking performance as well as the highest equalized data rate.

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