A Wide-Band, 5-Tap Transversal Filter With Improved Testability for Equalization up to 84 Gb/s

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Abstract—A millimeter wave integrated transversal filter operating at up to 84 Gb/s is presented. The implemented topology offers improved testability, which allows for filter characterization in both the time and frequency domain. The filter has an input and output return loss better than 10 dB up to 67 GHz. Using this filter, frequency equalization of an NRZ input to either an NRZ or a duobinary output is demonstrated at 84 Gb/s across a channel consisting of a 5 cm differential grounded coplanar waveguide trace and a pair of 80 cm coaxial cables. The filter is implemented in 130 nm SiGe BiCMOS process, has a die area of $2.5 \text{ mm} \times 1.4 \text{ mm}$ and consumes 210 mW from a 2.5 V power supply.

Index Terms—Design for testability, duobinary, equalization coefficients, impulse response, transversal filter.

I. INTRODUCTION

THE data rate of chip-to-chip/chip-to-module interconnects continuously increases to meet the demand for greater network capacity. However, operating at high data rates poses great challenges as it requires a very high bandwidth (BW) component across the electrical link, while increased data rates face excessive frequency dependent attenuation, reflection and inter-symbol interference (ISI) [1]. As a result, in high-speed communication links, the received data waveforms can be significantly distorted after travelling through coaxial cables or printed circuit board (PCB) interconnects [2]. To compensate signal degradation and to enhance the channel capacity, advanced modulation and/or equalization are widely used in transmitter and receiver circuits. Towards that end, duobinary modulation format holds great potential for attaining high-speed or long-reach electrical transmission, as it utilizes the available BW more efficiently compared to non-return-to-zero (NRZ) and allows for the confinement of a signal's power spectral density (PSD) to lower frequencies [3]. A duobinary signal is defined as the sum of the present bit and

the previous bit in a binary sequence, which is expressed in the frequency domain in (1), where T_s represents the bit period

$$H(f) = \frac{Y(f)}{X(f)} = \frac{1}{2} \cdot [1 + \exp(-j2\pi fT_s)]. \quad (1)$$

The original data can easily be recovered using a XOR gate at the receiver [2].

In this Letter, a 5-tap feed-forward equalizer (FFE) transversal filter extended with test buffers is presented. This proposed topology introduces an extra signal path along the transversal filter, such that the FFE can be individually characterized, in both frequency- and time-domain. Optimizing FFE tap weights with a least square error (LSE) fitting, the transmission channel is equalized for two data formats, either standard two-level NRZ signaling or three-level duobinary signaling. A serial electrical transmission, for both modulation schemes, is demonstrated at 84 Gb/s.

II. PROPOSED FFE TOPOLOGY

Using conventional FFE topologies [4], [5], a problem occurs when the FFE is integrated in a transmitter and needs to be characterized. Adding test ports next to the conventional input and output ports is a solution, however, it requires extra circuits such as switches in the high speed data path, which will increase the power consumption and degrade the signal quality due to additional parasitics. Meanwhile, the input and output delay elements of high-speed FFEs are traditionally implemented using a transmission line (TL), which requires an on-chip termination. In this Letter, by replacing this termination with additional test buffers, an extra path is introduced, so that the FFE can be used both in clockwise and counter-clockwise directions. During normal operation, these buffers are disabled, but their output loads will still function as TL terminations. The proposed topology is shown in Fig. 1.

The input test buffer and output test buffer are directly connected to chip IO pads, allowing us to probe the equalizer separately. Due to the symmetrical nature of the FFE, the signal can be supplied on both left- and right-hand side (shown in Fig. 1). At the left-hand side of the FFE, the input buffer connects with the output of an on-chip multiplexer (MUX) which combines four lower rate streams into an 84 Gb/s differential NRZ signal. The linear output buffer drives the equalized signal over an external channel. At the right-hand side of the FFE, applying an additional test input and output buffer, the FFE functionality can be also measured, either in frequency- or time-domain. However, the FFE is driven in the opposite direction. Therefore, the

Manuscript received May 11, 2015; revised July 29, 2015; accepted August 12, 2015. This work was supported by the Agency for Innovation by Science and Technology in Flanders (IWT) and the Special Research Fund (BOF) of Ghent University.

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Digital Object Identifier 10.1109/LMWC.2015.2479844

Fig. 1. Fully integrated FFE structure.

FFE tap weights have to be mirrored when employing this data path. Each input and output buffer has an individual enable/disable switch, in order to choose the operating mode.

In comparison to the conventional FFE topology with on-chip resistors as delay line terminations [5], [6], the introduced signal path ("FFE test signal path" as shown in Fig. 1) allows us to characterize the FFE individually without disconnecting the MUX. And the measured response of each FFE tap helps to do the difficult 5-dimension FFE parameter estimation algorithm to obtain optimal channel equalization.

The relationship of the FFE input and output is given in (2). A_i represents the tap weight and T_{apdelay} represents the time delay between neighboring taps

$$Y(t) = \sum_{i=1}^5 (A_i \cdot X(t - (i-1) \cdot T_{\text{apdelay}})). \quad (2)$$

III. IMPULSE RESPONSE

By using high frequency probes with a pitch of 150 μm , the frequency response of the integrated FFE is measured. Based on the response of each FFE tap at the maximum gain, the impulse response of each FFE tap is calculated and presented in Fig. 2. It can be observed that each FFE tap is separated in time by a delay of 12.4 ps, corresponding to the delay introduced by the on-chip TL. The later taps have a lower output power, which is caused by the frequency-dependent loss introduced by the on-chip TLs. Fig. 2 also presents the impulse response of the channel used in the experiments, consisting of a 5 cm RO4003C differential grounded coplanar waveguide (GCPW) trace [7] and a pair of 80 cm coaxial cables.

The equalized channel response can be simulated by convolving the measured channel response with a linear combination of the measured impulse responses. The coefficients of

Fig. 2. Impulse response.

Fig. 3. Equalized channel response fitting to NRZ or duobinary.

Fig. 4. Measured frequency response of FFE shaped channel response.

this linear combination are optimized using a gradient search algorithm to obtain a LSE fit between the simulated response and a desired reference pulse [8]. In this way, the optimal value of pre-cursors and post-cursors in the FFE is selected. The resulting impulse response after optimization for a serial data rate of 84 Gb/s is depicted in Fig. 3.

IV. FREQUENCY- AND TIME-DOMAIN VERIFICATION

The FFE is evaluated in the frequency-domain using an Agilent PNA-X N5247A. The methodology proposed above provides a good starting point for the FFE coefficients. As the positive and negative coefficients of the FFE tap are assumed to be exactly balanced in the simulation, during measurements, further optimization is performed by looking at the FFE frequency response on the VNA. Fig. 4 shows the measured uncompensated channel as well as the channel optimized for NRZ, the reference response of a duobinary channel, the measured response using the FFE parameters obtained with the above described method and the fine-tuned duobinary response.

The optimized duobinary response closely matches the reference response. The NRZ response is BW limited to 40 GHz,

Fig. 5. Time-domain measurement setup.

Fig. 6. Equalized 84 Gb/s output. (a) NRZ. (b) duobinary.

Fig. 7. Die micrograph.

TABLE I
PERFORMANCE COMPARISON WITH PREVIOUS PUBLICATIONS

Ref.	[4]	[5]	[9]	This work
Process	65 nm CMOS	180 nm SiGe	130 nm SiGe	130 nm SiGe
Topology	4-tap FFE	7-tap FFE	1-tap DFE	5-tap FFE
Data rate	64 Gb/s	49 Gb/s	80 Gb/s	84 Gb/s
Output swing	600-850 mV _{pp}	-	-	500 mV _{pp}
Power	78 mW	750 mW	4000 mW	210 mW *
FoM **	1.2 pJ/bit	15.3 pJ/bit	50 pJ/bit	2.5 pJ/bit

* Total chip power, including MUX, is 750 mW.

** FoM = Power / Data Rate.

which will degrade the eye opening as will be seen during the time-domain measurements.

The FFE functionality is verified in the time-domain using an Agilent 86100C mainframe and 70 GHz 86118A remote sampling heads. As discussed in Section II, thanks to the test configuration, the proposed FFE can be measured in two directions, with the FFE input either from the on-chip MUX, or from an external pulse pattern generator (PPG). As the maximum bit rate of our available PPG is limited to 50 Gb/s, the on-chip MUX and the counter-clockwise path of the FFE is enabled to perform the transient measurements. The experimental setup using the MUX-to-FFE signal path is depicted in Fig. 5. The FFE output port is connected to the sampling oscilloscope, via a 5 cm differential GCPW trace and a pair of 80 cm coaxial cables, to

evaluate the eye diagram for signal equalized with the proposed FFE and transmitted over the channel for both NRZ and duobinary signaling at 84 Gb/s.

By mirroring the FFE tap weights, the eye diagrams of the equalized NRZ and duobinary output at 84 Gb/s are captured after the channel, as presented in Fig. 6. The NRZ eye opening shows some BW limitation as expected from the frequency-domain measurement. On the other hand, the duobinary eye is constructed at the output of the channel, with a larger eye opening (vertical: 38 mV vs. 32 mV, horizontal: 8 ps vs. 7 ps). Without equalization, the eye is completely closed.

The total chip, including a FFE and a MUX, is fabricated in 130 nm STMicroelectronics SiGe BiCMOS technology, featuring a f_T value of over 200 GHz. Table I illustrates the performance comparison with previously published equalizers beyond 40 Gb/s [9]. Fig. 7 presents die micrograph of the chip.

V. CONCLUSION

In this Letter, we have demonstrated an 84 Gb/s integrated transversal filter as a FFE to improve signal integrity in serial electrical links. The transversal filter is implemented with a novel topology for improved testability, such that the FFE performance can be individually characterized, in both frequency- and time-domain, which also helps to perform the coefficients optimization of the 5-tap FFE. Apart from NRZ, duobinary signaling is implemented as an alternative modulation scheme, because of a higher spectral efficiency compared to NRZ, leading to a larger eye opening.

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