HIGH SPEED DIGITAL SIGNALING IN PRINTED, PLANAR MICROWAVE CONNECTORS WITH MULTIPLE SIGNAL LINES

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***Abstract*—Advances in additive manufacturing have led to demonstrations of printed electronics with new form factors (i.e. flexible, conformal, or embedded). Recent research has reported the development of printed, planar connectors that can be integrated with additively fabricated electronics [1]. A printed connector can be designed to support multiple format signals (RF, digital, DC), thus offering the designer the ability to customize connectors that are tailored to a printed circuit board. Prior work reported on the frequency response of these connectors for RF applications. This work reports on modeling the digital signal integrity of these connectors through time domain analysis. Circuit models have been developed to predict the eye diagrams, bathtub curves, Time Domain Reflectometry (TDR) and Time Domain Transmission (TDT) of these printed connectors.**

Keywords—Printed connector, High speed interconnects, Additive Manufacturing, Cross talk, Signal Integrity.

I. INTRODUCTION

Additive Manufacturing (AM) is being used increasingly to deploy printed electronic systems with new form factors that can be rapidly prototyped [2-3]. The interconnection of these printed systems has largely been ignored until recent efforts to devise connectors that can be printed and integrated with functional electronics [1,4]. This work has included printed planar microwave connectors with multiple signal lines. This approach allows the designer to print multiple transmission lines in a single connector, enabling a higher density of interconnects to a printed circuit. This is particularly important in RF systems where Commercial-Off-the-Shelf (COTS) connectors are bulky and support only one RF signal. The development of planar, printed connectors with multiple signal lines offers the ability to transmit multi-format signals (digital, RF, and DC) in the same connector package. Previous work on these multi-signal, printed connectors focused on the RF performance. This work focuses on the performance of the connectors in the digital domain.

The printed planar microwave connector with multiple signal lines, shown in Figure 1, involves an electrical and mechanical design to provide a separable interface between two overlapping planar substrates. The two substrates overlap over a length of 5mm where electrical signals are transferred from one half of the connector to another. This overlap distance is the optimum value to maintain a 50 Ω port impedance. The connector was designed for operation between 1-6 GHz. The connector shown has two RF lines and one DC/power line as an example of how multiple signals can be supported in a single connector. The high speed/RF lines are based on a Grounded Coplanar Waveguide (GCPW) structure. The substrate is 3D-printed PolyEtherEtherKetone (PEEK), a high temperature thermoplastic material. Conductive paste (Dupont CB028) was used to pattern the conductive elements of the connector. Conductive vias connect the top and bottom GCPW ground planes to minimize dispersion of electromagnetic waves from the signal line.

The mechanical design requires precise alignment of the signal lines on the two substrates in the overlap region. Alignment is achieved by creating slots on both substrates and using locking keys that provide accurate registration of the conductive traces. This arrangement serves to hold the two substrates together so the connector can be a make-and-break mechanical system. Alignment of the two substrates is important since our electromagnetic modeling (Ansys HFSS) predicts that vertical or horizontal misalignment causes RF reflections that degrade performance [6]. The alignment slots are located in the overlapping region and positioned to avoid negative impact on performance. Figure 1 is the CAD model used for frequency domain analysis in HFSS. The results were incorporated in Ansys circuit for the time domain analysis.

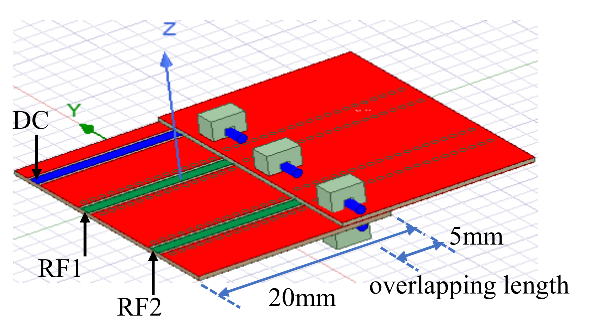

Figure 1. A CAD model of the proposed planar printed multiple signal (three) lines connector.

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The analysis in this report models the performance in response to digital signals, including eye diagrams, mixed modes parameters, time domain reflectometry (for spatial and time domain information) and a single pulse response.

II. CIRCUIT MODELS

A. Ansys Circuit design

Previous publications on these planar connectors reported development of electromagnetic models using Ansys HFSS to predict the frequency response of the connectors [1,4]. The modeling has been extended to the time domain using the Ansys Circuit tool to predict eye diagrams and time domain performance. With this model, other parameters such as Inter Symbol Interference (ISI) can be defined to determine pulses leaking into adjacent pulse channels. Insertion loss profile variations can trigger ISI.

The electrical circuit schematic for a 50Ω matched system is shown in Figure 2. A bit stream source for different modulated data launches into port 1 and port 3 pathways. Ports 5 and 6 are terminated since it was designed to be a DC line. This simulation involves input of results from the frequency domain simulation. The signal parameter inputs into the connector for examination of the system in time domain analysis were as follows. The UIBPS = 1E9s, Vlow = -1V, Vhigh = 1V, rise time = 100ps, and fall time =100ps and 2^12-1 bits generated.

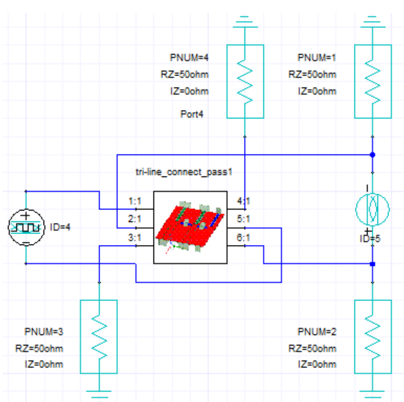

Figure 2. The multiple signal (three) line printed microwave connector imported in Ansys Circuit to do time domain analysis (Cosimulation).

In digital communication, the peak-peak voltage of the signal is what's important unlike the RF signals where the focus is average signal power. A high-speed signal may be single ended (one wire plus return path) or differential (two wires, with or without an additional reference path). When differential signaling is employed, the peak-to-peak differential signal level equals twice the peak-to-peak level on either wire alone [5]. PAM2 signaling protocol with two voltage levels is considered in this work for its high SNR.

B. Fabrication

The multi-format signal connectors were initially developed using commercially-available, double-sided copper laminate. Subsequent connectors were fabricated using an all-printed process. This approach was chosen since commercial microwave laminate materials are more fully-developed than materials based on printing. The detailed fabrication process is described in previous publications [4, 6]. The printed connector is shown in Figure 3. The RF transmission lines are spaced far apart to accommodate the size of the COTS connectors needed to test the printed connector. When used in real applications, one half of the planar connector would be integrated with the actual printed electronics (e.g., on a printed circuit board) and the other half would be integrated with a flexible, multi-signal cable. Removing the constraint of using COTS connectors would enable the transmission line spacing to be reduced, hence, increasing the I/O density of the interconnection.

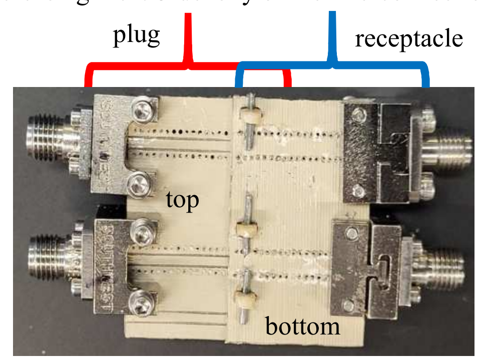

Figure 3. The fabricated planar printed multiple signal (three) lines connector.

The left-hand side of the connector can be regarded as a plug and the right-hand side as the receptacle for the conventional connectors with separable interfaces.

C. Simlations and Measurements

The simulation results are shown below for eye diagrams showing how the channel degrades the signal. An eye diagram of the printed connector channel, shown in Figure 4, has an open eye with distinct 1's and 0's.

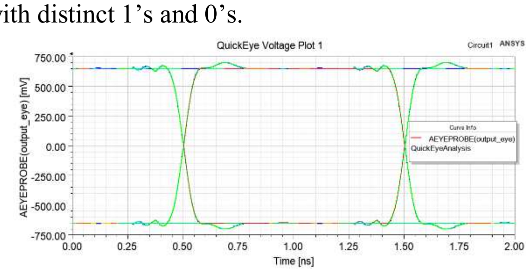

Figure 4. The eye diagram of the input signal for the bit rate of 1Gbps.

The bathtub curve in Figure 5 is helpful for indicating the fidelity of large data packets in this channel.

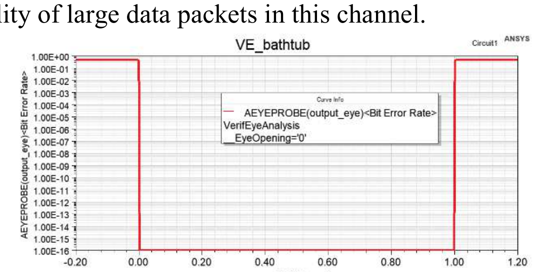

Figure 5. The bathtub curve of the input signal at 1Gbps.

At high bit rates and over longer distances, transmitting lines

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can have different effects and degrade the electrical signal to the point where errors occur, and the system or device fails. A TDT trace showing the modelled rise time for transmission for the connector appears in Figure 6.

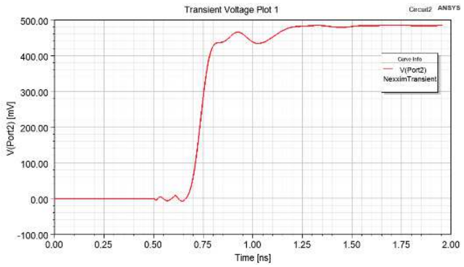


Figure 6. The TDT trace of multiple signal (three line) printed microwave connector in Ansys circuit at 1Gbps.

The TDR is for spatial and timing information. An inverse FFT of the frequency-domain results was performed to create time-domain reflectometer plots to identify major impedance discontinuities. Figure 7 illustrates inductive behavior (discontinuity) at 1ns as the impedance spike is observed.

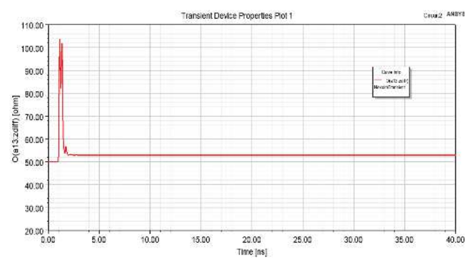
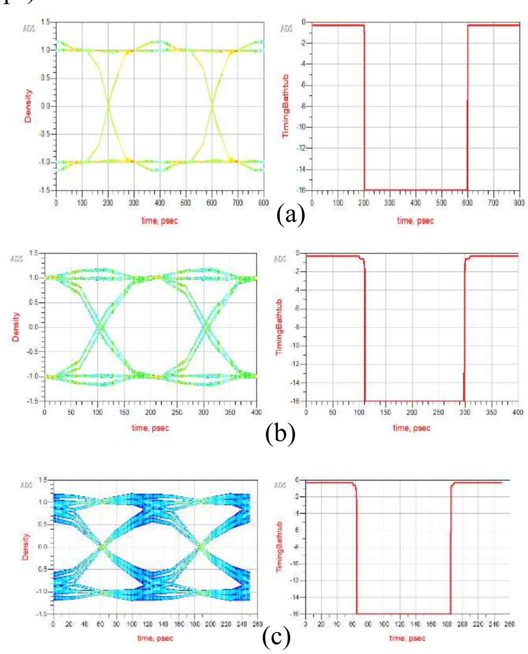


Figure 7. The differential TDR trace of multiple signal (three line) printed microwave connector in Ansys circuit at 1Gbps.

The eye diagrams and bathtub curves in Figure 8 show evaluation at faster data rates (2.5Gbps, 5Gbps, 8Gbps and 10Gbps).



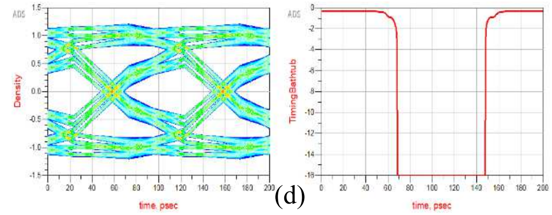


Figure 8. The eye diagrams and bathtub curves for data rates at (a) 2.5Gbps, (b) 5Gbps, (c) 8Gbps and (d) 10 Gbps.

III. DISCUSSIONS AND CONCLUSIONS

Modeling of multi-signal, printed connectors has been extended to the time domain to access their performance in digital applications. As a result, printed planar microwave connectors with multiple signal lines facilitated transmission of high-speed signals. The eye diagram is wide open and the zeros (0s) and ones (1s) are clearly distinguished. The bathtub curves all are reasonable for speeds up to 5Gbps. To extend the high-speed capability to higher data rates (>5Gbps), the bandwidth needs to be increased by developing higher frequency connectors. It is also noted that integration of all critical transitions during simulations facilitates proper relations with prototypes to determine all possible discontinuities in the channel.

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