Inductively Coupled Board-to-Board Connectors

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Abstract

This paper discusses the potential application of inductive coupling elements as backplane connectors. Tradeoffs in the choice of inductive elements are discussed and a simple circuit model for electrically large board-to-board transformers is presented. Measured data for a 10mm outer diameter transformer shows an acceptable eye opening for 400Mbps NRZ data, and over 1GHz of bandwidth in the frequency domain. We also discuss how inductive connectors could find application in future long range FR4 backplanes.

1. Introduction

Traditionally, the backplane industry has relied on press-fit style connector designs which are easy to assemble and are a well understood technology. However, these connectors require plated through hole vias, for mating with pins, which present impedance discontinuities that cause reflections and disrupt the return path. This increases return path inductance and crosstalk, particularly at Gbps+ data rates [1, 2]. Mechanically mated connectors are also subject to wear and tear due to insertion force and repeated use. Surface mount backplane connectors offer electrical advantages over conventional press-fit style designs, but they suffer from coplanarity issues and offer less mechanical robustness and reliability [2].

AC coupled interconnects show promise to enable multi-gigabit/second data rates between high pin count IC's within a multi-chip module, while achieving significant power savings as well [3]. AC Coupling can be realized with planar inductive or capacitive elements. Capacitors are easier to model compared to coupled inductors: however, the input impedance of the capacitors is more sensitive to the gap spacing compared to the coupled inductors. Inductive coupling offers many degrees of freedom for system design by varying geometric parameters to tune parasitic elements in the model, such as: the crossover capacitance between the spirals, the magnetic coupling coefficient, inductance ratio and impedance terminations. Our objective is to determine if a surface mount, zero-insertion-force connector can achieve pitches of 0.25mm or less using inductive coupling. In this work, we demonstrate the feasibility of a contactless connector using inductive coupling in a very low cost PCB process. We also discuss some of the tradeoffs involved in optimizing frequency domain and time domain performance of board-to-board inductive connectors.

2. Inductive Connectors

2.1 Design Approach

High magnetic coupling coefficient values are desirable in inductively coupled connectors for improving insertion loss and return loss, and increasing bandwidth. The magnetic coupling coefficient between two vertically stacked planar spiral inductors is a function of many factors, such as: gap spacing, inductance and effective loop area. In a board-to-board application, the achievable gap spacing between the coupling elements is limited by the surface roughness of FR4, and the thickness of the interlayer dielectric used to isolate the coupling elements. The surface roughness of FR4 can range from 1μm to 10μm [10], which produces a large and unpredictable variation in the gap spacing. Process limitations also constrain choice of trace width, trace spacing and realizable inductance values in a given area. These process variations limit the maximum value of the magnetic coupling coefficient between the inductors. Meanwhile, for high-speed applications, short decay times are required, which will affect the choice of inductance values for a particular design. Hence, the trade-offs among these factors will need to be balanced carefully.

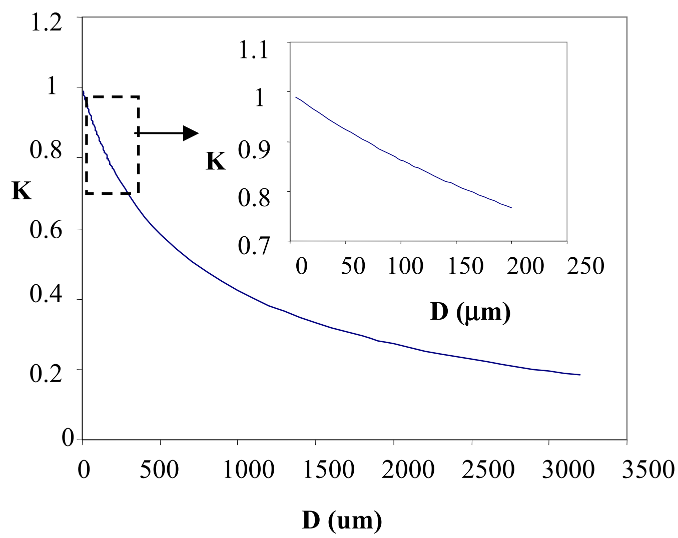

Figure 1: Coupling Coefficient (K) versus Gap Spacing (D) for a 10mm outer diameter symmetrical transformer with Inductance value of 27nH

Figure. 1 shows a plot of extracted value of coupling coefficient (K) versus gap spacing obtained using ASITIC for two 10mm outer diameter inductors with 1 turn each having an inductance of 27nH. Considering the surface roughness values of FR4 and the thickness values of readily available interlayer dielectric spacers (such as paper), the achievable gap spacing varies anywhere between 50um to 200um. When the gap spacing is 50um, K is 0.92 and when the gap spacing is 200um, K drops to 0.76 which limits the achievable bandwidth. Figure. 2 shows frequency response (S21) for a simple case of two parasitic free 25nH lumped inductors when K varies from 0.7 to 0.9. An ideal transformer is a high pass filter and its 3dB coupling frequency is determined by the chosen values of inductance. There is a significant roll-off at high frequencies when K is 0.7 and this roll-off would be more pronounced for higher inductance values. Addition of an optimum value of crossover capacitance (Cc) compensates for the high frequency roll-off in the frequency response. Since PCB trace widths are relatively larger compared to on chip features we can exploit the cross-over capacitance beneficially to obtain desired frequency response as the crossover capacitor acts as a high pass filter. The value of crossover capacitance to obtain an input impedance match can be determined using Z and ABCD parameter computation from lumped circuit model approximations for transformers. This value of crossover capacitance can be realized in a transformer by adjusting the trace width and loop area. The value of crossover capacitance in a transformer can be estimated to a first order using a parallel plate estimate over the physical length of the transformer.

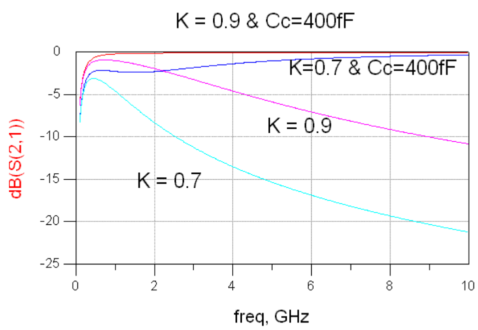

Figure 2: Simulated S_{21} for a 25nH transformer with variations in K and crossover capacitance

Inductors are short-circuits at DC and they have a rising impedance profile with frequency. While an ideal transformer with K=1 could provide a good impedance match over a broad range of frequencies from the 3dB frequency onwards, a transformer with even a K of 0.9 deviates from this desired characteristic as shown in Figure. 3. This can be mitigated by the crossover capacitance which improves impedance match as illustrated in Figure.3

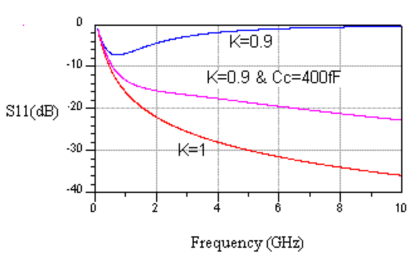

Figure 3: Simulated S11 parameters for a 25nH transformer

For a given area, trace width, and inter-turn spacing, the magnetic coupling increases with inductance. Therefore, adding more turns, within the constraints of area, would provide a boost in K, which is one way to improve the bandwidth of the coupled inductors. However, the step response of coupled inductors has an associated decay time which increases as the value of inductance increases and places a limit on the maximum signaling rate achievable, when using pulse signaling methods, due to ISI. Figure. 4 shows the step response of three different parasitic free coupled inductors with a coupling coefficient of 0.9. The settling times for equal value coupled inductors with inductance values of 5nH, 15nH, and 25nH, are 900ps, 2.2ns, and 4ns, respectively.

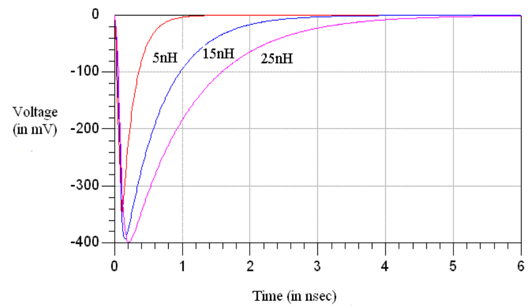

Figure 4: Step response of 3 different parasitic free coupled inductors with a coupling coefficient of 0.9.

From the Figures and discussion above, the choice of inductance values in a board-to-board system is influenced by the signaling data rate, the high frequency roll off, and the lowest frequency content of the random NRZ data stream. Higher inductance values are desirable for broad band impedance matching, but this also places constraints on the maximum signaling rate achievable. Typically, for a random NRZ data stream, impedance matching is desired from DC to the knee frequency, which is determined by the edge rate. One way to address this issue in our case is to minimize the low frequency energy in the input NRZ data stream so that impedance matching is required only over a narrow bandwidth. Also, the decay rate of the inductive elements can be impacted beneficially by high impedance load terminations to increase the signaling data rate. However, most systems use 50ohm interfaces and this imposes some constraints on the decay rates achievable by adjusting the termination.

2.2. Board to Board Inductive Coupling Test Vehicle

Board-to-board inductively coupled connectors with outer dimensions ranging from 2.5mm to 10mm were built in an inexpensive two layer PCB process with minimum feature size of 7mils (~0.175mm) for traces and 20mils (0.500mm) for via holes. The FR4 substrate is 62mils (~1.550mm) thick with a dielectric constant ranging from 4.2 to 5.0. Transformers with outer dimensions as large as 10mm were chosen to achieve sufficiently high magnetic coupling over a large range of vertical gap spacing between the boards. The test structures built have an inductance ranging from 5nH to 50nH. The loop area and trace width/spacing were chosen for optimal K and crossover capacitance using commercial tools, such as OEA and Asitic. Figure. 5 shows a picture of the test boards fabricated from ExpressPCB and Figure 6 shows the test-setup for measuring one of these transformers. A sheet of paper, approximately 90µm thick, was used as an interlayer dielectric between the two inductors. Screw holes and alignment traces were used on the boards to align the coils during measurement.

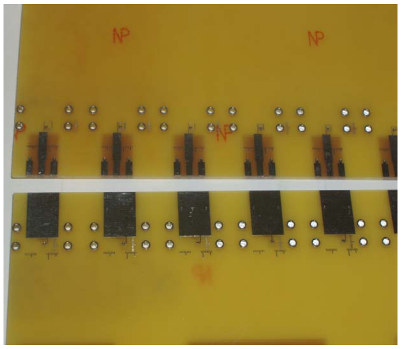

Figure 5: Photo of the Test circuits fabricated on PCB

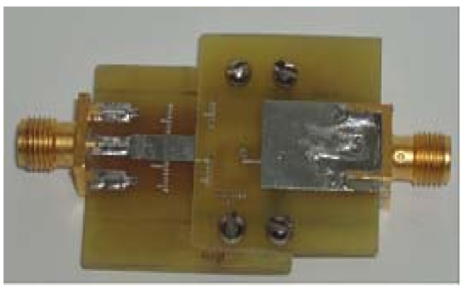

Figure 6: Photo of Test-setup of the transformer with SMA connectors and alignment Traces/screw Holes for alignment and control of the gap spacing

Figure 7 shows measured data for a 10mm outer diameter symmetric transformer with one turn each on primary and secondary, trace width of 20mils(~0.5mm) and an inter-turn spacing of 10mils(~0.25mm). Measurements were made using a HP8510C network analyzer and SOLT (Short-open-load-through) calibration was used. Copper foil ground shields and tapers were used to minimize impedance mismatch at transitions. Return loss is better than or equal to -10dB from 500MHz to 3GHz, and insertion loss is better than or equal to -3.7 dB from 220MHz to 3GHz. These performance metrics offer potential for deployment as backplane connectors [7].

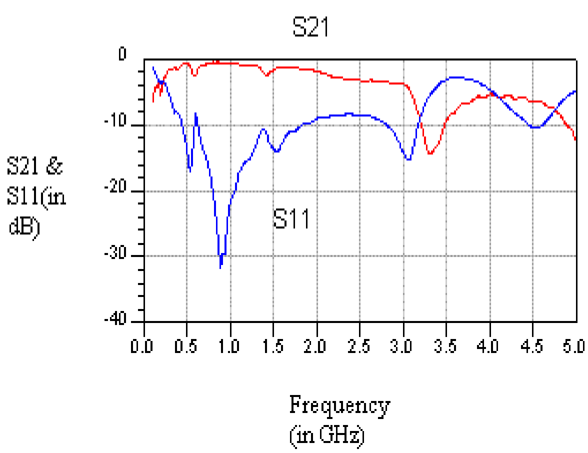

Figure 7: Measured data for 10mm Outer diameter transformer

2.3 Modeling of Board-to-Board Transformer

Figure. 8 shows a circuit model for the 10mm outer diameter transformer. The estimated inductance value from Asitic was 27nH and the extracted value of K was 0.86. Crossover capacitance was estimated using a parallel plate estimate over the overlap area of the inductors. On a PCB, long winding lengths are needed to realize reasonable inductance values, which in turn lead to distributed behavior. Hence, multiple π sections were needed to obtain a reasonable fit over a decade of bandwidth. Figure 9 shows the measured versus simulated data. While the correlation with S_{21} is reasonably good it is hard to numerically match S_{11} partly because return loss is more sensitive to the precise values of the parasitics in the model. However, the bandwidth of the simulated S_{11} follows the trend of the measured data.

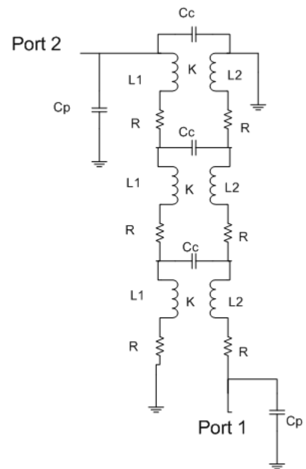

Figure 8: Circuit Model (L1=9nH; L2=9nH; R=1ohm; K = 0.9; Cc=1pF; Cp = 100fF)

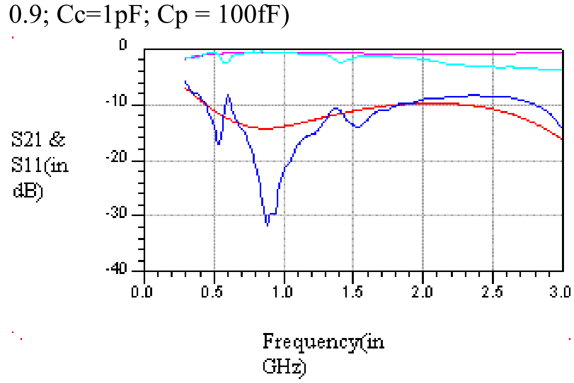

Figure 9: Measured versus Simulated Data for the 10mm outer diameter transformer

2.4 Time domain Measured data

Based on discussions in section 2.1, frequency domain data must be understood in combination with time domain results to determine the viability of inductive elements for pulse signaling. Figure 10 shows measured step response, for the 10mm transformer, to a 250mV step input from a Tektronix 11801A oscilloscope. The output signal has amplitude of 160mV. From Figure 10 we note that the output signal level of the transformer decays to 10% of its peak amplitude in 2.5ns which implies a maximum signaling data rate of 400Mbps. Figure 11 shows the measured “AC coupled eye diagram” at 400Mbps for a 2^{23}-1 random NRZ data stream. A transformer acts as a differentiator and converts the input NRZ data into pulses. A pulse receiver such as the one discussed in [8] can be used to recover NRZ data from the pulse output.

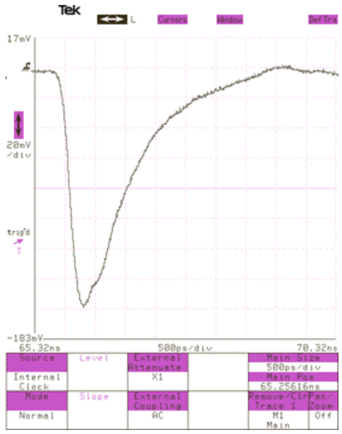

Figure 10: Measured Step Response of the 10mm Outer diameter transformer for a 250mV step input

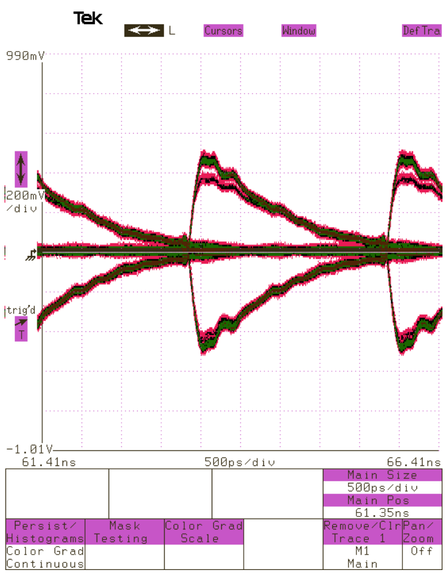

Figure 11: Measured Eye diagram for 10mm diameter transformer - 400Mbps random NRZ data

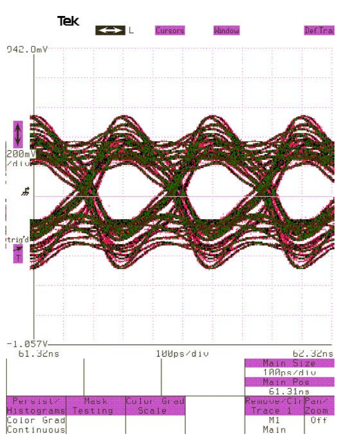

Figure 12: Measured Eye diagram for 5mm diameter transformer - 3.3Gbps coded 2^5-1 NRZ data

It must be noted that though ISI limits the performance of this test-structure at data rates beyond 400Mbps there are numerous high frequency signaling rates, when using coded data, at which board-to-board transformers produces an acceptable eye opening. For example, Figure 12 shows eye opening at 3.3Gbps for a 5mm outer diameter transformer which is limited, by ISI, to operation at 500Mbps, for pulse signaling. In this example, the signaling rate is high enough and the maximum run length is limited, so that more traditional signaling methods (non pulse) may be used.

Scaling to smaller transformers with smaller inductance values could potentially enable pulse signaling at higher data rates due to their faster decay times. Figure 13 shows the step response for a 2.5mm outer diameter transformer with one turn each on primary and secondary. In this case, the decay time is 1ns. The output signal has amplitude of 60mV for an input voltage of 250mV which is approximately 2.5x smaller when compared to the output signal level for the 10mm transformer. However, with a larger input signal the output signal level would increase to an acceptable value (e.g. 1V input = 240mV output). Figure 14 shows the measured AC coupled eye diagram for a 2.5mm outer diameter transformer with one turn each on primary and secondary for random NRZ data at 1.45Gbps.

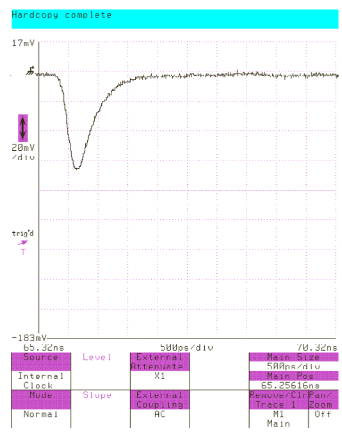

Figure 13: Measured step response for a 2.5mm outer diameter transformer for a 250mV step input

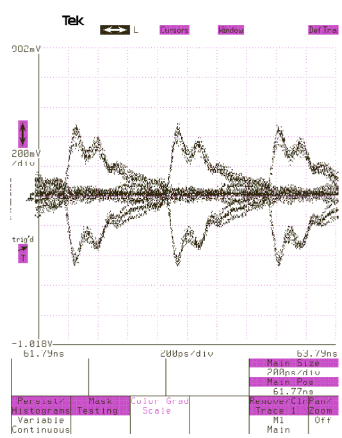

Figure 14: Measured Eye diagram at 1.45 Gbps

The ringing in the waveforms in figure 14 relative to the ideal step response observed in figure 13 is due to some noise from the HP8133 source. Some of the ringing could also be due to transmitting high bandwidth information over a band limited structure. One way to address this issue is to limit the edge rate so that excessive high frequency information is not being transmitted.

3. Application of Inductive Connectors in a System

Figure 15 shows a conceptual view of the projected system level application for inductively coupled connectors. In the short term, it may find application in Level 2 interconnections such as sockets as well. One of the issues in signaling across a complete system, as shown in Figure 15, is that a square pulse passing through a double differentiator produces a double pulse. This effect needs to be "passively" equalized through transformer parameter optimization. However, circuits have been built to handle double pulse signals at the receiver input [9].

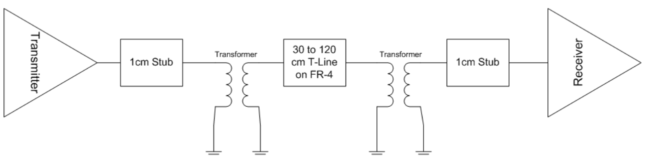

Figure 15: Conceptual View of the System with AC inductive interconnect

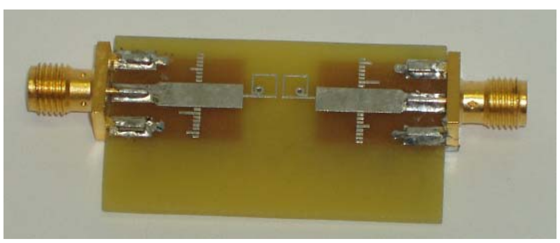

Figure 16: Test-setup for Measuring Crosstalk

Figure 17: Crosstalk between two 3mm outer diameter inductors spaced 0.65mm apart

From the results discussed in this paper, smaller inductance values with acceptable K, optimal crossover capacitance, and coded data streams may be required to enable high density AC coupled connections to signal at Gbps+ data rates as we scale PCB processes with advanced manufacturing capabilities. Figure 16 and Figure 17 show the test setup and measured isolation for two 3mm outer diameter inductors of one turn each with an inductance of 7.8nH. The results indicate that isolation is better than or equal to -20dB up to 4GHz even when the spacing is 20% of the outer diameter. This indicates potential for dense AC coupled connections as we scale to high density PCB processes with 1mil (~0.025mm) feature size for the traces with 50µm blind via capability.

4. Conclusion

AC coupled inductive interconnects have been designed and tested. We have demonstrated feasibility for a contactless connector using inductive coupling based on RF and digital measurement. Tradeoffs involved in optimizing time domain and frequency domain perfomance by tuning crossover capacitance, coupling coefficient and inductance values of the transformer have been discussed.

Acknowledgments

This work is supported by AFRL contract F29601-03-3-0135, by SRC task 1094, and by NSF under grant CCR-0219567. We would also like to thank Lei Luo and Jian Xu in the ECE department at NCSU for the useful technical discussions that we had during the course of this project.

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