Lower Loss and Process Friendly Multi-layer Flexible Interconnect

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Abstract
Most multilayer interconnect development at high speeds (>20 Gbps) has focused on rigid circuit board materials as transmission media. Similar higher speed trends are occurring in flexible circuitry. Until recently, multi-layer flexible circuits have been limited at high frequencies due to the lossy nature of the bondply (prepreg) material. This paper will discuss alternatives to the traditional high-loss adhesives to enable higher frequency applications of flexible circuits.

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**Introduction**

Anyone at DesignCon can appreciate some fundamental trends for high speed signals. Solutions to the challenge of signal integrity are the key foundational elements that led to the establishment of this conference. These challenges are not new, nor are they static. Challenges of increasing data rates and routing signal channels have been around from the beginning. For instance, at the first DesignCon (1993 High Speed Digital Design Symposium) the topics included “Feasibility of Moving a 50 MHz design to 100 MHz” and “Printed Circuit Design Techniques for the Control of Electromagnetic Interference”. [1] The fundamental challenges today are the same, but at different magnitudes. There was a time when the term “High Speed” could be separated from “High Frequency”. Those days are over. As bandwidth requirements and routing densities increase, it is necessary to deal with these problems with new approaches. Common techniques used to connect digital channels are by using backplanes or coaxial cables. Both of these schemes have limitations. For instance, backplanes are rigid both mechanically and from a design perspective. It only makes sense to use a backplane when there are a large number of channels that will not be re-routed after deployment. On the other hand, coaxial cables offer the maximum amount of interchangeability of interconnects, but are very large and bulky. Routing large cables can also restrict airflow and generally require a separate, large connector for each channel. Flexible printed circuits can offer an excellent compromise of routing density and design/mechanical flexibility. Figure 1 illustrates that printed flexible circuits are capable of many more signals in the same form factor than coaxial cable. [2,3]

![Figure 1 - Illustration of the density advantage provided by Flexible Circuits](image-url)
Flexible Circuit Technology

Flexible circuits are very similar to rigid printed circuits in that they both are based on printing and etching copper traces that are laminated together and connected with copper plated vias. However, the materials used in flexible circuits are fundamentally different. Instead of glass-reinforced resin, the basic material used in flexible circuits is polyimide which is often referred to as Kapton®. Instead of impregnating glass fabric with resin, adhesive is coated on polyimide. This adhesive may be acrylic based or epoxy based. Figure 2 illustrates the basic materials used to create rigid and flexible printed circuit boards. To bond layers together instead of using “prepreg”, flexible circuits utilize “bondply”. This is because the material is made differently and has slightly different considerations for lamination. Bondply has adhesive coated on both sides of polyimide instead of resin impregnated into a glass fabric in the case of prepreg. Unlike prepreg, only the adhesive layer flows. The polyimide layer does not compress so this must be taken into consideration during design. Similarly, rigid and flexible circuits are covered with different materials. Soldermask is typically very brittle and will crack when flexed so “coverlay” is used for outer layers of flexible circuits. Coverlay is just like bondply in that adhesive is coated on polyimide and only differs in that the adhesive is coated on one side only. Coverlay is different from soldermask in that openings are usually defined mechanically since polyimide generally is not defined by photoimaging.

Figure 2 - Typical materials used in printed circuit fabrication for rigid circuits (left) and printed circuits (right).
Another key difference between rigid and flexible circuit technologies is that the optimum dielectric thickness of flexible copper clad laminates is 0.051 mm or less. To make thicker cores, multiple layers of dielectric must be stacked and copper laminated to the surfaces. Since flexible circuit materials are made from films, they naturally tend to be thin. This is the reason that Figure 2 purposefully shows the flexible layers being thinner than the rigid layers. Note also that the type of copper is usually different between the two types of circuits. Rigid circuits typically utilize electrodeposited (ED) copper while flexible circuits typically use rolled-annealed (RA) copper. RA copper is significantly more ductile than ED copper since the manufacturing process of the copper manufacture creates large copper grains. These large grains also result in less possible fracture sites which make the copper more reliable when deformed.

**Signal Transmission of Traditional Flexible Circuits**

The thin nature of flexible circuits presents some unique challenges with respect to characterizing key properties like permittivity and loss tangent. The common test methods in practice are optimized for thicker dielectrics (greater than 0.125 mm). The most common method used to measure the permittivity normal to the plane of the dielectric is the clamped stripline resonator. [4] Since flexible circuits are so thin, an accurate direct measurement of the permittivity normal to the plane of the dielectric is not possible due to the need to stack dozens of layers to get the required 1.5 mm thickness of stripline dielectric. [5] Perturbation based resonant cavity methods like split cylinder and split post can directly measure permittivity of thin layers of dielectric, but the electric field is oriented in the same plane as the dielectric. A method capable of repeatable measurement of in-plane permittivity of dielectric layers less than 0.03 thick has been demonstrated. [6] This method uses a rectangular waveguide cavity with resonances between 2-11 GHz. Since the loss tangent is a ratio of the real and imaginary components of permittivity, there are not significant differences between the in-plane and normal values of loss tangent no matter which measurement technique is used.

Figure 3 summarizes permittivity and loss tangent measurements of typical flexible circuit materials. One standard acrylic adhesive is shown since there are not big differences in the properties of commercially available flex acrylic adhesives. However, there are differences between epoxy adhesives due the different additives used for various formulations. Two extremes of epoxy adhesives are shown here to indicate that the more flexible an epoxy adhesive is made, the higher the dielectric loss. The figure also shows two different types of polyimide. This is because there are different types of polyimide used in flex cores than in flex bondply / coverlay. The core polyimide is made to have a higher modulus to improve dimensional stability for fabrication. This difference in formulation also makes the core polyimide have lower dielectric loss.
High Frequency Flex State of the Art

One of the subtle differences between rigid circuits and flexible circuits is that Rolled Annealed (RA) copper is the standard rather than electrodeposited (ED) copper. The
reason for this is that RA copper has higher ductility than ED copper and is less likely to fracture due to bending. A side-benefit of RA copper is that the surface profile is also very low. In general, RA copper with the same measured roughness as ED copper will have lower insertion loss. Figure 4 illustrates the measured difference of three microstrip lines with the same line width and same dielectric. The only difference is the type and thickness of copper.

![Figure 4](image)

**Figure 4 - Effect of Copper Type and Thickness on Loss Measured on 50 Ohm Lines**

One way to decrease loss is to lower the permittivity and the loss tangent of the dielectric material. Previous study has shown the benefits of using a structure based on a composite Teflon® / Kapton® dielectric. [3] Figure 5 shows the effect of just changing the clad material. Standard flex coverlay is used for both examples and no exotic processing steps are required. An all-polyimide (AP) material is etched to the same line width as a Teflon® / Kapton® (TK) composite material. The insertion loss difference is due to both the dielectric and the type of copper. The TK example uses RA copper while the AP material uses ED copper.
Traditional adhesive materials have a higher dielectric loss than cladply dielectrics because adhesives are more susceptible to moisture absorption than Teflon® materials. Figure 6 shows examples of single-ended stripline with a 50 ohm line width produced on AP and TK composites. The thin structure of 150 um thick has inherently high loss due to the narrow line widths. Both examples utilize RA copper. The primary reasons for the higher loss is the acrylic-based adhesive versus the Teflon®/Kapton® based bondply.

**Figure 5** - Covered Microstrip Comparison of All-Polyimide (AP) versus Teflon® / Kapton® (TK) Composite Cladply Structure

**Figure 6** - Stripline Comparison of All-Polyimide / Acrylic versus Kapton® / Teflon® Composite Structure
The superior performing bondply used in the example shown in Figure 6 utilizes Teflon® instead of acrylic. Of course, there are challenges when it comes to manufacturing multilayer structures that contain high temperature thermoplastics. Lamination temperatures of 285°C are required to achieve adhesion. The softening of the material during lamination can make registration more challenging. Drilling of Teflon® can create smear, which cannot be removed chemically so the manufacturing process must be optimized with care.

**Flexible Low-Loss, Low Temperature Curing Thermosets**

A low loss flexible prepreg/bonding ply is not a trivial exercise for the polymer scientist. A flexible prepreg needs to have the following characteristics (1) flexibility (2) resistance to thermal shock (3) adhesion to copper and any copper clad laminates that the bond ply is laminated to (4) low dielectric loss. Flexibility and resistance to thermal shock usually behave in polar opposite directions. Thermosetting polymers are basically a collection of chemicals that chemically crosslink. Polymers are sometimes described as a bowl of spaghetti. If you can chemically connect the individual spaghetti pieces in a few spots, crosslinking occurs. If the spaghetti is loosely cross-linked in only a few places, the larger bowl of spaghetti will move as one mass but there will be a lot of individual movement possible. If the bowl of spaghetti is densely cross-linked in many places, the bowl of spaghetti becomes one mass, one molecule, much like a tire, and there is little if any movement left to the individual pieces of spaghetti. For rigid printed wiring boards, a denser crosslink is desired to achieve (1) stiffness (2) high resistance to thermal shock (3) resistance to softening (4) the lowest coefficient of thermal expansion (CTE), which is tied to molecular mobility or immobility. The challenge with an inherently flexible bondply/prepreg is that it generally needs a lower crosslink density to have good flexibility and that means a higher CTE value and less resistance to thermal shock.

The next challenge is dielectric loss and adhesion to substrates. Polar molecules or molecules with polarizable electrons have the greatest tendency for adhesion. Oxygen and nitrogen are commonly found in thermosetting polymers. Oxygen is one of the building blocks of epoxy. Epoxies are the gold standard for adhering to almost all substrates and that is due to the nature of oxygen. Polyacrylates (acrylic polymers) are organic polymers based on oxygen, carbon and hydrogen. However, because oxygen has polarizable electrons, it is a poor choice for dielectric loss. Low loss polymers are based on carbon-hydrogen chemistry, aromatic carbon-carbon chemistry, and carbon fluorine chemistry, tightly bound atoms whose electron clouds do not interact with rising and falling electromagnetic waves. Secondly, tacky polymers such as glues stick well to substrates. Tacky or sticky polymers typically have glass transitions below room temperature. This tackiness or stickiness, however, usually results from low cross link density and a lot of molecular movement available over a large temperature range. This is not good from a dimensional stability, thermal shock, and low CTE perspective. The challenge is to design a polymer system that passes tough reliability testing but still adheres to stiff, high modulus, not so polar, dimensionally stable clad copper laminates like Pyralux® AP.
Thermoplastics solve some of the challenges because they can be very flexible and function at high temperatures. Polytetrafluoroethylene...PTFE...or fluoropolymers in general are known for their temperature resistance and non-stick properties. Polyethylene and polypropylene behave in a similar fashion to PTFE with regard their adhesive properties but aren’t temperature stable. Synthetic rubber (sometimes called hydrocarbon) shares many of the properties of polyethylene in that it has no oxygen or nitrogen and is inherently attractive from a low dielectric loss and dielectric constant standpoint. However, synthetic rubber is prone to oxidation, thereby adding oxygen, driving the dielectric constant and loss tangent higher with high temperature exposure. Lastly, Kapton®/polyimide as a class of organic polymers have relatively low dielectric losses owing to the aromatic carbon–carbon, carbon–hydrogen nature of the backbone polymer. Polymides contain some nitrogen content that drive their dielectric losses a bit higher. Like PTFE or polyethylene, polymers such as polyimide all suffer from a lack of adhesion to substrates. The challenge is to design an overall system that meets all the requirements of a low loss flexible bonding ply when many of the basic characteristics move in opposing directions.

One solution is to combine the most attractive properties of the thermoset and the thermoplastic in one bondply/prepreg using a layered structure. fastRise and fastRiseEZp are designed in many ways similar to today’s acrylic bondplys. fastRise/EZp are based on an internal flexible thermoplastic film coated on top and bottom with a thermoset. Depending on the part number in question, fastRise or fastRiseEZp uses a PTFE or a ceramic filled PTFE center carrier film. Unlike a thermosetting resin, a thermoplastic does not derive its basic properties from crosslink density. A thermoplastic film can have high temperature properties and still be very flexible. Thermoplastics derive their mechanical properties from their crystalline structure, some chain entanglement, and their basic chemistries. The downside of a thermoplastic is that it re-melts repeatedly with each temperature exposure exceeding their melting points. However, if a thermoplastic like PTFE or polyimide is chosen with extremely high softening / gel / melting / decomposition temperatures, they can be simultaneously both extremely flexible and have high service temperatures. As a bondply the high temperature thermoplastic does not lend itself to making multilayer stripline temperatures without heating the thermoplastic to its melting point. Coating the high temperature thermoplastic with a low temperature curing adhesive escapes the problems associated with high temperature fabrication. [7] US Patent 6,500,529 describes a dielectric layer such as a PTFE film that is coated on the top and bottom with a low temperature curing thermosetting adhesive.

| Low Loss, Low curing temperature flexible adhesive |
| Flexible High Temperature Thermoplastic |
| Low Loss, Low curing temperature flexible adhesive |

*Figure 7 – Layered structure of fastRise and FREZ*
The low cure temperature adhesive allows the fabricator to bond together higher temperature etched copper clad laminate cores at the low curing point of the thermosetting adhesive. Therefore, the ease of fabrication can be directly linked to the low temperature curing point of the adhesive systems. Copper clad cores are more dimensionally stable at lower temperature. Hybrid structures containing epoxy laminates or other polyimide laminates can be co-bonded at the lower temperature. Low temperature lamination opens many possibilities to the PWB designer and reduces cost. The thermosetting adhesive of fastRise and fastRiseEZp is a careful balance of low loss dielectric material with enough crosslink density for thermal shock resistance and enough chemistry for adhesion. fastRise EZp is the most attractive for adhesion to polyimides or other hard to adhere thermoplastics like PTFE or liquid crystalline polymers (LCP). Standard fastRise is used at 77 GHz for collision avoidance radar. FR25-0021-45 has a loss tangent of approximately 0.0012 at 10 GHz. Standard fastRise part numbers are most suitable for PTFE based cores. fastRise EZ22p (loss tangent = 0.0018@10 GHz) and EZ33p (loss tangent = 0.0024@10 GHz) have somewhat higher loss tangent values than the standard fastRise family due to the compromises necessary to get acceptable adhesion to non polar substrates like Pyralux® AP.

**Summary of Experiments**

The objective of the initial set of test vehicles was to compare the performance of the low-loss thermoset bondply material to a traditional acrylic-based flex bondply. Figure 8 illustrates these test cases. The “AP-LF-AP” case uses Pyralux® LF bondply which consists of a low modulus polyimide coated with acrylic-based flex adhesive. The “AP-FREZ-AP” case utilizes a 2.2 mil thick version of the structure described in the previous section. Striplines were constructed on 12”x18” panels that had 16” (41 cm) long lines of six different single ended stripline and differential line widths. All the differential lines were edge-coupled and had a constant edge-to-edge spacing of 0.005” for all structures. A break-out length of about 0.35” (0.9 cm) is required to launch the connectors. The line widths ranged from 0.003”-0.0055”. The initial experiment was to demonstrate thin stripline structures with a ground plane spacing B<=0.006” (0.15mm). At the time of this study, the manufacturer did not have the capability of lamination at 285°C, so the “TK-TK” case was manufactured previously and included as the control “best-case” condition. Figure 8 shows time domain reflectometer (TDR) waveforms of each measured line in addition to a summary of measured impedance versus line width. Since the lines are so narrow, the impedance measured at both ends of the line (0.2 ns and 2 ns) are shown to reinforce the fact that narrow lines have some DC resistance contribution to impedance.
Figure 8 - Descriptions of initial structures & corresponding impedance measurements.
Figure 8 (cont.) - Descriptions of initial structures & corresponding impedance measurements.
Figure 9 shows vector network analyzer (VNA) measurements on the 16” (41 cm) single ended lines that were closest to 50 ohms. The insertion loss is normalized to length (divided by 16) for easier comparison. One of the known challenges of acrylic adhesive is that moisture is more readily absorbed than other materials. This is difficult to test in the lab because the moisture diffusion rate is very fast. For each line, measurements were made after a 2 hour, 121°C bake…a 2 hour water soak at 85°C in-situ…and 2 hours after removal from hot water. A week-long soak at 85°C/85% relative humidity did not show any change since the samples re-equilibrated to ambient environment almost immediately after removal from the chamber. This is why the water measurements were done in-situ.

![Figure 9 - Loss performance of initial structures tested before and after hot water immersion.](image)

Results of the first set of experiments led to a modified test vehicle design. The original structure for FREZ bondply was too thin to assess the performance since narrow lines and impedance mismatch made the results unclear. Four additional test vehicles were constructed. The first two of these are shown in Figure 10. Thicker structures were accomplished by eliminating layer 3 and utilizing the clad dielectric inside the stripline instead of utilizing it as a cap layer. TV1 is a thicker structure using the FREZ bondply
between two AP cores. TV2 is a thicker structure using FREZ bondply between TK cores.

Figure 10 shows the details of the modified structures in the same format as shown previously in Figure 8. Impedance was measured at time of manufacture by PFC in the center of the line. Also, impedance was measured at the time of high frequency testing with a TDR at 0.2 ns and 2 ns while terminated with SMA connectors (the same way as described in Figure 8). Note that the line widths were wider for the lower permittivity TV2 structure in order to maintain impedances near 50 ohm singled ended and 100 ohm differential. One can clearly see that the wider line widths have a lower slope (impedance versus time). The wider lines have less DC resistance, which reduces this slope.

Figure 10 - Descriptions of redesigned structures & corresponding impedance measurements.

Figure 11 describes insertion loss testing using the same technique outlined as described in Figure 10. The results show that the FREZ bondply used in conjunction with the AP
and TK clads perform far superior to the case AP-LF-AP case shown in Figure 10. Figure 12 shows similar test structures to Figure 10. TV3 and TV4 were manufactured at the same time as TV1 and TV2. The designs are intended to verify feasibility of alternate approaches for manufacture. TV3 has two plies of FREZ bondply and uses copper foil instead of cladply copper. This is important to demonstrate adhesion of the bondply to itself. TV4 demonstrates a more balanced stripline construction with the theory that the 50 um can be reduced from the height of the stackup without a negative impact compared to TV2.

Figure 11 - Loss performance of redesigned structures tested before and after immersion in hot water.
Figure 12 - Descriptions of further redesigned structures and corresponding impedance measurements.

Figure 13 shows insertion loss results using the same method described and compared in Figure 8 and Figure 11. As expected, the results of Figure 13 are very similar to those reported in Figure 11. TV1 performs very similarly to TV4 and TV2 performs very similarly to TV3.

Figure 13 – Loss performance of further redesigned structures tested before and after immersion in hot water.

Analysis

Comparison data is shown in Figure 14. The flexible thermoset adhesive provides a clear and significant insertion loss benefit when using AP copper clad laminates. Note that the performance difference is not solely due to the adhesive. Part of the benefit shown is due to the thicker structures enabling wider line widths. Similarly for cases utilizing TK cores, the flexible thermoset adhesive enables similar insertion loss performance to high temperature laminated TK cores.

One obvious conclusion from the data is the effect of moisture on the acrylic. Note that this is an extreme condition. Most circuits will not be deployed submerged in water at 85°C. For applications where the environment is relatively stable, this factor should not be of concern. If a circuit is operating inside a “box” when the temperature is elevated above ambient, there is little risk of moisture causing variation of the loss behavior. However, variable environments where moisture can be entrained can lead to inconsistent loss performance. For applications operating on the “hairy edge” of the loss budget, this environmental factor must be considered.
Figure 14 – Comparison of test cases based on cladply (TK or AP)

Figure 15 – Comparison of cases in the change of loss due to hot water immersion.
Due to the thin nature and high moisture diffusion rate of acrylic compared to epoxy, the time it takes for moisture to enter and exit the circuit is on a different time scale as rigid boards. Previous DesignCon work presented by Intel has shown that rigid boards indeed entrain moisture, but it takes a very long time for the moisture to get in…and get out. [8] The results of this experiment should not be construed to indicate that ONLY traditional acrylic-based flexible circuits entrain moisture. Rather, the nature of the acrylic based adhesive has a much higher diffusion rate of moisture to the ambient environment than rigid epoxy.

A more subtle conclusion from this work revolves around the “bumpiness” observed in the loss data of the cases utilizing the thermoset (FREZ) bondply. To investigate this observation, the phase of the insertion loss was unwrapped and group delay (GD) was calculated. The composite relative permittivity (Er) of the stripline structure was calculated from the length of the line (L) and the speed of light (c) using the following equations.

\[ GD = \frac{\Delta \phi}{\Delta \omega} \quad Er = \left( \frac{L}{c \cdot GD} \right)^2 \]

Plots for the calculated Er for each case are shown in Figure 16. Note that the cases utilizing the FREZ bondply were not as stable as the ideal “TK-TK” case at any frequency. FREZ also has more variation between 5-15 GHz than for the “AP-LF-AP” case. These variations in Er indicate phase instability for the cases using FREZ.

Figure 16 – Permittivity extracted from phase measurements of all cases
Cross section analysis was performed to verify dimensions and investigate the source of the phase variation. Representative photos of each structure are shown in Figure 17. Note in the cases utilizing the flexible thermoset adhesive, FREZ, the PTFE appears “wavy”. This may explain the phase instability pointed out in Figure 16. Since the permittivity of PTFE is different from that of the adhesive, this local variation in permittivity may account for this observation. Fortunately, there are steps that can be taken to optimize the lamination to minimize this local variation.

Conclusions
An expanded base of fabricators can now participate in the market for high speed flexible circuits now that a bondply is available that can be processed at lower lamination temperatures. The insertion loss performance is very close to fusion-bonded flexible circuits. Since the material is relatively new to the flex circuit market, lamination conditions have not been fully optimized to induce the PTFE carrier film to lie in a flat horizontal plane. As a result, the phase is not as stable over a broad band of frequencies like the fusion bonded Teflon®/Kapton® circuits.

Figure 17 – Representative cross sections of each test vehicle analyzed.
**Future Work**

Follow-on work will focus on optimizing the lamination conditions to eliminate the "waviness" observed in the bondply and thus improve the phase stability of the resulting transmission lines. Work will also be done to characterize the circuit performance in downstream assembly operations. The bondply material also has great promise for high speed rigid-flex applications, so there will be much support given to determining the extent of designs for which this bondply is suitable. Finally, applying this low-loss adhesive to Kapton® substrates instead of PTFE will be explored. This offers the promise of improved dimensional stability and may increase the window of designs that may be suitable for this technology.

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