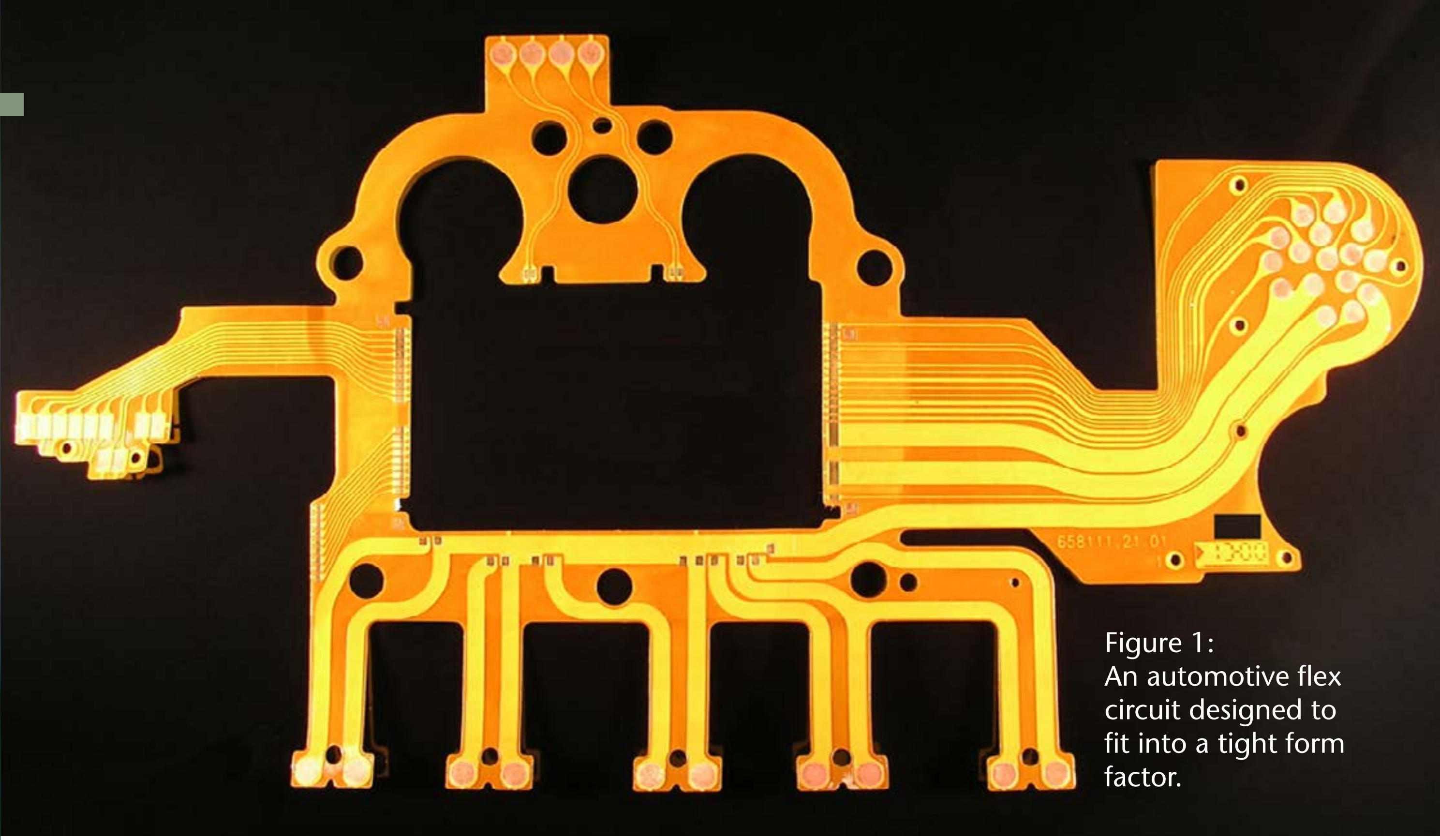

Figure 1: An automotive flex circuit designed to fit into a tight form factor.

Using Flex in High-Speed Applications

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Copper clad circuits in the printed circuit industry have evolved into four different classes, each having different sets of standards. For instance, IPC has separate sets of standards for rigid, flexible, high speed and high frequency, and HDI. Further, there are separate standards within these families for design, acceptance, and base materials. These standards provide logical organization to the design, process, and material considerations of each class of circuit[1]. In many applications, however, designs may utilize all four classes of boards in a single assembly. This presents significant challenges for the designers, fabricators, and materials suppliers because choices made using design rules from one type of board may significantly limit utilization of another type of board on the same assembly. For example, a designer may be forced to use a complex and bulky connector system to link two rigid boards together due to design choices, instead of utilizing a small interconnect utilizing a rigid-flex circuit. The result could be that the assembly does not fit into the assigned form factor. This article will focus on flexible circuit technology and specifically, on the material properties that account for the broader use of flexible circuits in high frequency and high-speed applications.

How Flex and Rigid Materials Differ

Of the four types of circuits mentioned, flex suffers from being the least understood in the design community. There are many reasons for this, but this is mainly due to the fact that flexible circuits comprise a much smaller market than do rigid circuits. In addition, flex designs generally have to fit into a pre-defined form factor which means that very few flex designs look alike. These realities make it a significant challenge for standard design tools to adequately plug flex into their design flow. Figure 1 shows an example of a flex circuit design driven primarily by the form factor in which it must fit. The traditional deployment of flex in these applications facilitates the need for fundamental differences in flex materials from typical rigid

PCB materials. One fundamental difference about flex materials is that the base dielectric generally does not contain glass reinforcement. Most flexible circuits contain various grades of polyimide as the dielectric to provide both mechanical integrity and flexibility. Some may refer to this polyimide by the DuPont brand name Kapton. The flexible copper clad laminate, or flex core, provides the "backbone" to the circuit and usually is made with Advanced Kapton that has higher elastic modulus. Another fundamental of flex is that soldermask is generally not used to cover the outer layers of the circuit. This is because soldermask is usually very brittle and will crack when flexed. Instead of soldermask, adhesive is coated on one side of a thin, conformable, elastic standard Kapton layer. This is called a coverlay to distinguish it from soldermask, since it is processed differently. In a similar way, a layer used to bond copper clad flex cores together with adhesive coated on both sides of a polyimide layer is called a bondply instead of a prepreg. This is because the polyimide in the center does not flow. Only the adhesive coated to the polyimide flows.

Not only are the dielectrics that go into flex circuits made of different materials than are rigid, but the processes used to make the base dielectrics are also significantly different. Some insight into this difference can be seen in the cross-sections of 50 ohm controlled impedance lines in Figure 2. Most rigid copper clad laminates are made by impregnating resin into a glass cloth. This means that the composite dielectric is created at the same time it is laminated. This is not the case for flex materials. Flex dielectrics are manufactured on large rolls of coated film and laminated to copper as a separate step. The advantage of this manufacturing method is that the thickness of these cast films are very consistent. This additional process step makes it less efficient to make constructions more than 100 um thick. While 100 um thick dielectric layers are considered to be "very thin" and thus challenging to make consistently using a glass/resin lamination process, this thickness range is considered to be "thick" for flexible circuit designs and by comparison relatively easy to manufacture.

Significant differences also exist between the copper typically used in flex and in rigid circuits. Electrodeposited (ED) copper is by far the most common type of copper used for rigid circuits. This type of copper is made by "growing" copper on a large electrified drum that rotates in a solution. The result is very consistent, but with fine copper grains when viewed microscopically. Another way to make copper foil is to start with a large ingot and run it through successively closer rolls. This rolling process anneals the copper making it more ductile by creating relatively large copper grains, leading to

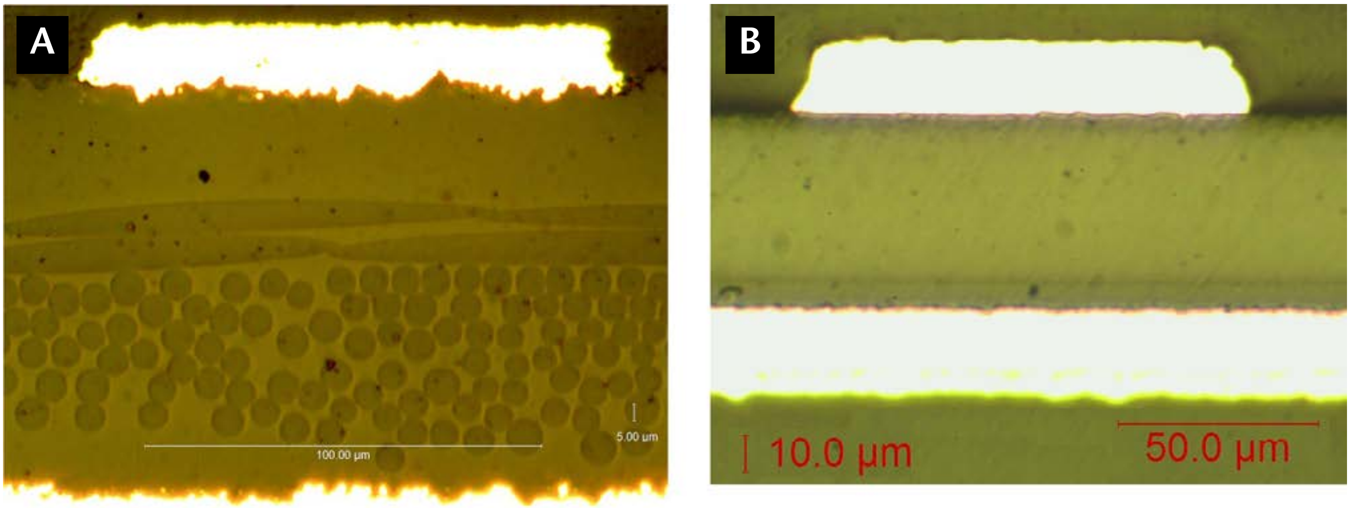

Figure 2: 50 ohm signal lines with rigid (A) and flex (B) materials.

the name rolled-annealed (RA). The improved ductility and larger copper grains make the copper more and less likely to crack due to bending. For this reason, many flexible circuits utilize RA copper instead of ED copper. Another difference between RA and ED copper is how the surface finish must be considered with respect to design and fabrication. Figure 3 shows a low magnification visual microscopic view of the outer copper surface of ED and RA copper clad laminates. Note that there is directionality in the RA copper which is why flex fabricators must always consider the machine direction (MD) in line with the rolls and the orthogonal transverse direction (TD). If one refers back to Figure 2, the impact of this directionality can be seen in the copper profile. The ED copper in Figure 2 (A) is much rougher while the telltale grooves of the smooth RA copper can be seen in Figure 2 (B).

Behavior of Flex Materials at High Frequencies

Traditionally, the electrical properties of flex materials were not considered to be critical since flexibility and copper adhesion were of paramount concern. The dramatic increase in bandwidth requirements and the miniaturization of devices has brought properties like dielectric constant and loss tangent to the forefront of concern. Higher frequencies and speeds require tight control of impedance with very small loss budgets. These current applications require consistent dielectric thickness, low dielectric constant and low dielectric loss.

Dielectric Constant and Loss Tangent

At frequencies above 1 GHz, the term "dielectric constant" is actually a misnomer. This property is not constant with frequency in this region for most organic materials used in printed circuits. The reason for this is that the molecules in these polymers vibrate when RF or microwave energy is applied. The property must be described with a complex quantity called relative permittivity. The real component most closely aligns to the concept dielectric constant and describes the energy stored in the dielectric by capacitance. The imaginary component describes the energy lost in the dielectric. If you take the tangent of the ratio of these two components, you get the loss tangent of the material. Materials with high loss not only are problematic since more energy is absorbed, but the relative permittivity will change a lot more with frequency. This phenomenon called dispersion is not unique to flex materials. Typical epoxies used in rigid circuits have very similar behavior electrically to the acrylic adhesives more typically used in flex circuits. Due to differences in processing preferences, epoxy is more commonly used as a flex adhesive in Asia while acrylic is more commonly used in North America and

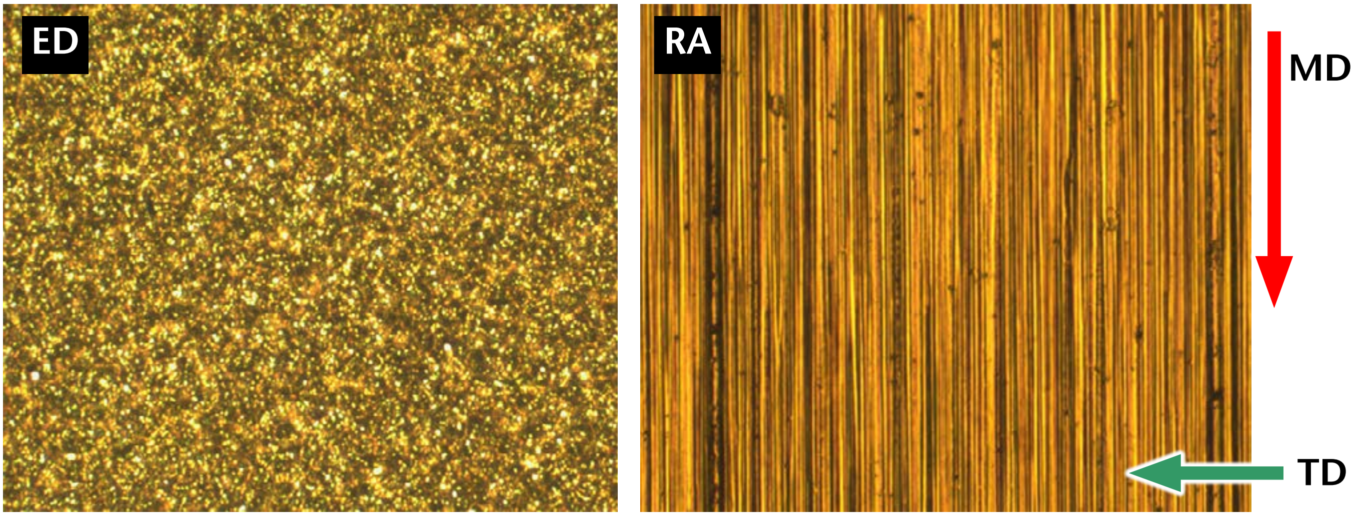

Figure 3: (l) Optical microscope images of electrodeposited and (r) rolled annealed copper.

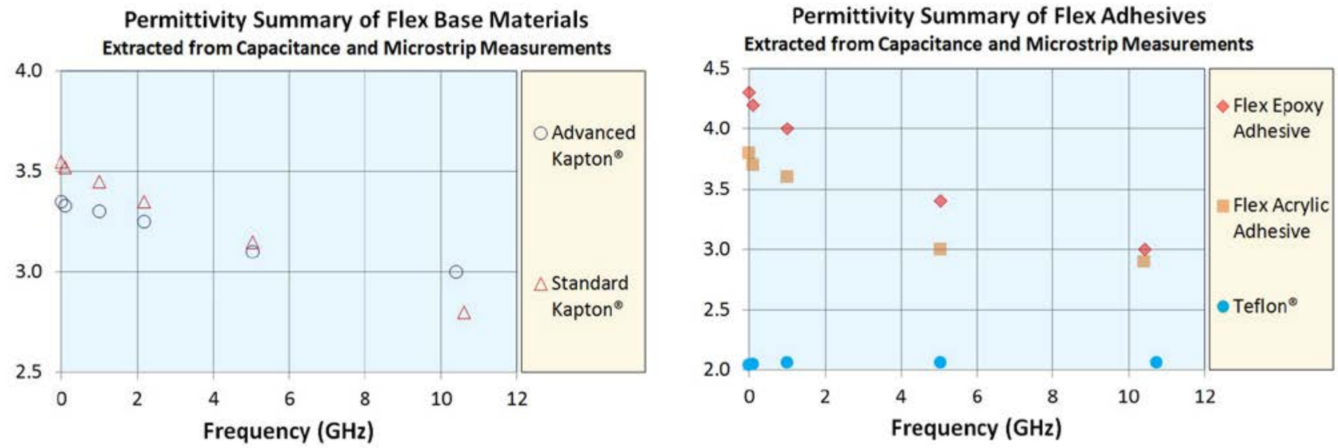

Figure 4: Relative permittivity versus frequency of flex dielectrics and adhesives.

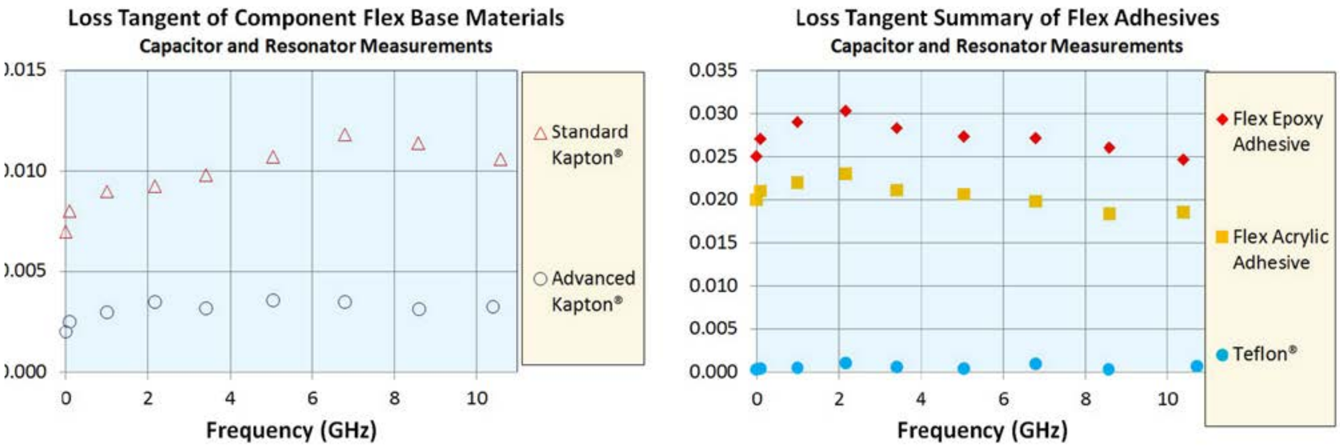

Figure 5: Loss tangent versus frequency of flex dielectrics and adhesives.

Europe. Figure 4 summarizes the relative permittivity versus frequency for Kapton®, Teflon® and the common adhesive materials used in flex circuits. Notice that Advanced Kapton used for high-frequency copper clad flexible laminates has lower dispersion compared to standard Kapton used for coverlay.

Loss tangent values for these same materials are also shown in Figure 5. When analyzed in concert with Figure 4, one will notice that the materials with the least amount of dispersion have the lowest loss tangent. Low loss and low dispersion are two of the primary reasons why Advanced Kapton and Teflon are used to maximize signal integrity for high-speed flexible circuits.

Lower Loss Copper

Not just the dielectric has a great impact on signal integrity. As thickness of layers reduces, the copper has an exponentially increasing impact on signal loss compared to the dielectric. If you suppose the air had dielectric loss at varying levels, then Figure 6 shows the signal loss of a stripline for a thick structure, a nominal structure, and a thin structure. Note that the loss is inherently larger due to the fundamental resistivity of copper for thin structures. For thick

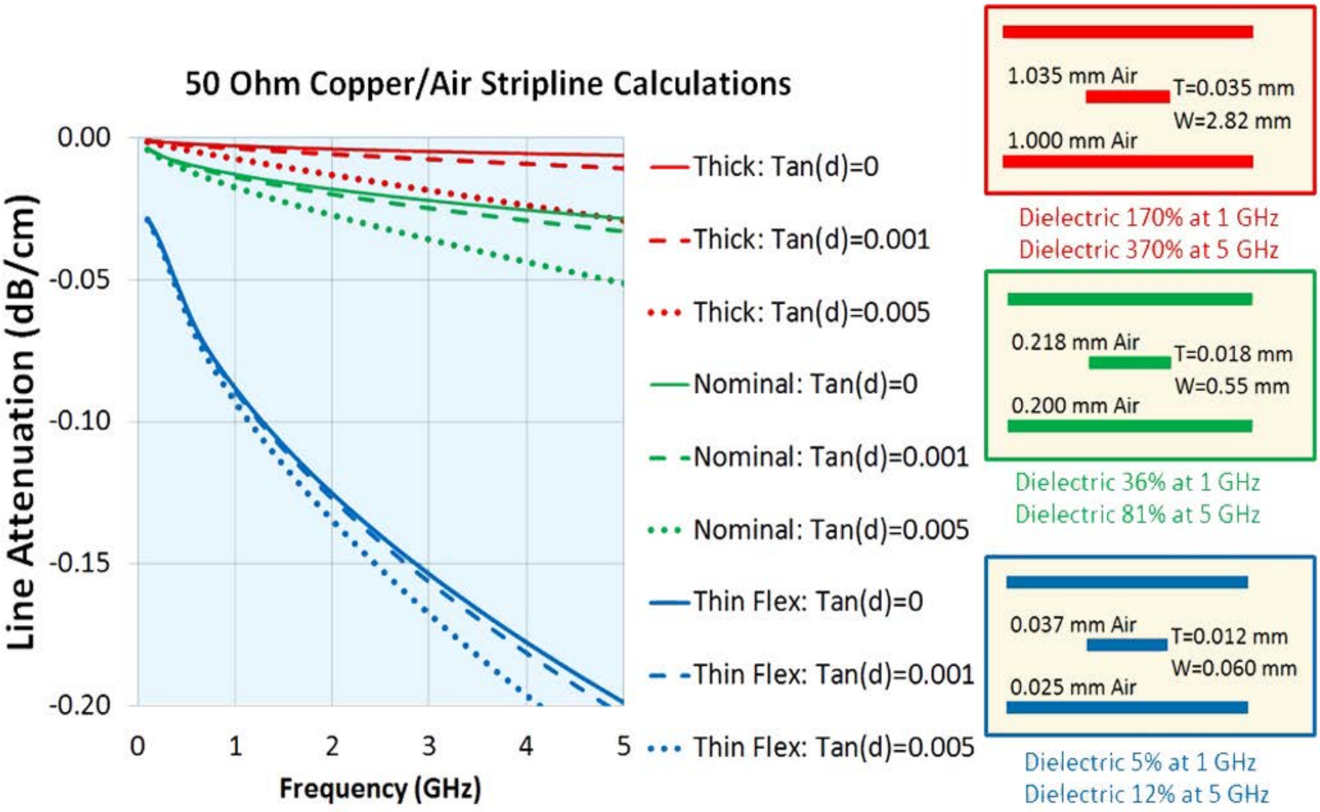

Figure 6: Calculated values from the effect of thickness and dielectric loss.

structures, decreasing the loss of the dielectric has a huge impact[2]. For thin structures the conductor accounts for most of the loss so lowering the dielectric loss only has a significant impact at high frequencies.

Signal Integrity Analysis Tools

One source of frustration for flex designers having to meet controlled impedance requirements is that using the known permittivity values of flex materials in field solvers to calculate line width can be off. The reason for this is that most of these field solvers assume the use of glass reinforced copper clad laminates like FR-4. The software is optimized and verified by use of relatively thick layers and wide conductor lines compared to flex. In general, the designer or fabricator must bias the dielectric constant lower than the actual values reported on data sheets to get consistent line width predictions.

Overall Impact on Loss Performance

It is possible to utilize Teflon and Advanced Kapton together to construct flexible circuit materials[3]. The low dispersion and low loss tangent of these materials shown in Figures 4 and 5 combine to make the optimum platform for high-speed signals in a flex circuit. Figure 7 summarizes measurements taken from microstrip transmission lines made at the same time. Common materials used in high-speed transmission (Meg4 and Meg6) are directly compared to a Teflon-Kapton composite (TK). As frequencies increase, the impact of the smoother RA copper becomes quite significant. The copper weight and type are denoted on the plot legend.

Summary Takeaways

- Flex circuits offer great advantages to designers, but there are big differences between flex materials and rigid materials. These include design, fabrication, and materials. Understand-

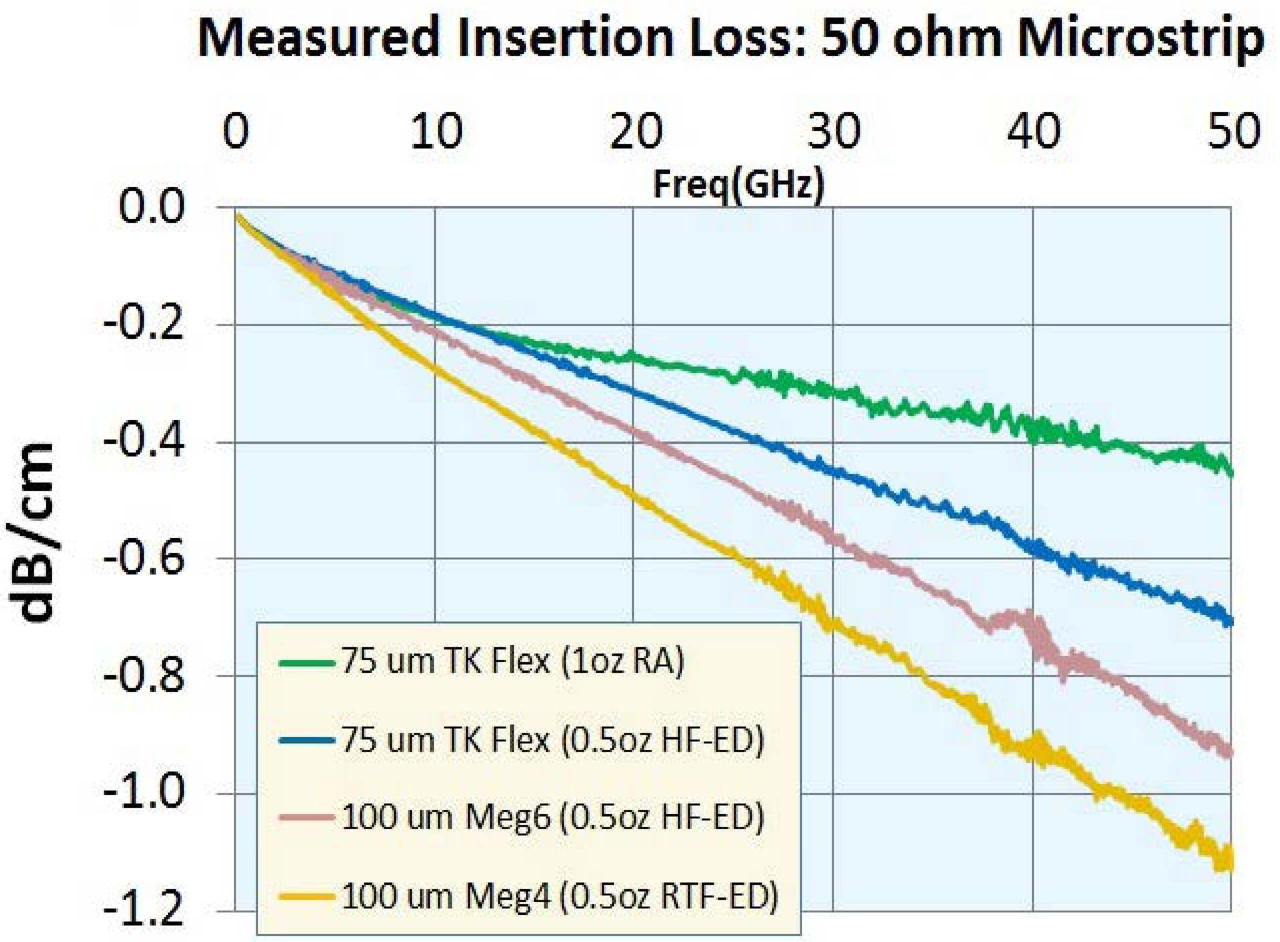

Figure 7: Comparison of high-speed flex to high-speed rigid microstrip lines.

ing the differences between the materials can help both fabricators and designers better utilize flex circuits to meet their goals.

- To utilize flex in high-speed and high frequency applications, the effect of the Kapton, adhesive must be understood in the same way that the effects of the glass and resin must be known for rigid designs.
- Not all Kapton are created equal. Advanced, high modulus Kapton has low loss and low dispersion compared to Kapton used for coverlay.
- As high-speed circuits get thinner, the more it makes sense to utilize flexible circuits in these designs because of the inherent properties of flex materials. **PCB**

References

1. Specification Tree of Standards organized by IPC.

2. Oliver, G and Coonrod, J. Practical Measurements of Dielectric and Loss of PCB Materials at High Frequencies, DesignCon 2014.

3. More information on the composite materials can be found at www.pyralux.com/tk.

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