High-Volume Print Forming, HVPF™
A New Method for Manufacturing Large Volumes of Complex Metal-Ceramic and Hybrid Components

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Abstract

EoPlex Technologies, is a Redwood City, CA company that is commercializing a family of new technologies to manufacture miniature electronic components and subassemblies. The company is backed by Draper Fisher Jurvetson, Labrador Ventures, and Draper-Richards.

The company's proprietary print-forming technology can produce large volumes of three-dimensional structures from a wide range of metallic and non-metallic materials. The EoPlex process is called High Volume Print-Forming™ (HVPF™). It allows for thousands of small, complex structures to be built simultaneously. Parts are designed in layers and customized printing machines are used to deposit special "inks" which carry ceramic, metallic or polymer materials to millions of locations. Materials are then cured, fused, sintered, cofired or bonded in post processing steps.

With the EoPlex process complex shapes such as three-dimensional grids, interwoven circuits, assemblies with multiple parts, and multiple materials can be produced at the same time. The process also makes it cost effective to mass-produce products which would be difficult or impossible to manufacture using conventional techniques. Virtually any shape can be produced, including complex components with cavities, chambers and moving parts. The greatest cost advantage is with miniature structures but larger sizes are also possible. Identified market applications include: electronic packaging, passive electronic components, RF and microwave components, antennas, unique 3-D circuits, fuel cells, batteries, mechanical components, switches, connectors and sensors.

This presentation will focus on the basic technology, manufacturing and materials that make the EoPlex process possible; the new design rules that are enabled and how this translates to advantages for customers.

Introduction

In 1995, Taylor et al. published a paper [i] in the IEEE proceedings describing work that was done by his team at Advanced Cardiovascular Systems in Santa Clara, CA; on a three dimensional printing process which he called "spatial forming". At that time Taylor described his selection of this term as follows:

> "….spatial forming was chosen to denote the lack of restrictions on the possible geometries that can be created. Objects are generated by combining thin layers of material in shapes defined by cross section data from computer models. The negative space around parts is printed concurrently with solid material, leaving a planar supporting surface for the next layer. Our definition of the terms states that the materials of which a 'spatially formed' object is made can exist, or not exist, at any point within the space the object occupies, at the will of the designer. Thus assemblies, parts within parts, three-dimensional grids, totally enclosed voids, multiple material structures, and complex shapes are possible."

The method that Taylor and his team developed and patented [ii] is not a rapid prototyping method although it is often confused with rapid prototyping. A typical definition of rapid prototyping is that given by McGraw-Hill below: [iii]

> (n) A broad term used to describe several related processes that create physical models directly from a CAD database. Prototyping systems use a variety of techniques, including stereolithography and fused deposition modeling. Rapid prototyping is used to create prototypes for concept modeling, injection molds, and investment casting.

In contrast, Taylor envisioned spatial forming as a way of high-speed manufacturing of large volumes of finished parts rather than prototypes. In this respect, spatial forming is similar to metal or ceramic injection molding, although the design freedom of spatial forming is orders of magnitude greater and the tooling costs are very low. However, since spatial forming does utilize layered designs and creates parts by rapid build up of many layers it is often initially confused with rapid prototyping.

In 2002, Mr. Taylor recruited me from Solectron Corporation to head up EoPlex Technologies, a company he had formed in 2001 specifically to develop and commercialize this technology. I was attracted to the company by the enormous potential of the technology and the quality of the core staff. I realized right away that there was much more to the basic technology than originally envisioned and EoPlex soon developed advanced versions of "spatial forming" in the form of "High Volume Print Forming™" or HVPF™.

HVPF™ is a true manufacturing technique with the following attributes:

- Parts can be made in true 3-D designs
- Multiple materials can be incorporated into the same "green" part so long as they are compatible and cofireable or coprocessable
- Millions of "pixel" of material can be printed simultaneously
- Thousands of parts can be built at once
- Parts can have a few layers or hundreds of layers
- Circuit elements, conductors, and passive components can be formed as the part is being made
- Physical elements, mechanical parts, chemical channels and even moving parts can be produced
- Tooling consists of only printing screens or plates and can be changed quickly and inexpensively allowing design changes to be put into production immediately
- Parts can be made from ceramics, metals, combinations of ceramics & metals and from various polymers and fillers

Many of the parameters and techniques of the process are covered by an issued patent [ii] and other pending patents. However, the bulk of the intellectual property is essentially in the form of trade secrets that cannot be covered in this paper. Instead, the scope of this paper will focus on the key features of HVPF™, how it works and what progress is being made at commercialization.

Requirements necessary to develop HVPF™

A number of processes exist to produce various parts from layering. As already discussed rapid prototyping or stereolithography is one of these. Other processes use laser erosion and deposition techniques. [iv] Another process, although not exactly layering, that is similar is the LIGA process. [v]

What EoPlex wanted to develop with HVPF™ was a way to do high speed manufacturing of unique components, with multiple materials including conductors. To do this we required the following:

- A new method that would allow all layers of each part to be printed simultaneously in individual locations on movable substrates
- A way to index substrates to high accuracy to achieve proper layer alignment
- A method to print different materials side by side to make a finished layer (like a jigsaw puzzle) rather than printing one material on top of a substrate (like ink on paper)
- A way to "freeze" or "set" each print image quickly so that the next layer would not distort the prior one
- High speed, high accuracy printing platforms
- A new binder system that would achieve a strong chemical bond between layers prior to either curing, for polymer parts; or firing, for ceramic & metal parts
- Printing inks with high loadings of the final materials including ceramic and metal powders

- A negative or sacrificial material that could be printed and set in the same manner as the main inks but which could be burned, etched, or dissolved away to create openings, holes, spaces, and even moving parts
- Imaging systems to check both XY patterns and Z thickness during production
- New design rules for cofired parts where all the starting materials were "wet" and based on similar binder systems rather than printing "wet ink" on dry ceramic tape

Forming Methods

The spatial forming method called Progressive Wedge described and patented by Taylor[ii] et al. had not been demonstrated at the time that EoPlex was formed. Our first action was to set up a printer line in the laboratory to prove that this method was viable. The original equipment used for this purpose consisted of refurbished screen printers, a special UV cure box, substrate holders and an index and shuffle machine. This equipment is shown in Figure 1.

It soon became obvious that instead of a single process we actually had a family of three related processes, see Table 1. These processes varied primarily in the number of dimensions changed between each layer of printing and the number of printing screen, plates or masks utilized. The original Progressive Wedge method (Z_) steps down in two dimensions, while the basic Plane Method (Z_) steps in only one dimension.

The newest method (Z_) which we named Ziggurat Printing™ steps down in three dimensions. The name Ziggurat came from the similarity to ancient temples or pyramids that have a stepwise construction. Of course, once we named the substrate carried the Ziggurat the smaller carriers themselves became the Ziggys. A photo of a 12 station Ziggurat with Ziggys is shown in Figure 2. The Ziggurat and related printing method is patent pending.

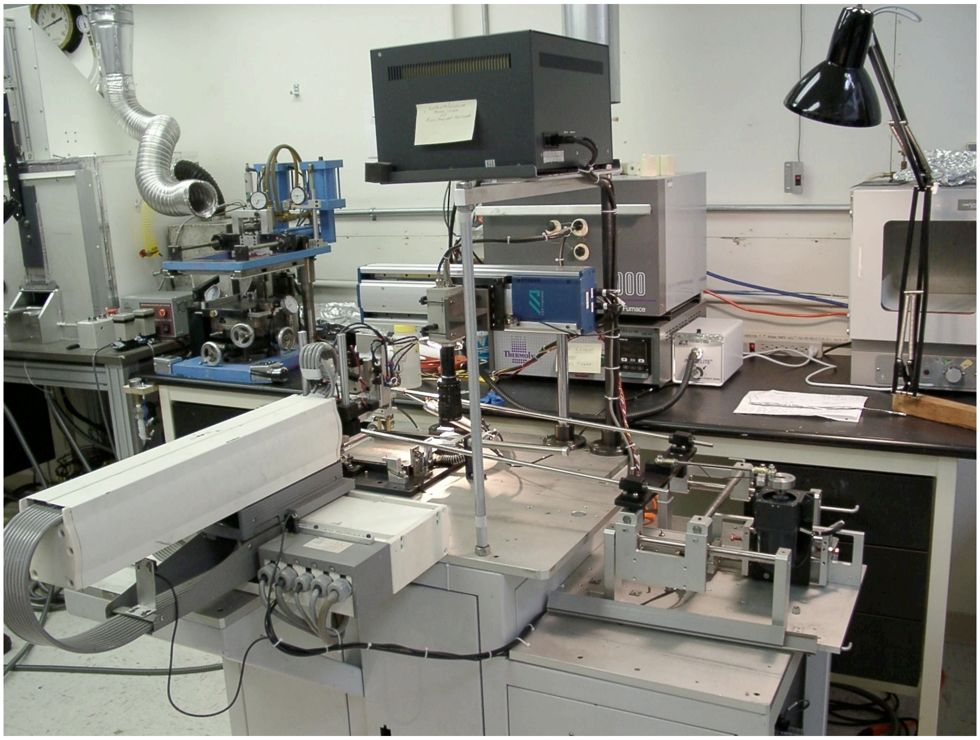


Figure 1 - Original development equipment

Table 1 – EoPlex HVPF^{TM} Variations

Variation	Z^1 = Plane	Z^2 = Wedge	Z^3= Ziggurat
Dimension Changes	Height	Height & Length	Height, Length & Width
Complexity	Medium to High	Medium	High
Best Use	Prototype or High Volume	Medium Volume and High Aspect Ratio	Medium to High Volume
Relative Capital Cost	High to Medium	Medium	Medium to High
Start/Shutdown Scrap	Minimum	2(n-1 layers)	2(n-1 layers)
Screen Changers	Required for high layer count	No	No
Shuffle Machines	No	Required	Required
Type of Process	Batch	Continuous	Continuous

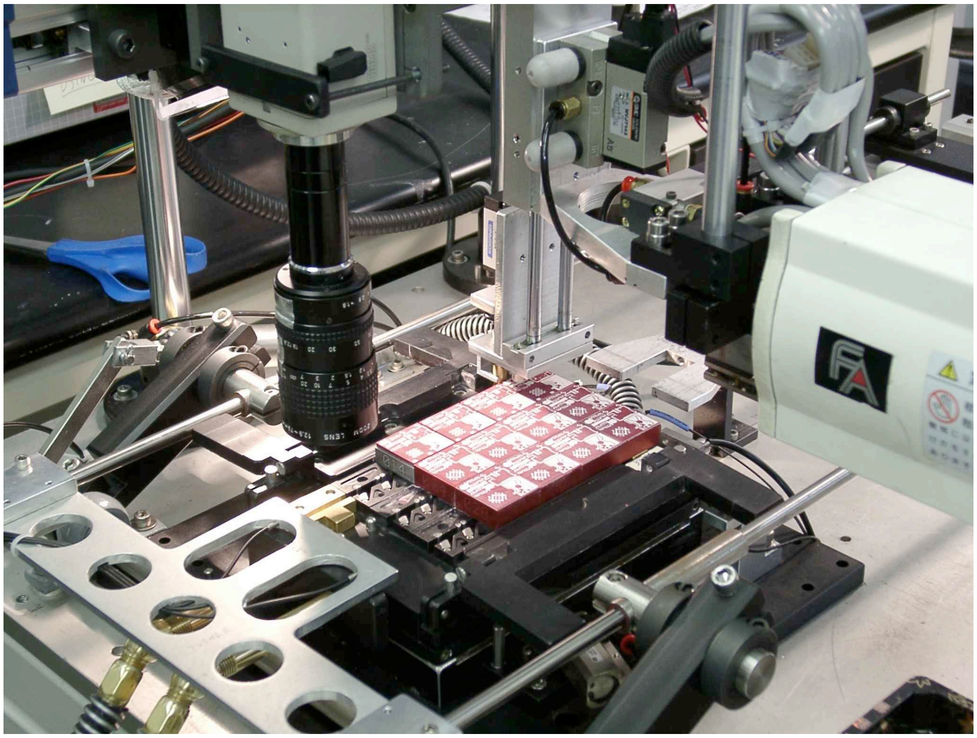


Figure 2 - 12 station Ziggurat with Ziggys

Inks and Binder Systems

At the same time that we were setting up the laboratory print line, we began developing the proprietary inks and binder systems that would provide the properties needed to make the system work. Although the HVPM™ system will work with a wide range of materials we wanted to begin development with ceramics and metals that were already proven in commercial use. To facilitate this we selected commercially available LTCC ceramic and metal conductor compositions that were known to be compatible and were already being used to produce electronic components. This choice reduced the time needed to develop custom inks and lowered the risk to both our investors and our initial customers.

The inks that we needed to formulate fell into four general categories:

- Release layers which needed to bond strongly to the temporary substrate but release cleanly when the printing cycle was finished
- Inorganic "positive inks", which were the carriers for the ceramic or metal powders and that would leave behind ceramic and metal structures after firing
- Organic "negative inks" which were used to create temporary structures such as holes, channels, and layers that would separate positive inks in moving parts
- Organic inks with and without fillers for use when the design required a finished polymer part rather than a fired ceramic or metal one

All of these inks had to share certain characteristics in order for our system to produce commercial parts at high speed. The primary requirements included:

- All layers had to form a strong chemical bond with each other

  For ceramic and metal layers this was a key success factor since getting a strong temporary chemical bond resulted in a very tight structure and an excellent ceramic-ceramic; ceramic-metal; and metal-metal bond forming during firing

  For Polymer parts it was also a key requirement since this would be the primary bond in the final product
- The chemistry of the binder systems had to be designed so that we could set the layer instantly when desired. This was required so that multiple layers could be built up without distortion between layers
- Positive inks had to have loading levels of ceramics and metals that were as high as possible and still print clearly to a very fine level of detail.
- The "negative inks" needed to burn away cleanly during firing for ceramic/metal structures and be removed by chemical means for polymer structures without any interference with the remaining "positive materials"
- Ideally all inks would be water based and nontoxic to minimize special processing, handling and clean up and to protect the environment

All of these goals were achieved resulting in a series of proprietary formulations that can be modified for use with a wide range of both organic and inorganic systems.

The Prototype and Production Line

The initial work done to prove out HVPF™ was accomplished on the small manual screen printers of the type used many years ago for basic printed circuit boards. Figure 3 shows three of these printers; one for a ceramic ink, one for metal and one for a negative ink. This early "prototype line" was all manual and each step in the process had to be done by hand. In practice, a substrate was placed in printer #1, aligned, printed and then moved to a special UV cure station. It was then inspected and moved on to printer #2 where the process was repeated and then to printer #3 where the process was again repeated. When all three print cycles were finished a layer would be complete. At that point either the substrates would be shuffled, as in the wedge or Ziggurat method, or the screens would be changed, as in the plane method, and the next cycle would begin.

These early printers were effective for proof of concept and small prototype runs but the process was very slow and the accuracy limited.

In June 2004, we closed our B-series investment and immediately began specifying a full scale prototype line that would allow commercial accuracy and production rates. For this initial line we chose Ekra[vi] E5 printers for their large size and flexibility. For all the custom equipment such as special UV cure stations, sensing and QC measurement cells, conveyors and system integration we chose Promation Corporation[vii] for their excellent reputation. Figure 4 shows the current configuration of the prototype line. Because this line was built with full size commercial equipment it can also be used for new product introduction and initial production.

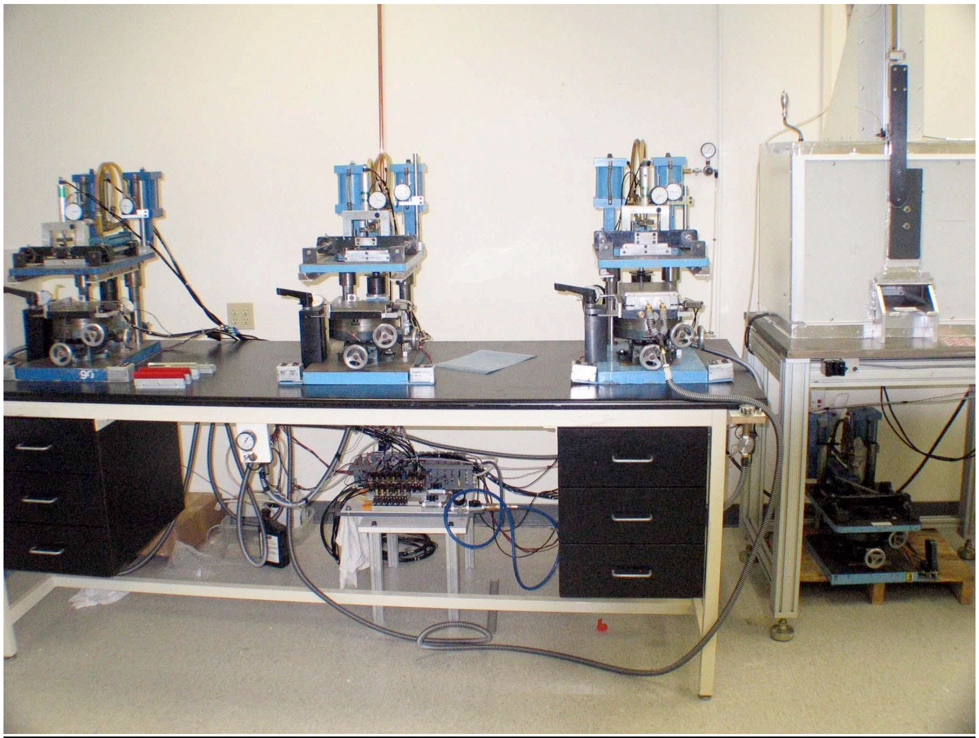


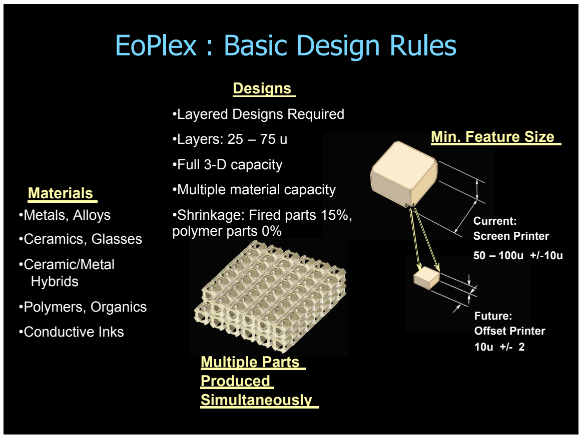
Figure 3 - EoPlex Prototype line as of June, 2004

Figure 4 – EoPlex - Prototype Production line as of January 05, 2005

Basic Design Rules

The EoPlex technology makes possible a new set of design rules. As a result our customers now have new flexibility to produce designs that were not possible before. In addition, very expensive designs that typically required multiple steps are now possible in a single process and at a competitive price.

EoPlex allows true 3-D designs to be created in a layered format. The number of layers required is determined by the resolution and design of the part. Parts with over 100 layers are easily accommodated. The current EoPlex production equipment is based on large-scale state-of-the-art screen printers, which can provide minimum feature sizes of 50 to 100 microns. Layer thickness is typically from 25 to 75 microns although thinner layers have been produced. Laboratory parts have also been produced on an offset press and this equipment can achieve minimum feature size of 10 microns. Shrinkage for ceramic and metal parts is typically about 15% while shrinkage for polymer parts is virtually zero. Many materials can be incorporated into the same part including ceramics, metals, glasses, alloys, cermets, polymers, and conductive organics. However, all materials must be compatible in post-processing. Figure 5 outlines the Basic Design Rules of the EoPlex process.



EoPlex : Basic Design Rules

Designs
- Layered Designs Required
- Layers: 25 – 75 u
- Full 3-D capacity
- Multiple material capacity
- Shrinkage: Fired parts 15%, polymer parts 0%

Materials
- Metals, Alloys
- Ceramics, Glasses
- Ceramic/Metal Hybrids
- Polymers, Organics
- Conductive Inks

Min. Feature Size

Current:
Screen Printer
50 – 100u +/-10u

Future:
Offset Printer
10u +/- 2

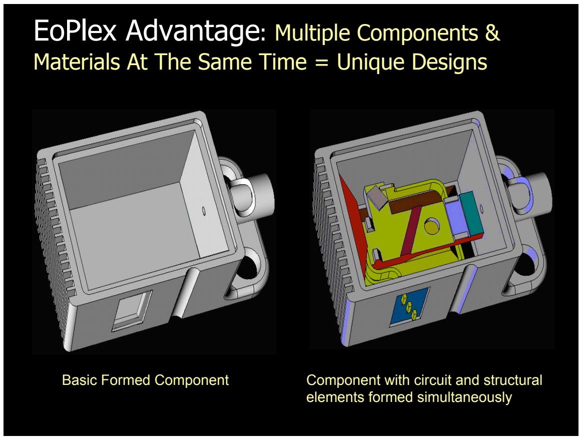
Multiple Parts Produced Simultaneously

Figure 5 - Basic Design Rules

Multiple Materials

All products produced with HVPF™ employ our proprietary ink systems. For inorganic materials each ink is loaded to a very high level with a carefully engineered distribution of ceramic and/or metal powders. During the firing process these powders retain their printed shape but sinter to high density. In production a “negative” ink or sacrificial material is also used to fill all the areas of each surface where there is no “positive” ink and therefore provide a flat surface for the next layer. The “negative” ink burns away during firing to create cavities, holes, channels or whatever shapes are required.

Printing shapes from several materials is relatively easy as long as the materials selected and the designs required allow compatible cofiring. This advantage allows EoPlex to print structures like the electronic package shown in Figure 6 from multiple materials. The package on the left is the basic structure made from a single ceramic ink. The package on the right contains components such as circuit elements, mounts, and passives (shown in different colors) that have been formed simultaneously and cofired. Not shown is the negative structure that was printed with each layer during production and removed in post production.



EoPlex Advantage: Multiple Components & Materials At The Same Time = Unique Designs

Basic Formed Component

Component with circuit and structural elements formed simultaneously

Figure 6 - Multiple Components & Materials

Low Tooling Costs and Fast Turnaround

Unlike many processes for forming small complex components the EoPlex process requires no expensive molds, dies, or hard tooling. Thousands of parts are printed at once and the only tooling required is the printing screens, stencils, or plates. Print screens or plates are good for a very large number of cycles and unlike molds are very low cost. As a result the printing approach allows great flexibility when dealing with complex parts that are still evolving, or where the customer wishes to make changes. In these cases, all that is required is taking the design changes from the CAD system, creating new printing screens, installing these into our process and proceeding to create the new part. In practice this process can be accomplished routinely in only a day or two.

The part shown in Figure 7 is a model of a component used in gas test instruments. The EoPlex process allowed this type of part to be created quickly. It also offers the potential for changes in this complex structure to be implemented just as quickly, and at low cost.

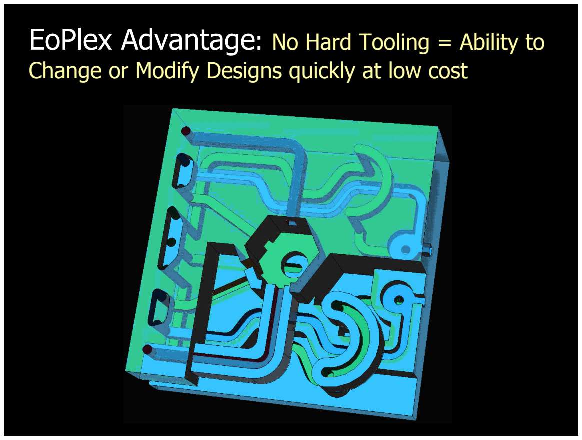

EoPlex Advantage: No Hard Tooling = Ability to Change or Modify Designs quickly at low cost

Figure 7 - Component - Gas Test Instrument

Figure 8 shows an example of four recent demonstration parts produced by the EoPlex process. All four parts are shown in a build using a 60-layer stack. The stack is shown both with the negative material still present (left side) and with the material removed to show the individual parts (right side). The gas test part that was shown in Figure 7, as a model, appears in Figure 8 as a finished part in the lower left corner.

The next example (Figures 9 and 10) is a demonstration of a moving reconfigurable component made from two materials. As can be seen in the illustration the vanes can be moved from side to side (arrows) and the spring will return the vanes to a neutral position when the force is removed.

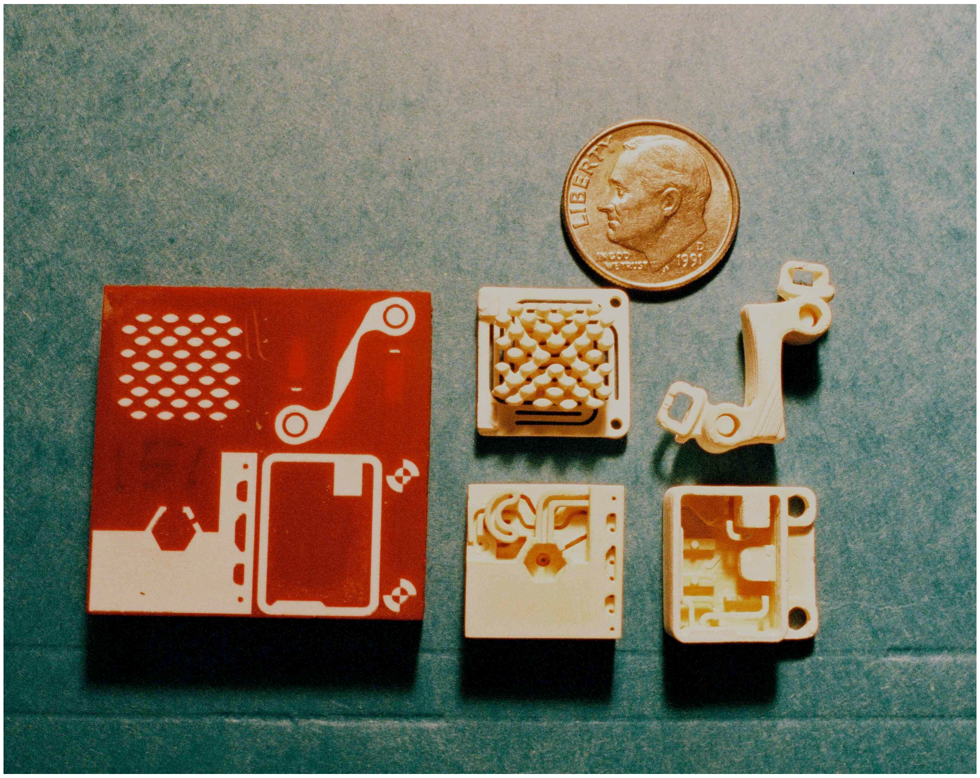


Figure 8 - Demonstration parts of 60 layer stack

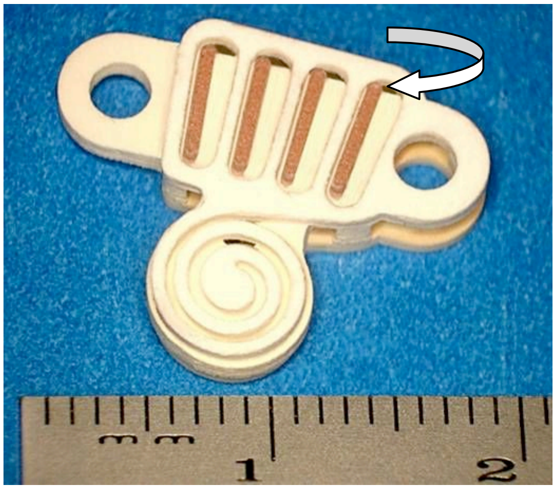


Figure 9
Reconfigurable component in "left" side position

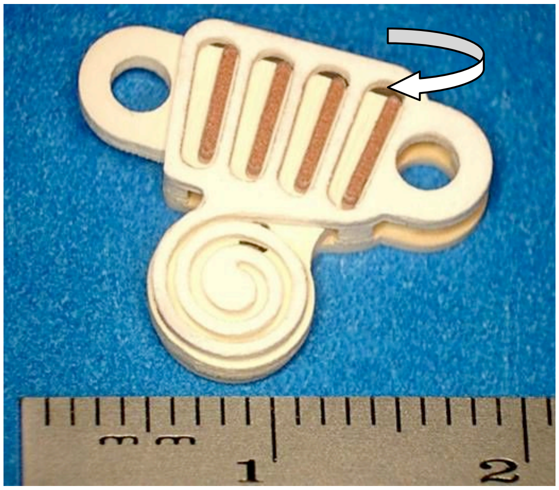
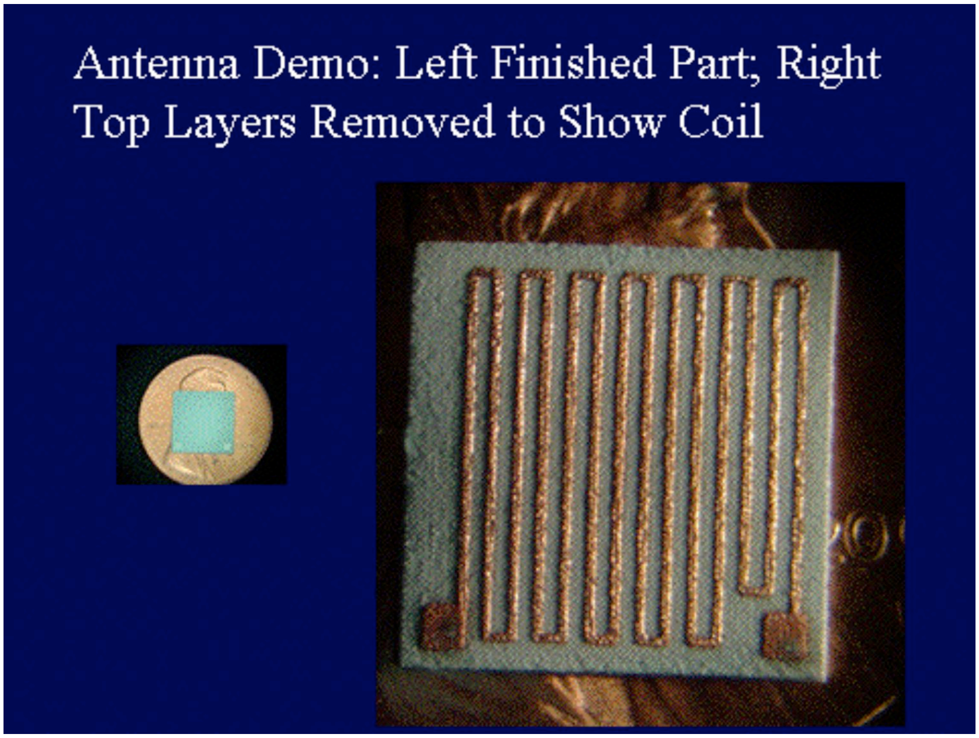


Figure 10
Reconfigurable component in "right" side position

The final example that will be discussed in this paper is shown in Figure 11. The part is a demonstration antenna model with a multiple layers and imbedded components. On the left is the finished part with only the two vertical vias visible at the bottom. On the right is an enlargement of one of the internal layers showing the serpentine conductor and vertical vias.



Antenna Demo: Left Finished Part; Right Top Layers Removed to Show Coil

Figure 11 - Antenna Demo part

EoPlex is currently working with customers on microwave, sensor and RF concepts. Our plan is to first develop products to customer specifications and designs, then to offer improvements that will require changes to the design and finally to offer totally new designs that take full advantage of the EoPlex capabilities and that provide customers with strong competitive advantage.

REFERENCES

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[1] Charles S. Taylor, Paul Cherkas, Hilary Hampton, John J. Frantzen, Bob O. Shaw, Dr. William B. Tiffany, Dr. Leonard Nanis, Dr. Philip Booker, Amr Salahieh, Richard Hansen, "Spatial Forming" A Three Dimensional Printing Process"; 29 January – 2 Feb, 1995; IEEE Publication

[ii] US Patent number 5,348,693; Taylor et al.

[iii] http://highered.mcgraw-hill.com/sites/0072322098/student_view0/glossary_q-r.html

[iv] T.M. Bloomstein, D.J. Ehrlich, "Laser-Chemical Three-Dimensional Writing of Multimaterial Structures for Microelectromechanics, Proceedings, IEEE Micro Electro Mechanical Systems Workshop, pp. 202-203, Feb 1991

[v] W. Ehrfeld et al., "Fabrication of Microstructures Using the LIGA Process," Proceedings, IEEE Micro robots and Teleoperators Workshop, Nov., 1987.

[vi] EKRA America, Inc., 34 Saint Martin Drive, Marlborough, MA 01752 – USA – www.ekra.com

[vii] Pro-mation, Inc. 7323-92nd Avenue, Kenosha, WI 53142 - USA – www.pro-mation-inc.com