1. Introduction

The evolution of products with time does not always advance the development of technology. Sometimes, it rather hinders it. Consider a mobile phone as an example. As it is in the engineers’ nature to develop products that are “lighter”, “thinner” and “smaller”, the antenna as a component of the mobile phones also advanced its technology in weight reduction, thinning, and downsizing, in order to demonstrate its performance within a limited volume. This resulted in the modularization of the antenna, causing a paradigm shift in the technical design and changed them from being built externally antenna to internally (built-in).[1]

At the same time, however, the modularization of antenna caused its commoditization, and in consequence, turned the antenna technology into a “black box” where its contents cannot be seen by the engineers. With time the number of these invisible “black boxes” increased, and correspondingly the engineers became more and more as “assemblers” who combine these boxes. While the “patterns” of combination - on which kind of combination yields best results - can certainly be investigated, the increase of these “black boxes” stripped the opportunity from the engineers to think about the basic principles of antenna including “why such a phenomenon occurs”. This is exactly the reason why the technology stagnates - since the engineers do not know the contents of the “black box,” they stop to think about its principles.

One specific example that demonstrates this stagnation is the deterioration of antenna performance in mobile phones. As the size of the antenna was reduced, the radiation resistance decreases as the conductor loss ratio increases, and resulted in the decrease in antenna gain. In this way, when the antenna was built in, the performance of the antenna itself clearly started its deterioration.[2]

Antenna performance is the results of the efforts coming from analog technology, meaning that it is the results of countless adjustments through “trial and error” that develops together with peripheral technology; its performance depends on the shape of the antenna and the locational relationship with its peripheral components. Although it is certainly necessary to miniaturize the antenna, this is only for meeting the needs of its installation within a limited volume when installed in communication equipment while still thinking of the antenna as a “module.” Thus, in future antenna technologies, antenna mounting technology taking into consideration the balance with peripheral technologies becomes important, not merely developing technology of antennas.

Historically, the deliberation of the basic principles of antenna was the driver for the evolution of its technology. Its “miniaturization” seems to have much focus these days, but antenna technology does not only mean “miniaturization” but encompasses much more. Too much focus on “miniaturization” by the engineers would cause superficial debates that actually create new problems. This means issues at a technical level like new noise problems caused by unnecessary radiation due to the shortage of ground-
ing, and therefore causing at a larger level the hindrance of or even the degradation of the antenna and wireless (RF) technology.

On the other hand, along with the globalization of mass production industries such as the automotive and electronics industries, the mold industry depending on these industries is also forced to follow up on this trend. While product life is shorter, orders for molds are in a situation that is determined by delivery time and cost rather than mold quality. The author has been studying development of functional materials with environmental resistance by applying technology that does not require secondary processing to molds.

In order to respond to the change in the external environment of globalization, it was found that “decoration molding technology,” one of the applications of die designing technology, was found to be very effective for antenna design. In this paper, this is demonstrated by reviewing the die design process from design to manufacture from the viewpoint of design architecture.

In other words, by applying decoration molding technology to antenna design, it becomes possible to add decorativeness on the element patterns of antennas. This creates a new category of “attractive antennas,” as the placing of the antennas becomes possible without disturbing the surrounding aesthetic environment. In this paper, the author describes the fundamental investigation on the processing method to make antenna pattern realizing antenna characteristics to decoration.

2. Design Architecture

Why is the decoration molding technology effective for antenna design? This is because it was found that as a result of examination from the viewpoint of the design and architecture, both mold design and antenna design adopt an integration design process “to study the design and to feed back the results to the design.” Therefore, in terms of architecture, antenna design can be actually familiar to the mold designer.

Before moving further, first, the paper will define what “design architecture” is.

“Architecture” can be defined as “products whose design information is on a certain media.”[3] Its basic types can be categorized in four types: “combination (modular type),” “integration (integral type),” “open type,” and “closed type.”[4]

a. “Closed type” and “open type”

In the case of the above-mentioned modular product, the process is different between when combining “in-house common components (IHCC)” (designed in-house in the company itself) and when combining “industry standard components (ISC)” (designed separately by different companies). IHCC is called “closed type” because the loop of “combination design” is closed inside the company. On the other hand, ISC is called “open type” in the sense that the ring of “combined design” is open to the outside of the company.

b. “Modular type” and “integral type”

“Modular type” is an architecture in which the relationship between functions and parts is nearly one to one and is a clear/open architecture. Typical examples are personal computers as shown in Fig. 1. As each “component,” in other words “module,” has a self-contained function even if a product is constructed in advance by combining separately-designed parts, it becomes an excellent product as a whole.

On the other side of this is “integral type.” In this type, the correspondence between functions and parts is very complicated. Despite the complication, the functions and parts are “perfectly corresponding with each other,” which

---

**Fig. 1** Product architecture as functional design and structural design.[5]
is a reflection of the values of Japanese manufacturing.

Because the total system stands through the balance between the subtle design parameters, a design change will oblige the redesigning of various parts from the beginning.

2.1 Architecture of mold technology

Generally, in the case of process industries such as mold molding, the product architecture is difficult to design unlike the machines that become products by combining components.

For example, when a new “C” is synthesized by combining “A” having a certain function “a” and “B” having another function “b,” it can be said that C is a module if a simple combination of the functions “a” and “b” is sufficient.

However, if a delicate process control is required, such as the decoration processing which is proposed in this paper, it means that there is a possibility to have function “c” which is completely different from functions “a” or “b.” Based on the definitions presented above, this complication can be categorized as “integral type” as shown in Fig. 2.

In short, it can be said that the strength of molding technology lies in process architecture focusing on process control process.

2.2 Architecture of antenna technology

Product technology whose architecture changes depending on the ways to balance is generally difficult to make it commoditized. Figure 3 shows the antenna technology when this concept is applied.
When an antenna is regarded as one of the electric components of the product in the manufacturing process, it is treated as an antenna module as shown in Fig. 3-(a). However, when looking at the antenna as a role which is played by the antenna in the circuit design process, antennas also must balance with invisible objects, such as the quality of communication established by ensuring communication with unspecified and distant persons, interference of electromagnetic waves or unnecessary radiation, as shown in Fig. 3-(b).

That is, the architecture of antenna is considered to be modular type when handled as an electronic component, but also an integral type when handled as an antenna technology.[6] However, due to the nature of the antenna, scenes where antennas can be treated as modules except for component placement in equipment during the development process are extremely rare and usually should be treated as integration type.

The design of the antennas can be familiar to mold designers, because both the die design and the antenna design adopt integral design process, where the design is studied and a feed back is given back to the design. This also means that even mold design engineers will be able to learn antenna technology through integration.

3. What is “Decoration Molding Technology”?  
One of the applications of die molding technology is decoration molding technology. The decoration molding technology is a method that makes direct molding processing of designs or patterns possible on metal mold. The advantage of this technology is that it eliminates secondary processing work.

In general, the decorative shape of the antenna element and the antenna element spacing influence the antenna characteristics. First, the antenna designer and the mold designer discuss the required specifications such as concavity/convexity and element spacing via the CAD data in the work preparation process of Fig. 2. Then, considering how to process the workpiece (object to be machined) based on the design drawing, and select the optimum drill method in “setup and preparing tool” process. In order to always maintain the gap between the material and the cutting edge in parallel, the adjustment of the jig when fixing the material to the processing machine becomes very important in decorating processing (as shown in Fig. 4).

Through setup for carrying out the machining process, the integration between the mold designers and the antenna designers is promoted, and the mutual design culture is understood.

As described above, in order to produce a machining program in consideration of the condition of the material fixed to the machine, it is necessary to repeat the cut and try before the desired machining program is completed. Conversely, it can be said that integration between “Preparation of cutting program” process and “Start of machining” process is a key to decoration molding technology in Fig. 2.

Our proposed method in addition realizes the reduction of the difference in heights between the cut and uncut part, when compared with conventional etching technology, by cutting via the machining center as shown in Fig. 5. This creates two additional advantages: first, in terms of tactile sensation, this makes it possible to produce a smooth surface. Second, in terms of visual display, this provides excellent light reflection characteristics (as shown in Fig. 6).[7]
The proposed method realized dimensions with better precision compared to conventional methods such as binding copper tape or etching process. Therefore, it became possible to produce antenna patterns with accurate dimensions even on self-complementary antennas having narrow spaces between antenna elements (as shown in Fig. 7).[8]

As mentioned above, the decoration molding technology in this paper has a lot of integration process compared with ordinary mold technology. Because there is a lot of integration, it is not easy to commoditize, and as a result, differentiation from ordinary die molding technology is realized.

Figure 8 shows the antenna design process when proposed decoration molding technology is applied. Decoration molding processing is designed while integrating against the electrical characteristics of the antenna in the upstream process in the antenna design process. Since it takes cost to remake die fabrication, electromagnetic field simulation at the design stage of the upstream process becomes extremely important. In this figure, although the number integration steps increases by adding the process of decoration molding technology, mutual understanding between the mold designers and the antenna designers shall be promoted through such integral process.

![Fig. 5](image_url) Machining process of decoration molding technology.

![Fig. 6](image_url) Examples of surface design processing by decoration molding technology.

![Fig. 7](image_url) Prototype and specification.
4. Investigation on Feasibility of Self-complementary Antennas by Decoration Molding Technology

Generally, the antenna characteristic evaluation can be broadly divided into circuit characteristic evaluation and radiation characteristic evaluation. The evaluation items are the input impedance of the antenna, the voltage standing wave ratio (VSWR), and the reflection coefficient as the circuit constants of the antenna, when evaluating from the viewpoint of the circuit characteristics of the antenna. Also, there are antenna efficiency, radiation directivity, and antenna gain, when evaluating radiation characteristics.

In this paper, the author examined the circuit characteristics of the antenna as a fundamental study.

4.1 Self-complementary antennas

First, in this section, the author explains why the authors chose self-complementary antennas as research targets.

The self-complementary antenna is the foundation of extremely broadband practical antennas, having constant input impedance independent of the frequency used or the shape of its structure.[9] In general, the input impedance of an antenna is an important constant as an electric circuit when supplying power to a transmitting antenna, and this value varies with frequency. However, since the impedance of the self-complementary antenna is almost constant over a broadband, it might be possible to reduce the number of considerations concerning the parameters and to reduce the difficulty for the antenna production by the mold designers. In addition, it is also one of the reasons for choosing to have design-potential that can be decorated as it is as a wall material because the design of the antenna pattern has symmetry.

As an example a self-complementary antenna was made using the design molding technology on plastic material as shown in Fig. 7.

As an example a self-complementary antenna was made using the design molding technology on plastic material as shown in Fig. 7.

4.2 Integration of mold architecture and antenna architecture

In this way, by grasping the rough antenna size that can be processed with one processing jig of the currently held machining center, the results of trial production taking into account the size of the antenna to be processed and the parallelism at the time of cutting are shown in Fig. 9, as a preparation. Since it is a feature of the decoration molding technology that the desired design can be “transferred” to an arbitrary shape, unless the parallelism at the time of cutting, which is the processing condition, can not be maintained, peel-off occurs as in the case of “50 mm x 50 mm.” On the other hand, in the case of “40 mm x 40 mm,” it seems a beautiful finish irrespective of the antenna element width.

4.2 Integration of mold architecture and antenna architecture

In this way, by grasping the rough antenna size that can be processed with one processing jig and by setting constraints on the manufactur-
ing process for the antenna design, the antenna design parameters (to be considered) can be reduced at the design stage.

In other words, in the conventional antenna design process as shown in Fig. 8, trial production is carried out at the downstream stage of the design, after conducting various parameter calculations in the upstream stage of the design. Therefore, the number of trial productions is limited. However, in the proposed process, trial machining is done many times during programming preparation and jig preparation stage so that it becomes possible to feed back the knowledge -preliminary information on antenna design- obtained in this work to the upstream process of antenna design. Since the viewpoint of actually making things is put into the upstream process of antenna design, parameter analysis can also be calculated with narrowing down the items. It is presumed that the communication skill is enhanced by the fact that the antenna designers and the mold designers are located in the vicinity of each other.

Figure 10 is an enlarged view of a part of Fig. 8. As shown in Fig. 10-a, the information flowing in the decoration molding process is information in which the antenna is regarded as a module. On the delivery of information to the antenna simulation, the dimensions of the antenna are delivered. On the contrary, attention is paid to the fact that all feedback from the antenna design process is information on antenna performance. The visible design information as the antenna module was converted back to the invisible relative evaluation as the antenna performance. Even if the nature of the information exchanged with each other is different, the information flow is circulated, whereby the information is naturally integrated with each other. As shown in Fig. 10-b, the information flow gradually becomes thicker as the number of times increases. The process of making the trunk of information flow thick is equivalent to antenna education for mold designers.

4.3 Analysis of self-complementary antenna using decoration molding technology

Figure 11 shows the analysis result when the pitch of the antenna pattern is used as a parameter (See in the “calculating parameter to achieve specifications” process in Fig. 8). It is found that the band where VSWR <3 of the antenna becomes broader, as the antenna pitch increases.

Figure. 12 shows the result of calculation before entering the prototype process, as to whether or not the antenna size change obtained in the above-mentioned preparatory stage affects the antenna characteristics. Figure 12 shows the analysis result when the size of base material is changed. The results show that the size has no fatal influence on the antenna characteristics. From the results in Figs. 9 and 12, it can be inferred that it is possible to fabricate a self-complementary antenna with a broadband even with an antenna of “40 mm × 40 mm” which is easier to prototype. This is also a feature of the self-complementary antenna, and this feature makes it possible to miniaturize the antenna.

Furthermore, in the simulation process for prototyping stage, the author investigated the case where a self-complementary antenna is applied to a three-dimensional shape in order to take advantage of the features of decoration molding technology.

Figure. 13 shows the analysis result when changing the angle of the antenna constituent face. It can be also seen that due to the characteristics of the self-complementary antenna, no noticeable deterioration of the antenna characteristics is observed even if the angle is changed.

Based on the results in Figs. 9 and 11 to 13, it was
Fig. 11 Analysis results of self-complementary antenna using decoration molding technology.

Fig. 12 Analysis results when changing the size of base material.

Fig. 13 Analysis results in the case of changing the angle of the antenna constituent face.
decided to manufacture 40 mm × 40 mm antenna as the VSWR characteristic is relatively stable and easy to make. The result of actually fabricating and measuring the antenna is described in the next section.

4.4 Measurement results of self-complementary antenna using decoration molding technology

Based on the earlier analysis results, Fig. 14 shows the comparison of the measurement of the actual antenna made and its analysis results. As a cause of the difference between the experiment result and the analysis result, it is considered that the installation of the connector at the antenna feeding part may not be good, and it is to be studied in the future. However, the errors of the antenna element junction are all within 3 microns.

Fig. 14 Comparison of experiment result and analysis result.

Fig. 15 Potential for application of decoration molding technology to antennas.
When the frequency to be used shifts to a higher frequency range, mismatching will occur if the antenna width differs at the antenna edge and the antenna junction portion, and radiation from the edge can not be ignored. However, by using the decoration molding technology, adjustment on the order of microns becomes possible even in mass production and it seems to give a very good suggestion for the production of millimeter wave antenna.

5. **On the Possibility of Realizing an Arbitrary Shaped Antennas by Decoration Molding Technology**

In the last section, the author describes the possibility of antenna design by decoration molding technology. Figs. 15-a and b are examples of antennas in the case where the decoration molding technology is applied to the antenna base material. Instead of applying decoration molding technology to only antenna elements, it is possible to create glossy antennas by applying the technology to the antenna base material or by combining a transparent antenna base material (dielectric material).

In addition, the decoration molding technology can be applied independent of the shape of the transferring material. This means that the design of the antenna can be changed to a three-dimensionally curved shape such as that shown in Fig. 15-c. This indicates that antenna designs can be expanded from conventional planar designs to three-dimensional designs. For reference, the time required for prototyping the self-complementary antenna and the diamond antenna, and the estimated number of useful life of molds are shown in Fig. 15-c. From the figure, it seems that decoration molding technology can sufficiently deal with antenna manufacturing for medium-volume production.

6. **Conclusion**

This paper demonstrated that decoration molding technology, an application of die design technology, has proved extremely effective for antenna design technology by reviewing the conventional die design process from the viewpoint of architecture. It first established the fact that; Mold design and antenna design are both integration architecture, and therefore antenna design can be familiar to mold designers. Then it also showed the potential of decoration molding technology, by demonstrating its capability to produce antenna patterns with accurate dimensions even on self-complementary antennas having narrow spaces between antenna elements, and its capability to design an antenna pattern to a three-dimensional arbitrary shape.

In order to free us from today’s stagnation and deterioration of the antenna technology, the engineers in modern days should turn around their way of thinking and return to the basic principles – from “thinking of the antenna as a module” to “thinking of antenna’s principle on how to generate performance” – to contribute to its evolution for the future.

**Reference**

[1] H. Haruki and A. Kobayashi, “Inverted-F Antenna for a Radio Terminal,” IEICE General Conference, No. 613, pp. 3–66, 1982.
[2] H. Arai, “Small Antennas: Downsizing Techniques and Its Index Factor,” IEICE, B, Vol. J87-B, No. 9, pp. 1140–1148, Sep., 2004.
[3] T. Nakaoka, “Koujyo no tetsugaku -Factory philosophy-,” Heibonsha, 1974.
[4] K. B. Clark and T. Fujimoto, “Product Development Performance: Strategy, Organization, and Management in the World Auto Industry,” Harvard Business School Press, 1991.
[5] T. Fujimoto, “Competing to Be Really, REALLY Good,” iHouse Press, 2007.
[6] A. Maeda and K. Ohizumi, “A study into the effect of smartphone development on antenna design,” IEEE Symposium on Product Compliance Engineering (ISPCE2013), pp. 1–6, 2013.
[7] http://www.ibki-inc.com/kasyoku.html
[8] A. Maeda, T. Haga, Y. Watanabe, and Y. Abe, “A self-complementary antenna for WLAN and WiMAX applications using traditional molding skills and techniques,” 2017 International Conference on Electronics Packaging (ICEP2017), pp. 247–249, 2017.
[9] Y. Mushiake, “Self-Complementary Antennas: Principle of Self-Complementarity for Constant Impedance,” Springer London, 2011.

**Atsushi Maeda** is Design Executive Officer (DEO) of Wireless Business Unit, IBUKI Inc., Yamagata, Japan. He is also research fellow of O2 Lab., and his main interests are: fractal antennas, EMC-management, and optimization of antenna design process. He also teaches RF-management based on patent engineering.