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Development of Millimeter-Wave Planar Devices Using Low-Loss Substrates

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As the importance of advanced millimeter-wave diagnostics increases, the fabrications of high-performance devices and components become essential. This paper describes the development of millimeter-wave planar components, such as antennas using low-loss fluorine substrates. The problems to be solved for the present purpose are the low degree of adhesion between copper foil and fluorine substrate and the accuracy of device pattern using conventional fabrication techniques. In order to solve these problems, surface treatment of fluorine films and a fabrication method using Electro-Fine-Forming (EF^2) are proposed. The peel adhesion strength between the metal and the fluorine films, and the value of dielectric constant of the fluorine films before and after grafting, are reported. In order to confirm the performance of the treated films, microstrip lines (MSL) are fabricated on the conventional fluorine substrates and on the grafted-PTFE (Polytetrafluoroethylene) films. The prototype antenna using fluorine substrates with EF^2 fabrication technique is also introduced.

Key words: *millimeter wave, graft polymerization, electron beam, surface treatment, peel strength, dielectric constant, adhesion, PTFE, planar antenna*

1. Introduction

In recent years, the development and application of low-loss components have progressed rapidly in millimeter-wave region [1].

As the importance of these millimeter-wave systems increases, the fabrication of high performance planar components, such as high-frequency antennas and filters, becomes essential. One of the methods is to use fluorine resin as an antenna substrate. If the planar antennas are used as transmitting or receiving antennas, one can easily control the beam direction of irradiation and decrease the height in comparison with horn antenna.

The use of low-loss fluorine substrate is essential to obtain low cost, high performance millimeter-wave planar components. However, there are two problems to be solved, the low degree of adhesion between copper foil and fluorine substrate and the accuracy of shape and dimension of circuit pattern.

For the first problem, there have been several studies on improving the surface properties of fluorine resin using various surface modification methods [2-7]. Along with wet chemical treatment, plasma and ion beam treatments have been considered to be efficient surface modification techniques. It has also been reported [7] that the adhesion between the fluorine resin and metal can be substantially improved by graft copolymerization with certain functional monomers. However, the method requires many processes, and the dielectric constant after the treatment has not been investigated.

We have proposed two key technologies to solve these problems. One is a surface treatment of fluorine substrate using radiation-induced graft polymerization to increase the peel strength between copper foil and dielectric films. The other is a fabrication method using the EF^2 technology that produces excellent fine patterns without side edges.

2. Experimental Method

2.1 Surface Treatment

PTFE films with 0.3 mm thickness were used in this experiment. An acrylic acid (AAc) monomer was used for the graft polymerization.

The processes of the surface treatment, graft polymerization and metallization are shown schematically in Fig. 1. When the fluorine binding was cut by the electron beam, radicals were generated at cut points in the PTFE films. After the grafting reactions were performed, the carboxyl group of AAc, a hydrophilic group with good compatibility with metal, was introduced onto the surface of the PTFE.

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Different degrees of grafting were achieved by immersing the films for different intervals in the monomer solution. The degree of grafting is calculated as follows:

$$\text{Degree of Grafting [\%]} = (W_g - W_0) / W_0 \times 100, \quad (1)$$

where W_0 is the initial weight of the film and W_g is the grafted weight of the film.

After the graft polymerization, metal was sputtered onto the surface of the films, and then the copper was electrolytically plated to a thickness of 20-30 μm.

In this experiment, there are two methods of reaction. One is called the liquid phase method and the films are immersed in the liquid during the reaction. The other is called the impregnation method and the films are immersed with wrapping a cloth to ensure uniform reaction onto the surface of the films.

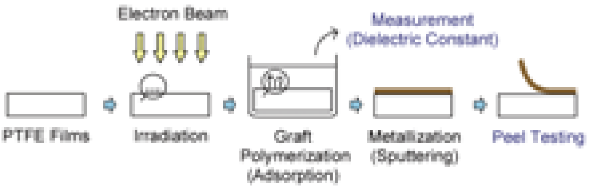

Fig. 1. Processes of surface treatment by graft polymerization.

2.2 Advanced Fabrication

When we use conventional fabrication technique, etching, there are a few problems such as the shape of circuit pattern (side edges), the irregularity between the substrate and the copper foil, the limitation of line width and gap width of the circuit pattern.

In this paper, we have proposed a method to solve the above problems. That is a fabrication method using the EF^2 technique, which gives an ultrafine pattern.

The processes of the EF^2 fabrication technique include the lithography process and the electrotyping process. EF^2 abilities are made possible by the integration of two unique technologies. One is a micro-lithography exposure technique used to enhance forming resolution and provide precise aperture patterns with micron level tolerances. The other is "Stay-Land Technology", which controls plating thickness and ensures an evenly distributed metal deposition so that parts are formed in a very controlled and uniform manner.

3. Results and Discussion

3.1 Surface Treatment

Figure 2 shows the effect of the degree of grafting on the peel strength of metal-AAc-PTFE. The peel strength of untreated metal-PTFE was 3.9 N/cm. Note that a considerable increase in peel adhesion strength is obtained by AAc graft polymerization on the PTFE surface. The achieved peel adhesion strength of PTFE was 16.1 N/cm.

The dielectric constant measured by a cavity resonance method is shown in Fig. 3. The dielectric constant of the PTFE film before the surface treatment is 2.13. It is seen that the values of the dielectric constant are not significantly changed by the surface treatment.

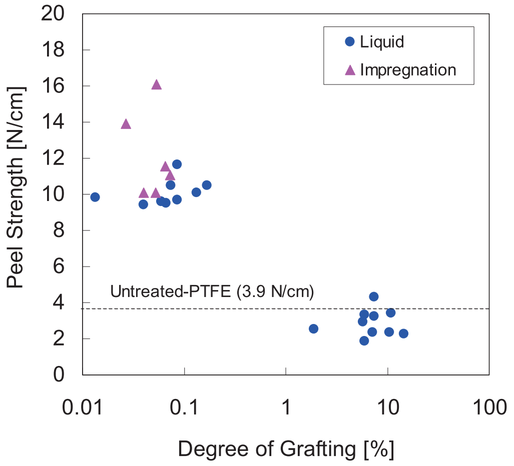

Fig. 2. Peel strength of metal on AAc-grafted PTFE as a function of degree of grafting.

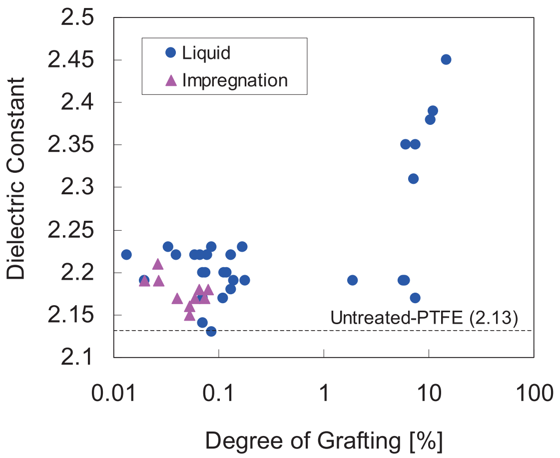

Fig. 3. The dielectric constant as a function of degree of grafting.

3.2 Transmission Property of MSL

In order to confirm the performance of the treated films, microstrip line (MSL) prototypes were fabricated on the conventional fluorine substrates with etching fabrication and on the grafted-PTFE films with EF^2 fabrication techniques. The measurement of the insertion loss (S_{21}) of the microstrip line was performed using a Vector Network Analyzer (37297C, etc / Anritsu Co., Ltd.).

Figure 4 (a) and (b) show the insertion loss (S_{21}) of the MSL using conventional fluorine substrates with etching fabrication and using grafted-PTFE films with EF^2 fabrication at the frequency ranges of 10 GHz, 20 GHz, 30 GHz, 40 GHz, and 50 GHz.

In these results, the transmission line using grafted-PTFE films with EF^2 fabrication are expected to be lower loss than that using conventional fluorine substrates with conventional fabrication technique, etching. We believe that arises because the transmission loss is increased owing to the conventional fluorine substrates, which have large roughness between the substrates and copper, and change of the characteristics such as impedance owing to the generation of side edges in circuit pattern.

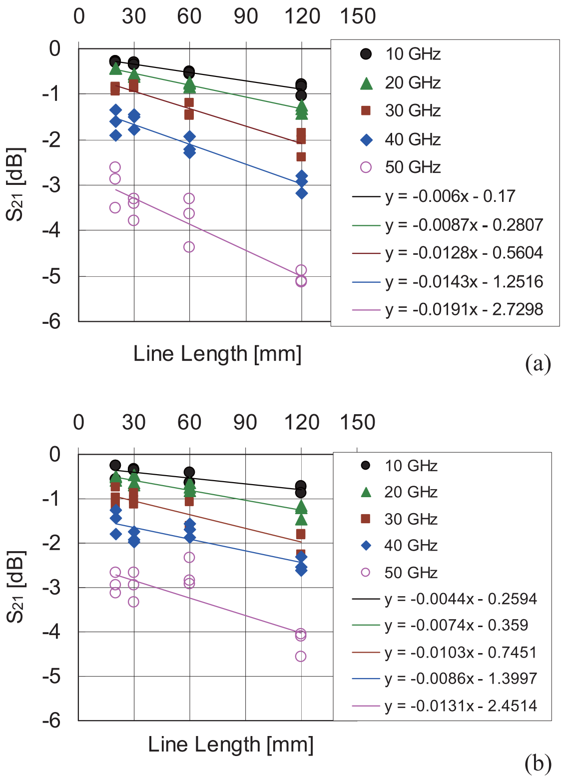

Fig. 4. Measured insertion loss (S_{21}) of the MSL using (a) conventional fluorine substrates with etching fabrication and (b) grafted-PTFE films with EF^2 fabrication.

3.3 Planar Antenna Prototype

We designed an antenna pattern by CST Microwave Studio. The traditional fluorine substrates with 0.254 mm thickness were used for planar patch antennas in this experiment with the EF^2 fabrication technique. The millimeter-wave antenna array has 280 elements and the size of the array is about 75 mm by 64 mm.

The measurement of the antenna radiation pattern is carried out using a near-field measurement system. The far-field pattern of the antenna is derived by conversion software. Figure 5 shows the characteristics of antenna patterns of a prototype at 76 GHz.

We changed the antenna array structure to symmetric structure at E-plane for the purpose of reducing the undesired reflection and the spurious radiation from each antenna elements. And then, the phase of feed power is shifted 180 degree for the simultaneous excitation of both one side and the other side in E-plane. Figure 6 shows the calculated antenna radiation patterns of the patch antenna. In this figure, it is seen that the level of sidelobe, in the E-plane is improved approximately 20 dB.

In addition, the size of patch antenna was reduced for the purpose of introducing to the actual systems. The miniaturized size is 39 mm by 87 mm.

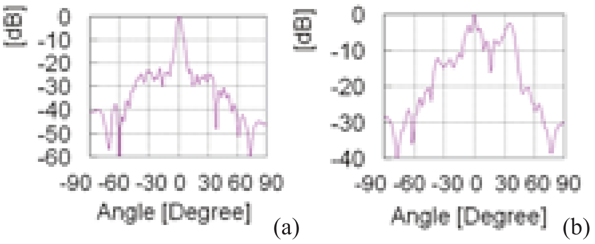

Fig. 5. Measured relative directivity at 76 GHz in the H-plane (a) and the E-plane (b).

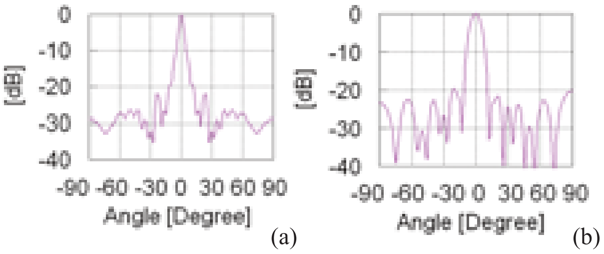

Fig. 6. Improved relative directivity at 76 GHz in the H-plane (a) and the E-plane (b) (Calculated).

4. Summary

In summary, we have implemented surface treatment using radiation-induced graft polymerization with AAc. The peel strength of the sputtered metal to the PTFE films is significantly enhanced and the achieved peel adhesion strength is 16.1 N/cm. The values of the dielectric constant are confirmed to be not significantly changed before and after the grafting.

In order to confirm the performance of the treated films, microstrip lines (MSL) are fabricated. It is shown that the transmission losses of the MSL fabricated using grafted-PTFE films with EF^2 fabrication are lower than those of using conventional fluorine substrates with conventional fabrication technique, etching.

The planar patch antennas are designed and fabricated using conventional fluorine substrates and grafted-PTFE films with EF^2 fabrication technique for the purpose of application to automotive radar.

The measured radiation patterns are in good agreement with the calculation by CST Microwave Studio. And we have proposed new antenna circuit pattern, which has low sidelobe level and small size.

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