PAPER

Design and Fabrication of PTFE Substrate Integrated Waveguide Coupler by SR Direct Etching

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SUMMARY The microfabrication technique based on synchrotron radiation (SR) direct etching process has recently been applied to construct PTFE microstructures. This paper proposes a PTFE substrate integrated waveguide (PTFE SIW). It is expected that the PTFE SIW contributes to the improvement of the structural strength. A rectangular through-hole is introduced taking the advantage of the SR direct etching process. First, a PTFE SIW for the Q-band is designed. Then, a cruciform 3-dB directional coupler consisting of the PTFE SIW is designed and fabricated by the SR direct etching process. The validity of the PTFE SIW coupler is confirmed by measuring the frequency characteristics of the *S*-parameters. The mechanical strength of the PTFE SIW and the peeling strength of its Au film are also additionally investigated.

key words: microstructure, X-ray lithography, dielectric loaded waveguides, couplers, millimeter wave circuits

1. Introduction

Micromachining technologies such as laser cutting, lithography, etc. have been applied to the development of components in the field of microwave and millimeter-wave engineering as well as in the field of mechatronics, optics, and fluidics [1]–[3]. Polytetrafluoroethylene (PTFE) is known as one of the most suitable materials for various applications, such as electrical (including microwave), medical [4], [5], biological [6] applications, etc., because of its excellent properties. It has been reported that PTFE microstructures can be fabricated by direct exposure to X-ray from synchrotron radiation [7]–[9]. The SR direct etching process or the X-ray lithography process has been applied to the fabrication of various PTFE-filled WG circuits [10]–[13]. The fabrication process is considered useful to construct the components for millimeter-wave and submillimeter-wave frequencies.

A waveguide whose sidewalls are replaced with densely arranged metallic posts has been proposed. This guide enables the easy realization of circuit patterns by arranging metallic posts periodically in a parallel-plate wave-

guide or a grounded dielectric substrate. This type of waveguide is called the post-wall waveguide (PWW) [14]–[16] or the substrate integrated waveguide (SIW) [17], [18], and is applied, for example, to a feed waveguide for a slot array antenna, or a leakage wave antenna. In particular, for the purpose of making use of merits such as low loss, low cost, and high-density integration of microwave and millimeter-wave components and subsystems, a short-slot 90° hybrid coupler, a cruciform directional coupler, a six-port receiver consisting of the 90° couplers and/or power dividers, etc. have recently been developed [19]–[24].

In this paper, a PTFE substrate integrated waveguide (PTFE SIW) structure with rectangular through-hole is proposed. At higher frequencies over 100 GHz or terahertz region, the PTFE-filled WG circuit becomes weaker than paper and it bends or snaps off easily. Therefore, the circuit must be supported by other substrate and fixed with adhesive as shown in Ref. [12]. The authors consider the PTFE SIW structure is one valid approach to solve the problem. Then, the SR direct etching process is newly applied to the realization of the PTFE SIW with rectangular through-hole. The SIW coupler of cruciform is selected as a design example, and a practical designing and trial fabrication is performed. Basically, the SIW coupler of cruciform consists of two SIWs crossing each other at right angles, two rectangular metallic slits arranged symmetrically in the crossed region for producing directional properties, and one metallic slit placed properly at each port for making a matched state. It is shown that a 3-dB quadrature property for the SIW cruciform coupler can be realized by replacing the side walls of the conventional waveguide type cruciform coupler [25], [26] with rectangular through-holes.

After the designing, the outline of the fabrication procedure for the PTFE SIW coupler is described. It consists of the SR direct etching of PTFE and coating the PTFE substrate with Au by sputter deposition and electroplating. Finally, the measured results of the *S*-parameters of the fabricated PTFE SIW coupler are shown. The frequency characteristics of the *S*-parameters inclusive of the transformers are simulated using Ansys HFSS. The validity of the fabricated coupler is confirmed by comparing with the results obtained using HFSS. In addition, the mechanical strength of the PTFE SIW and the peeling strength of the Au film are measured to show how effective the SIW structure is.

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2. Design Procedure

2.1 Propagation Constant

In this section, the propagation constant of the PTFE SIW is derived in advance to design the directional coupler. Figure 1 shows a basic structure of the PTFE SIW. The rectangular areas ($R_x \times R_y$) in the PTFE sheet with relative permittivity ϵ_r represent through-holes that work as the side walls of the SIW. They are arranged at spacing s and width W . When the etching process is applied, we do not necessarily need to utilize “circular” through-holes as the side walls. It is assumed that the thickness of the PTFE sheet is much less than the wavelength used in its circuit system. Therefore, since the electromagnetic field is considered constant in the height direction, the propagation and non-propagation modes excited in the PTFE SIW are TE_{n0} -like modes. Namely, the PTFE SIW has equivalently the same propagation characteristics with the conventional rectangular waveguide.

Figure 2 shows the calculated frequency dependences of the phase and the attenuation constants of the PTFE SIW for the Q-band (33-50 GHz). The H-plane planar circuit approach along with the TRL calibration technique is utilized to analyze the dispersion characteristics [24], [27]. The dimensions W , s , R_x , and R_y are adjusted so as to have the cutoff frequency of 26 GHz, which is comparable with

Fig. 1 Basic structure of PTFE SIW. (view of H-plane)

Fig. 2 Calculated phase and attenuation constants of PTFE SIW for Q-band. ($W = 4.00$ mm, $s = 0.40$ mm, $R_x = 1.60$ mm, $R_y = 0.50$ mm, substrate thickness = 1.0 mm, $\epsilon_r = 2.04$)

that of Q-band standard waveguide, and propagate only the TE_{10} -like mode at the Q-band frequency range. The spacing s and the dimensions of the through-hole R_x and R_y should be selected so that the leakage field is kept sufficiently small. As a result, $W = 4.00$ mm, $s = 0.40$ mm, $R_x = 1.60$ mm, $R_y = 0.50$ mm are obtained under the assumption that the thickness and the relative permittivity of the PTFE sheet are 1.00 mm and 2.04, respectively. In the analysis, the PTFE sheet is treated as lossless and the metal parts are treated as perfect conductors. In Fig. 2, the TE_{10} -like mode occurs at $f_{c10} = 26.1$ GHz and the first higher order mode (TE_{20} -like mode) occurs at $f_{c20} = 52.2$ GHz. These facts mean that the present PTFE SIW works as a Q-band single mode waveguide. Note that $W = 4.00$ mm is the same width as the PTFE-filled WG for the Q-band [11], which means that it is straightforward to transform the PTFE-filled WG circuits into the PTFE SIW circuits. It is found from Fig. 2 that the attenuation constant is less than 0.001 Np/m at the operation band. The ripples found in Fig. 2 will be caused due to the accuracy of the TRL calibration technique, since the attenuation constant is designed to have very small value.

2.2 Cruciform Coupler

Figure 3 exhibits a photograph of the Q-band PTFE-filled WG cruciform 3-dB coupler examined and fabricated in Ref. [28]. It consists of four H-plane input/output waveguides filled with PTFE, which are connected at right angles. Two rectangular slits are arranged symmetrically on the diagonal line of the crossed region to control directivity. The rectangular slit at each port is inserted as a matching element. Therefore, the cruciform coupler in Ref. [28] can be designed by two steps. First, the length of the rectangular slits on the diagonal line is optimized to realize the desired coupling coefficient. Then, to obtain a matched state for all the four ports, the position and the length of the rectangular slit inserted at each port are optimized. If the coupling coefficient deviates from the desired value, repeat the first step. In this paper, the PTFE SIW coupler of cruciform is designed based on the structure shown in Fig. 3. The design is straightforwardly performed by transforming the waveguide structure into the SIW structure.

Figure 4 shows the structure of a PTFE SIW cruciform coupler. The side walls of the PTFE-filled WG are replaced with the rectangular through-holes such as in Fig. 1, and the same cruciform configuration is reproduced in the

Fig. 3 Photograph of Q-band PTFE-filled WG cruciform 3-dB coupler. Cruciform structure of waveguide is examined in Ref. [28].

Fig. 4 Structure of PTFE SIW cruciform coupler. (view of H-plane)

Fig. 5 Frequency characteristics of S -parameters of PTFE SIW cruciform 3-dB coupler designed for Q-band operation.

PTFE sheet. The spacings s between the through-holes support the waveguide substrate. As mentioned in the introduction, the PTFE-filled WG circuit becomes tiny and fragile at higher frequencies. The jointed structure of the PTFE substrate represented by the width s reinforces the mechanical strength of the circuit. The dimensions W , s , R_x , and R_y are the parameters connected with the PTFE SIW, while the dimensions l_1 , l_2 , t_1 , t_2 , and p are the parameters from the cruciform coupler. The dimensions of the cruciform coupler in Ref. [28] can be utilized without modification. As a result, the dimensions for the Q-band PTFE SIW cruciform 3-dB coupler are obtained as $W = 4.00$ mm, $s = 0.40$ mm, $R_x = 1.60$ mm, $R_y = 0.50$ mm, $l_1 = 0.74$ mm, $l_2 = 0.83$ mm, $t_1 = t_2 = 0.20$ mm, and $p = 1.03$ mm.

Figure 5 shows the frequency characteristics of the S -parameters of the PTFE SIW cruciform 3-dB coupler calculated using HFSS. It is found that low reflection (S_{11}), good

Fig. 6 Electric field distributions of Q-band cruciform 3-dB couplers of (a) PTFE-filled WG, and (b) PTFE SIW at 42 GHz.

isolation (S_{21}), and flat 3 dB coupling (S_{31} , S_{41}) properties are realized around the center frequency 42 GHz. The phase difference between the outputs becomes 90° . The fractional bandwidth is 12.4%. Assuming that port #1 is an input port, port #2 and port #3 become an isolation port and a coupling port, respectively. Figure 6(a) and (b) display the electric field distributions of the Q-band cruciform 3-dB couplers of the PTFE-filled WG structure and the PTFE SIW structure, respectively. It is found that both the field distributions are almost the same, because the parameters for the SIW are selected so as to suppress the leakage field to sufficiently small level. In fact, the frequency characteristics of the S -parameters between the conventional structure (Fig. 6(a)) and the proposed structure (Fig. 6(b)) differ only in calculation error. Averaging from 38 GHz to 46 GHz for S_{11} , S_{21} , S_{31} , and S_{41} , the numerical differences are 0.52 dB, 0.49 dB, 0.01 dB, and 0.01 dB, respectively. Accordingly, the present structure in Fig. 4 could maintain sufficient properties of the directional coupler.

3. Fabrication Procedure

3.1 SR Direct Etching Process

The SR etching process is introduced to create PTFE patterns directly from X-ray irradiation. The SR direct etching is conducted with large-area X-ray exposure system “BL-2” in NewSUBARU synchrotron radiation facility.

First, a PTFE sheet (thickness 1.00 mm) and a stencil mask representing the coupler patterns are prepared. In this fabrication, VALFLON Sheet [29], [30] is used for the PTFE sheet, and SUS304 of thickness 100 μm is used for the mask. The mask patterns are fabricated within errors of $\pm 7.5 \mu\text{m}$. Figure 7(a) illustrates the experimental situation of the etching process. The stencil mask is put on the PTFE sheet and they are fixed onto the exposure stage. Since it is possible to expose up to A4 size at one time in BL2, three PTFE sheets are put on the stage in a line as shown in Fig. 7(b). The each stencil mask (silver color) on the PTFE sheet is fastened with four screws at the corners. Then the exposure chamber is evacuated and the temperature of the PTFE sheet is kept at about 200°C by heating the stage. X-ray is irradiated and then the PTFE sheet of 1.00mm-thick is etched

according to the stencil pattern. As a result, the rectangular holes of 1.00mm-depth are produced, and a 3-dimensional PTFE structure of 1.00mm-thick can be obtained without chemical treatment.

3.2 Sputter Deposition and Electroplating

After etching the PTFE structure, the SIW structure covered with thin metal film can be realized by sputtering Au all over the surface of the PTFE structure as shown in Fig. 8 (a). First, the PTFE structure is exposed to Ar plasma for several minutes to perform surface modification. It is expected that anchor effect increases the adhesive strength. Then, the Au film is deposited on the entire surface. Au is sputtered on one side and subsequently on the other. The Au film can be formed on the through-holes and the sides of the slits by sputtering the front and back sides. Figure 8 (b) shows a photograph of sputtering chamber, where one PTFE structure is put with holding plates. The PTFE sheet becomes dark brown after sputtering Au as shown in Fig. 8 (b). It is presumed that carbon jumped out of PTFE is mixed, as Ar ions collide with PTFE for the surface modification. In this process, the Au film of about $0.5\ \mu\text{m}$ in thickness is formed.

Then, electroplating is used to increase the thickness of the Au film. The electroplating is performed on the entire surface including the slit surface, based on the sputtered Au film. It has been confirmed that the sputter deposition and the electroplating can be satisfactorily performed up to a slit width of 0.1 mm for the PTFE sheet of thickness 1 mm. The deposition thickness must be determined considering the skin depth of the Q-band. The Au film is increased up to $10\ \mu\text{m}$ as the sufficient thickness for the Q-band. Finally, after removing the unnecessary frame of the PTFE structure, the PTFE SIW coupler is obtained.

Fig. 7 SR direct etching process. (a) PTFE sheet is etched by direct exposure to X-ray. (b) Photograph of irradiation chamber. Before irradiation. Three PTFE sheets are arranged on stage.

Fig. 8 Sputter deposition process. (a) Coating PTFE structure with Au. (b) Photograph of sputtering chamber. PTFE structure becomes dark brown after sputtering Au.

4. Fabrication and Measurement

4.1 Fabrication

Based on the process described in 3., the PTFE SIW cruciform 3-dB coupler for the Q-band operation was fabricated. Figure 9 (a) and (b) display the PTFE structure of the cruciform coupler obtained by the SR direct etching process. The amount of X-rays exposed is 7600 Asec. That is, it takes about 7.5 hours to obtain the PTFE structure in BL-2. It is found that the rectangular through-holes and hence the coupler structure can be etched directly with high aspect ratio. Note that the PTFE structure in this fabrication contains four rectangular waveguide patterns at the ends of the cruciform pattern. These waveguide sections are utilized for the later measurement to connect the SIW coupler to the waveguide adapters. The excitation of the present PTFE SIW coupler is performed via the PTFE-filled WG.

Figure 9 (c) shows the photograph of the PTFE structure covered with Au film obtained after the sputter deposition and electroplating process. Since the skin depth of Au for the Q-band is $0.4\ \mu\text{m}$, the thickness of the Au film was increased up to about $10\ \mu\text{m}$. It is considered that the sufficient thickness is accomplished. The Au film maintains adhesive force enough to prevent exfoliation for general handling. In the true meaning, the waveguide circuit is embedded and integrated into the substrate.

Fig. 9 Fabrication results of PTFE SIW cruciform 3-dB coupler. (a) PTFE structure obtained directly by SR etching process. (b) Enlarged rectangular through-holes and slit. (c) PTFE structure covered with Au film by sputter deposition and electroplating.

Fig. 10 Connection of standard Q-band waveguide transformers for measurement. (a) Structure of PTFE SIW to hollow standard Q-band waveguide transformer. (b) Photograph of SIW cruciform 3-dB coupler and transformers.

4.2 Frequency Characteristics of S -Parameters

In order to measure and evaluate the frequency characteristics of the fabricated 3-dB coupler, the standard waveguide transformers utilized in Refs. [11], [31] are connected. Because the PTFE SIW cannot be connected directly to the standard Q-band waveguide (5.70 mm $\times$ 2.85 mm), a connection form through PTFE-filled rectangular WG section is used. Figure 10 (a) illustrates the structure of the PTFE SIW to hollow standard Q-band waveguide transformer. The transformer consists of a widening section (from the PTFE-filled WG of width 4 mm to the Q-band standard waveguide of 5.70 mm), a matching section using finite-length iris window, and a $\lambda/4$ transformer in the waveguide E-plane to raise the height 1.00 mm to 2.85 mm. As mentioned before, the PTFE-filled rectangular WG sections must be embedded at the ends of the SIW pattern in advance.

Figure 10(b) shows the photograph of the SIW cruciform 3-dB coupler with the four transformers connected. The periphery of the PTFE structure in Fig. 9 (c) is removed so as not to interfere with the transformers. The each waveguide port of the cruciform coupler is fixed between the upper and lower parts of the transformer by screws.

The frequency characteristics of the S -parameters of the PTFE SIW cruciform 3-dB coupler are measured using Agilent's vector network analyzer E8361C. Figure 11 shows the measured results, which contain the characteristics of the four transformers. The simulated frequency characteristics of the cruciform coupler including the transformers are also shown in Fig. 11 for comparison. The measured and simulated S -parameters are represented by $S_{nl}^{(\text{meas.})}$ and $S_{nl}^{(\text{sim.})}$, respectively ($n = 1, 2, 3, 4$). In the simulation, the loss tan-

Fig. 11 Measured frequency characteristics of S -parameters of PTFE SIW cruciform 3-dB coupler designed at 42 GHz. Simulated values are also plotted for comparison. (a) Absolute values of reflection S_{11} and isolation S_{21} . (b) Absolute values of coupling S_{31} and through S_{41} . (c) Output phase difference between S_{31} and S_{41} .

gent of PTFE ($\tan \delta = 0.0003$) and the conductivity of Au ($\sigma = 4.098 \times 10^7$ S/m) are considered.

It is found from Fig. 11 (a) that the measured characteristics of reflection $S_{11}^{(\text{meas.})}$ and isolation $S_{21}^{(\text{meas.})}$ achieve about -20 dB or less in the proximity of 42 GHz. Although their bandwidth (approximately 4 GHz; 41 - 45 GHz, FBW = 9.5%) is slightly shifted toward higher frequency and not completely agree with the simulated results, the reflection and isolation levels are small enough as a directional coupler.

The coupling $S_{31}^{(\text{meas.})}$ and through $S_{41}^{(\text{meas.})}$ in

Fig. 11 (b) indicate -5.0 ± 0.7 dB for the frequency range of the operation. The measured coupling and through levels of -5.0 is about 2 dB smaller compared with the simulated values -3.2 ± 0.2 dB represented by $S_{31}^{(\text{sim.})}$ and $S_{41}^{(\text{sim.})}$. The cause of the deterioration is considered the insertion losses of the transformers. The transformers utilized in this paper contain the insertion loss of about 2 dB. It was previously examined by measuring the through connection of the two transformers (back-to-back connection), and estimated that the insertion loss was 1.2 - 2.0 dB [11], [31]. Therefore, the magnitude -5.0 dB is within acceptable level. Judging from allowable imbalance level ± 0.5 dB, though the power split imbalance ± 0.7 dB is somewhat large, a relatively good coupling property can be observed. The reason for the imbalance is supposed accountable by fabrication error and poor connection alignment. However, to investigate the detailed reason for the imbalance, measuring some other fabricated samples would be required. Because of limited fabrication chance, only one sample could be provided for the measurement purpose.

The frequency characteristics of the phase difference between the measured outputs $S_{31}^{(\text{meas.})}$ and $S_{41}^{(\text{meas.})}$ are shown in Fig. 11 (c). The averaged value for the operation frequency range (41 - 45 GHz) is $-89.3 \pm 6.4^\circ$. The simulated phase difference becomes almost -90° for that range. Although the phase variations of $\pm 6.4^\circ$ are measured in association with the outputs in Fig. 11 (b), a quadrature phase difference property can be realized. The phase variations would be caused by the above mentioned reasons, that is, fabrication error and poor connection alignment. Consequently, the validity of the design results is confirmed experimentally.

In this fabrication method, it is additionally noted that the PTFE SIW coupler indicates the stable measured responses such as metallic waveguide circuits, unless the connection parts consisting of the PTFE-filled WG collapse. Because the Q-band waveguide transformer used for this measurement bites the PTFE-filled WG tightly, the Au film could be broken when removing from the transformers. Moreover, only one circuit in the fabricated 3 circuits indicated the sufficient coupler characteristics. The PTFE sheet and the mask are fixed by screws during the etching process, however, the thermal expansion of PTFE (about 2%) sometimes causes the fabrication errors. The improvement of the fixing method and the taking the thermal expansion into the design would be one of further subjects.

4.3 Mechanical Strength

The mechanical strength of the PTFE SIW is examined. Figure 12 shows the testing condition of the mechanical strength of the PTFE SIW. The PTFE-filled WG is also examined for comparison. One end of the SIW or WG is put between the fixing stage, and force is applied to the other end. The force point is selected 8 mm away from the fixing stage. In this examination, the force that bends the waveguide by 1 mm (1 mm down) and the force that breaks the

Fig. 12 Testing condition of mechanical strength of PTFE SIW and PTFE-filled WG. (side view)

Fig. 13 Photograph of PTFE SIW straight section put between fixing stage. (a) Before applying force. (b) After applying force.

waveguide (broken) are measured using A&D's force gauge AD-4932A-50N. The Q-band straight lines with/without one iris, and G-band straight lines were tested, for the SIW and WG structures, respectively. For each case, the applied force was measured under the condition of PTFE only or with Au coating.

Figure 13 (a) displays a photograph of the PTFE SIW straight section put between the fixing stage. It is cut out from the PTFE SIW cruciform 3-dB coupler for the Q-band. The length is about 10 mm, however the force is applied to the point 8 mm from the fixed end. Figure 13 (b) shows a photograph after the force is applied. The PTFE SIW is broken, and a mark can be seen at the 8 mm point.

Measurement results of the mechanical strength of the PTFE SIW and the PTFE-filled WG for several conditions are summarized in Table 1. In the Q-band straight structure consisting of PTFE only, the force required for "1 mm down" is 1.45 N for the WG and 2.02 N for the SIW. The applied force ratio SIW/WG is 1.39. It is found that the SIW case is about 39% stronger than the WG case. The force required for "broken" condition is 2.21 N for the WG case, and 2.66 N, 4.84 N for the SIW case (Measured 2 samples. In reality, it is expected to be between 2.66 N and 4.84 N. At least the SIW has been shown to be 1.20 times stronger.). For the Q-band straight structures with Au coating, the forces required for broken are increased in the both cases. The SIW/WG ratio is 1.18. Especially in the SIW case, when the force is also evenly applied to the substrate outside thru holes, that means a linear force is applied instead of a point force, the SIW/WG ratio becomes 5.53. It is found that the mechanical strength is increased by dispersing the force on the substrate outside the SIW.

The Q-band straight structures including one iris discontinuity (thickness $t_2 = 0.20$ mm, width $l_2 = 0.83$ mm as found in Fig. 4) are also tested. The iris discontinuity is placed adjacent to the fixed stage and the SIW/ WG ra-

Table 1 Measurement results of mechanical strength of PTFE SIW and PTFE-filled WG. Q-band straight lines with/without one iris, and G-band straight lines are tested under condition of PTFE only or with Au coating.

test structure (length = 8 mm)	condition	applied force (N)		ratio SIW/WG
		case: WG	case: SIW	
Q-band straight, PTFE only	1 mm down	1.45	2.02	1.39
	broken	2.21	2.66, 4.84	1.20, 2.19
Q-band straight, Au coating	broken	3.84	4.53	1.18
	broken*		21.23	5.53
Q-band straight with iris, PTFE only	broken	0.98	1.01	1.03
Q-band straight with iris, Au coating	broken	1.16	2.03	1.75
G-band straight, PTFE only	1 mm down	<0.04	/	/
	broken	0.10		
G-band straight, Au coating	1 mm down	0.42	/	/
	broken	0.56		

*The force is also evenly applied to the substrate outside thru holes (width 8 mm x2) .

tion is evaluated in the same manner. It is found at least the SIW/WG ratio >1.03 can be obtained.

In addition, the mechanical strength of the G-band straight waveguide (cross section $0.90 \text{ mm} \times 0.40 \text{ mm}$) used in Ref. [12] is also evaluated. For the structure of PTFE only, the applied force is $<0.04 \text{ N}$ (undetectable) and 0.10 N under the condition “1 mm down” and “broken”, respectively. For the G-band straight structures with Au coating, these values are increased to 0.42 and 0.56 , respectively. The results suggest that the PTFE-filled WG above 100 GHz are weak and fragile. There is no G-band PTFE SIW sample that can be evaluated at this time, however in the case of the SIW structure, it can be expected to be several tens of percent stronger.

The peeling strength of the Au film is also measured, with adhesive tape attached to the waveguide surface (Au thickness $10 \mu\text{m}$). When the adhesive tape is pulled in the 180 degree direction, it was found that the Au film partially peels off at the force around 1.54 N/4mm - 4.42 N/4mm . The result of peeling strength tests for an electroless Ni plating on a treated PTFE film is found in Ref. [32], in which the maximum peeling strength of 14.8 N/25mm (2.4 N/4mm) has achieved. Because metallic element is different, the measured results cannot be directly compared, however it can be seen that the peeling strength in Ref. [32] is within the range of present results. Since the Au thickness of the G-band waveguide is $1 \mu\text{m}$, the strength is considered to reduce to $1/10$. If the test piece contains the edge (cut surface) of the Au film, it becomes weak and peels off at around 0.22 N/4mm - 0.66 N/4mm . In addition to this Au film strength, it can be said that the SIW structure contributes to the increase in mechanical strength.

5. Conclusion

The SR direct etching process has been applied to the fabri-

cation of the SIW, and the PTFE SIW cruciform 3-dB coupler has been designed and fabricated at the Q-band. The rectangular through-holes have been introduced to form the SIW, instead of using conventional circular through-holes. The SR direct etching process has the advantage that can etch any pattern depicted on the stencil mask.

The dimensions of the PTFE SIW have been determined by deriving the phase and the attenuation constants of the guide. It has been demonstrated that the dimensions of the PTFE SIW coupler can be designed straightforwardly using the design results of the PTFE-filled WG coupler. Then, the PTFE SIW cruciform 3-dB coupler has been fabricated, and the frequency characteristics of the S -parameters have been measured. Though the output imbalance of the coupler should be made much smaller, the validity of the PTFE SIW and its coupler have been confirmed. By measuring the mechanical strength and the peeling strength of the Au film, it has been confirmed that the PTFE SIW contributes to the improvement of the structural strength.

The present circuit structure embedded in the PTFE substrate is considered useful especially at higher frequency such as short millimeter wave and terahertz wave, where the waveguide circuit becomes quite small, fragile and delicate. In the SIW design of this paper, the attenuation constant is kept small and the spacing s between through holes is narrow. Optimizing the through holes in consideration of both the mechanical strength and the radiation loss would be a further subject.

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