Development of a "Laminated Waveguide"

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***Abstract*—A waveguide of new structure has been developed for millimeter-wave applications. The dielectric waveguide is constructed with sidewalls consisting of lined via-holes and edges of metallized planes. This structure can be manufactured by lamination techniques, so we refer to the waveguide as a "laminated waveguide." The laminated waveguide can be embedded in a substrate and is able to be wired in three dimensions. The transmission characteristics are evaluated using glass-ceramic substrate of dielectric constant, $\varepsilon_r = 5$, and loss, $\tan\delta = 0.0008$. Insertion loss per unit length of the guide is estimated to be less than 0.5 dB/cm at 83 GHz. Furthermore, it was confirmed that the laminated waveguide is suitable to feeding lines for a small sized plane array antenna. By electromagnetic simulation, it has been confirmed that fundamental structures, such as bends, branches, power dividers, and inter connections between upper and lower layers can be realized with sufficient performances.**

***Index Terms*—Branch, ceramic circuit board, ceramic package, dielectric waveguide, feed waveguide, inter connection, laminate, millimeter-wave, power divider, via-hole, waveguide.**

I. Introduction

RECENTLY, device systems for millimeter-wave frequencies, such as collision avoidance radar or wireless LAN, are attracting much attention. The development of such devices is rapidly advancing. These devices are mounted on circuit boards or in packages, being finally connected to antennas by circuits.

Up to now, circuit boards and antennas have been made as separate parts. Combining the circuit board or a package with antenna, we can get a small and high-performance device system [1]–[3]. For this purpose, antennas and feeding lines have to be made by the same production technique as the process for circuit boards. For a feeding line in a circuit board, a microstrip line has the simplest structure. However, the microstrip line opened to the air radiates electromagnetic wave at discontinuous parts such as bends and branches [4]. A coplanar waveguide is easy to be wired to devices. The coplanar waveguide, constructed by signal lines and grounds on the same plane, also radiates in the same way to a microstrip line, and transmission characteristics are worse than a microstrip line.

A surface line, like a microstrip and coplanar line, can be used for a feeding line to an array antenna. Concerning a miniaturization, however, it is desirable to wire high-frequency circuits underneath the antenna. Therefore, the feeding line should be embedded in a substrate and should have low insertion loss. Such a typical line is a triplate line. Since the triplate line has a symmetric structure, it does not radiate electro-magnetic wave at a bending point. It is well known, however, that parallel plate modes occur on the triplate line at a feeding point. This phenomenon is the major obstacle in the development of high performance antennas. Several studies have been conducted on restraining the phenomenon [5], [6].

Waveguides have the best transmission characteristics among many transmission lines, because they have no electromagnetic radiation. Waveguides, however, are impractical for circuit boards and packages for two major reasons. First, the size is too large for a transmission line to be embedded in circuit boards. For example, the cross-sectional size of a WR-15 type waveguide is 5.76 × 3.38 mm. Second, waveguides must be surrounded by metal walls. Vertical metal walls cannot be manufactured by lamination techniques, a standard fabrication technique for circuit boards or packages.

Recently, an idea of making a waveguide in a dielectric sheet has been reported [7]. The new waveguide is a dielectric waveguide constructed of two sidewalls of lined via-holes. According to this structure, the waveguide can be built in a circuit board by a traditional technique for making circuit boards. The size of the waveguide can be reduced using a high dielectric material. However, transmission characteristics of the new waveguide have not been demonstrated in the report. Hirokawa *et al.* has applied this structure to parallel plate slot array antenna. They call this structure post-wall waveguide, and have analyzed the characteristics [8].

The post-wall can have electric current flow only in the vertical direction. Namely, it can reflect the vertical component of electric field, but not the horizontal direction along the wall. Post-wall waveguide has no problem for the case of TE_{10} mode using post-walls as E planes, since the traveling electromagnetic wave has only the vertical component of electrical field. However, the waveguide can have horizontal components of electric field at the feeding and three-dimensional connection points, then electromagnetic waves will leak at these points.

The authors have introduced a new transmission line structure that does not have the above problem. The new transmission line is manufactured using lamination technologies; consequently, it is named the laminated waveguide. In this paper, transmission characteristics of the laminated waveguide are studied by electromagnetic simulations and experimental analyses. It will be also shown that a fundamental structure for feeding line for array antenna can be built up easily.

II. The Structure of the Laminated Waveguide

The schematic diagram of the laminated waveguide is shown in Fig. 1. Vertical walls of laminated waveguides consist of filled via-holes and edges of conductive layers.

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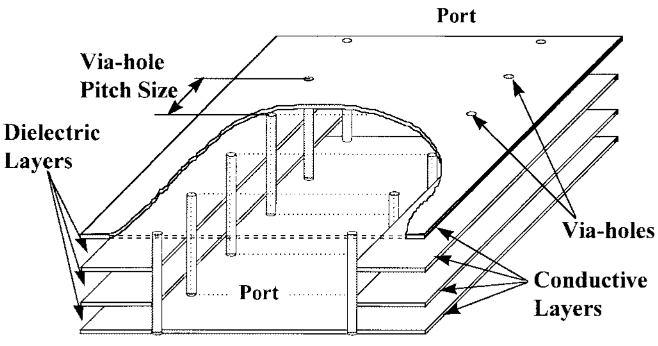

Fig. 1. Schematic diagram of laminated waveguide.

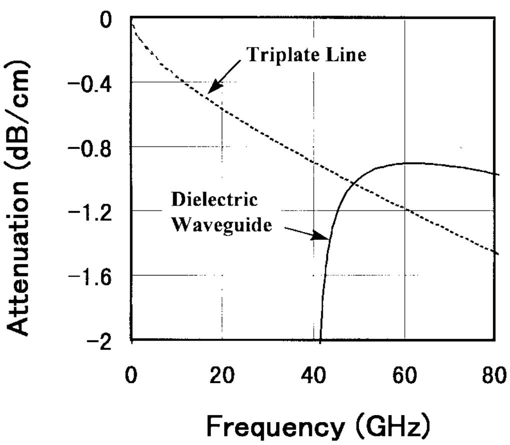

Fig. 2. Transmission losses versus frequency of triplate line and dielectric waveguide. Material used is D as shown in Table I. The thickness of both circuit boards are 0.63 mm.

Waveguide structure can be manufactured by standard lamination techniques. Here, we call conductive layers playing the role of upper and lower walls as main-conductive layers, and that of a part of sidewalls as subconductive layers. In this structure, the vertical walls have a mesh structure and are able to reflect all components of electric field.

Fabrication processes of the laminated waveguide are as follows. At first, raw ceramic tapes are made from ceramic ingredient and binder. Second, via-holes are made on the tapes at the points of walls of laminated waveguide, and the holes are filled with conductive material. The tapes are then printed with main/subconductive layers using a metallized paste. Finally, stacked tapes are fired at set temperature in controlled atmosphere. These processes are the same to that of ceramic circuit boards and packages.

Alumina is normally used for ceramic packages. As the dielectric constant of alumina is 9.0, the cross section of waveguide equivalent to WR-15 is reduced to 1.25 $\times$ 0.63 mm, this size is small enough to be embedded in substrates or packages. Insertion loss of this waveguide of alumina is estimated and compared with that of triplate line.

Fig. 2 shows insertion losses as functions of frequency of the dielectric waveguide and a triplate line for a comparison. Both of them are made using alumina layers of $\varepsilon_r = 9.0$ and $\tan\delta = 0.003$. The cross section of the dielectric waveguide is 1.25 $\times$ 0.63 mm. In the case of the triplate line, the thickness of the alumina layer is 0.63 mm, the signal line electrode is 0.1 mm wide and 0.015 mm thick. A solid line and a broken line show losses of the dielectric waveguide and triplate line, respectively, in Fig. 2. The insertion loss of the dielectric waveguide was calculated from electromagnetic equations and that of triplate line by an approximate equation [9]. Adding conductive loss and dielectric loss, the total loss of the dielectric waveguide is ten times as large as that of the traditional waveguide. Comparing with the triplate line, however, the transmission characteristic of the dielectric waveguide gets better beyond 50 GHz.

III. Electromagnetic Simulations

Electromagnetic simulation has been carried out to investigate via-hole pitch size dependencies on the transmission characteristics of the dielectric waveguide. High-frequency structure simulator (HFSS) was employed for the simulation. In this simulation, metals were modeled as a perfect conductor, and the dielectric constants were set as $\varepsilon_r = 5.0$ and $\tan\delta = 0.0008$. The electric field strength distributions of H plane at 60 GHz are shown in Fig. 3 in the case of via-hole diameter of 0.1 mm. In Fig. 3, the main/subconductive layers are not drawn. The via-hole pitch size of condition I is 0.52 mm and condition II is 1.04 mm. From Fig. 3, it is obvious that electromagnetic waves leak through the gap of via-holes in the case of condition II, but no leakage in the case of I. In these cases, the wavelength is 2.24 mm. Therefore, it seems that the electromagnetic wave does not leak from the waveguide of a via-hole pitch smaller than a quarter wavelength.

The result of TE_{10} mode, using main-conductive layers as H planes, is shown in Fig. 4. The S parameters were $S_{21} = -0.06$ dB and $S_{11} = -24.0$ dB at 77 GHz with 4 mm waveguide length. Although the electric field is perpendicular to sidewalls, it is found from Fig. 4 that electromagnetic waves transmit in the laminated waveguide. These sidewalls consisting of mesh structure can cause the electric current to flow in the vertical and horizontal directions, so electro-magnetic wave does not leak from the sidewalls. If these sidewalls do not have subconductive layers, the electromagnetic wave will leak.

IV. Laminated Waveguides for Experimental Measurements

Laminated waveguides are made using alumina-ceramics and glass-ceramics for experimental studies. Table I shows dielectric constants and losses of these materials at 60 GHz. These materials are developed by Kyocera. Materials A and D are alumina, and A has low $\tan\delta$. B and C are low-temperature cofiring glass-ceramics in which copper can be used as metallized material. Both of them have low dielectric constant. C, especially, is designed for low $\tan\delta$.

This laminated waveguide is composed of four dielectric layers and five metal plates corresponding to the H planes of the waveguide. The diameter of via-holes is 0.1 mm. For signal I/O, we set a feeding pin and attached metal piece in the upper main-conductive layer as shown in Fig. 5. The feeding pin is composed of three stacked via-holes. The pin is

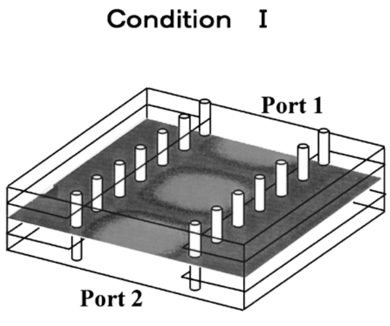

Fig. 3. Electric field strength distributions of H plane at 60 GHz. Via-hole pitch size of condition I is 0.52 mm and condition II is 1.04 mm.

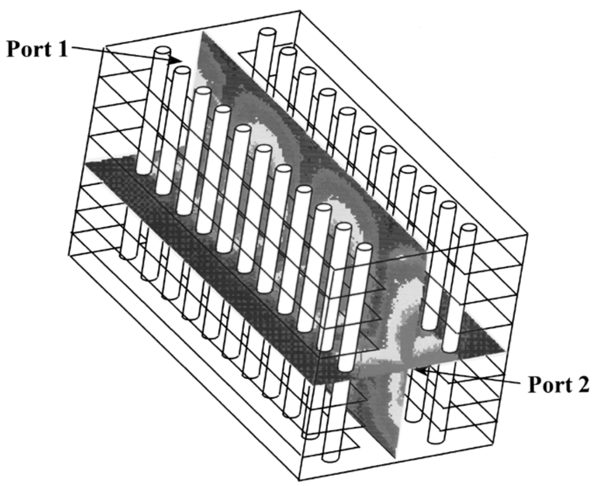

Fig. 4. Electric field strength distribution of TE_{10} mode using main-conductive layers as H plane.

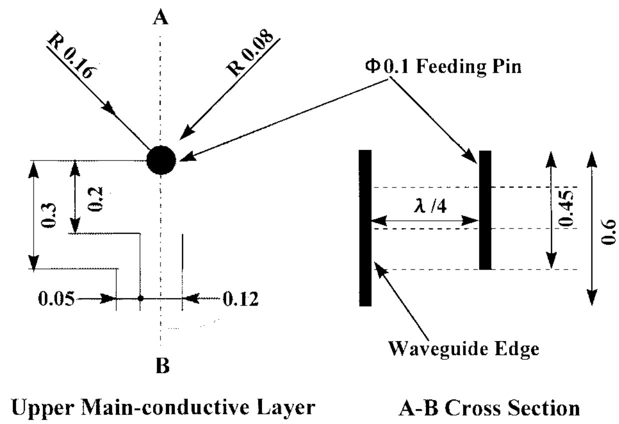

Fig. 5. Configuration of feeding part.

TABLE I
CERAMIC MATERIALS AND DIELECTRIC CHARACTERISTICS AT 60 GHz

	A	B	C	D
Ceramic	Alumina	Glass	Glass	Alumina
Dielectric constant	9.8	5.5	5.0	9.0
Dielectric loss (tan δ)	0.0002	0.0030	0.0008	0.0030
Conductive material	Mo	Cu	Cu	W

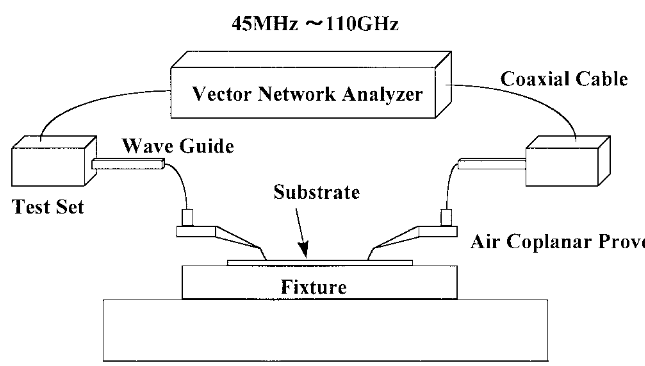

Fig. 6. Evaluation system diagram.

located a quarter wavelength apart from the end of a laminated waveguide. The "keyhole" shape pattern on the upper main-conductive layer is adjusted to the size of contacting probes. The feeding pin is attached to the metal piece in the center of the pattern.

Our evaluation system is illustrated in Fig. 6. We used a vector network analyzer of Hewlett Packard Corporation and air coplanar probes of Cascade Microtech Corporation Transmission characteristics from 45 to 110 GHz can be evaluated by this system. The system was calibrated using an impedance standard substrate by LRRM correctional method.

V. Experimental Results and Discussions

Fig. 7 shows the measured transmission characteristics of laminated waveguides. Solid and broken lines show the data of waveguides with subconductive layers and without subconductive layers, respectively. The laminated waveguides used material D and the cross section of 2.3 $\times$ 1.2 mm. Via-hole pitch size is 1.0 mm and the distance to feeding pins is 25.0 mm. It can be seen that signals transmit above 22 GHz from Fig. 7. The cutoff frequency of the laminated waveguide is in good agreement with a calculated frequency. We have confirmed that laminated waveguide with subconductive layers also has less fluctuation in other via-hole pitch sizes.

Measured results of transmission characteristics for various via-hole pitch sizes are listed in Table II. In this case, laminated waveguides used material C, the cross section of 2.3 $\times$ 1.2 mm, and the distance to a feeding pin was 30.0 mm. S parameters shown in Table II are mean values from 42.5–43.5 GHz. Insertion losses and reflections increase as the via-hole pitch size increases. Fig. 8 shows the relationship

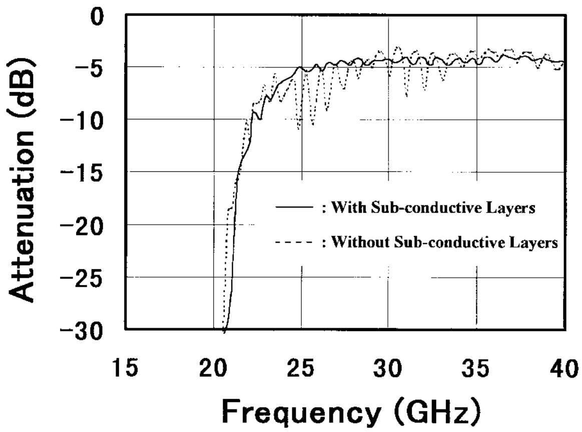

Fig. 7. Insertion losses versus frequency of laminated waveguide with subconductive layers and without subconductive layers.

TABLE II
EXPERIMENTAL RESULTS OF TRANSMISSION CHARACTERISTICS FOR VARIOUS VIA-HOLE PITCH SIZE. THE CROSS SECTION OF LAMINATED WAVEGUIDES USING MATERIAL C WERE 2.3 × 1.2 MM, AND THE DISTANCES OF BOTH FEEDING PINS WAS 30.0 MM. THE S PARAMETERS ARE MEAN VALUES FROM 42.5–43.5

Via-hole pitch size (mm)		0.26	0.52	0.78	1.04
S parameter	S21 (dB)	-1.1	-1.8	-3.4	-8.6
	S11 (dB)	-23.3	-17.5	-14.5	-13.7

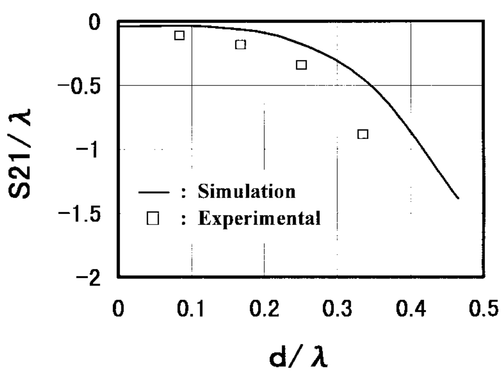

Fig. 8. Variation in insertion loss with via-hole pitch size.

between the insertion loss and via-hole pitch size normalized by λ (wavelength in the dielectric material). The solid line and square symbols show the simulation and experimental results, respectively. Both of these data show that insertion loss increases abruptly above $d/\lambda = 0.25$. This phenomenon comes from the electromagnetic wave leakage through via-holes, which is larger than the quarter wavelength, as was explained in Section III.

Insertion losses of laminated waveguides of materials A and B are shown in Fig. 9. Here, the broken line is A and the solid line is B. Fig. 10 shows the transmission characteristics of laminated waveguide of material C. Here, solid and broken lines show the insertion loss and the reflection, respectively. The cross section of the laminated waveguide was 1.2 × 0.6 mm, and via-hole pitch size was 0.26 mm. All the waveguides were straight and the distance of a feeding pin was 36.0 mm. The insertion loss of A is about 3.5 dB at 60 GHz and that

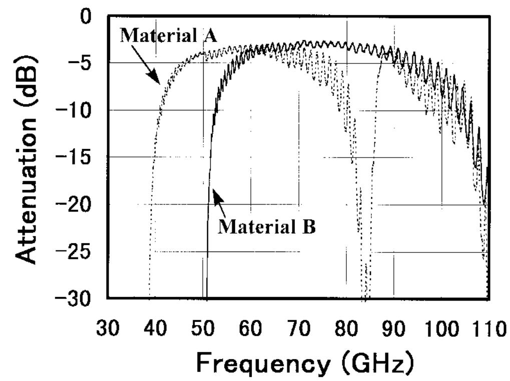

Fig. 9. Comparison of insertion losses between A and B.

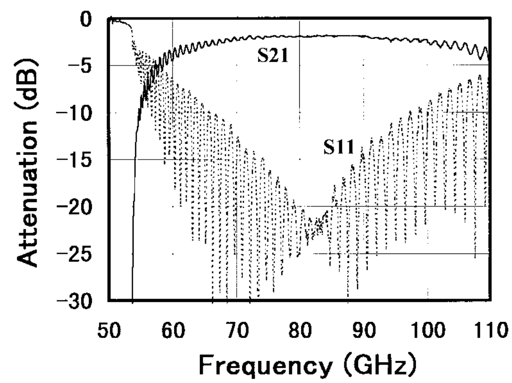

Fig. 10. Transmission characteristics using material C.

of B is about 2.9 dB at 75 GHz. In the case of C, it is also found that the insertion loss is lower than 2 dB and reflection is lower than −15 dB over the wide range of 75–90 GHz. The insertion loss reaches to 1.8 dB at 83 GHz. Insertion loss of the waveguide per unit length is lower than 0.5 dB/cm, since the loss of 1.8 dB includes additional loss of the feeding structure. The minimum insertion loss of material A is nearly equal to that of B. Total loss of A is rather dominated by conductive loss. On the contrary, total loss of B is dominated by dielectric loss. Considering the difference between C and A, B, good transmission characteristics can be realized by both low conductive and low dielectric losses.

VI. BASIC UNITS FOR ANTENNA FEED LINES

For antenna feed lines, isolation between lines is necessary, as well as basic units such as bend, branch, interconnection of upper/lower layer, and so on. It is not easy to build up these basic units using triplate lines, but it is easy using laminated waveguides. To estimate capabilities of the laminated waveguides, electromagnetic simulation has been carried out at 77 GHz. All via-hole pitch sizes were 0.26 mm.

First, isolation between lines has been investigated. Neighboring laminated waveguides used a common sidewall of one-lined via-holes. Each laminated waveguide width is 1.3 mm. This result is shown in Fig. 11. It can be seen that the isolatoin between waveguides is sufficient. Isolation at 77 GHz was lower than −30 dB.

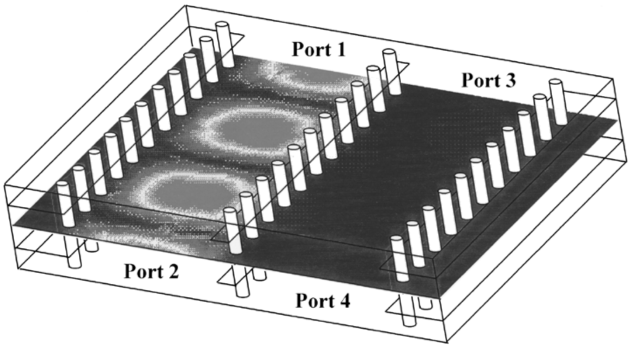

Fig. 11. Isolation characteristics of laminated waveguide.

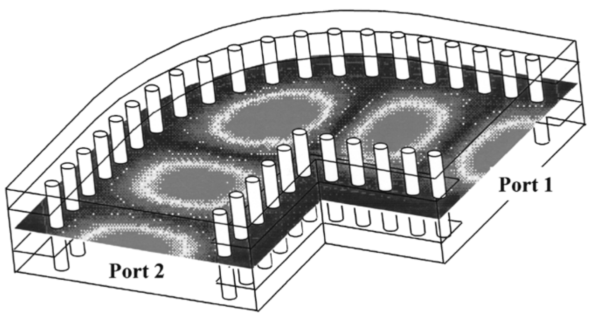

Fig. 12. Electric field strength distribution of a right angle bent line.

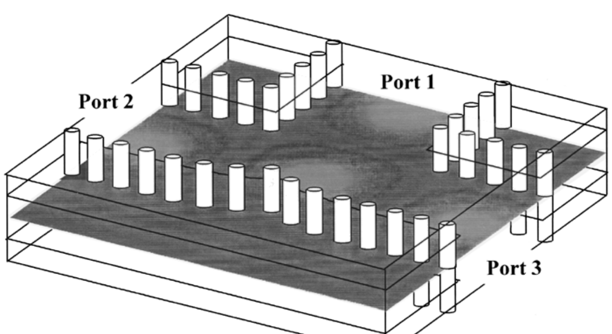

Fig. 13. Electric field strength distribution of T-branch.

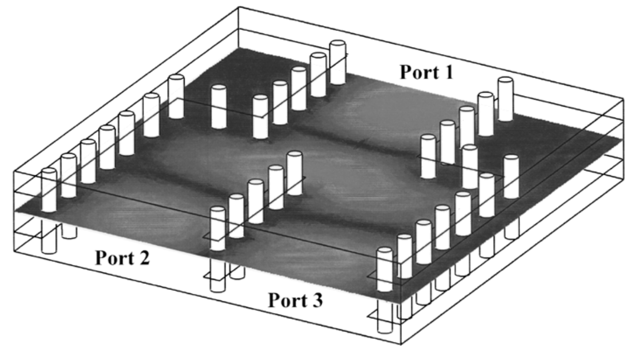

Fig. 14. Electric field strength distribution of new type branch.

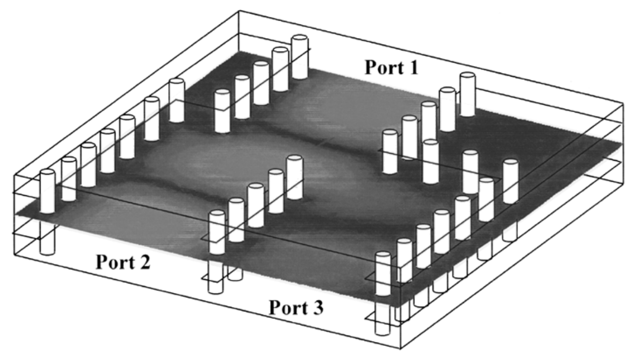

Fig. 15. Electric field strength distribution of power divider. Sifting length is a quarter of waveguide width.

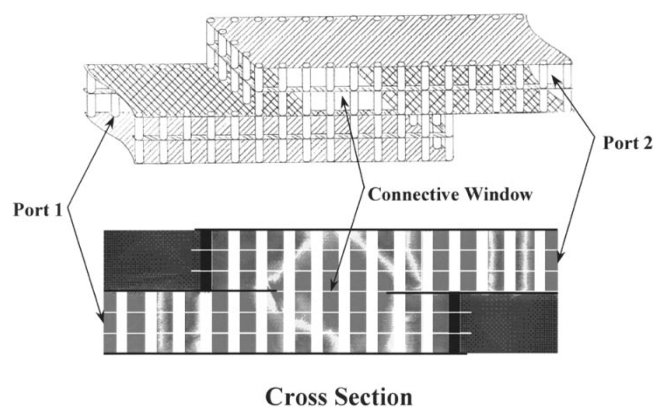

Fig. 16. Configuration and electric field strength distribution of interconnection between upper and lower layers.

Next, transmission characteristics of a bend line have been investigated. The inner wall of the waveguide is bent at 90°, which is a hard condition. The laminated waveguide width is 1.6 mm. The result of analysis is shown in Fig. 12. It is found that the reflection is −26.4 dB at 77 GHz.

Figs. 13 and 14 show the electric field strength distribution of T-branch and a new type branch, respectively. The laminated waveguides width was 1.3 mm. The reflection of T-bend was −14.2 dB and that of the new type branch was −15.2 dB at 77 GHz. The new type branch consists of input port waveguide 1, output port waveguides 2 and 3, and a matching waveguide. This structure is not easy to build by traditional waveguides, but can be easily built by laminated waveguides. Furthermore, the ratio of output powers can be easily changed by shifting the position of the input port waveguide. Namely, a power divider construction is easy. In the case that shifting length was a quarter of waveguide width, the simulation result is shown in Fig. 15. The S parameters were $S21 = -0.55$ dB, $S31 = -9.95$ dB and $S11 < -20$ dB.

A simulation of interconnection between upper and lower layers has also been carried out. The laminated waveguide width is 1.54 mm, a connection window size is 1.44 × 1.2 mm, and the distance from the edge of the laminated waveguide to the center position of connective window is set at 1.2 mm. The result is shown in Fig. 16. The reflection of interconnection at 77 GHz was −19.2 dB. In this case, if the laminated waveguide does not have subconductive layers, electromagnetic wave will leak, since the horizontal component of the electrical field is generated at connection part. Using this structure, three-dimensional wiring is possible.

VII. Conclusion

The laminated waveguide has been introduced, which can be fabricated by a standard lamination technology. Electromagnetic wave leakage is suppressed by sidewall via-holes with a pitch smaller than a quarter wavelength. Samples are designed and fabricated for experimental analyses using a newly developed low-temperature cofiring glass-ceramic. The results show that the laminated waveguide has low loss and is suitable for high performance transmission lines. Furthermore, the isolation between two lines has been checked, as well as basic units of bends, branches, interconnections between upper and lower layers, and power dividers. All the results have shown good performance of units.

Consequently from the above results, the laminated waveguide is suitable for feed lines of a small size array antenna.

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