A 60-GHz-Band Planar Dielectric Waveguide Filter for Flip-Chip Modules

Masaharu Ito, *Member, IEEE*, Kenichi Maruhashi, *Member, IEEE*, Kazuhiro Ikuina, Takeya Hashiguchi, Shunichi Iwanaga, and Keiichi Ohata, *Member, IEEE*

***Abstract*—A planar dielectric waveguide filter with coplanar waveguide (CPW) I/O ports suitable for flip-chip bonding is proposed and is demonstrated for 60-GHz-band applications. The filter is formed incorporating metallized through holes in an alumina substrate. In order to improve stopband rejection, short-circuited CPW resonators with a half-wavelength are added to waveguide-to-CPW transitions. A fabricated four-resonator filter exhibits an insertion loss of 3.2 dB with a 3-dB bandwidth of 3.0 GHz and rejection of 35 dB at 3-GHz lower separation from a center frequency of 59.5 GHz. The filter is mounted by using flip-chip bonding in a multilayer ceramic package with structures to suppress parasitically propagating electromagnetic waves. No degradation of the stopband rejection is observed from 50 to 80 GHz.**

***Index Terms*—Bandpass filters, coplanar waveguides, dielectric waveguides, flip-chip devices, millimeter-wave filters, waveguide filters.**

I. Introduction

In ORDER TO satisfy recent demands for low-cost millimeter-wave applications, several multichip modules have been developed using a flip-chip technology that provides high reproducibility and good electrical performance in a millimeter-wave range [1]–[3]. Active devices such as amplifiers and oscillators in these modules employed a coplanar monolithic-microwave integrated-circuit (MMIC) configuration because the coplanar approach not only eliminates backside processing, but also is suitable for flip-chip bonding. Filters, which are usually required for wireless communication systems, such as wireless local area networks [4] and wireless home networks [5], [6], should have a planar configuration with coplanar waveguide (CPW) I/O ports for easy integration with flipped CPW MMICs in a module. Millimeter-wave flip-chip filters, however, have not been reported. CPW filters are seldom used in the millimeter-wave range due to their large insertion losses. Special types of filter, such as a filter with high-temperature superconductors, have exhibited limited success [7]. It is well known that microstrip filters with wide lines show good performance. However, in a flip-chip structure, the microstrip configuration is sensitive to a proximity effect between a chip and a mounting substrate [8]. Therefore, a planar filter with low loss and less sensitivity to the proximity effect is strongly needed.

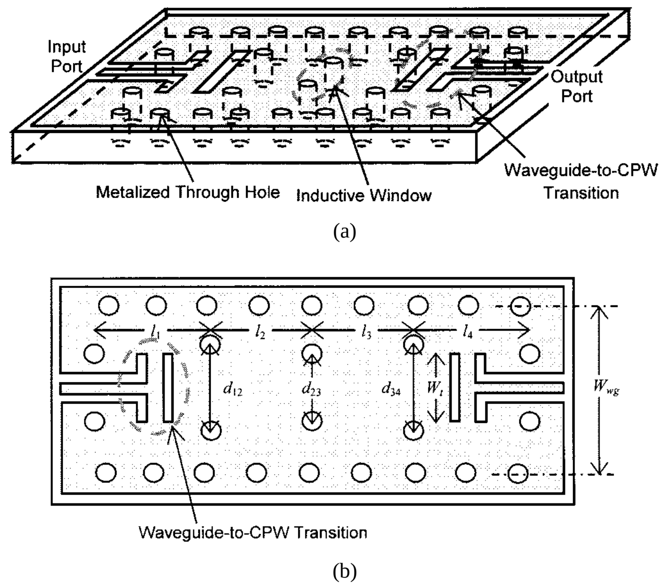

Fig. 1. Basic structure of the dielectric waveguide filter with CPW I/O ports. (a) Over view. (b) Plane view.

In this paper, we propose a planar dielectric waveguide filter with CPW I/O ports for 60-GHz-band applications and demonstrate high performance of the developed filter after flip-chip bonding for the first time. Waveguide-to-CPW transitions of the filter are directly formed on the surface of the waveguide. To improve stopband rejection, short-circuited resonators with a half-wavelength are added to the transitions. The filter is mounted in a multilayer ceramic package with a cavity using flip-chip bonding. The flipped filter shows good performance with low insertion loss and high stopband rejection.

II. Waveguide Filter With CPW I/O Ports

The basic structure of the proposed bandpass filter is shown in Fig. 1. The waveguide structure is formed incorporating two lines of metallized through holes in a alumina substrate with metallized top and bottom surfaces. The filter is composed of four dielectric waveguide resonators with a half-wavelength. Waveguide-to-CPW transitions, which lead to CPW I/O ports at both ends of the filter, are directly patterned on the waveguide resonators. The dimensions of transitions determine the external quality factor. An inductive window between ith and jth resonators consists of a pair of metallized through holes with a spacing d_{ij} in the waveguide.

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M. Ito, K. Maruhashi, and K. Ohata are with the Photonic and Wireless Devices Research Laboratories, NEC Corporation, Otsu, Shiga 520-0833, Japan.

K. Ikuina and T. Hashiguchi are with the Functional Devices and Materials Research Laboratories, NEC Corporation, Kawasaki 216-8555, Japan.

S. Iwanaga is with NEC Kanasai Ltd, Otsu, Shiga 520-0833, Japan.

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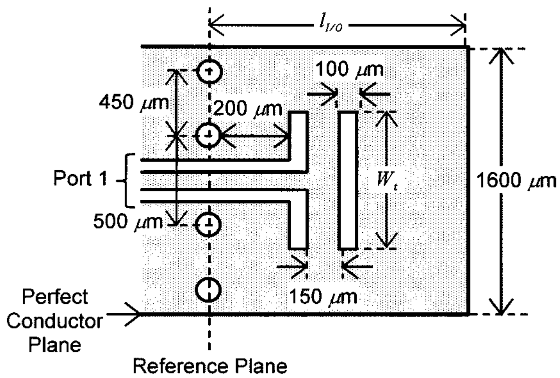

Fig. 2. Plane view of the analysis model for the external quality factor $Q_{\rm ext}$.

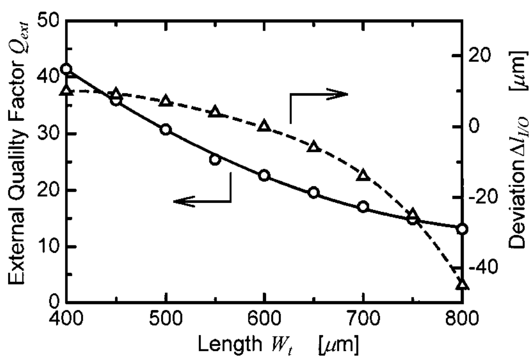

Fig. 3. Calculated quality factor $Q_{\rm ext}$ and deviation $\Delta l_{\rm I/O}$ from the length of a perfectly enclosed box resonator with the same resonant frequency.

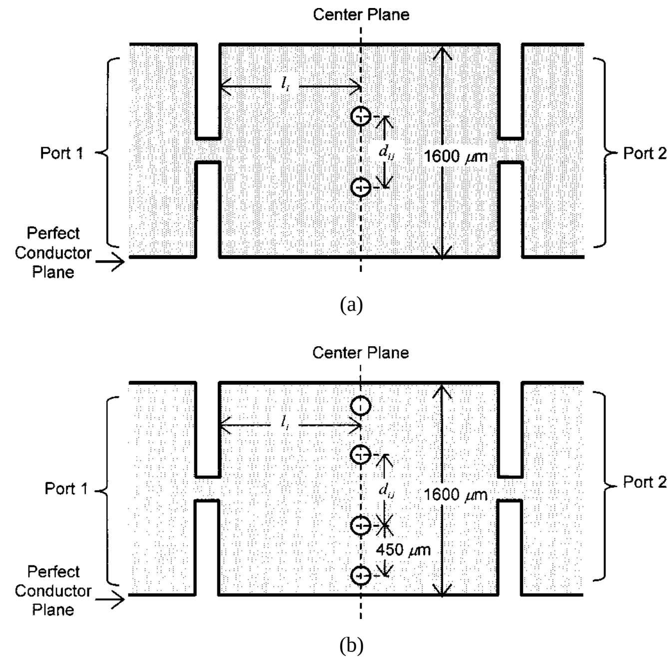

Fig. 4. Plane view of the model to calculate the coupling coefficient k_{ij} between ith and jth resonators: (a) for the structure with just one pair of metallized through holes (type 1) and (b) for the structure with metallized through holes put inside the dielectric waveguide (type 2).

Before the design of the whole filter, we have calculated the external quality factor $Q_{\rm ext}$ and the coupling coefficient k_{ij} between ith and jth resonators by using a three-dimensional (3-D) electromagnetic simulator. Fig. 2 shows a model to calculate the $Q_{\rm ext}$. A perfect conductor plane was assumed instead of the line of metallized through holes surrounding the resonator for a calculation efficiency. The $Q_{\rm ext}$ is controlled by changing the length W_t of the waveguide-to-CPW transition. The length $l_{\rm I/O}$ of the resonator is different from the length l_0 of a perfectly enclosed box resonator with a same resonant frequency. We defined the difference between the lengths $l_{\rm I/O}$ and l_0 as the deviation $\Delta l_{\rm I/O}$. In this calculation, the length between the pattern of the transition and the metallized through holes at the input side end of the resonator was fixed. The $Q_{\rm ext}$ is obtained by [9]

$$Q_{\rm ext} = \frac{f_0}{\Delta f} \tag{1}$$

where f_0 is the resonant frequency of the resonator and Δf is the 180° bandwidth centered at the resonant frequency. Fig. 3 shows the calculated $Q_{\rm ext}$ and the deviation $\Delta l_{\rm I/O}$ with a resonant frequency of 60 GHz. The $Q_{\rm ext}$ gradually decreases as the length W_t becomes large. On the other hand, the deviation $\Delta l_{\rm I/O}$ rapidly changes in the large W_t region. This means that a filter with a wider bandwidth has a higher tolerance for the variation of the length $l_{\rm I/O}$ determined by a punching process of through hole formation. We can realize a four-resonator filter with a bandwidth in a range from about 3% to 8% using the W_t from 400 to 800 μm.

Fig. 4 shows models to calculate the k_{ij} for two coupling structures. The first coupling structure (type 1) has just one pair of metallized through holes to couple two resonators at the center of the waveguide, as shown in Fig. 4(a). In the second coupling structure (type 2), metallized through holes consisting of the wall of the waveguide are put inside the waveguide with separation of 450 μm from the central pair of metallized through holes, as shown in Fig. 4(b). The k_{ij} is obtained by [10]

$$k_{ij} = \frac{f_e^2 - f_m^2}{f_e^2 + f_m^2} \tag{2}$$

where f_e and f_m are two resonant frequencies with perfect electric and magnetic plane at the center plane, respectively. Fig. 5(a) and (b) shows the calculated k_{ij} and the deviation Δl_{ij} of the length of the resonator, respectively. The larger k_{ij} is obtained for the larger spacing d_{ij}. The k_{ij} of type 1 hits bottom in a range where the spacing d_{ij} is small and the coupling structure cannot provide small enough k_{ij} to design a narrow-bandwidth filter since the coupling outside of the pair of metallized through holes is dominant at a small spacing d_{ij}. On the other hand, the k_{ij} of type 2 decreases even at a small spacing d_{ij}.

Using these calculated coupling parameters, we have designed a 0.1-dB-ripple Chebyshev four-pole filter with a 5% bandwidth centered at 60 GHz. For this filter characteristics, $Q_{\rm ext} = 22$, $k_{12} = k_{34} = 0.042$, and $k_{23} = 0.033$ are required by the conventional filter design technique [11]. These values are obtained at $W_t = 610$ μm, $d_{12} = d_{34} = 450$ μm in type 1 and $d_{23} = 470$ μm in type 2, according to Figs. 3 and 5. The

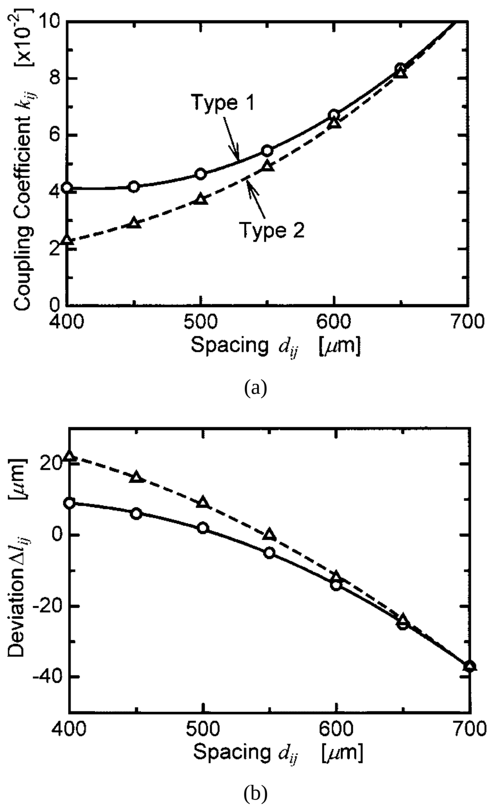

Fig. 5. Calculated: (a) coupling coefficient k_{ij} and (b) deviation Δl_{ij} from the length of a perfectly enclosed box resonator with a same resonant frequency.

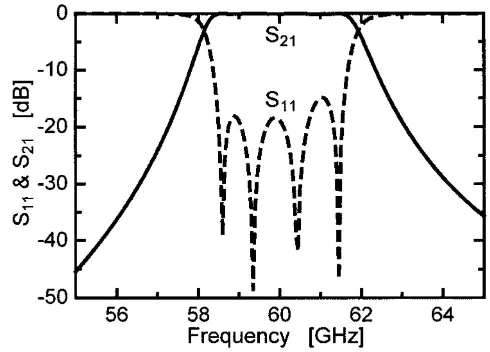

Fig. 6. Calculated transmission and matching characteristics of a 0.1-dB-ripple Chebyshev filter with a 5% bandwidth.

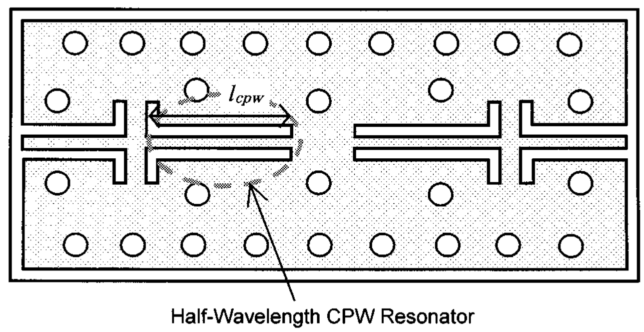

Fig. 7. Plane view of structure of the dielectric waveguide filter with additional shunt CPW resonators.

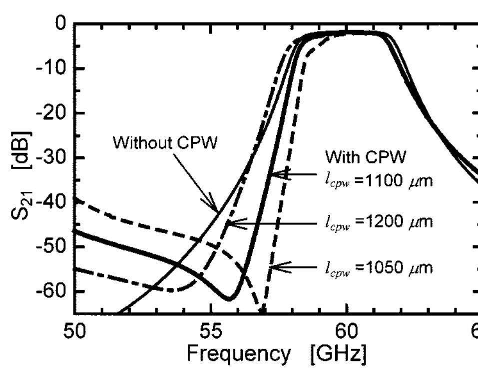

Fig. 8. Calculated transmission characteristics of filter with and without additional CPW resonators.

length of the ith resonator for the n-pole filter is determined from

$$\begin{aligned} l_1 &= \frac{\lambda_{g0}}{2} + \Delta l_{\mathrm{I/O}} + \Delta l_{12} \\ l_i &= \frac{\lambda_{g0}}{2} + \Delta l_{i-1,\,i} + \Delta l_{i,\,i+1}, \qquad i = 2, \ldots, n-1 \\ l_n &= \frac{\lambda_{g0}}{2} + \Delta l_{n-1,\,n} + \Delta l_{\mathrm{I/O}} \end{aligned} \tag{3}$$

where λ_{g0} is a wavelength in the dielectric waveguide structure at the center frequency f_0 of the filter. λ_{g0} is derived from the following equations:

$$\lambda_{g0} = \frac{c}{\sqrt{\varepsilon_r (f_0^2 - f_c^2)}} \quad f_c = \frac{c}{2W_{\mathrm{wg}}\sqrt{\varepsilon_r}}. \tag{4}$$

Here, f_c is the cutoff frequency of the waveguide mode, c is the velocity of light, ε_r is the dielectric constant of the substrate, and W_{wg} is the width of the waveguide structure. According to Figs. 3 and 5, and (3) and (4), $l_1 = l_4 = 930$ μm and $l_2 = l_3 = 945$ μm are obtained at the center frequency of 60 GHz. Using these structural parameters initially, we finely optimized these parameters to realize the required filter response. The calculated filter response is shown in Fig. 6. We neglected the conductor loss and the loss tangent of the dielectric substrate for this calculation. The metallized through holes composing the wall of the waveguide were considered. The required filter response was realized at $d_{23} = 480$ μm (the other parameters were the same as initial ones). This indicates that the design procedure works well enough.

III. Waveguide Filter With Additional CPW Resonators

In order to attain higher stopband rejection while maintaining the size of the filter fixed, shunt CPW lines with the length l_{cpw} are added to the transitions so that these lines can act as short-circuited resonators with a half-wavelength, as shown in Fig. 7. As a result, attenuation poles are introduced in the stopband to improve the rejection characteristic. The filter with CPW resonators was designed to have an attenuation pole at the lower frequency side of the passband. Fig. 8 shows the calculated transmission characteristics of filters with CPW resonators. That of the filter without CPW resonators is also shown. The filter with CPW resonators has the same spacing d_{23} as the one without CPW resonators. The length l_{cpw} was fixed at 1100 μm, while the spacing d_{12}, d_{34}, the length W_t, and lengths of resonators were modified so as to compensate

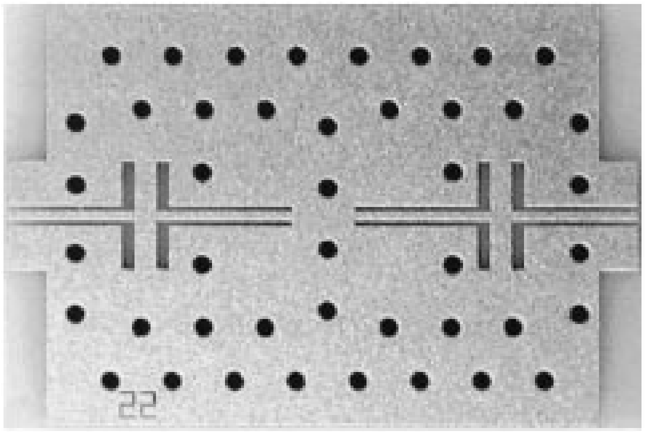

Fig. 9. Fabricated dielectric waveguide filter with CPW I/O ports and CPW resonators.

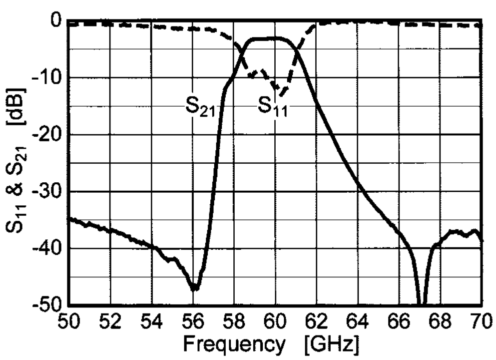

Fig. 10. Measured transmission and matching characteristics of the filter with CPW resonators.

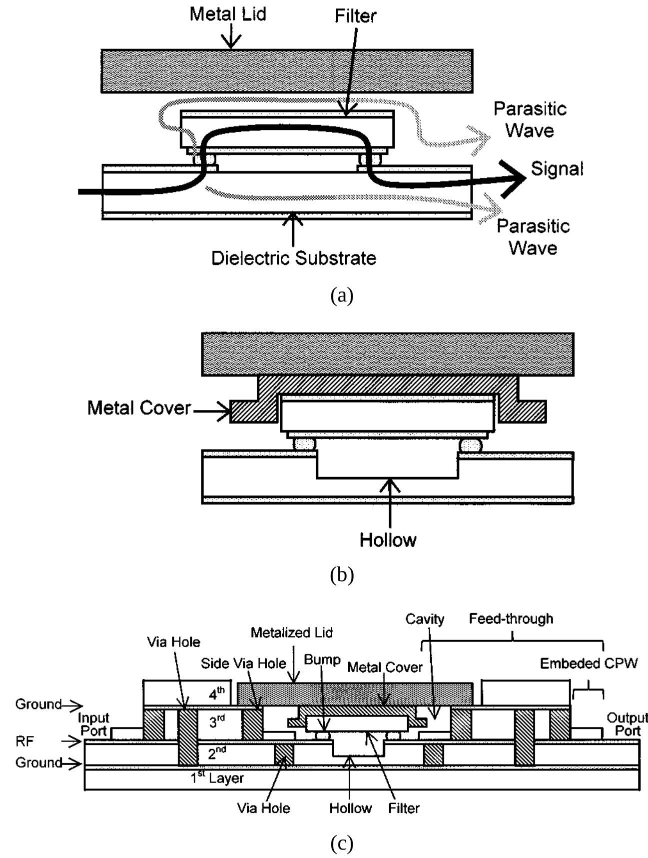

Fig. 11. Cross-sectional view of the package structure for mounting the filter. (a) Conventional flip-chip package structure. (b) Flip-chip package structure with a hollow and metal cover. (c) Whole structure of a multilayer ceramic package.

the change of the passband characteristic due to additional CPW resonators. The rejection in the lower frequency side of the passband is remarkably improved by incorporating CPW resonators. When the length l_{cpw} is varied from 1050 to 1200 μm with the other structural parameters fixed, the attenuation pole shifts to the lower frequency side as the length l_{cpw} becomes longer. This implies that the rejection characteristic can be tuned by changing the length after the fabrication.

IV. Experimental Results

We have fabricated a filter with an attenuation pole at the lower frequency side of the passband. Fig. 9 shows a photograph of the fabricated filter. The filter is formed in an alumina substrate with a relative dielectric constant of 9.7. The size is 4.7 mm $\times$ 3.2 mm $\times$ 0.25 mm. The dimension of metallized through holes is 0.15 mm in diameter. Two lines of metallized through holes composing walls of the dielectric waveguide are formed in a pitch of 0.45 mm along the propagation direction and are separated with the distance W_{wg} of 1.6 mm from each other (Fig. 1). This pitch is much less than a half-wavelength in the operating frequencies. To reduce a radiation loss further, an additional line of metallized through holes is formed at each side of the dielectric waveguide.

Fig. 10 shows the measured transmission and reflection characteristics of the filter using on-wafer probes. The insertion loss is 3.2 dB at a center frequency of 59.5 GHz and the return loss is better than 8 dB in the passband. The 3-dB bandwidth is 3.0 GHz. An attenuation pole is successfully introduced at 56 GHz by CPW resonators with a half-wavelength. The rejection at 3-GHz lower separation from the center frequency is 35 dB. This is better than higher frequency side rejection by 20 dB. Another attenuation pole appears at 67 GHz. This is caused by peripheral paths outside the waveguide structure, which directly couple input with output ports.

Fig. 11(a) shows a conventional flip-chip package structure with a metal lid to shield electrically. For this package structure, we should consider suppressing the degradation of the isolation between the input and output due to undesired coupling. This coupling may excite two parasitically propagating electromagnetic waves. One is the wave, which is excited by bump discontinuities and propagates through the substrate below the filter. The other is the wave, which is excited by the radiation at the edge of the filter substrate and propagates through the space between the filter and the lid. To avoid the degradation of the isolation, we introduced two structures, as shown in Fig. 11(b). To suppress the wave propagating through the substrate, a hollow is formed in the substrate. Moreover, the hollow reduces the proximity effect between the chip and substrate, which causes the shift of the frequency response. The wave propagating through the space between the filter and the lid is suppressed by putting a hat-shaped metal cover on the backside of the filter. Since the edge of the

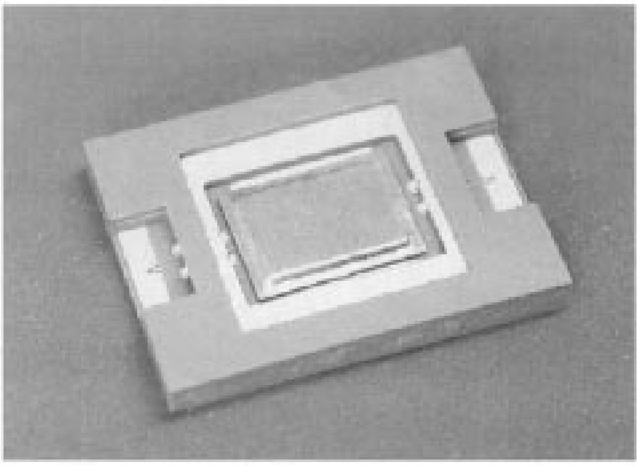

Fig. 12. Filter mounted in the ceramic package. The metal cover is attached on the filter.

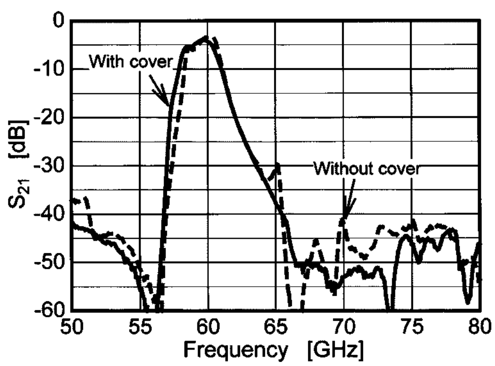

Fig. 13. Measured transmission characteristics of the flipped filter with and without the metal cover on the backside of the filter.

filter is covered with the metal, the coupling due to the radiation is suppressed sufficiently. Besides, the cover blocks the space between the filter and lid. Fig. 11(c) shows a whole structure of a multilayer ceramic package for mounting the filter. The package consists of a cavity and a pair of feed-throughs to connect external I/O ports [12].

Fig. 12 shows a photograph of the packaged filter with the metal cover. The size of the package is 13 mm $\times$ 10 mm $\times$ 1.2 mm. The filter was mounted in the cavity whose size is 6.6 mm $\times$ 4.9 mm $\times$ 0.4 mm by using a thermal compression method. Fig. 13 shows the measured transmission characteristics of the flipped filter with and without the metal cover. In case of the filter without the metal cover, slight degradation is observed in the stopband and the shoulder of the passband deteriorated at the lower frequency side, compared to the filter response before flip-chip bonding. The filter with the metal cover shows excellent rejection characteristic without any degradation. The insertion loss of approximately 5 dB in the passband is a reasonable value considering the loss of two feed-throughs in the package (1 dB $\times$ 2).

V. Conclusion

A planar dielectric waveguide filter with CPW I/O ports has been developed. The design procedure of the basic filter with CPW I/O ports has been described. The stopband rejection of the filter has been improved by adding CPW resonators to waveguide-to-CPW transitions. The filter has been fabricated in an alumina substrate by using metallized through holes. The fabricated filter has shown good performance with low insertion loss and high stopband rejection. The filter flipped in a multilayer ceramic package has also been demonstrated. In order to attain high stopband rejection by suppressing a parasitically propagating wave, a cover on the filter and a hollow in the package have been introduced. The filter has exhibited high stopband rejection without any degradation after flip-chip bonding. It is promising for this filter to be applied to low-cost millimeter-wave systems.

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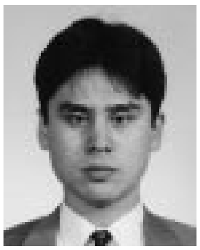
Masaharu Ito (M'00) received the B.E. and M.E. degrees in electronic engineering from Kobe University, Kobe, Japan, in 1995 and 1997, respectively.

In 1997, he joined the NEC Corporation, Otsu, Shiga, Japan, where he is currently involved in the development of millimeter-wave integrated circuits (ICs), passive components, and their packaging systems. His current research interests include passive and active filters.

Mr. Ito is a member of the Institute of Electronics, Information and Communication Engineers (IEICE), Japan.



Kenichi Maruhashi (M'95) was born in Aichi, Japan, on February 11, 1967. He received the B.S. and M.S. degrees in physics from Kobe University, Kobe, Japan, in 1989 and 1991, respectively.

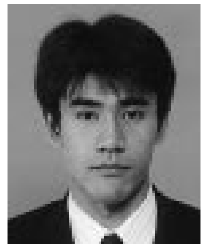
In 1991, he joined the NEC Corporation, Otsu, Shiga, Japan, where he was involved with modeling, design, and characterization of heterojunction FETs and development of millimeter-wave MMICs based on their technologies. He is currently a Principal Researcher with the Photonic and Wireless Devices Research Laboratories, NEC Corporation. His current research interests include development of millimeter-wave ICs and RF front-end modules for high-speed wireless communication systems.

Mr. Maruhashi is a member of the Institute of Electronics, Information and Communication Engineers (IEICE), Japan.

Kazuhiro Ikuina received the B.E. and M.E. degrees in material science from Waseda University, Tokyo, Japan, in 1988 and 1990, respectively.

In 1990, he joined the NEC Corporation, Kawasaki, Japan, where he has been engaged in research and development of low-temperature co-fired ceramic (LTCC) materials and process technology.

Mr. Ikuina is a member of the American Ceramic Society, the Institute of Applied Physics, and the Institute of Electronics, Information and Communication Engineers (IEICE), Japan.



Takeya Hashiguchi received the Mechanical Engineering degree from the NEC Technical College, Kawasaki, Japan, in 1988.

In 1986, he joined the NEC Corporation, Kawasaki, Japan. In 1988, he joined the Functional Devices and Materials Research Laboratories, NEC Corporation, where he is currently involved in the development of LTCC packaging materials. His current research interests include functional embedded passive elements in LTCC.

Shunichi Iwanaga received the Mechanical Engineering degree from Sasebo Technical College, Sasebo, Japan, in 1985.

He is currently a member of the Packaging Technologies Development Team, Packaging Development Group, Semiconductor Division, NEC Kansai Ltd., Otsu, Shiga, Japan.

Keiichi Ohata (M'86) received the B.E. and M.E. degrees in electronic engineering from Kyoto University, Kyoto, Japan, in 1970 and 1972, respectively.

In 1972, he joined the Central Research Laboratories, NEC Corporation, Kawasaki, Japan, where he was engaged in research of ohmic contacts to GaAs, development of low-noise GaAs MESFETs, and research and development of microwave and millimeter-wave heterojunction devices. From 1991 to 1996, he temporarily joined the Advanced Millimeter Wave Technologies Corporation Ltd., Otsu, Japan, where he was responsible for the research of 60-GHz-band MMICs for short-range communication systems. He is currently a Senior Principal Researcher with the Photonic and Wireless Devices Research Laboratories, NEC Corporation, Otsu, Shiga, Japan, where he conducts research and development on millimeter-wave devices for multimedia communications.

Mr. Ohata is a member of the IEEE Microwave Theory and Techniques Society (IEEE MTT-S), the IEEE Electron Devices Society, and the Institute of Electronics, Information and Communication Engineers (IEICE), Japan.