Application of the Planar I/O Terminal to Dual-Mode Dielectric-Waveguide Filters

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***Abstract*—Planar input/output terminals have been applied to dual-mode dielectric-waveguide filters. Two types of the filter, for a 13-GHz Ku-band and a 22-GHz K-band were designed and fabricated only by metal plating on the surfaces of a ceramic block. They are realized with very small volumes of less than 0.05 cm^3.**

***Index Terms*—Bandpass filters, dielectric waveguides, waveguide excitation.**

I. Introduction

DIELECTRIC-WAVEGUIDE components with metallized surfaces have been expected to be utilized in microwave circuits because of its higher Q values comparing to dielectric coaxial counterparts [1]. Their applications have ever been mainly considered at the frequency of S-band or below. Recently, the planar I/O terminal was proposed as an efficient excitation structure for the dielectric-waveguide filter [2]. It has the advantages that the fabrication is easy, height is reduced, and loss is small. Moreover, this structure is useful for other types of dielectric-waveguide component that use the TE mode as well. In this paper, the planar I/O terminals are applied to dual-mode dielectric-waveguide filters at Ku/K-band frequencies. They are realized by very simple monolithic structures with very small volumes.

II. Basic Structure of the Dual-Mode Dielectric-Waveguide Filter

Dual-mode filters constructed by waveguides having a square cross section have been studied. Cutting one corner for the dielectric filled construction is an especially efficient way to realize filters [3]–[6].

Fig. 1 shows the basic structure of the dual-mode dielectric-waveguide filter with planar I/O terminals. Its shape is nearly a cube, except that one corner is made to dent. This dented corner serves to control the coupling coefficient. All surfaces are plated by metal, except that there are isolation gaps around two I/O terminals. These I/O terminals are only plated in each of the center of right-angled two planes. In this structure, whole surfaces are almost covered by metal, and nothing is inside. The inside electromagnetic field is not disturbed consequently, and this structure can operate at higher frequencies.

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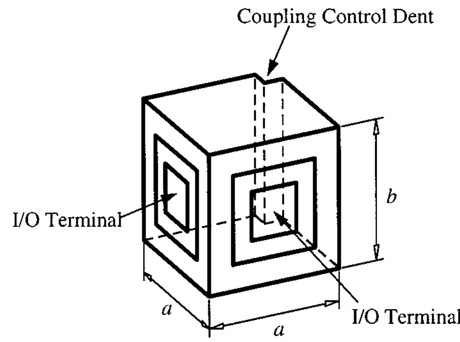

Fig. 1. Dual-mode dielectric-waveguide filter with planar I/O terminals.

III. Functions of the Planar I/O Terminals on a Dual-Mode Dielectric-Waveguide Filter

It has been indicated that the planar I/O terminal is applicable for the effective excitation structure of the dielectric-waveguide filter and can control the resonator's external $Q(Q_e)$ value by changing its size [2]. In [2], the Q_e value was being controlled by changing the I/O terminal size and fixing the isolation gap length around it. In this paper, the Q_e value is controlled by changing the isolation gap length with fixing the I/O terminal size.

The planar I/O terminal essentially acts as a coaxial port and the rectangular waveguide connected to the planar I/O terminal can be expressed by an equivalent circuit of Fig. 2 as a three-port model. That equivalent circuit is almost the same as that of the H-plane T-junction of the rectangular waveguide [7]. The only exception is that the additional reactance $(-jX_e)$ exists at the entrance of the TEM port. That reactance $(-jX_e)$ corresponds to the capacitance between the I/O terminal and the bottom metal plate that surrounds it. The changing of the isolation gap length changes that capacitance value widely. It is increased when the isolation gap length is shortened and is decreased when lengthened. This Q_e control technique has an advantage that the I/O terminal can be kept in practical size within a wide range of the design.

Furthermore, there is another significant function in an application of the planar I/O terminal to a dual-mode dielectric-waveguide filter. That is the controlling of the coupling coefficient, as described in the following. Fig. 3 shows the electric and magnetic fields that are calculated by HFSS simulations. That analysis model is a cubic dielectric-waveguide resonator connected with two coaxial lines. Fig. 3(b)–(d) shows the cross section so that it cuts two coaxial lines at the center. The electric-field vectors are parallel to the cross section and the magnetic field vectors are vertical. It should be noticed that there are no dents on

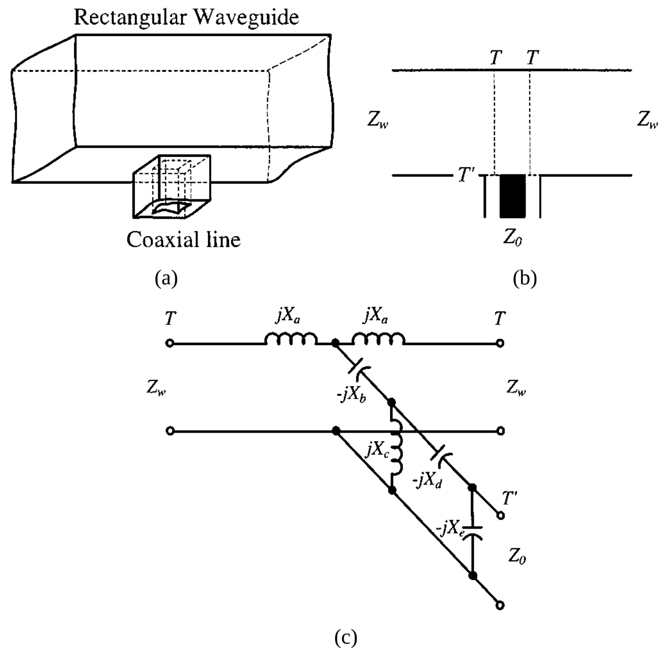

Fig. 2. Rectangular waveguide connecting with a coaxial line. (a) General view. (b) Side view. (c) Equivalent circuit.

the resonator. The magnetic-field intensity becomes zero on the diagonal (A-A'), as with the even mode. However, if the coaxial lines do not exist, it becomes zero on the diagonal (B-B'), as with the odd mode; it does not become zero due to the influence of the coaxial lines. Fig. 4(a) shows a rectangular waveguide resonator having a square dent, and there is a coupling between two degenerate resonant modes (TE_{101} and TE_{011} modes) [3]. That magnetic-field distribution shown in Fig. 4(b) has an analogy to that of the odd mode shown in Fig. 3(d). This means the making of the two planar I/O terminals on a waveguide resonator having a square cross section that also yields that coupling. Therefore, the changing of the dimensions of the planar I/O terminals has influences on not only the Q_e value, but also the coupling coefficient.

IV. Design

A. Ku-Band Filter

The design of the bandpass filter is made at the center frequency of 13 GHz. A dielectric ceramic with its constant of 21 is used. In the case of a general filter design, the Q_e value and coupling coefficient can be determined independently. However, in this case, the filter design should be done with special care because the TEM ports' dimensions have the influence both on the Q_e value and the coupling coefficient, as mentioned above.

A side length of the dielectric filled rectangular waveguide having a square bottom section becomes 3.56 mm with a dielectric constant of 21 to get the dominant resonant frequency of 13 GHz. Thus, a cubic-shaped resonator with side length of 3.5 mm having one I/O terminal is analyzed by HFSS to obtain the Q_e value. Fig. 5 shows the calculated Q_e value as a function of the isolation gap length. Here, the side length of the square I/O terminal was fixed to 1.2 mm. The Q_e value is decreased against the increasing of the isolation gap length.

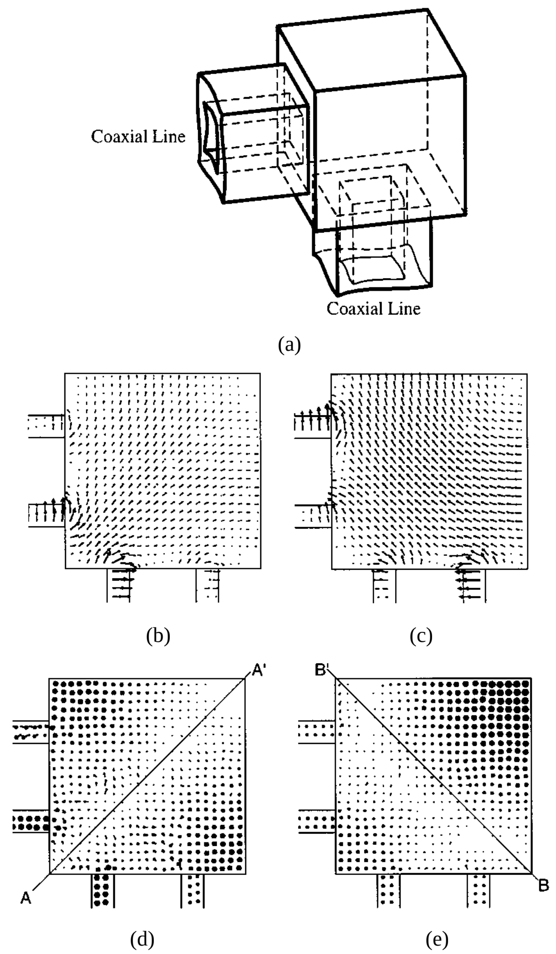

Fig. 3. (a) Cubic dielectric resonator connected to two coaxial lines for HFSS analysis. (b) Electric field of the even mode. (c) Electric field of the odd mode. (d) Magnetic field of the even mode. (e) Magnetic field of the odd mode.

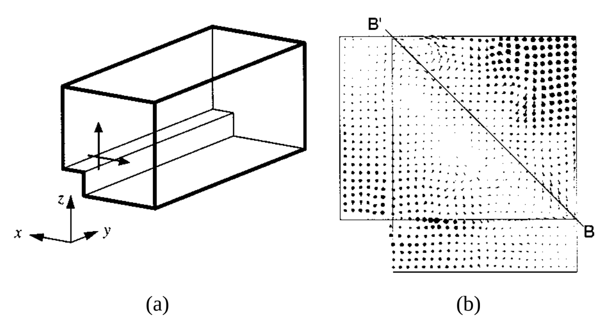

Fig. 4. (a) Square corner cut rectangular resonator. (b) Magnetic-field distribution of the second resonant mode at the center cross section.

The required Q_e value for a 0.1-dB-ripple Chebyshev bandpass characteristic with a bandwidth of 280 MHz at 13 GHz is 76, and the gap length around the I/O terminal that corresponds to that is 0.5 mm (searching for it from Fig. 5).

The coupling coefficient is also calculated by HFSS as a function of the side length of the dent made at one corner. Fig. 6 shows the analysis model to obtain the coupling coefficient. This model is one-half of the actual filter that split at the virtual coupling plane, which is defined because of the symmetry of the electric and magnetic fields at the resonance. Two resonant frequencies at the reference plane of the port2(T2) are calculated

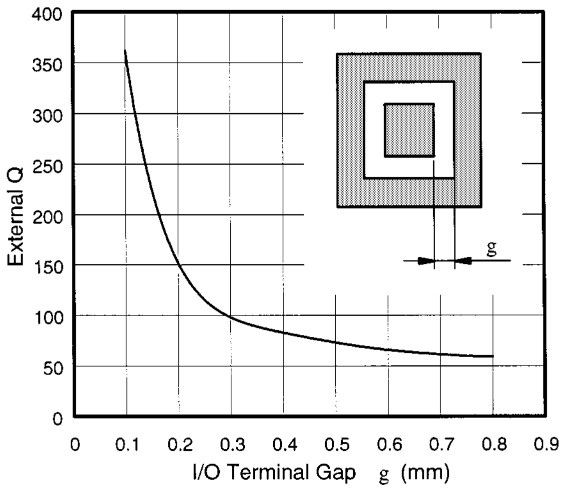

Fig. 5. Calculated external Q value versus isolation gap length.

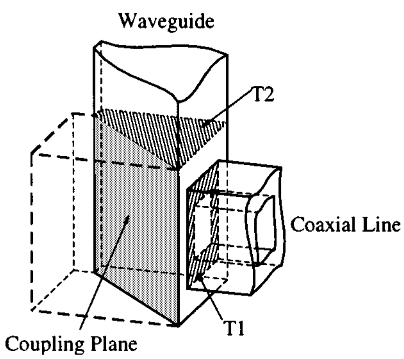

Fig. 6. Analysis model for HFSS simulation to obtain the coupling coefficient.

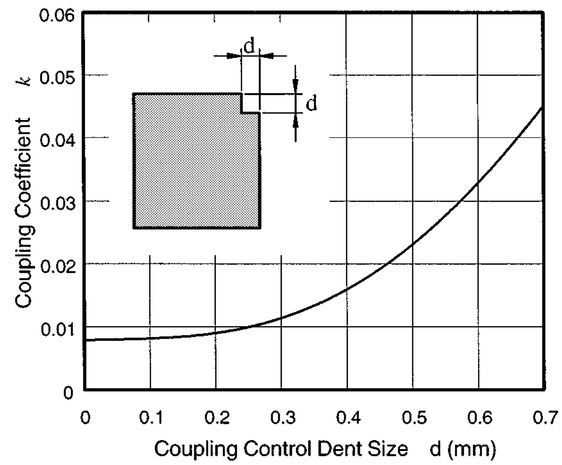

Fig. 7. Calculated coupling coefficient versus coupling control dent size d.

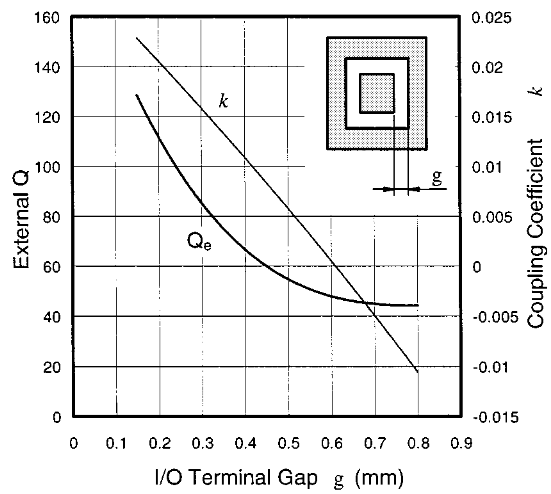

Fig. 8. Calculated external Q value and coupling coefficient versus isolating gap length.

under two conditions. The even-mode resonant frequency (f_e) is obtained when the coupling plane is set as a magnetic wall, and the odd-mode resonant frequency (f_o) is obtained when the coupling plane is set as an electric wall. The coupling coefficient is then calculated by

$$k = \frac{2 \times (f_o - f_e)}{f_o + f_e}.$$

At this time, the port1 terminated with 50 Ω is necessary to consider its influence for the resonant frequency.

Fig. 7 shows the calculated value of the coupling coefficient as a function of the coupling control dent size. In this calculation, the isolation gap length at the port1 was fixed to 0.45 mm. The required value of the coupling coefficient is 0.015, and it is obtained by a 0.4-mm dent size.

B. K-Band Filter Without the Dent

A filter design for K-band is tested here as one more trial. As shown in Fig. 7, when the coupling control dent size is zero, the coupling coefficient still has a considerable value. It suggests there are possibilities that the dual-mode filter can be made without the coupling control dent under the specific condition.

The Q_e values and coupling coefficients are calculated in a similar way again with a dielectric material having the relative constant of 7.9. Fig. 8 shows the Q_e value and the coupling coefficient as a function of the isolation gap length. This calculation is done without a coupling control dent. It is recognized that the isolation gap evidently has a function that control not only the Q_e value, but also the coupling coefficient. The coupling coefficient becomes nearly zero at $g = 0.6$ and negative at a region of $g > 0.6$. Here, positive values mean coupling is inductive and negative values mean coupling is capacitive.

For a 0.1-dB ripple Chebyshev characteristic with bandwidth of 400 MHz at 22 GHz, the Q_e value and the coupling coefficient become 82 and 0.014, respectively. These values are almost satisfied by choosing the gap length of 0.32 mm.

V. Fabrication and Measurement

The designed filters were fabricated and measured. Dielectric materials have relative dielectric constants of 21 and 7.9 for 13 and 22 GHz, respectively, and their details of the characteristics are described in Table I. The conductor $Q(Q_c)$ in this table is estimated by using a conductivity of 3.0 $\times$ 10^7 s/m that the plated silver on the dielectric materials has.

Sizes of the filters are 3.5 mm $\times$ 3.5 mm $\times$ 3.4 mm, for 13 GHz, and 3.5 mm $\times$ 3.5 mm $\times$ 3.0 mm, for 22 GHz. Both of them are less than 0.05 cm^3 in volume. The planar I/O terminals

TABLE I
CHARACTERISTICS OF THE MATERIALS

	Ku-band	K-band
f (GHz)	13	22
ε_r	21	7.9
τ_f (ppm/°C)	5	-9
Q_d	3900	730
Q_c	1305	1840
Q_u	978	523

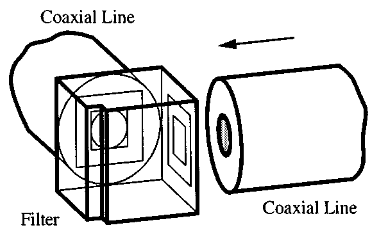

Fig. 9. Connection of the filter and coaxial lines.

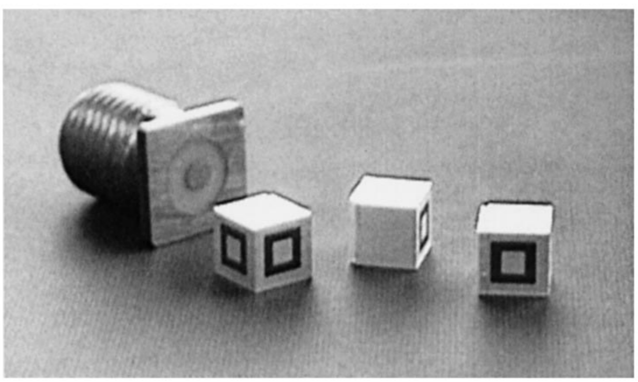

Fig. 10. Fabricated dual-mode dielectric-waveguide filters for 13-GHz center frequency.

applied here essentially act as TEM mode ports and can be used by connecting with signal lines like strip lines or coaxial lines that have 50-Ω specific impedance, as shown in Fig. 9. One of the easiest ways is to connect the coaxial SMA connectors to the planar I/O terminals directly, and this is also useful for accurate measurements. In this paper, the SMA-type coaxial connectors[1] are processed so that their connection planes become flate and used. Fig. 10 shows the fabricated filters for 13 GHz and an SMA connector processed for measurement.

The measured frequency responses of Ku- and K-band filters are shown in Figs. 11 and 12, respectively, and the measured characteristics are described in Table II. These characteristics include two SMA connectors. Though measured results are slightly different from the designed value, with both filters exhibiting practical characteristics. The filter design with the higher precision will become possible due to the improvement of the ceramic processing.

Furthermore, temperature dependence of the filter response is measured with the K-band filter. The result is shown in Fig. 13. Changes are less than 0.1% for the center frequency and 3.7% for the bandwidth, in the temperature range from $-40°$ to $+85°$.

[1]Radiall SMA connect type R124.426.123.

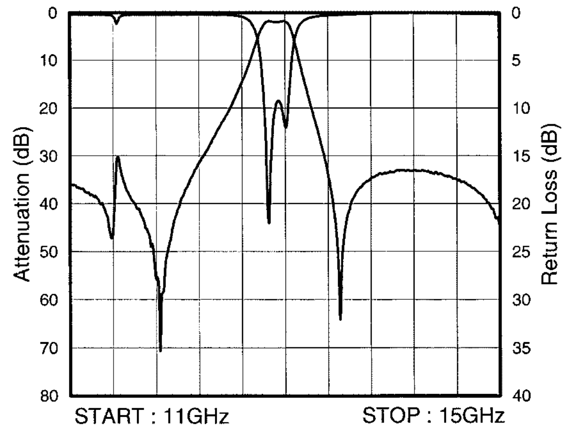

Fig. 11. Measured response of the filter designed for Ku-band (13 GHz).

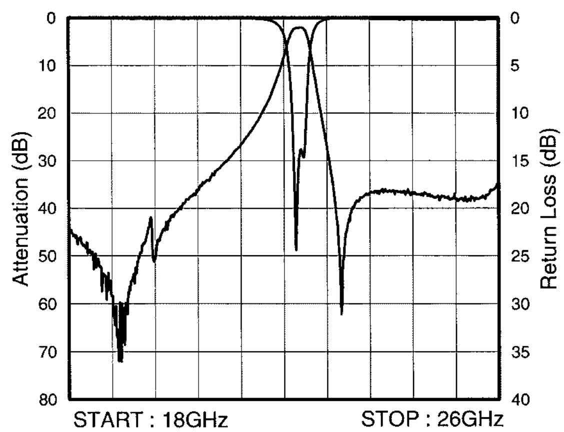

Fig. 12. Measured response of the filter designed for K-band (22 GHz).

TABLE II
MEASURED CHARACTERISTICS

	Ku-band	K-band
Center frequency (GHz)	12.92	22.28
Bandwidth (MHz)	319	384
Insertion Loss (dB)	1.8	2.1

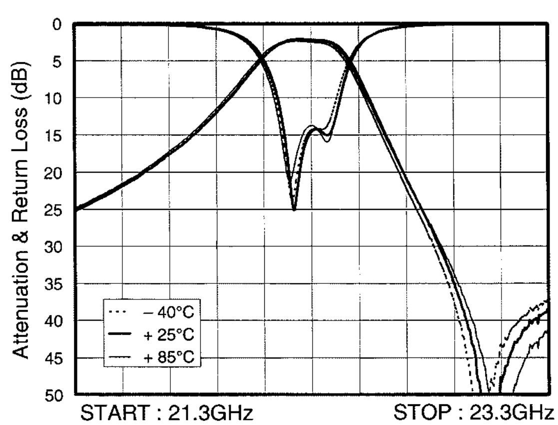

Fig. 13. Temperature dependence of the K-band filter's response.

It can be said that a good temperature coefficient of the dielectric ceramic material is reflected to the stability of the filter response.

VI. CONCLUSION

In this paper, the planar I/O terminals have been applied to fabrications of dual-mode dielectric-waveguide filters. It became clear that the planar I/O terminal can be used for controlling the coupling coefficient of the dual-mode dielectric-waveguide filter, and that utilization makes the filter structure very simple. Ku- and K-band filters were fabricated with monolithic ceramics less than 0.05 cm^3 and showed practical characteristics. This proposed filter structure is drastically miniaturized compared with a conventional type of dual-mode waveguide filter, and can be applied in portable terminals. Moreover, the filter size become smaller with using higher dielectric-constant material or higher operation frequency, and there is a possibility that a multilayered circuit board can embed this filter structure due to its simplicity. The filter structure proposed in this paper is expected to contribute to miniaturizations of microwave communication equipments.

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