26 GHz $TM_{11\delta}$ Mode Dielectric Resonator Filter and Duplexer with High-Q Performance and Compact Configuration

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***Abstract* — A novel structure of 26GHz bandpass filters using $TM_{11\delta}$ rectangular-mode dielectric cavity resonators is introduced. The resonator of high-permittivity ceramics shows a high quality factor (Q) value of 2600, which is roughly comparable to that of waveguide type ones, in spite of its small structure. A three-stage Tchebyscheff bandpass filter with 0.4 % relative bandwidth was fabricated and the passband insertion loss was measured to be 1.7 dB. The filter has input/output ports of microstrip lines for the surface mounting. A duplexer, consisting only of two $TM_{11\delta}$ mode filters and a microstrip T-junction, is also presented. These filter and duplexer have a configuration compact and easy to manufacture as well as the high-Q performance.**

I. Introduction

Millimeter wave communication systems show considerable promise for high-bit-rate wireless data transmissions. In order to widely spread such systems, it is of great importance to develop small-sized and high-performance devices and components of reduced production costs.

Filters consisting of resonating elements are key in most of microwave or millimeter-wave circuits, and the performance of these circuits is, in many cases, limited by the resonant quality factor (Q). In millimeter-wave frequencies, waveguide type filters are usually used for low insertion-loss and sharp skirt because of their high-Q value, although their configuration is considerably large and unfavorable for connecting with planar circuit components. Millimeter-wave filters with both compact configuration and high-Q performance are intensively desired. Using the dielectric resonator structure[1-3] should be an effective way to realize such filters.

Various types of dielectric resonators have been widely used in microwave wireless communications. The primary advantage in usage of dielectrics is to miniaturize the filter configurations. Above all, $TE_{01\delta}$ and $TM_{01\delta}$ circular-mode dielectric cavity resonators[1,2] are well known to exhibit especially high-Q performance in microwave frequencies as well as the compact configuration. There are, however, few reports on application of dielectric cavity resonators in millimeter-wave frequencies, as far as the authors know. The planar type TE_{010} dielectric resonator filters have been introduced for K-band applications.[3] Although their configuration is very small and suitable for mounting on circuit boards, the reported resonator Q value is roughly a half of those of conventional waveguide filters.

This paper introduces new structures of 26 GHz dielectric cavity resonator filter and duplexer. These were developed to aim for realizing both a compact configuration and electrical performances comparable with waveguide type ones.

II. $TM_{11\delta}$ Rectangular-Mode Dielectric Resonator

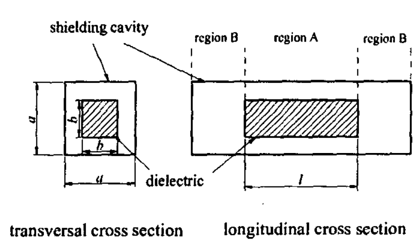

Fig.1 Basic structure of the $TM_{11\delta}$ mode dielectric resonator

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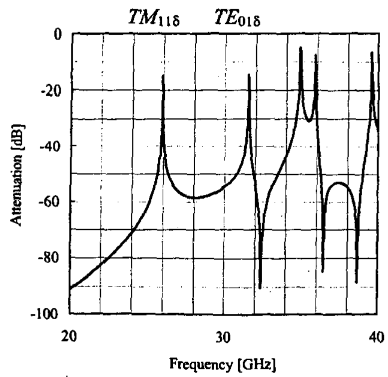

Fig.2 Calculated transmission frequency response of the $TM_{11\delta}$ rectangular-mode dielectric resonator

Here, the $TM_{11\delta}$ rectangular-mode resonator is considered for applying to bandpass filters and duplexers operating at millimeter-wave frequencies. The $TM_{11\delta}$ rectangular-mode is excited in a dielectric square rod and is related to the $TM_{01\delta}$ circular-mode in a dielectric cylinder. Practical advantages of the $TM_{11\delta}$ rectangular-mode over the $TE_{01\delta}$ circular-mode are that the resonator size is small and that the field distribution is suited for strong coupling with coaxial or microstrip lines.

Figure 1 shows a $TM_{11\delta}$ rectangular mode resonator consisting of a dielectric square rod placed in a shielding cavity of the square cross section. In the case of using the dielectric of 21 relative permittivity and the cavity of square cross section with a=3 mm, the size of the dielectric is estimated that b=1 mm and l= 5.6 mm for 26 GHz resonant frequency by the eigen-mode analysis. The space between the dielectric rod and inner walls of the cavity is assumed to be filled with supporting stuff, which consists of another dielectric material of lower relative permittivity, 2, in order to fix the dielectric at center of the cavity. Figure 2 shows the calculated frequency response of the resonator, where two signal ports of microstrip lines were weakly coupled to the resonator. A field simulation tool was used in this calculation. The $TM_{11\delta}$ mode is the fundamental resonance at around 26 GHz. The next higher order resonance, which is attributed to two degenerated $TE_{01\delta}$ rectangular modes, is separated more than 5 GHz in frequency from the fundamental one.

With regard to the cavity structure, the cross sectional dimension of the cavity is much smaller than that of the waveguide type filters in the same operation frequency because the cavity is designed under the condition where all the waveguide propagation modes are in cutoff. The cutoff frequencies f_c [GHz] in a waveguide of square cross section with side length a [mm] is given by Eq. (1), where ε_r is relative permittivity inside the waveguide.

$$f_c = 150\frac{\sqrt{m^2+n^2}}{a\sqrt{\varepsilon_r}} \qquad (1)$$

The integers of m and n correspond to, so-called, TE_{mn} or TM_{mn} propagation waves, where TE waves exist with either m or n zero, whereas in TM waves neither m nor n can be zero. The lowest cutoff frequency is therefore $f_c = 150/\left(a\sqrt{\varepsilon_r}\right)$ [GHz] for a TE_{01} wave. At the part of region B in Fig. 1, where the cavity is filled only with the supporting stuff, f_c is estimated at around 35 GHz by substituting ε_r=2 and a=3mm for the equation. All the waveguide propagation modes are therefore in the cutoff condition less than 35 GHz in region B. This means that the cavity resonant modes can not exist less than 35 GHz. Consequently, when bandpass filters are constructed with this $TM_{11\delta}$ resonator structure, it is supposed that spurious responses caused by the higher order dielectric-resonant modes disappear within a 5-GHz upper range from the passband and that the cavity resonant modes are suppressed less than 35 GHz.

With respect to the configuration, the $TM_{11\delta}$ fundamental mode resonator exhibits long and narrow shape as shown in Fig.1. That is a desirable for reducing the height of the filter package and mounting on circuit boards. Moreover the $TM_{11\delta}$ rectangular-mode resonator is structurally suited for efficient coupling with microstrip lines.

Table 1 shows sizes and characteristics of 26 GHz $TM_{11\delta}$ resonators fabricated with three kinds of dielectrics, where the resonators were supported in the cavity by a

Table 1 Characteristics of 26GHz $TM_{11\delta}$ mode dielectric resonators in different dielectric materials

Resonator materials		Dimensions at 26 GHz [mm]		Cutoff frequency f_c [GHz]	Unloaded quality factor Q_u (measured)
Material name	Electrical properties (measured)	Resonator	Cross section of cavity		
Zr-Ti-O_4	ε_r=42.5, fQ=44000[GHz]	1 x 1 x 4.2	2 x 2	53	1000
$MgTiO_3$-$CaTiO_3$	ε_r=21, fQ=70000[GHz]	1 x 1 x 5.6	3 x 3	35	2000
Ba(Mg,Ta)O_3	ε_r=24, fQ=120000[GHz]	1 x 1 x 5.1	3 x 3	35	2600

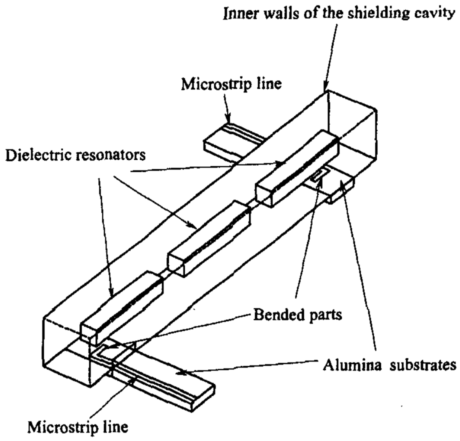

Fig.3 Three-stage bandpass filter configuration

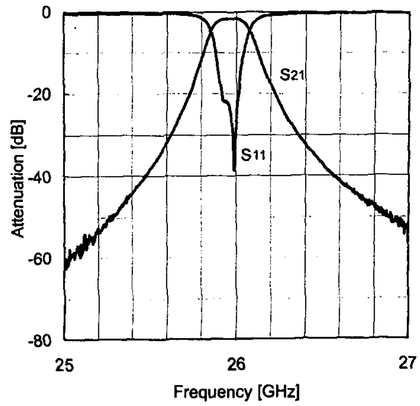

Fig.4 Frequency responses of the filter

PTFE resin of which relative permittivity is 2. The inner wall surfaces of the cavity were plated with gold. For the measurement of unloaded quality factor, Q_u, two microstrip lines were inserted into the cavity to weakly couple with the resonator at its both ends. A network analyzer and an on-substrate testing fixture for microstrip devices were used for the measurement. The Q_u value of the resonator using $Ba(Mg,Ta)O_3$ ceramics was 2600, which is roughly comparable to that of waveguide type resonators. Millimeter-wave filters with both low insertion-loss and steep properties are expected by using this resonator structure.

III. Bandpass Filter

Figure 3 shows a three-stage bandpass filter configuration designed using $TM_{11\delta}$ resonators with the same structure as in the previous experiment. The resonator material was assumed to be $MgTiO_3$-$CaTiO_3$ ceramics (ε_r=21). Microstrip lines of 0.3mm width on alumina substrates of 0.5mm thickness are inserted into the cavity for input/output coupling. The inserted end of each line is bended to the right angle for the strong coupling with the $TM_{11\delta}$ mode. The bottom surface of the cavity is partially grooved under the outer-side ends of dielectric rods to fix the microstrip substrates as shown in Fig.3. The strength of the input/output coupling can be controlled by the length of the bended part of the strip lines. The inter-resonator coupling strength depends on their distance. Three PTFE boards of 1 mm thickness were piled in the cavity as the supporting stuff. Resonators were fixed in the middle of the PTFE boards. Metal screws are inserted into the cavity from its top surface for adjusting the filter parameters. The resonant frequencies and the inter-resonator coupling strength are changed by using the screws located over each resonator and over each gap between the resonators, respectively. Thereby the filter properties can be adjusted after assembling, which relaxes the accuracies in manufacturing. From the practical point of view, this feature is very important for reducing the production costs. Total length, height, and width of the filter experimentally fabricated are 30mm, 6mm, and 9mm, respectively. These dimensions are much less than those of conventional waveguide type filters.

By using this configuration, a three-stage Tchebyscheff bandpass filter was designed with 26GHz center frequency, 0.01 dB passband ripple and 0.4 % relative bandwidth. As $MgTiO_3$-$CaTiO_3$ ceramics rods were used as the resonator, the resonant quality factor is supposed to be 2000 from Table 1. Figure 4 shows the frequency responses of the filter. The passband insertion loss, L_0, is measured to be 1.7 dB, where the length of the bended part of the strip lines and the inter-resonator distance were fixed at 0.95 mm and 1.9 mm, respectively. The L_0 of the resonator-coupling type bandpass filter depends on the dissipation loss in each resonator, which is indicated by the Q_u value.[4] In this case, the L_0 is theoretically given by $2400/Q_u$ from the filter specifications and is calculated at 1.2 dB from the Q_u of 2000. The calculated L_0 is 0.5 dB lower than the measured one. This difference is attributable to unconsidered losses induced, for examples, in the microstrip lines or at the adjusting screws.

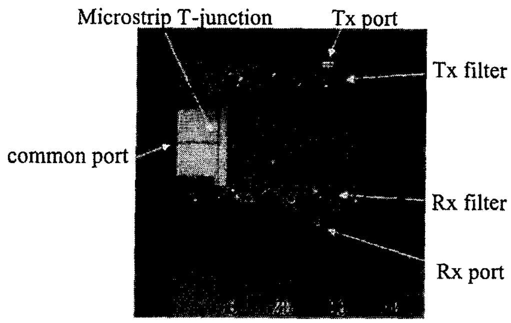

Fig.5 Photograph of the duplexer designed for 26 GHz bands

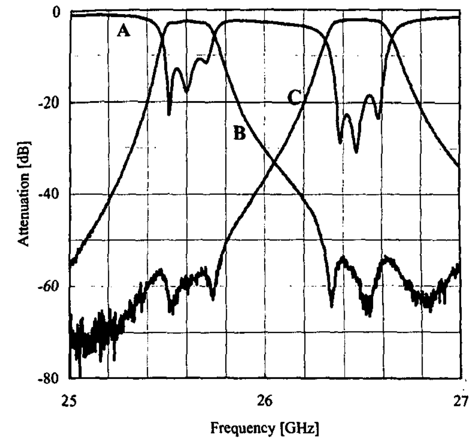

Fig.6 Frequency responses of the duplexer

A: Return loss at the common port
B: Transmission loss from the Tx port to the common port
C: Transmission loss from the common port to the Rx port

IV. DUPLEXER

A duplexer is a key element of wireless communication systems employing the FDD (frequency division duplex). Here, we designed a duplexer that consists of only three major parts, two $TM_{11\delta}$ mode dielectric resonator filters, Tx and Rx filters, and a microstrip T-junction. Figure 5 shows a photograph of the fabricated duplexer. The structure of the filters is the same as described in the previous experiment. Two branches of the T-junction are individually connected to the microstrip-lines of the filters as shown in Fig.5. Ideally, electrical lengths of the two branches should be determined as that in the Tx band the input impedance of the Rx filter at the junction-point is infinite, in other word in the open circuit condition, and vice versa. Required electrical lengths of the two branches were calculated by a circuit simulation tool using electrical properties of the filters measured in advance. Figure 6 shows the frequency responses of the duplexer. The total insertion loss is about 2 dB. The isolation between Tx and Rx is more than 55 dB. The performances can satisfy requirements of some practical FWA systems.

V. CONCLUSIONS

26GHz $TM_{11\delta}$ rectangular-mode dielectric resonator filter and duplexer with high-Q performance and compact configuration were proposed. The resonator of high-permittivity ceramics showed a high Q value roughly comparable with that of waveguide type ones. A three-stage Tchebyscheff bandpass filter and a duplexer consisting of two bandpass filters and a microstrip T-junction were designed using the $TM_{11\delta}$ mode resonators. Their performance based on the high-Q resonance was experimentally confirmed. The results revealed effectiveness of using the $TM_{11\delta}$ dielectric resonator structure in millimeter-wave frequency regions. These filter and duplexer are expected to take the place of the waveguide type ones in applications where the performances of low insertion loss and compact configuration are required.

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