# 60-GHz-band Dielectric Waveguide Filters with Cross-coupling for Flip-chip Modules

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*Abstract* — **Small-size planar dielectric waveguide filters are presented for 60-GHz-band flip-chip modules. The filters have cross-coupling to introduce an attenuation pole for higher stop-band rejection. We develop two types of three-resonator filters: one has a medium bandwidth and the other has a narrow bandwidth. The former filter shows 1.1-dB insertion loss at a center frequency of 58.3 GHz and 33-dB suppression at a 3-GHz-higher separation. The latter filter shows 3.1-dB insertion loss at a center frequency of 58.4 GHz and a 10-dB-bandwidth of 2.7 GHz. The size of each filter is 3.4 mm x 3.5 mm.**

## 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, which provides high reproducibility and good electrical performance in a millimeter-wave range [1], [2]. Active devices such as amplifiers and oscillators in these modules employed a coplanar 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 [3] and wireless home networks [4], should have a planar configuration with CPW I/O ports for co-integration with flipped CPW MMICs in a module.

We have recently proposed and developed a planar dielectric waveguide filter with CPW I/O ports [5], and successfully implemented it in transceiver modules by using flip-chip bonding for the first time [6]. However, the size reduction is strongly required for less expensive filters as well as modules in commercial use. The filter had four resonators to achieve the required performances. It measured 4.7 mm × 3.2 mm and was the largest component in the modules. Therefore, the size reduction of the filter is effective to realize small-size modules.

In this paper, we describe newly developed three-resonator dielectric waveguide filters. The reduction in the number of resonators contributes to the size reduction to 3.4 mm x 3.5 mm, which is smaller than the previous one by 25 %. To improve stop-band rejection for filters with a smaller number of resonators, cross-coupling between 1st and 3rd resonators is introduced by two-dimensional arrangement of resonators, which provides an attenuation pole at the higher frequency-side of the pass-band. The fabricated filters showed good filter response measured by on-wafer probes and successfully mounted in a multi-layer ceramic package using flip-chip bonding.

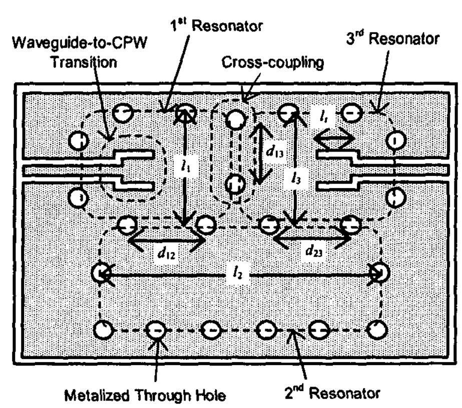


Fig. 1. Plane view of a three-pole dielectric waveguide filter with cross coupling.



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II. THREE-POLE DIELECTRIC WAVEGUIDE FILTER WITH CROSS-COUPLING

The waveguide structure is constructed by forming metalized through holes in a dielectric substrate with metalized surfaces [5]. In order to introduce cross-coupling for an attenuation pole, the resonators are arranged two-dimensionally as shown in Fig. 1. The structure facilitates realization of cross-coupling by the space between through holes. U-shaped waveguide-to-CPW transitions lead to I/O ports, which enable flip-chip bonding.

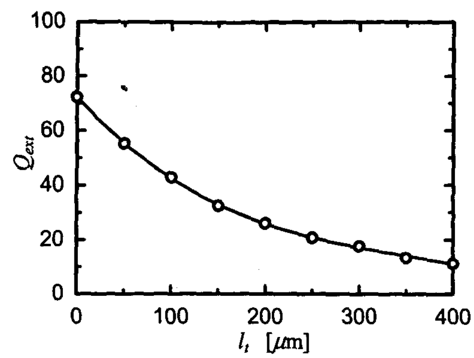


Fig. 2. Calculated external quality factor.

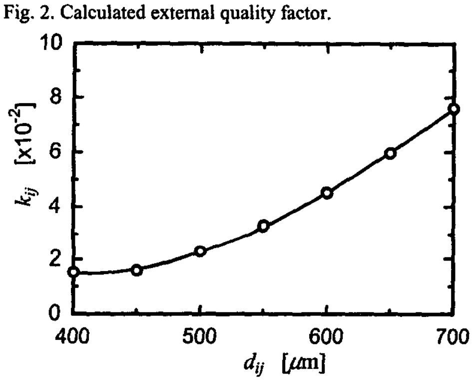


Fig. 3. Calculated coupling coefficient.

III. DESIGN OF FILTER

In this work, we developed two types of filters for different purposes in the transceiver. The first one (type 1) was a medium-bandwidth filter used for the receiver module and it suppresses a leakage signal from a transmitter module operating at different frequencies. The second one (type 2) was a narrow-bandwidth filter used for the transmitter module and it limits the bandwidth of a transmitted signal. We designed Chebyshev-type filters with specifications as shown in Table I.

Before starting the design of the whole filter, we calculated the external quality factor $Q_{ext}$ and the coupling

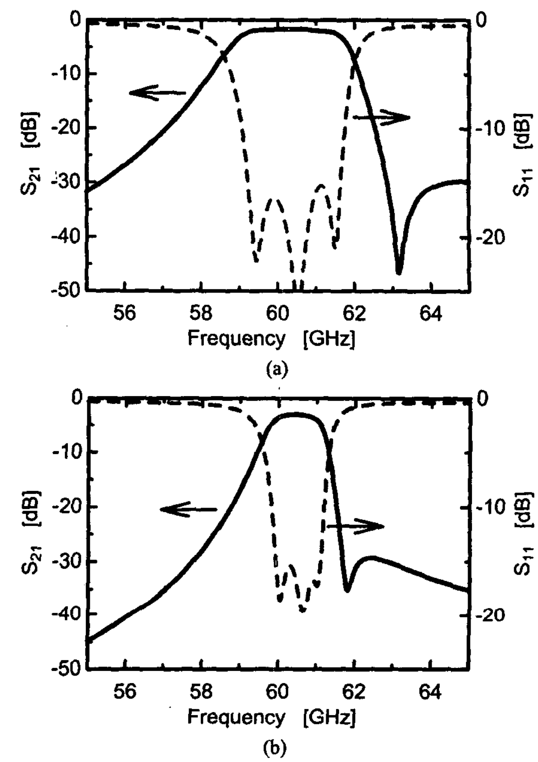


Fig. 4. Calculated filter responses for (a) type 1 and (b) type 2.

TABLE I
DESIGN SPECIFICATION OF THE FILTER

| Type | $f_0$ | Bandwidth | Ripple | Insertion Loss | Note |
|---|---|---|---|---|---|
| 1 | 60.5 GHz | 4 % | 0.1 dB | < 3.0 dB | > 20 dB-suppression @3 GHz-separation |
| 2 | 60.5 GHz | 2 % | 0.1 dB | < 3.0 dB | < 2.5 GHz @10 dB-bandwidth |

coefficient $k_{ij}$ between $i$th and $j$th resonators using a 3-D electro-magnetic simulator. The $Q_{ext}$ was determined by the length $l_t$ of the U-shaped waveguide-to-CPW transitions. In this calculation, the shape of the resonators was treated as rectangular parallelepiped for calculation simplicity. Fig. 2 shows the calculated $Q_{ext}$. The $Q_{ext}$ gradually decreases when the length $l_t$ increases. In the range of the length $l_t$ from 0 to 400 $\mu$m, a three-resonator filter with a bandwidth from 1.5 to 10 % can be realized.

The $k_{ij}$ was determined by the space $d_{ij}$ between a pair of through holes. Fig. 3 shows the calculated $k_{ij}$ for the main coupling (except cross-coupling).

Based on the conventional filter design rule [7], the $Q_{ext}$ and the $k_{ij}$ were found to be $Q_{ext}$ = 26, $k_{12} = k_{23}$ = 0.037 and $Q_{ext}$ = 52, $k_{12} = k_{23}$ = 0.018 to satisfy the required specifications for type 1 and 2, respectively. These values were obtained at $l_t$ = 200 $\mu$m, $d_{12} = d_{23}$ = 565 $\mu$m and $l_t$ = 65 $\mu$m, $d_{12} = d_{23}$ = 470 $\mu$m for type 1 and 2, respectively. Using these values initially, structural parameters were finely optimized to realize the required filter response. The coupling coefficient of the cross-coupling ($k_{13}$), which was determined by the space $d_{13}$, was tuned to obtain the required stop-band rejection. In the case of type 1, the attenuation pole was set at 63.0 GHz so that the suppression can be larger than 20 dB at the 3-GHz-separation from the center frequency. In the case of type 2, the attenuation pole was brought as close to the center frequency as possible so that the pass-band characteristic would not be degraded. These $k_{13}$ values were 0.013 and 0.0069 for type 1 and 2, respectively. The structural parameters after optimization were $l_t$ = 175 $\mu$m, $d_{12} = d_{23}$ = 620 $\mu$m and $l_t$ = 65 $\mu$m, $d_{12} = d_{23}$ = 500 $\mu$m for type 1 and 2, respectively. These values are close to the initial values and the simplification for the shape of the resonators is reasonable. Fig. 4 shows the calculated filter responses. An attenuation pole is clearly observed at a higher frequency-side of the pass band.

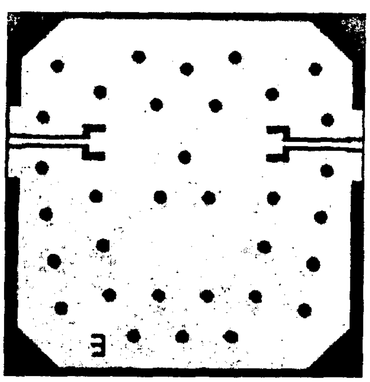

Fig. 5. Photograph of a fabricated filter.

## IV. Experimental Results

Designed two types of filters were fabricated using 0.25-mm–thick alumina substrates. Fig. 5 shows a photograph of the fabricated filter. The size of the filter is 3.4 mm × 3.5 mm. This is smaller than the previously reported filter by 25 % [5]. To avoid unwanted resonance and radiation, the metalization at corners and around I/O ports was eliminated.

Fig. 6 shows the measured filter responses for type 1 and 2. An attenuation pole was successfully introduced at the higher frequency-side of the pass-band due to cross-coupling and improved the stop-band rejection. In the case of type 1, the insertion loss was 1.1 dB at a center frequency of 58.3 GHz and suppression at a 3-GHz-higher separation from the center frequency was 33 dB. Compared to the previously reported filter with a same bandwidth [5], the insertion loss was improved by 1.7 dB due to reduction in the number of resonators and

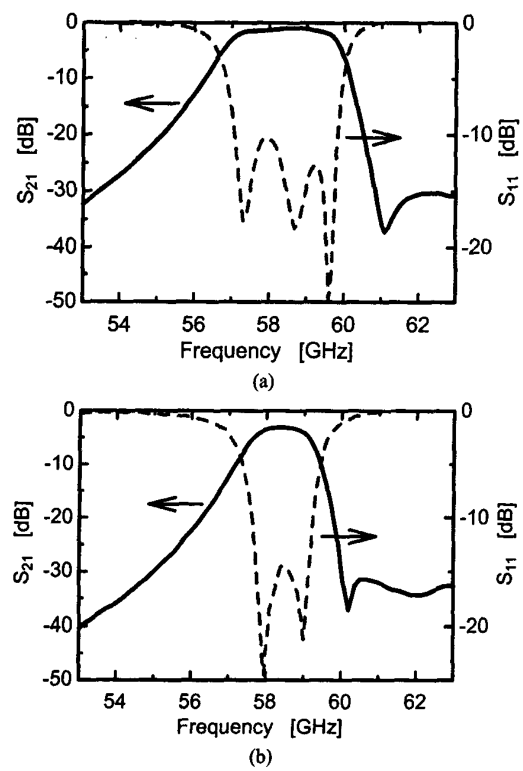


Fig. 6. Measured filter response for (a) type 1 and (b) type 2.

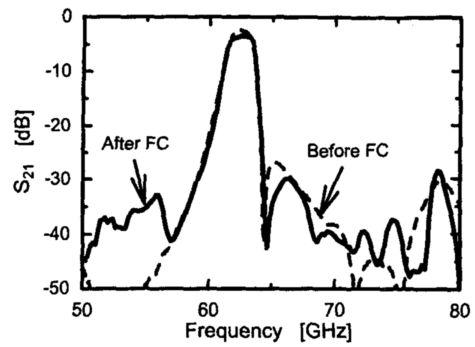


Fig. 7. Measured transmission characteristics for type 2 before and after flip-chip bonding.

elimination of CPW resonators on the dielectric resonators. In the case of type 2, the insertion loss was 3.1 dB at a center frequency of 58.4 GHz and the 10-dB-bandwidth was 2.7 GHz. The center frequencies of both filters were lower than the required ones by 2 GHz. This discrepancy may be associated with the estimation of dielectric constant of the alumina substrate. The measured frequency response indicates a dielectric constant of 10.4, which is confirmed by simulation, while we used 9.7 in the filter design. The other performances except the center frequency agreed well with designed ones.

The filter of type 2 with another center frequency of 62.5 GHz was mounted in a cavity of a ceramic package. The measured transmission characteristics before and after flip-chip bonding are shown in Fig. 7. The degradation was not observed in the pass- and stop-bands after flip-chip bonding. The stop-band suppression was better than 25 dB from 50 to 80 GHz. The insertion loss was about 4 dB in the pass-band. The increase of the insertion loss was explained by the loss of the feed-through in the package (about 1 dB $\times$ 2).

## V. Conclusion

Planar dielectric waveguide filters with cross-coupling were developed for 60-GHz-band applications. The design procedure of the filter was described. Two types of filters were fabricated using alumina substrates for the receiver and transmitter modules. The fabricated filters exhibited low insertion losses and good stop-band rejection near the pass-band due to cross-coupling. These filters will be applied to high-speed wireless communication systems.


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