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Polymer-based micromachined rectangular coaxial filters for millimeter-wave applications

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In this paper, micromachined devices for millimeter-wave applications at U- and V-bands are presented. These structures are designed using a rectangular coaxial line built of gold-coated SU-8 photoresist layers, where the coaxial center conductor is suspended in air by stubs. The designs include a stepped coplanar waveguide (CPW)-to-coaxial transition at 63 GHz, with an insertion loss of 0.39 dB at 67.75 GHz and a return loss better than −10 dB across the band of operation between 54.7 and 70.3 GHz. Two filters have been designed; one centered at 42 GHz with a 10% bandwidth, and another at 63 GHz with a 5% bandwidth. Measured insertion losses of 0.77 and 2.59 dB were obtained for these filters, respectively. Measured return loss lower than 13.8 dB over the passband was achieved for both designs. The structures presented in this paper involve a low-cost manufacturing process suitable to produce integrated subsystems at millimeter waves.

Keywords: Micromachining, Coaxial cables, Filter, SU-8, Millimeter-waves

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I. INTRODUCTION

In recent years the rapid expansion in wireless communications has led to emerging applications at millimeter-wave frequencies, such as satellite transmission at 35 GHz, short-range communications, wireless communications systems, and local area networks (WLAN's) at 60 GHz or vehicular collision avoidance radar at 77 GHz. Micromachined devices operating at millimeter-wave frequencies are aimed to be miniature components with high performance, these include EFAB™ [1, 2], PolyStrata™ [3, 4], and SU-8 technology [5, 6]. EFAB™ and PolyStrata™ technologies involve multiple thin layer depositions to achieve tall structures. EFAB™ allows the deposition of up to 40 layers with a thickness between 5 and 25 μm. PolyStrata™ technology uses a layer thickness of 20–100 μm. SU-8 technology can produce tall structures by bonding a few thick layers (100–700 μm), offering the possibility to produce high aspect ratio structures in a partially or completely shielded structure for the design of high-Q millimeter-wave devices.

Table 1 shows a comparison between several micromachined filters operating at millimeter-wave frequencies. The unloaded quality factor for each design has been calculated from simulated and measured results using equation (1). Where the g values are the lowpass element prototype values, BW is the filter bandwidth and IL is the mid-passband insertion loss. It is apparent from Table 1 that the devices presented in this paper offer a good quality factor with respect to other technologies, using a relatively compact design for its Q. Additionally, the polymer-based fabrication process used is inexpensive compared to other processes [1–4]:

$$Q_o = \frac{4.34 \sum_{i=1}^{n} g_i}{BW\, IL}. \quad (1)$$

This paper presents the design and development of U- and V-band filters, using suspended coaxial lines. The filter designs include the use of inline coaxial resonators, adequate for narrowband filters, where previous designs have been focused on a wideband response using long perpendicular stubs [6]. Also the designs presented in this paper include Q optimization of the coaxial line. The fabrication process used to implement the devices presented in this paper is discussed in [5, 6].

II. SUSPENDED COAXIAL LINE

This section describes a suspended coaxial line designed to interface the proposed filter topologies with any coplanar waveguide (CPW) circuit, and used to measure the devices with microwave probes. The suspended coaxial line was designed to operate at V-band with a center frequency of 63 GHz. The design is a CPW-to-coaxial transition in a back-to-back configuration. The structure shown in Fig. 1 begins with a CPW having a pitch of 150 μm (center conductor width is 60 μm) and ends in a rectangular coaxial line whose inner conductor has a width of 360 μm.

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Table 1. Performance summary of several micromachined millimeter-wave filters implemented by different technologies.

Primary author	Bo [7]	Sung [8]	Ferrand [9]	Reid [10]	Lee [11]	Xia [12]	Chen [13]	Chen [14]	Kenneth [15]	This paper	This paper
Year	2008	2004	2004	2004	2006	2008	2005	2004	2006		
Fabrication	SU-8	Alumina	Silicon	EFAB	LTCC	LCP	EFAB	EFAB	Poly Strata	SU-8	SU-8
Technology	Cavity	Waveguide	Cavity	Coaxial	Cavity	Microstrip	Coaxial	Coaxial	Cavity	Coaxial	Coaxial
Central frequency (GHz)	60	62	46.7	57.5	61.6	60	29.1	29	26.9	42.15	63.4
Number of resonators	2	3	2	2	1	4	3	3	1	2	2
Simulated bandwidth (%)	1.7	3.3	8	5.5	2	30	6.3	25	-	9.16	4.87
Simulated insertion loss (dB)	1.7	1.6	0.7	14.28	2.22	2.5	1.6	1.17	-	0.43	0.64
Simulated return loss (dB)	>13	>20	>21	-	<33	>16	>14	<24	-	>25	>25
Extracted quality factor from simulations	294	346.1	151.7	10.8	107.1	28.8	139	73.5	500	215.7	272.6
Measured bandwidth (%)	1.9	3.3	6	4.35	4.13	30	3.7	20.7	-	7.8	3.92
Measured insertion loss (dB)	1.92	3	2.6	18.5	2.76	5	1.7	1.74	-	0.77	2.59
Measured return loss (dB)	>15	>15	>9	-	<38	>10	<13	<24	-	18.8	13.8
Extracted quality factor from measurements	232.9	184.6	54.5	10.6	41.7	14.4	222.8	61.8	449	141.5	83.7
Dimensions without feed lines (mm)	8.74 × 4.94	6 × 3	6.3 × 5.6	6.5 × 2	2.9 × 2.94	4.2 × 1.4	5.1 × 3.3	6 × 6	9.56 × 9.56	5.9 × 2.76	4.5 × 2.76
Overall dimensions (mm)	8.74 × 4.94	6 × 3	6.3 × 5.6	7.7 × 2	2.9 × 2.94	4.2 × 1.4	5.1 × 3.3	6 × 6	9.56 × 9.56	8.3 × 2.76	6.9 × 2.76

The cross-section of a rectangular coaxial line is shown in Fig. 2. This cross section can be optimized to provide low attenuation in the cable, while propagating a transverse electromagnetic mode for the band of operation, without interference from TE or TM modes. Table 2 provides details of the different section sizes used to make the transition, where the stepped coaxial transition is added to obtain a high-quality factor for the coaxial devices presented in this paper.

The suspended CPW-to-coaxial transition is divided into three parts: the coplanar input, the coaxial output, and the stepped connection between them. The interface is obtained by coaxial sections that increase their center conductor width by means of 50 Ω sections, used to match the coplanar line with the coaxial center conductor used for device design. The interconnections among coaxial sections have been optimized by simulations using HFSS to minimize reflection losses, all simulations were done using an ideal conductivity value of 4.1×10^7 S/m.

The suspended coaxial line used for the devices presented is formed by five layers (see Fig. 2). Layer 3 contains the CPW signal line and coaxial center conductor, layers 2 and 4 create the coaxial cavity and layers 1 and 5 shield the structure. All layers are 200 μm thick. The proposed transition is formed by sections of suspended coaxial cable; the center conductor is supported by quarter wavelength stubs at 63 GHz. The stubs provide a robust structure suspended in air. Figure 3 shows a 3D view of the suspended coaxial line with CPW interface in a *back-to-back* configuration. An appropriate location of the stubs allows a wide bandwidth response. Simulated and measured responses of the suspended coaxial transmission line with coplanar interface are shown in Fig. 4. Measurements display a minimum insertion loss of 0.39 dB at 67.75 GHz and a return loss better than −10 dB for the band from 54.7 to 70.3 GHz.

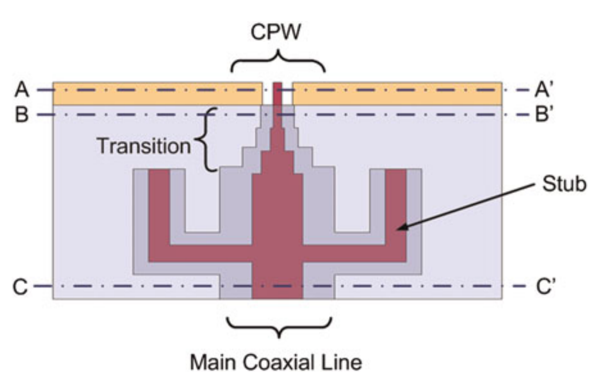

Fig. 1. Top view of the CPW-to-coaxial transition.

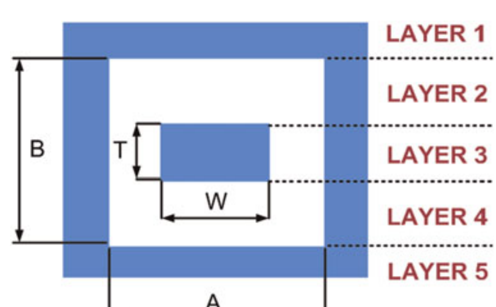

Fig. 2. Cross section of a rectangular coaxial line.

Table 2. CPW and rectangular coaxial section comparison.

Dimensions (μm)	Section A-A′ CPW $A = 218$ $W = 60$ $T = 200$	Section B-B′ coaxial $A = 236$ $B = 600$ $W = 60$ $T = 200$	Section C-C′ coaxial $A = 820$ $B = 600$ $W = 360$ $T = 200$
Quality factor of an ideal resonator (Q_o)	94.4	210.2	487.6
Propagation of higher order modes (GHz)	_	225	156.9
Attenuation constant (dB/cm)	0.2510	0.2405	0.1120

III. NARROWBAND RECTANGULAR COAXIAL FILTERS

This section presents two filters using inline resonators and the suspended CPW-to-coaxial transition discussed in the previous section. The designs have a center frequency of 42 and 63 GHz.

A) U-band filter

In this section a micromachined coaxial filter with a center frequency of 42 GHz, formed by two quarter wavelength resonators joined by a short circuit, is presented. The device is shown in Fig. 5. The input and output coupling to the resonators is achieved using the suspended CPW-to-coaxial transition described in Section II with a center frequency of 42 GHz.

The design procedure for this filter follows the methodology provided in [16], and begins with a lowpass prototype filter with g element values obtained from filter design specifications, and then a bandpass transformation is applied to obtain theoretical values for the external quality factor (Q_e) and the coupling between resonators (K_{ij}). For this design,

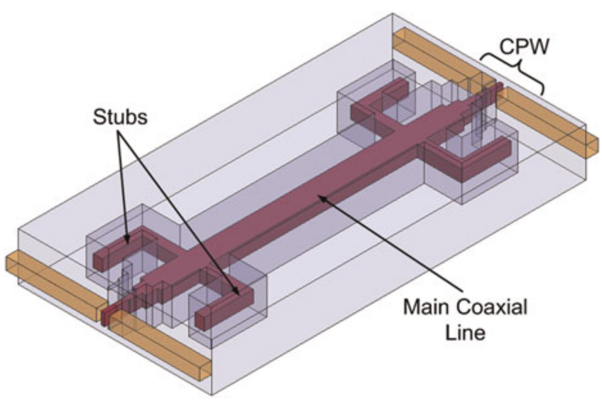

Fig. 3. 3D view of the CPW-to-coaxial line transition in a *back-to-back* configuration.

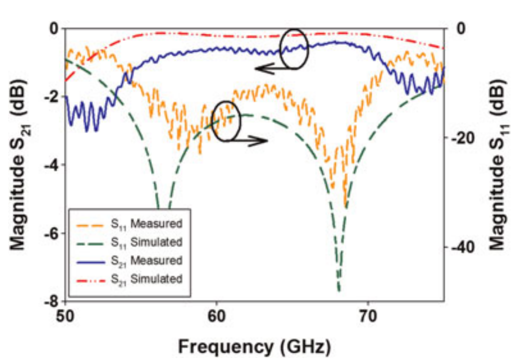

Fig. 4. Simulated and measured response of the suspended coaxial line.

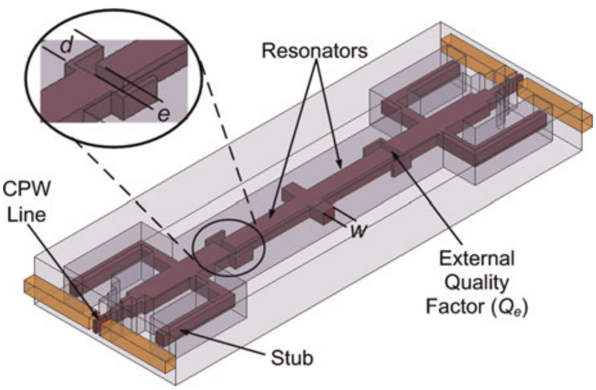

Fig. 5. 3D view of the U-band coaxial filter.

the lowpass prototype g values are $g_1 = 0.4489$, $g_2 = 0.4078$, $g_3 = 1.1008$, the coupling between resonators is $Kc_{12} = 0.2337$ and the external quality factor is $Q_e = 4.489$ for the 10% fractional bandwidth filter centered at 42 GHz discussed in this section. Once the theoretical values are known, the external quality factor and the couplings between resonators are extracted through full-wave simulations and matched to the theoretical values obtained from the lowpass prototype [16]. The external quality factor was obtained by using the 3D *fork* structure shown in the inset of Fig. 5, where the distance d is used to adjust the external quality factor to match the theoretical values required for the design, while keeping dimension e fixed. The coupling between resonators is extracted by varying the width of the short circuit w (see Fig. 5). The two resonators are coupled together by an inductive immittance inverter formed at the short circuit that suspends both resonators. Figure 6 shows the external quality factor values and couplings between resonators obtained by simulations.

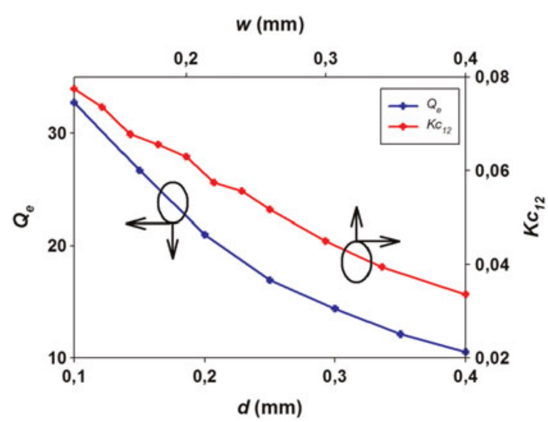

Fig. 6. External quality factor (Q_e) and coupling coefficient (Kc_{12}) for the U-band coaxial filter.

The device discussed in this section, and shown in Fig. 5, was designed to have a center frequency of 42 GHz, a 0.01 dB bandpass ripple, and a 10% fractional bandwidth with a Chebyshev response. This topology was implemented into a coaxial line built by five gold-coated SU-8 layers, where layer 3 contains the coaxial center conductor. The overall dimensions of this filter are 8.34 × 2.76 × 1 mm. Simulated and measured results are shown in Fig. 7. Measurements were performed after a Short-Open-Load-Thru calibration using cascade 101–190 standards. A good agreement between theory and experiment was obtained. The measured bandwidth is 7.8%, insertion loss is 0.77 dB, and return loss is 18.8 dB at 42.15 GHz.

B) V-band filter

In this section, a V-band filter with a 63 GHz center frequency is presented. The topology is similar to the filter in the previous section with the difference that the *fork* structure is not necessary to achieve the required external quality factor for this design. The lowpass element g values used for this design are $g_1 = 0.4489$, $g_2 = 0.4078$, $g_3 = 1.1008$, the coupling between resonators is $Kc_{12} = 0.1168$, and the external quality factor is $Q_e = 8.978$, based on the following design specifications: center frequency of 63 GHz, 0.01 dB bandpass ripple, and a 5% fractional bandwidth with a Chebyshev response. The external quality factor for different gaps e (see Fig. 5), where dimension $d = 0$, and the coupling coefficient between resonators for different short circuit widths w are shown in Fig. 8.

The filter is made of five SU-8 layers. The overall dimensions of the filter are 6.96 × 2.76 × 1 mm. In Fig. 9 simulated and measured results are shown, variations between the responses can be attributed to the misalignment of the stacked layers. Measured bandwidth is 3.92%, insertion loss is 2.59 dB, and return loss is 13.8 dB at a center frequency of 63.4 GHz.

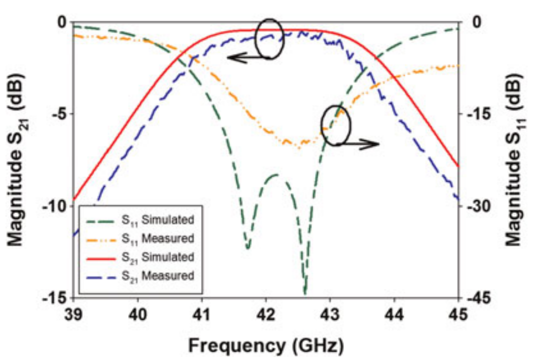

Fig. 7. Simulated and measured response of the U-band coaxial filter.

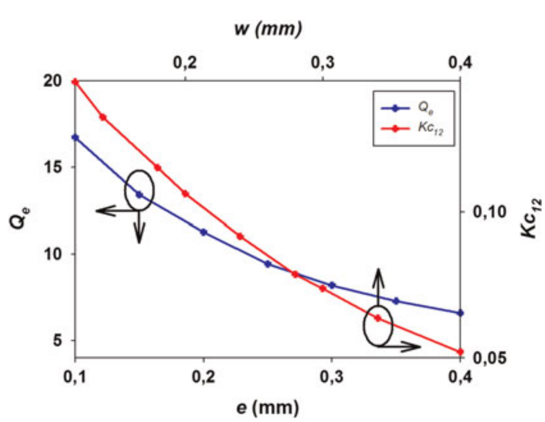

Fig. 8. External quality factor (Q_e) and coupling coefficient (Kc_{12}) for the V-band coaxial filter.

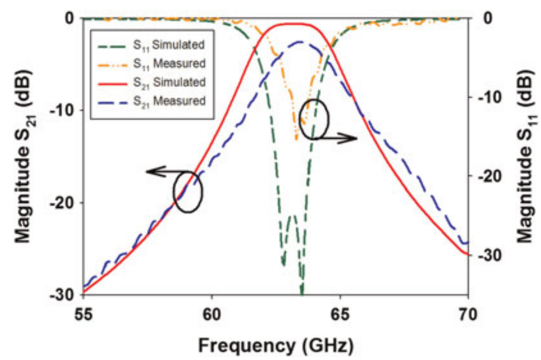

Fig. 9. Simulated and measured response for the V-band coaxial filter.

IV. CONCLUSION

This paper presented several micromachined coaxial components produced by the superposition of SU-8 layers. This technique offers a low manufacturing cost and enables the implementation miniature coaxial components. The devices obtained can be considered a good alternative to produce compact and integrated subsystems with high-quality factors.

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