Micromachined Polymer Based Components for Highly Integrated Millimeterwave Subsystems

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Tesis doctoral
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Febrero de 2012

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Apendix A
Coaxial Narrowband Filters Using a Versatile Suspended Resonator

Contenido

A. Jaimes-Vera, I. Llamas-Garro, A. Corona-Chavez, “Coaxial Narrowband Filters Using a Versatile Suspended Resonator”, Progress In Electromagnetics Research, PIER, Vol. 115, March 2011, pp. 79-94.

Abstract - *In this paper two four-pole filters at X-band are presented, both designs use a coaxial quarter wavelength resonator suspended in air by short circuits between the coaxial center and outer conductor. Different couplings between suspended resonators have been used to obtain a Chebyshev and a quasi-elliptic response. The Chebyshev filter was designed to have a 9.2 GHz centre frequency with a 4 % fractional bandwidth. The second design is a quasi-elliptic filter composed of two vertically stacked rectangular coaxial lines, where one pair of resonators is placed on the lower coaxial line and another pair is located on the upper line. Coupling between coaxial lines is achieved through an iris in the common coaxial ground plane. The quasi-elliptic filter has been designed to have a centre frequency of 9.1 GHz with a 4 % fractional bandwidth. Two transmission zeros located at the sides of the passband have been successfully achieved with the proposed filter topology. Experimental results for both designs are presented, where a good agreement with simulations has been obtained.*

A.1. Introduction

Combline and interdigital filters have been widely used in many applications, such as cellular communications base-stations. Present filter generations for mobile communications require high performance filters, with high selectivity and good out of band rejection, including device miniaturization. The performance of conventional filters can be improved by introducing transmission zeros at the sides of the bandpass response to achieve sharp selectivity with good out of band rejection [1–5].

Commonly coaxial-combline cavity filters with transmission zeros have been designed by means of coupling probes embedded in the filter fixture [6], also the use of extra cavities or small metal plates among the resonators [7, 8] have been used. The designs presented in this paper use a suspended resonator into a multilayer structure; allowing different coupling arrangements to produce electric, magnetic and mixed couplings, enabling quasi-elliptic function approximation or flat group delay responses, without using extra coupling probes, extra cavities or folded structures. The multilayer structure can provide a wide range of couplings, an easy introduction of cross couplings and size reduction [9–12]. The proposed resonator is a quarter wavelength long suspended by stubs, suitable for the design of narrowband filters using coaxial lines. A wideband coaxial filter can be found in [13]. This paper provides the design and implementation of a Chebyshev filter, a description of the feed line used to interconnect the devices with the measurement equipment, and a detailed design and characterization of a quasi-elliptic filter.

This paper presents the design and development of Chebyshev and quasi-elliptic filters at around 9 GHz, where only few works can be found [10, 14–16], since most of combline and interdigital filters are designed between 1 and 2 GHz for mobile communications. Table 1 shows a list of coaxial/combline/interdigital filters operating between 1 and 9 GHz including their most outstanding features. A comparison among combline or interdigital filters and the work presented in this paper has been done. The unloaded quality factor [17] for each design has been calculated from measured results using eq. B.1. Where the $g's$ are the lowpass element values, BW is the filter 3 dB bandwidth and IL is the mid passband insertion loss.

$$Q_o = \frac{4{,}34 \sum_{i=1}^{n} g_i}{BW \cdot IL} \tag{A.1}$$

It is apparent from table A.1 that the devices presented in this paper have a quality factor between the high Q obtained through optimized conventional coaxial-combline designs and interdigital or microstrip-combline filters. The filters presented in this paper are made from planar metal layers; this implementation allows scaling the designs to millimeter wave frequencies, using micromachined structures [18].

The structures here presented were implemented into air-filled coaxial lines using stacked planar layers, avoiding radiation and dielectric losses and crosstalk between adjacent lines. The use of a multilayer structure allowed size reduction and a wide range of possible couplings between versatile resonators. The introduction of cross couplings has been achieved without the use of additional cavities or coupling probes. These filters show a competitive response and a good balance among losses, size and quality factor; furthermore filter implementation using stacked planar layers allows scaling the devices to the millimeter wave region using micromachining techniques.

A.2. Suspended Coaxial Resonator and Feed Line

The quarter wavelength resonator suspended by short circuits inside an air filled rectangular coaxial cable used to design the filers presented in this paper is shown in fig. A.1(a). The resonator has the maximum magnetic field density next to the short circuited stubs, and the maximum electric field at the opposite side, as shown in fig. A.1(b) where surface current distribution at the resonant

Tabla A.1: Performance summary of coaxial, combline and interdigital filters operting in a frequency range from 1 to 9 GHz)

Primary Author	Chuma [19]	Zheyu [20]	Yi-Ming [21]	Yani [9]	Shih-Cheng [22]	Ying [8]	Huan [23]	Hoi-Kai [24]	Ting [25]	Tao [26]	Chi-Yang [27]	This paper	This paper
Year	2000	2008	2006	2005	2007	2009	2009	2004	2004	2007	2001		
Technology	Cx	Cb	Cb	In	Cb	Cx	Cx	In	In	Cb	In	Cx	Cx
Filter Function	E	C	E	E	E	E	E	B	B	C	C	C	E
Number of resonators	4	5	4	4	2	6	3	3	3	5	3	4	4
Central Frequency (GHz)	1.747	2.0175	2.4	2.25	1.43	1.54	1.73	0.7	0.9	9.6	9.5	9.2	9.1
Fractional Bandwidth (%)	4.3	0.75	4.2	31	11.5	3.2	4.5	12	15	8	10	5.7	2.88
Insertion Loss (dB)	0.46	1.49	1.2	1.0	2.78	-	0.77	1.3	1.5	1.93	2.5	1.07	1.7
Q_o from Eq.(1)	897	2602	352	57	-	-	343	139	96	188	56	355	166
Midband return loss (dB)	>15	>20	>25	>15	>18	>20	>17	>10	>9	>20	>12	>17	>20
Area (cm^2)			2.36	1.3	5.32			19.25	21	-	0.16		
Volume (cm^3)	57.5	30.34				284.47	90			-		23.14	29.03

Cx-Coaxial Filter Cb-Combline Filter In-Interdigital Filter
E-Elliptic Function C-Chebyshev Function B-Butterworth Function

frequency of 9.1 GHz is plotted. Therefore electric, magnetic and mixed couplings can be obtained by choosing adequate resonator configurations [28]. The different inter-resonator arrangements and coupling types that can be achieved with the proposed resonator are shown in fig. A.2. By placing

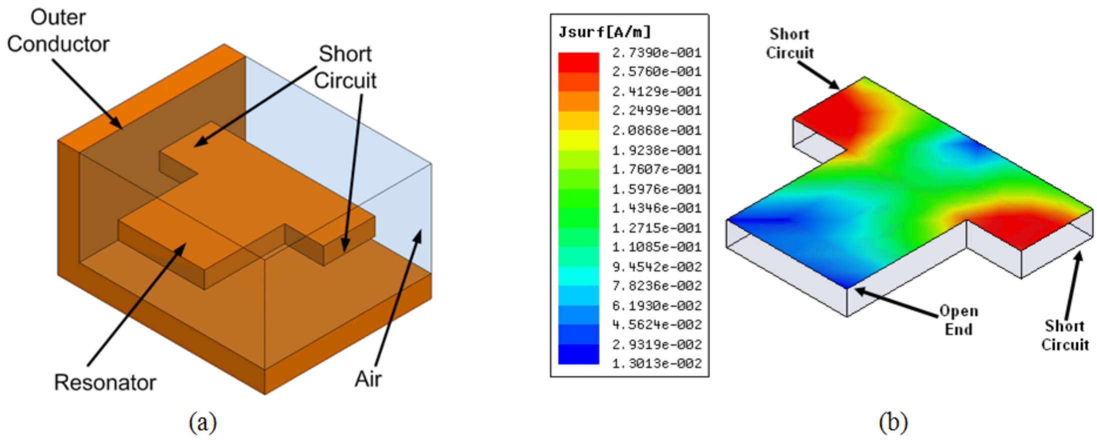


Figura A.1: *Supended quarter wavelnegth resonator (a)Schematic of the quarter wavelength resonator (side and top walls removed for clarity) (b)Surface current distribution at a resonant frequency of 9.1 GHz*

the two short circuited sides of the resonator facing each other, as shown in fig. A.2(a), a magnetic coupling can be obtained. Electric coupling can be attained by placing side by side the open end of the resonators as shown in fig. A.2(b). It is apparent from fig. A.2 that the response of the electric and magnetic coupling arrangements are out of phase; these couplings have been used to produce the quasi-elliptic filter discussed in section 4. Mixed couplings have been obtained by placing resonators on different coaxial layers, coupled by an iris on the common coaxial ground plane between them as shown in fig. A.2(c).

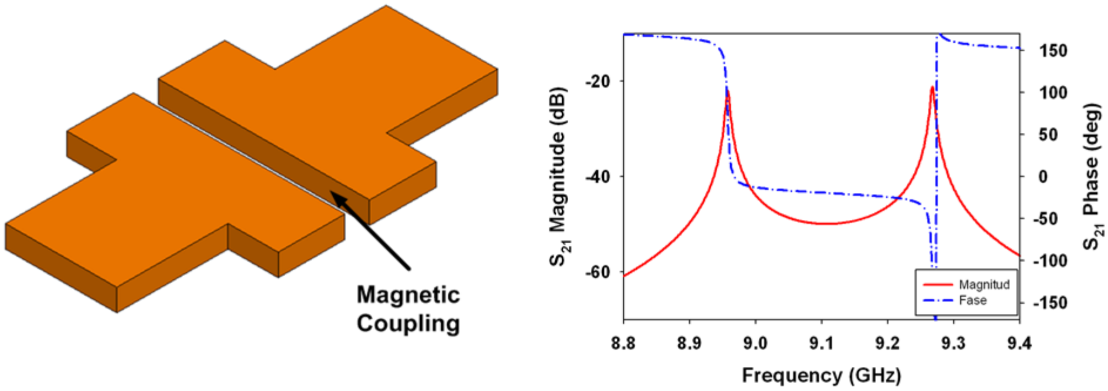
A suspended transmission line is used to interface the rectangular coaxial filters for measurements. Fig. A.3(a) shows a photograph of the 50 Ω suspended feed line used to input/output energy to the filter in a *back-to-back* configuration. This transmission line has been optimized by simulations to minimize reflection losses at the transitions with round connectors. A slot on both sides of the feed line is used to mount SMA connectors (see fig. A.3(b)). This transmission line is formed by the union of five copper layers, the overall dimensions of the transmission line are 26 x 29.8 x 12 mm^3, and the technical drawing of layer 3 is presented in fig. A.3(b). The final feed line is a piece of coaxial transmission line all surrounded by air, and suspended by quarter wavelength transmission line stubs at the center frequency of the filters; resulting in an open circuit were the stub makes contact with the coaxial center conductor.

Simulated and measured results of the suspended transmission line in a *back-to-back* configuration are presented in fig. A.4. All simulations were done using HFSS considering a copper conductivity value of 5.8 x 107 S/m. The differences between the simulated and measured response is caused by fabrication tolerances related to the designs presented in this paper, which are discussed in detail in section 5.

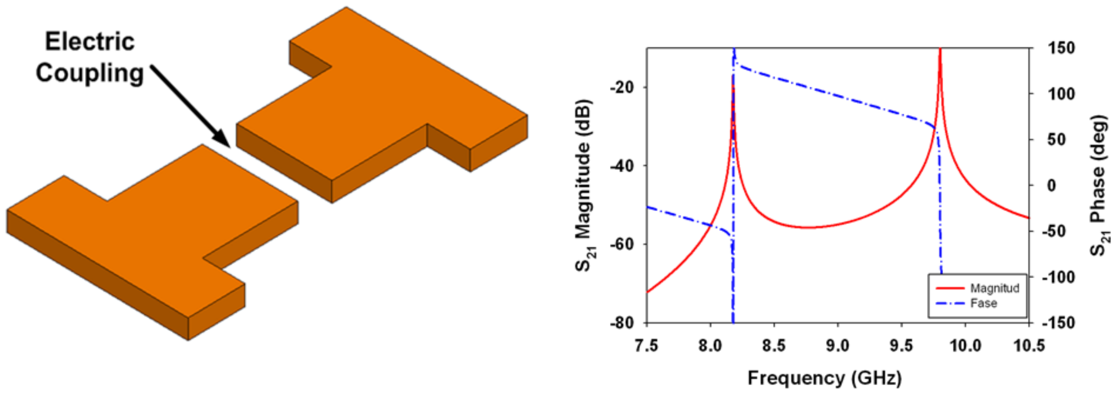
A.3. Narrowband Chebyshev Coaxial Filter

In this section a narrowband coaxial filter with a Chebyshev response is presented. The filter was designed using rectangular coaxial transmission lines, where the resonators are suspended along with the feed lines that provide the input/output to the device, as shown in fig. A.5. The entire topology is formed by five conductive layers stacked and compressed together to obtain the coaxial filter.

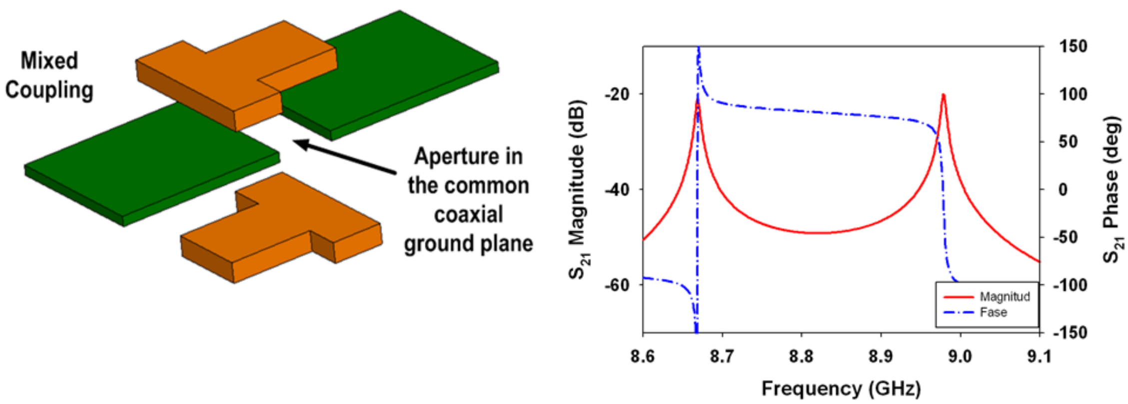
The design procedure for this filter follows the methodology provided in [17], which consists in calculating the coupling coefficients between resonators (K_{ij}) and the external quality factor (Q_e), achieved by full wave simulations using HFSS. The equations to obtain the theoretical couplings between resonators and the external quality factor can also be found in [17]. The design data and pa-



(a)

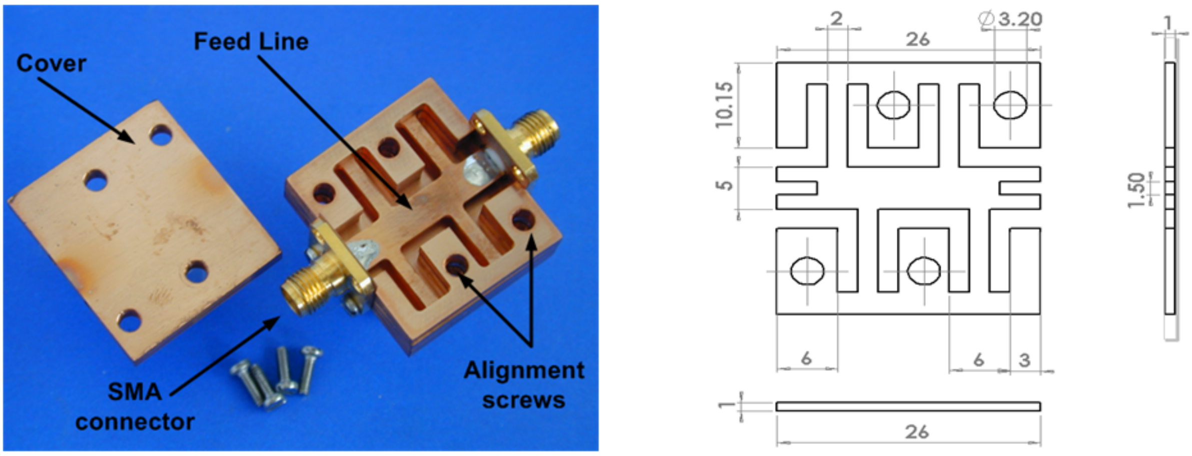


(b)



(c)

Figura A.2: *Inter-resonator couplings, (a)Magnetic coupling (b)Electric coupling (c)Mixed coupling*



(a) (b)

Figura A.3: *Coaxial feed line in a back-to-back configuration (a)Photograph of the coaxial feed line (b)Technical drawing of the coaxial feed line, layer 3 (dimensions in millimeters)*

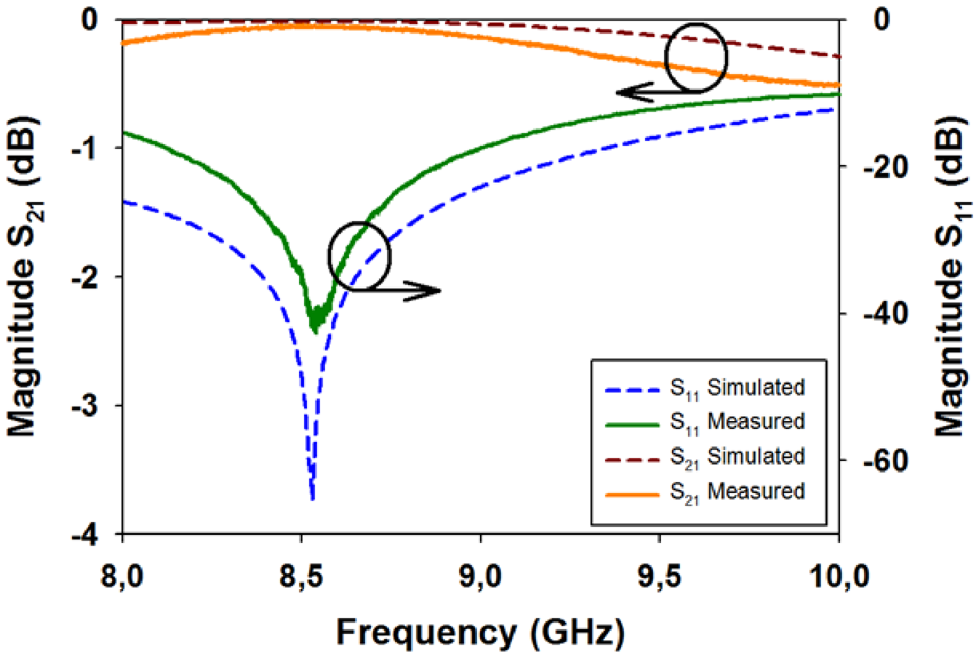


Figura A.4: *Simulated and measured response of the coaxial feed line in a back-to-back configuration*

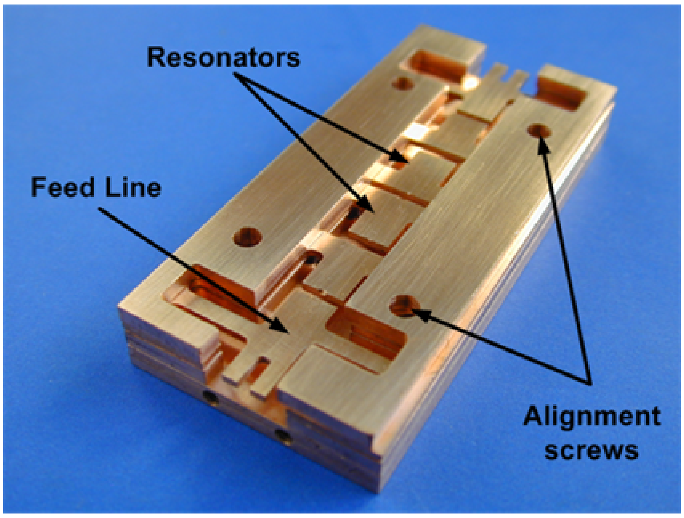


Figura A.5: *Photograph of the coaxial Chebyshev filter*

Tabla A.2: Chebyshev filter design parameters

Number of resonators 4					
Filter lowpass element g **values**					
g_0=1	g_1=0.7129	g_2=1.2004	g_3=1.3213	g_4=0.6476	g_5=1.1008
Q_e **and** K_{ij}					
	Q_{e_1}=17.82	Q_{e_2}=17.82	K_{12}=0.043	K_{23}=0.031	

rameters used for this filter are summarized in table A.2, which contains the lowpass element g values, the required K_{ij} and Q_e for the design. The external quality factor (Q_e) obtained by electromagnetic simulations is shown in fig. A.6, similarly inter-resonator couplings ($K - ij$) are shown in fig. A.7. The filter was designed at 9.2 GHz with a 0.01 dB passband ripple and a 4 % fractional bandwidth. A lumped element equivalent circuit for the Chebyshev filter is presented in fig. A.8.

The filter is formed by five layers, which are stacked and compressed together. Layer 3 is the main layer, which contains the four resonators and the feed lines, layers 2 and 4 create a coaxial cavity, and finally layers 1 and 5 shield the complete structure. The overall dimensions of the filter are 29.8 x 64.7 x 12 mm^3. Layers 1 and 5 are 3.25 mm thick, layers 2 and 4 are 2.25 mm thick, and layer 3 is 1 mm thick. Fig. A.9 presents the technical drawing of layer 3. In fig. A.10 simulated and measured results of the filter are presented. A good agreement between theory and experiment has been obtained. A slight bandwidth reduction and insertion loss increase can been observed in measurements, caused by fabrication tolerances, layer misalignment and the effect of using nine brass tuning screws to obtain the measured response. The use of tuning screws allowed adjusting couplings (Q_e and K_{ij}) during measurements, which resulted in an improved S11 response with respect to simulations.

A.4. Narrowband Quasi-elliptic Coaxial Filter Using Vertically Stacked Coaxial Lines

A quasi-elliptic function filter is designed using two vertically stacked coaxial cables. Two resonators are placed on the upper coaxial line, and two others on the lower line along with the feed lines that provide the input/output to the device. The entire topology is formed by nine conductive layers stacked and compressed together to obtain the two coaxial transmission lines. An iris in the common coaxial ground plane allows the cross coupling arrangement between resonators. In fig. A.11 a sche-

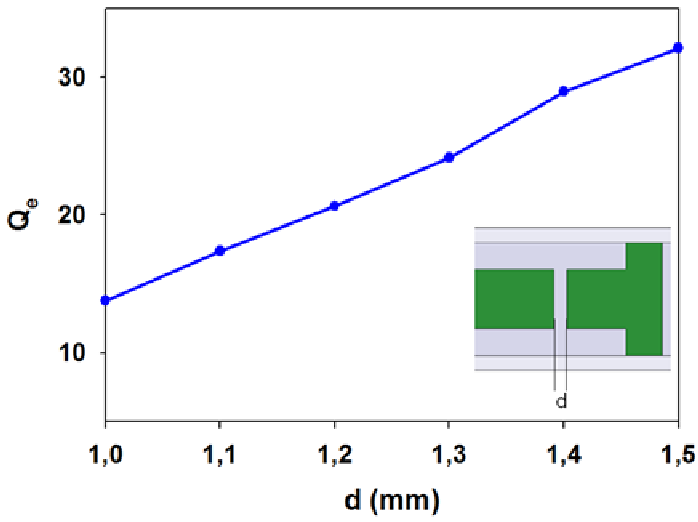


Figura A.6: *External quality factor Q_e for the coaxial filters*

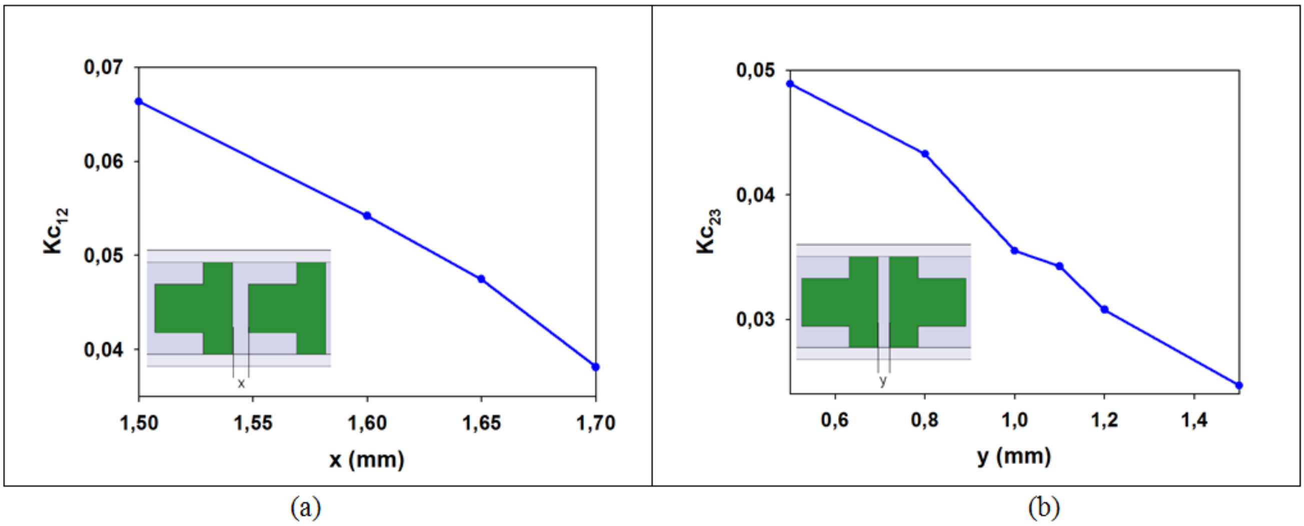


Figura A.7: *Coupling coefficients for the Chebyshev filter (a)Coupling coefficient between resonators 1 and 2 (b)Coupling coefficient between resonators 2 and 3*

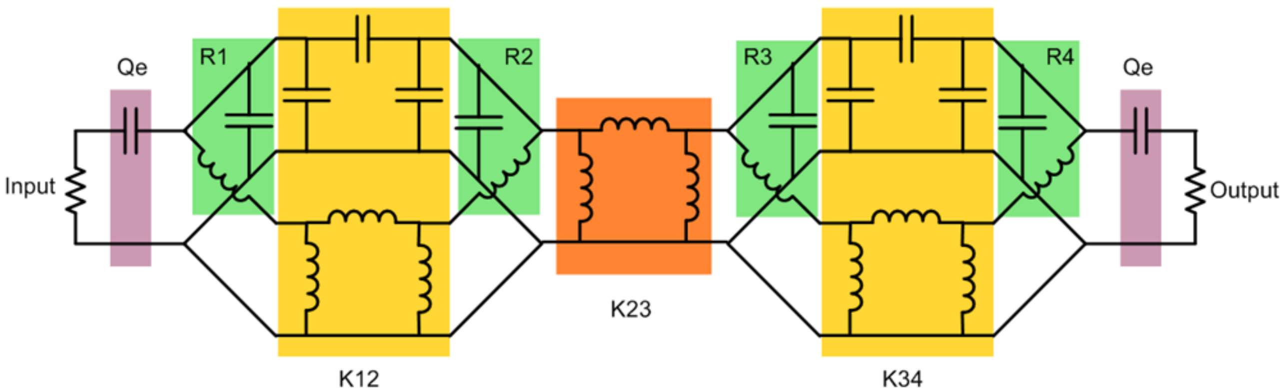


Figura A.8: *Equivalent circuit for the Chebyshev filter*

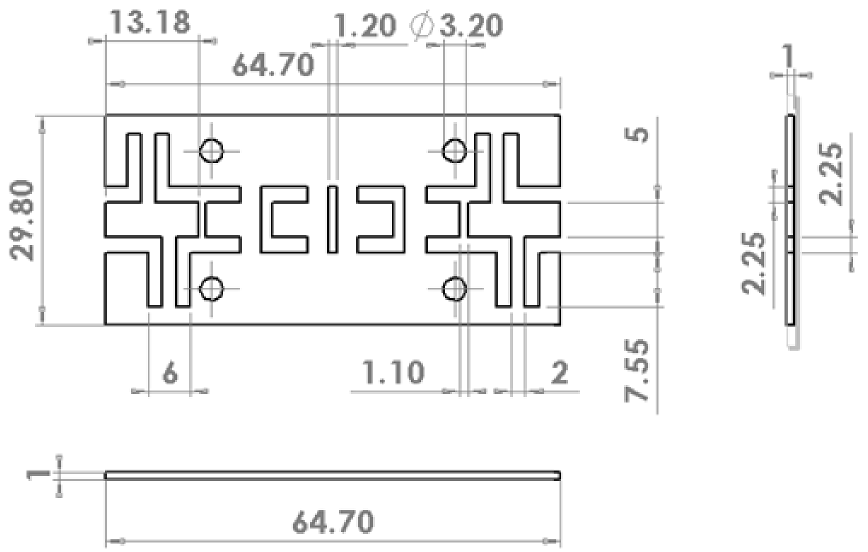


Figura A.9: *Technical drawing for layer 3 of the coaxial Chebyshev filter (dimensions in millimeters)*

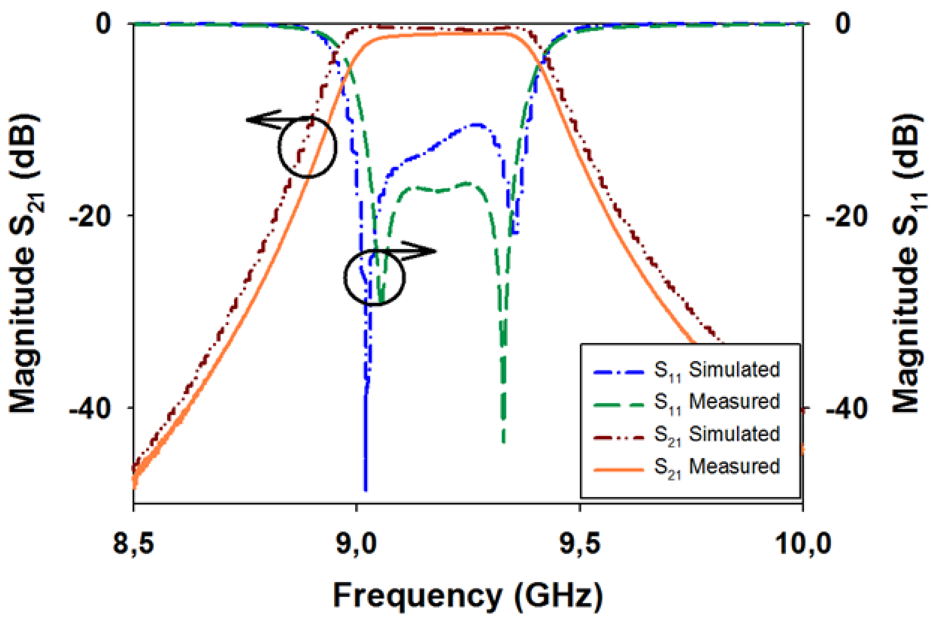


Figura A.10: *Chebyshev filter simulated and measured results*

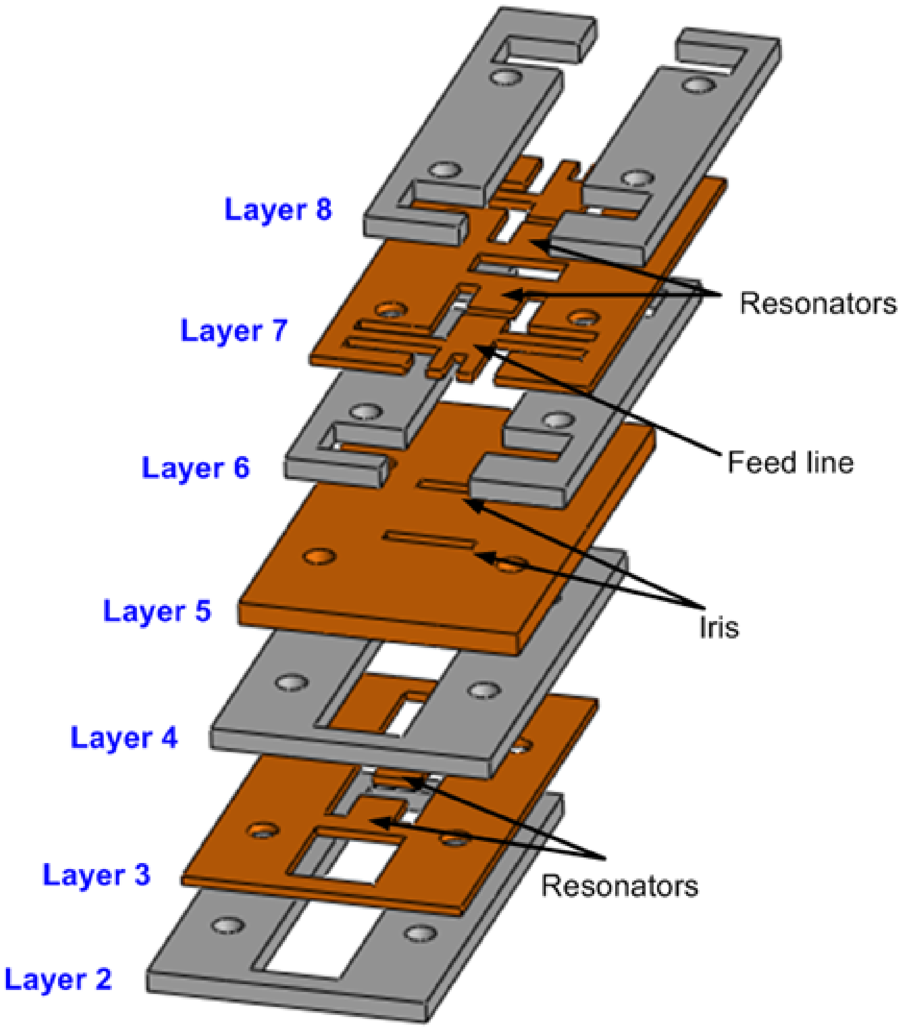


Figura A.11: *Exploted view of the quasi-elliptic filter (layers 1 and 9 omitted for clarity)*

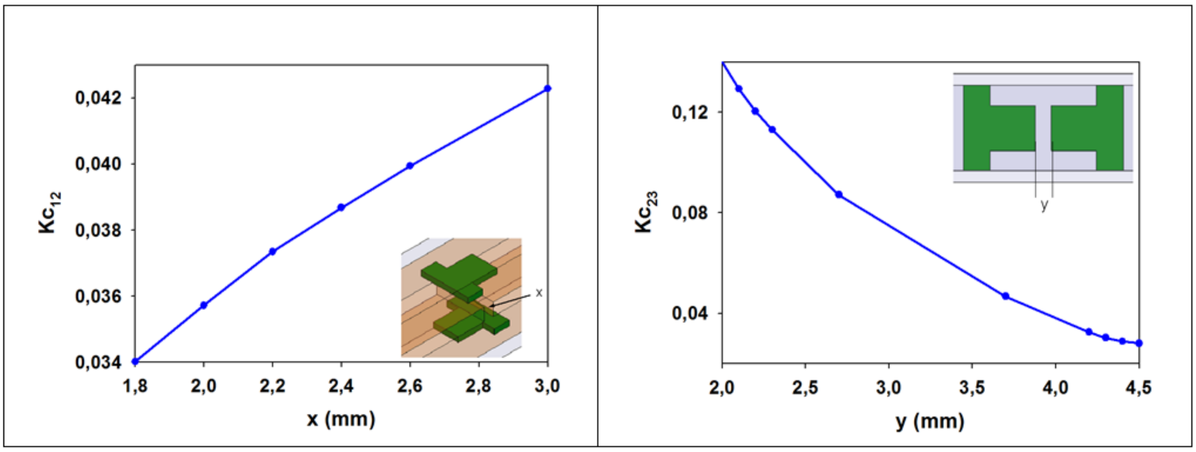
matic view of the layers that form the topology is presented (layers 1 and 9 have been omitted for clarity). The center conductors of the coaxial lines (layers 3 and 7) are shielded by layers 1, 2, 4 and 6, 8, 9 respectively. Layer 5 is the common coaxial ground containing two irises to couple between the adjacent coaxial lines.

The design procedure for this filter follows the same methodology described in previous section. The design data and parameters used for this filter are summarized in table A.3, which contains the lowpass quasi-elliptic element g values, the required K_{ij} and Q_e for the design, where Ω_d relates to the position of the transmission zeros in a quasi-elliptic topology. K_{14} has a negative sign since this coupling is out of phase with respect to K_{23}. The external quality factor obtained by simulations for this design is shown in fig. A.6. In fig. A.12(a) and (b), inter-resonator couplings between resonators 1-2 and 2-3 are shown, respectively. The coupling between resonator 1 and 4 is shown in fig. A.7(b). The filter was designed at 9.1 GHz with a 0.01 dB passband ripple and a 4 % fractional bandwidth.

After obtaining the optimum spacing between resonators and feed lines, the filter can be realized. Fig. A.13 shows a lumped element equivalent circuit for the quasi-elliptic filter. Fig. A.14(a) shows two photographs of this filter, referring to fig. A.11, showing an open view of the two coaxial lines that compose this filter. Fig. A.14(b) contains the technical drawings of the two center conductors for the coaxial lines (layers 3 and 7) and their corresponding dimensions. Overall dimensions of the filter

Tabla A.3: Quasi-elliptic filter design parameters

Number of resonators 4					
Lowpass filter element g values for Ω_d = 2.00					
g_0=1	g_1=0.95449	g_2=0.38235	g_3=1	J_1=-0.16271	g_5=1.06062
Q_e **and** K_{ij}					
	Q_e=23.862	K_{12}=K_{34}=0.0348	K_{23}=0.0307	$K_{14} = -6{,}8x10^{-3}$	



(a) (b)

Figura A.12: *Coupling coefficients for the quasi-elliptic filter (a)Coupling coefficient between resonators 1 and 2 (b)Coupling coefficient between resonators 2 and 3*

are 29.8 x 48.7 x 20 mm^3. Layers 1 and 9 are 3.25 mm thick, layers 2, 4, 6 and 8 are 2.25 mm thick, layers 3 and 7 are 1 mm thick, and layer 5 is 2.5 mm thick.

Simulation and measurements of the filter are shown in fig. A.15, 8 simulations were done displacing the layers that compose the filter randomly, using values ranging between 100 and 300 μm (this misalignment range was extracted from the fabricated filter using an optical microscope). One of these simulations was arbitrarily selected to be included in fig. A.15. The effect of fabrication tolerances is discussed in detail in section 5. A good agreement between simulated and measured results was obtained. The increase in losses is attributed to the use of eight brass tuning screws and a reduction in bandwidth which is associated with higher insertion losses in general filter implementation. The measured bandwidth decreased from 4 % considered for the design to 2.88 % experimentally, the simulation with misaligned layers showed a bandwidth of 3.44 %. The transmission zero on each side of the passband was successfully achieved using the proposed vertically integrated coaxial filter topology.

A.5. Tolerance Study

This section presents an analysis of the fabrication tolerances associated with the devices presented in this paper. Fabrication tolerances include: layer misalignment, rounded corners and fabrication inaccuracies. Rounded corners arise from using a 2 millimeter diameter tool to manufacture the devices, layer misalignment is related to unwanted displacements between the layers that form the devices, and finally fabrication inaccuracies relate to deviations in the dimensions of each fabricated layer with respect to device blueprints.

A fabrication tolerance study has been carried out on the quasi-elliptic filter, to understand the inherent fabrication inaccuracies related with the devices presented in this paper. These tolerances have

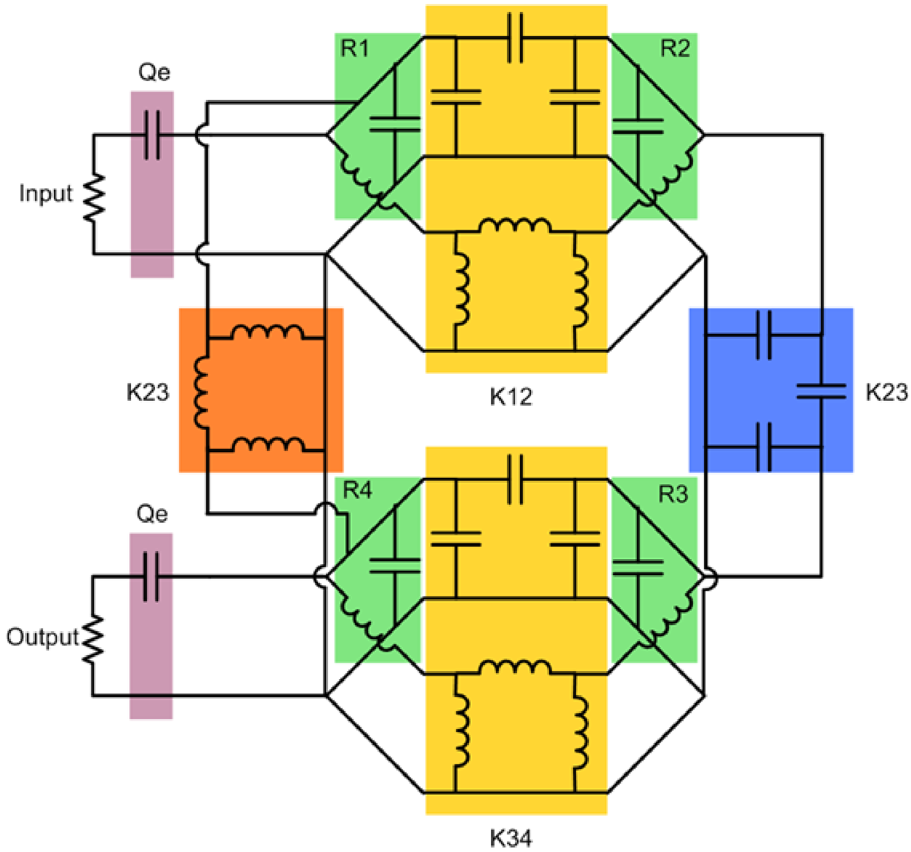
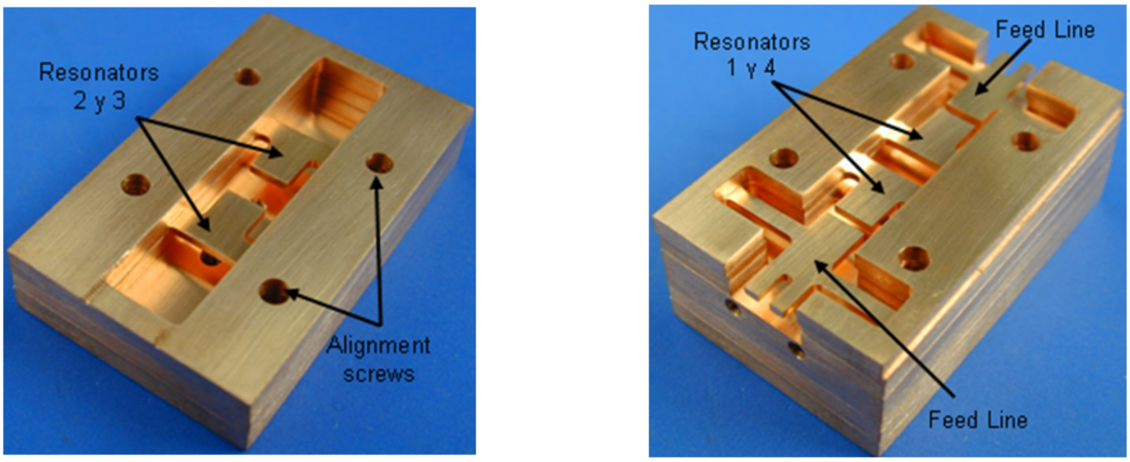
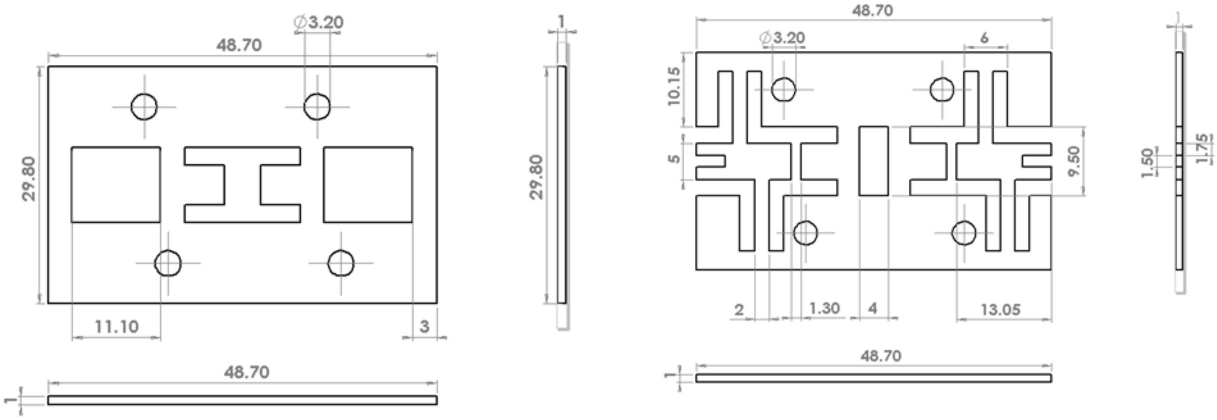


Figura A.13: *Equivalent circuit for the quasi-elliptic filter*



(a)



(b)

Figura A.14: *Quasi elliptic filter (a)Open view photographs of the quasi-elliptic filter (b)Technical drawings of layers 3 and 7 of the quasi-elliptic filter (dimensions in millimeters)*

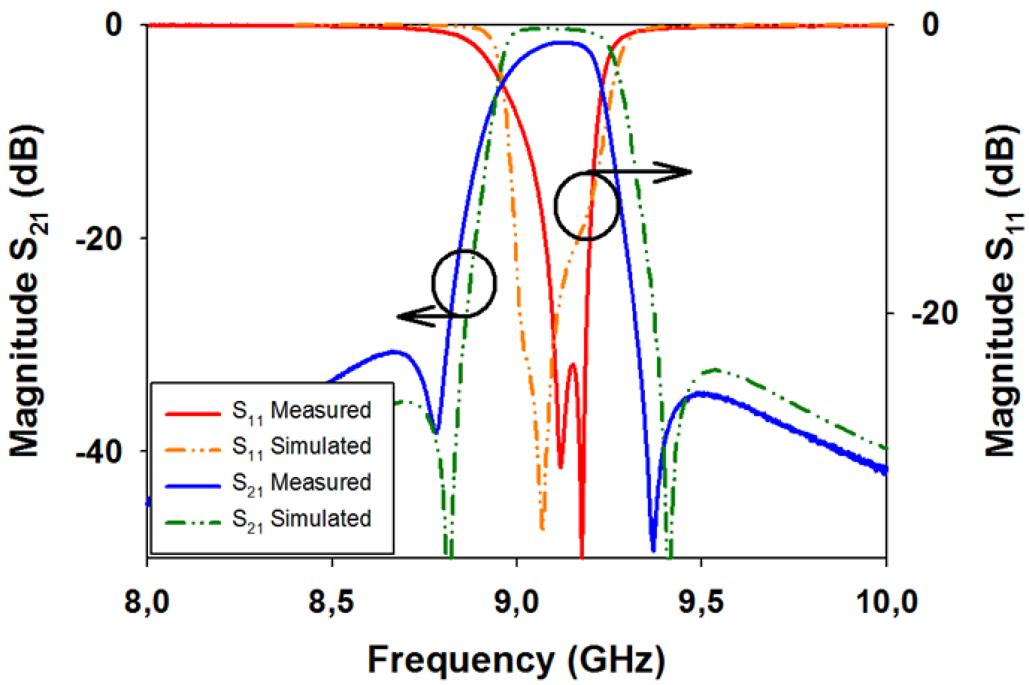


Figura A.15: *Simulated and measured results for the quasi-elliptic filter implemented on stacked coaxial lines*

been characterized and studied. Firstly each piece of the device has been measured using an optical microscope and compared with the blueprints provided for their fabrication. A fabrication deviation inaccuracy between 40 and 100 μm has been observed on the pieces. Using the optical microscope, the misalignment tolerances between layers have been extracted, and found to be in between 100 and 300 μm among layers. Misalignment tolerances have been simulated using HFSS to understand the diverse effects that these produce on the frequency response of the device (note that piece inaccuracy contributes to this overall misalignment among layers). Layer misalignment produces overlaps between layers that result in a reduction of coupling coefficients, producing bandwidth reductions between 7 and 23.8 %. These overlaps also slightly change resonator dimensions, which causes slight frequency shifts on the filter response.

The effect of rounded corners present on the manufactured device has been studied. Through simulations, rounded corners on the resonators produce a 13.5 % reduction in bandwidth with respect to a device presenting perfectly straight edges. Rounded corners on other parts of the device present negligible effects.

The combination of the diverse fabrication tolerances on implemented devices produces deviations in the filter measured responses with respect to simulations. In this section, the effect of each type of tolerance has been considered separately. Considering a simulation with all tolerances together has been avoided due to the complexity of the optical measurements and simulations, nevertheless good understanding of the deviations present in the responses due to fabrication tolerances has been addressed. Micromachining techniques can provide more precisely constructed layered devices operating at higher frequencies.

A.6. Conclusions

Two coaxial filters have been successfully designed and characterized at X-band using the proposed versatile suspended coaxial resonator, which allows the design of cross coupled filters. A new type of narrowband quasi-elliptic filter using vertically stacked coaxial lines has been presented. The filter uses cross-couplings to produce a quasi-elliptic response with a pair of transmission zeros. The filter implementation using planar machined metal layers allows scaling the designs to millimeter wave frequencies using micromachining techniques.

A.7. Acnowledgement

This work has been financed by research Project PIB2010BZ-00585 from the Spanish ministry of science and innovation. Jaimes V. Aline wishes to thank CONACYT for scholarship No. 198264°.

All authors wish to thank Nahu Pérez Pérez at the Aspheric Surfaces Laboratory, Large Millimeter Telescope at the National Institute for Astrophysics, Optics and Electronics, Mexico for machining the prototype filter.

All authors wish to thank Joaquim Giner at the Signal Theory and Communications Department, Technical University of Catalonia, Barcelona, Spain, for polishing and assembling the device.

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B

Apendix B
Polymer Based Micromachined Rectangular Coaxial Filters for Millimeter-wave Applications

Contenido

Aline Jaimes-Vera, Ignacio Llamas-Garro, Maolong Ke, Yi Wang, Michael J. Lancaster, Lluís Pradell , "Polymer Based Micromachined Rectangular Coaxial Filters for Millimeter-wave Applications", International Journal of Microwave and Wireless Technologies (Special Issue on 60-GHz-Communication-Systems), Vol. 3, No. 2, March 2011, pp. 115-120.

Abstract - *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 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 loss of 0.77 dB 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.*

B.1. 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^{TM} [1, 2], PolyStrata^{TM} [3, 4] and SU-8 technology [5, 6]. EFAB^{TM} and PolyStrata^{TM} technologies involve multiple thin layer depositions to achieve tall structures. EFAB^{TM} allows the deposition of up to 40 layers with a thickness between 5 and 25 μm. PolyStrata^{TM} 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 B.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 eq. 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].

$$Q_o = \frac{4{,}34 \sum_{i=1}^{n} g_i}{BW \cdot IL} \tag{B.1}$$

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].

B.2. 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. B.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.

The cross-section of a rectangular coaxial line is shown in fig. B.2. This cross section can be optimized to provide low attenuation in the cable, while propagating a transverse electromagnetic mode (TEM) for the band of operation, without interference from TE or TM modes. Table B.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 in 3 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 $4{,}1x10^7\ S/m$.

Tabla B.1: Performance summary of several micromachined millimeter-wave filters implemented by diferen 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	PolyStrata	SU-8	SU-8
Technology	Cavity	Waveguide	Cavity	Coaxial	Cavity	Microstrip	Coaxial	EFAB	Caviity	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
Q_o 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
Q_o 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)	8.74x4.94	6x3	6.3x5.6	6.5x2	2.9x2.94	4.2x1.4	5.1x3.3	6x6	9.56x9.56	5.9x2.76	4.5x2.76
Overall dimensions (mm)	8.74x4.94	6x3	6.3x5.6	7.7x2	2.9x2.94	4.2x1.4	5.1x3.3	6x6	9.56x9.56	8.3x2.76	6.9x2.76

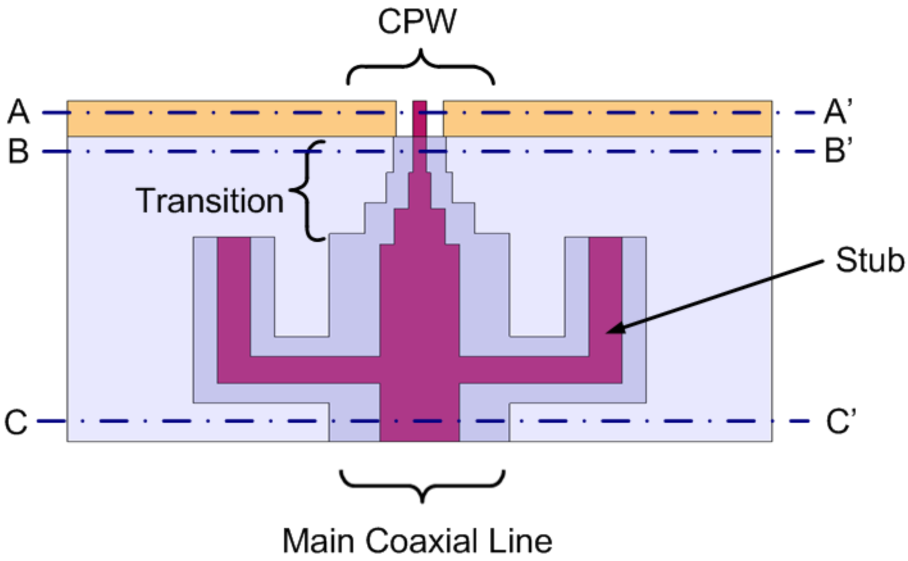

Figura B.1: *Top view of the CPW-to-coaxial transition.*

Tabla B.2: CPW and rectangular coaxial section comparison

	Section A-A' CPW	Section B-B' Coaxial	Section C-C' Coaxial
Dimensions μm	A=218 W=60 T=200	A=236 B=600 W=60 T=200	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

The suspended coaxial line used for the devices presented is formed by five layers (see fig. B.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. Fig. B.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. B.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.

B.3. Narrowband Rectangular Coaxial Filters.

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

B.3.1. 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. B.5.

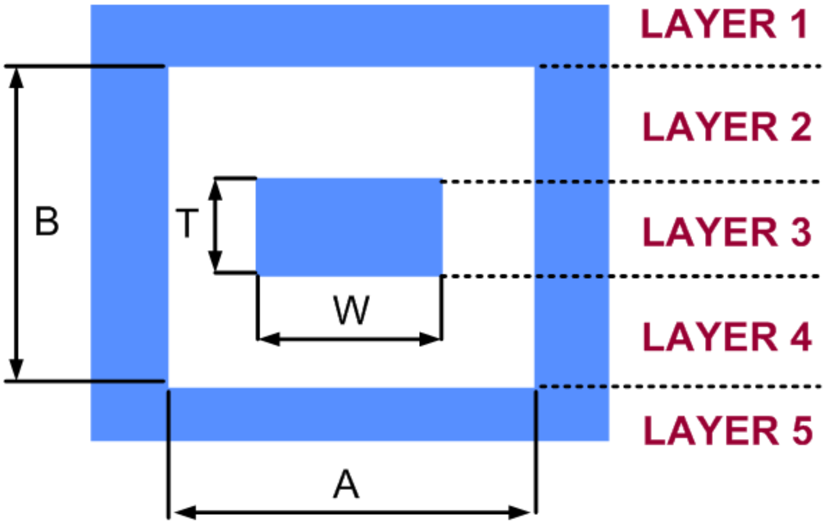

Figura B.2: *Cross section of a rectangular coaxial line.*

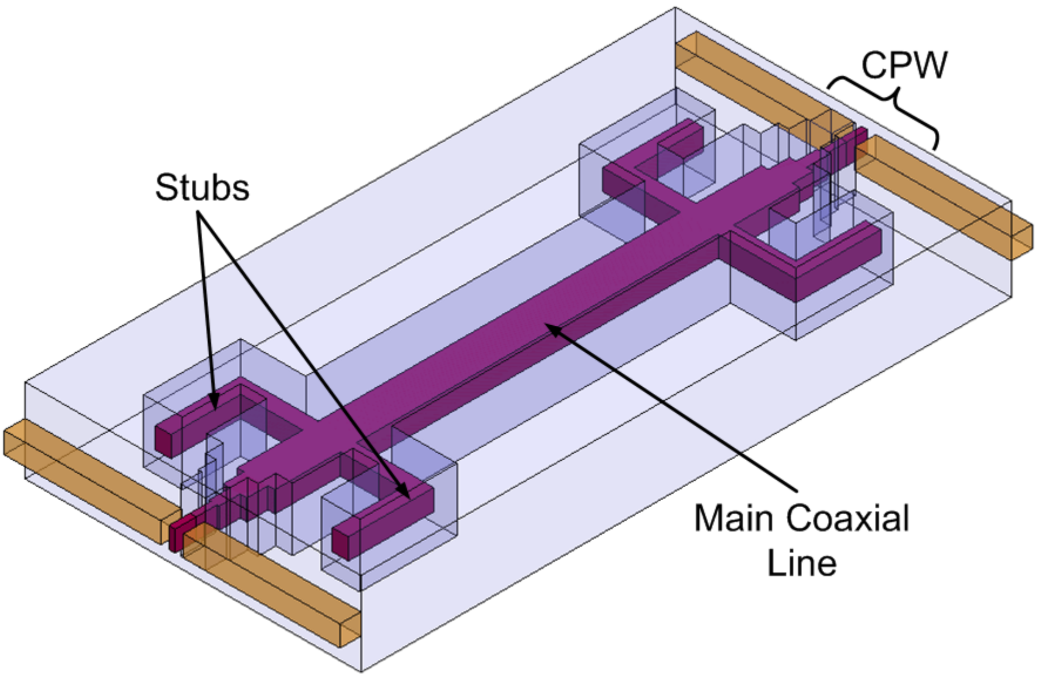

Figura B.3: *3D view of the CPW-to-coaxial line transition in a back-to-back configuration.*

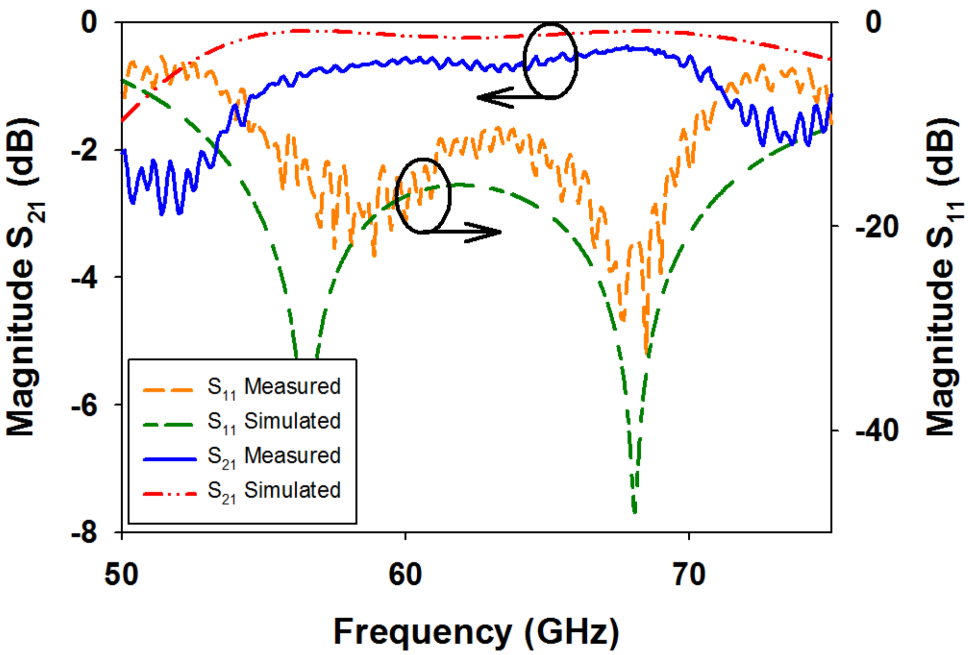

Figura B.4: *Simulated and measured response of the suspended coaxial line.*

The input and output coupling to the resonators is achieved using the suspended CPW-to-coaxial transition described in section II with a centre 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, the lowpass prototype g values are $g_1 = 0{,}4489$, $g_2 = 0{,}4078$, $g_3 = 1{,}1008$, the coupling between resonators is $K_{c12} = 0{,}2337$, 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. B.5, where the distance d is used to adjust the external quality factor to match the theoretical value 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. B.5). The two resonators are coupled together by an inductive immittance inverter formed at the short circuit that suspends both resonators. Fig. B.6 shows the external quality factor values and couplings between resonators obtained by simulations.

The device discussed in this section, and shown in fig. B.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 x 2.76 x 1 mm. Simulated and measured results are shown in fig. B.7. Measurements were performed after a Short-Open-Load-Thru (SOLT) 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.

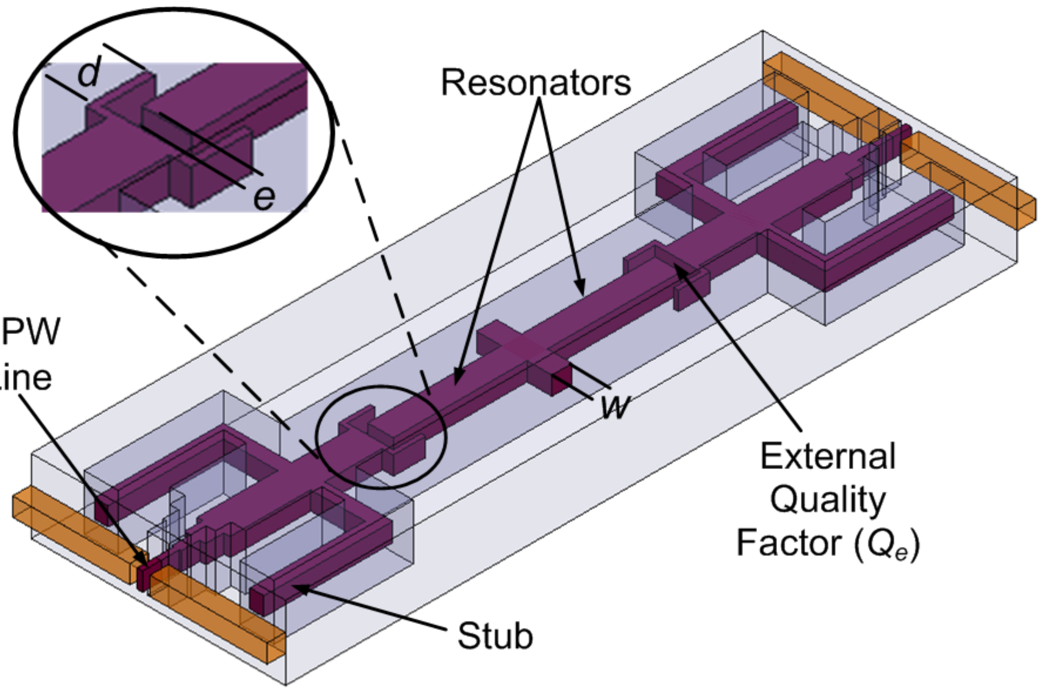

Figura B.5: *3D view of the U-band coaxial filter.*

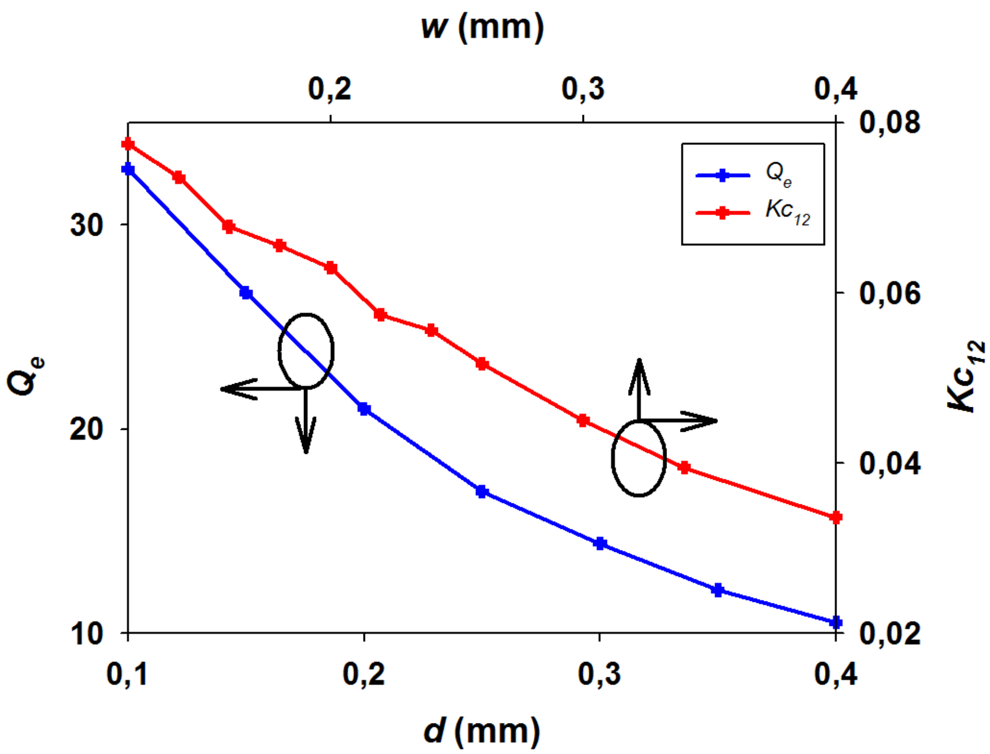

Figura B.6: *External quality factor (Q_e) and coupling coefficient (K_{c12}) for the U-band coaxial filter.*

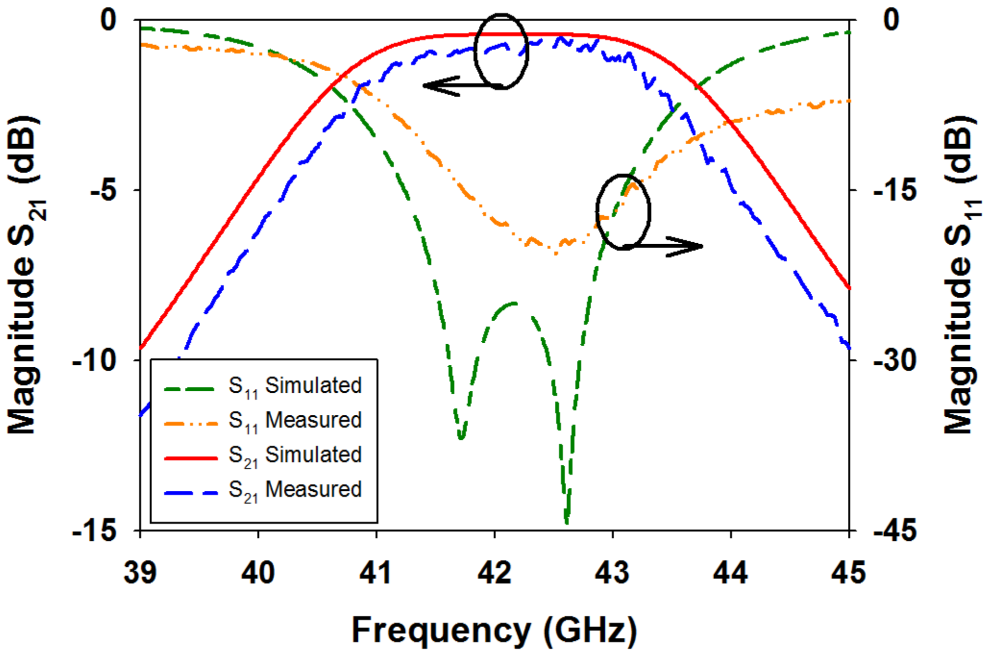

Figura B.7: *Simulated and measured response of the U-band coaxial filter.*

B.3.2. 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 $K_{c12} = 0{,}1168$ 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. B.5) w is shown in fig. B.8.

The filter is made of five SU-8 layers. The overall dimensions of the filter are 6.96 x 2.76 x 1 mm. In fig. B.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.

B.4. Conclusions

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.

B.5. Acnowledgement

This work was supported by research project TEC2007-65705/TCM from the Spanish ministry of science and innovation. Aline Jaimes wishes to thank CONACyT and Alβan for scholarships No. 198264 and No. E07D402796MX, respectively. The fabrication work was supported by the UK Engineering and Physical Science Research Council.

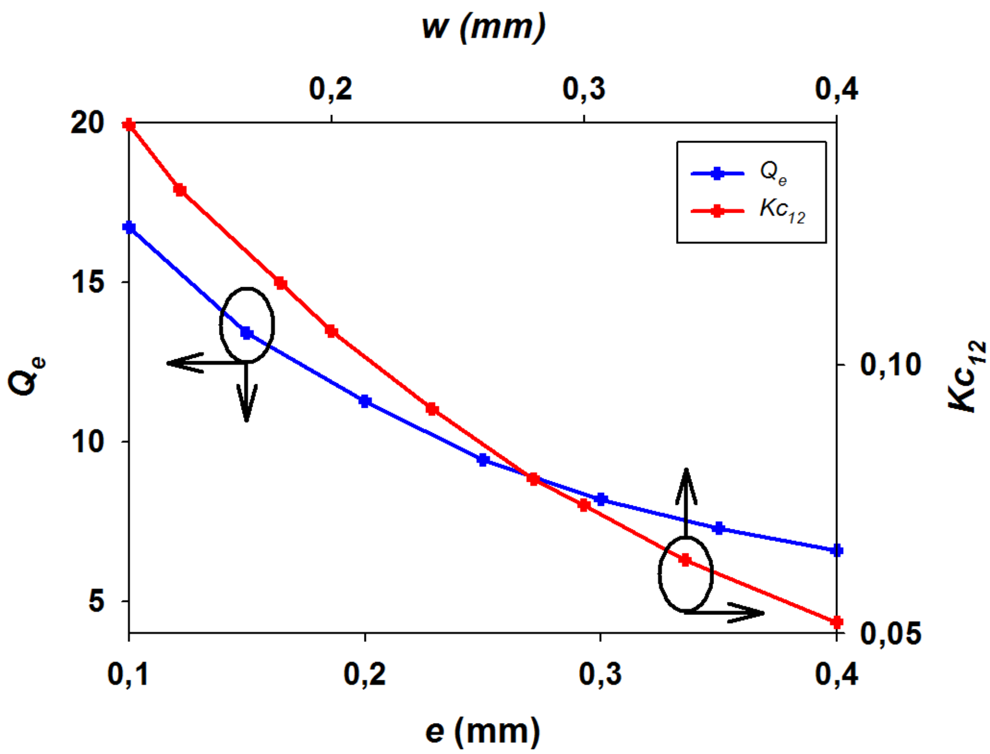

Figura B.8: *External quality factor (Q_e) and coupling coefficient (K_{c12}) for the V-band coaxial filter.*

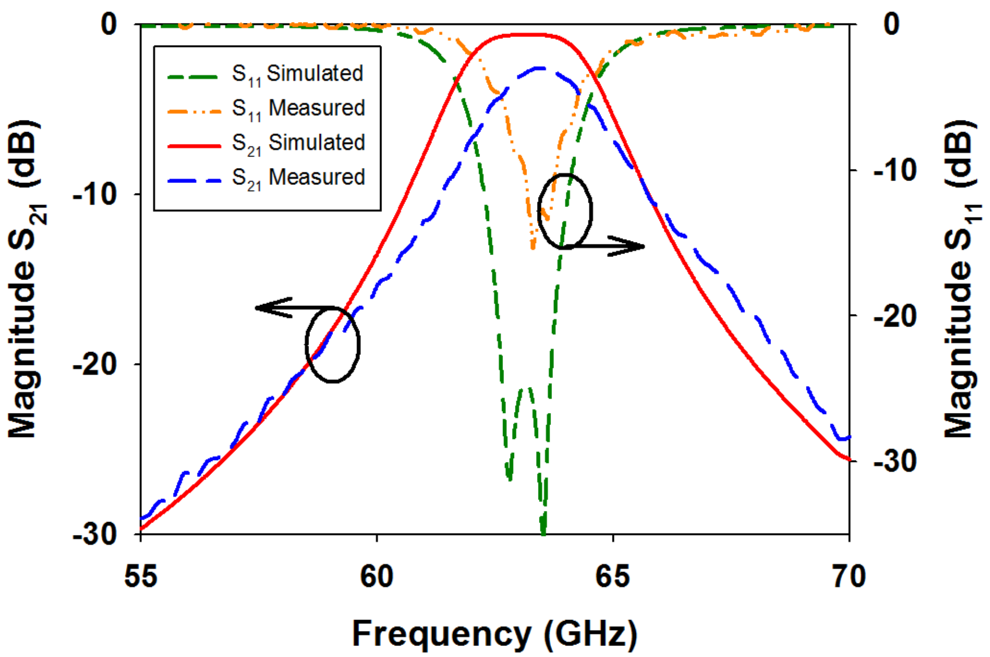

Figura B.9: *Simulated and measured response for the V-band coaxial filter.*

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