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Compact bandwidth tunable IF filters for reconfigurable converters

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Research Paper

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Abstract

This paper aims to present some outcomes from a European Space Agency (ESA) Technology Research Programme (TRP) project on R&D of new design techniques, concepts, and filtering configurations for tunable IF (intermediate frequency) filters with a compact footprint, wide bandwidth tuning range (covering from 49 to 478 MHz at $f_0 = 1$ GHz) as well as equivalent high-Q performance (i.e. low insertion loss variation and high selectivity by using low-Q resonators). In order to obtain a wide tuning range, the proposed filtering configuration utilizes a new tuning technique that only necessitates control of coupling values with simple DC control circuits, without the need of tuning the electrical length of resonators to avoid deviating the center frequency. Furthermore, in order to achieve the equivalent high-Q performance, a novel lossy technique by using a centrally resistor-loaded half-wavelength resonator is adopted. For the proof of concept, a six-pole prototype filter is designed, fabricated, and tested.

Introduction

Flexible satellite payloads using reconfigurable filters have found considerable interest as they have the potential to address two important areas: (a) adaptability to changing business plans via capacity (i.e. bandwidth) re-allocation in response to traffic variability. (b) Reductions in the number of RF components needed and front-end complexity lead to reduced cost and longer lifespan. In the open literature, most of the research in tunable filters has concentrated on the technology of frequency tuning or bandwidth controlling by using semiconductor, RF micro-electromechanical system devices, ferroelectric diode, p-i-n diode, silicon or GaAs varactor diodes, and so on [1–9].

However, it can be noted that most of the planar tunable filters that have been reported in the literature were low-order (≤ fourth order) designs [7, 9]. Generally, their control mechanism and circuit structure are difficult to be applied in high-order filters due to increased complexities, and thus limits the application of tunable filters in satellite communication system. Additionally, the performance of tunable filters will commonly deviate somewhat from the expected specifications or theoretical response of the ideal prototype due to the effects of limited low Q factors of tuning elements and other dissipation loss associated in the circuit. This can be seen as an increased insertion loss in passband and a rounding of the passband edges leading to a poorer selectivity which become more pronounced in narrowband filters. Like recently, the 1.5–2.2 GHz three-pole tunable combline filters published in [4] suffer from degraded insertion loss and rounded passband responses owning to the finite Q (40–90) of varactor diodes. So how to enhance the performance of the tunable filters that can sustain narrow bandwidths over the tuning ranges is a big challenge. One way of compensating is integrating the active devices into the tunable filter design, which suffers from nonlinear distortion of active devices and complex structures [10, 11]. In addition, development of synthesis techniques that take into account the limited Q of the filter resonators allows to enhance the filter selectivity and passband flatness, at the expense of other filter parameters (such as absolute insertion loss in the passband) that might not be critical in IMUX filters [12–22]. The most promising approaches are predistortion [12–14] and lossy circuit techniques [15–22]. In [12–14], the key to predistortion is to move the transmission poles of the filter function toward $j\omega$ axis by an amount (fixed or adaptive) to compensate for the network losses. This can flatten the passband loss variation other than for increased absolute insertion loss. But it is noted that in the predistortion technique synthesis process, uniform dissipation loss was required. Guo *et al.* [15] and Ni *et al.* [19] proposed lossy circuit techniques by using nonuniform dissipation and resistive coupling to improve the filter response, respectively. But these synthesis methods presented are limited to specific filtering configurations/topologies. Furthermore, the above published techniques mainly focused on the designs of fixed-frequency filters.

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Table 1. Specification of this study

Parameters	SPEC.	Unit
Center frequency (C_IF)	1000	MHz
Channel Bandwidth	From 50 to 450 MHz	MHz
Insertion loss (IL) at C_IF	TBA	dB
IL variation versus frequency		
C_IF ± 30%BW	<0.4	dB
C_IF ± 40%BW	<0.6	dB
C_IF ± 50%BW	<1	dB
Narrowband isolation		
C_IF ± 80%BW	>20	dB
C_IF ± 160%BW	>40	dB
Input/output return loss	TBD	

In this paper, a novel and compact six-pole bandwidth tunable IF lossy filter base on half-wavelength resonators is designed, fabricated, and tested, considering the specifications detailed in Table 1. Unlike the above-mentioned reported tunable filters, the proposed structure puts great effort into the enhancement of in-band insertion loss variation and out-of-band selectivity at each tuning state to obtain the equivalent high Q performance, which is realized by centrally loading resistors at half-wavelength resonators. Additionally, the proposed filter utilizes a novel tuning technique that only requires control of coupling values with simple DC control circuits, without the need of tuning the electrical length of resonators to keep the center frequency unchanged. Theoretically, such tuning techniques can be applied to design any low (<3) and high orders of filter with reconfigurable bandwidths. This work is a continuous effort on applying the lossy circuit technique to design tunable filters, in addition to the reported group's work [23, 24]. To the author's knowledge, such high-order microstrip lossy filter with promising bandwidth reconfigurability has not previously been reported.

Proposed tunable IF filters

The configuration of the proposed six-order tunable bandpass filter with biasing scheme is shown in Fig. 1, which consists of six half-wavelength resonators, with resistors centrally loaded at middle resonators to flatten the passband. Controllable tapped external coupling by using varactor *Ce* is adopted. Combinations of three varactors (i.e. two varactors *Cs* connected in series and one shunted varactor *Cp*, see in Fig. 1) are utilized to tune the bandwidth. Additionally, in order to flatten the passband, the middle resonators (2nd, 3rd, 4th, and 5th) are loaded by a Pin attenuator that offers a continuously tuned resistor. The detailed operating mechanism will be described in the following.

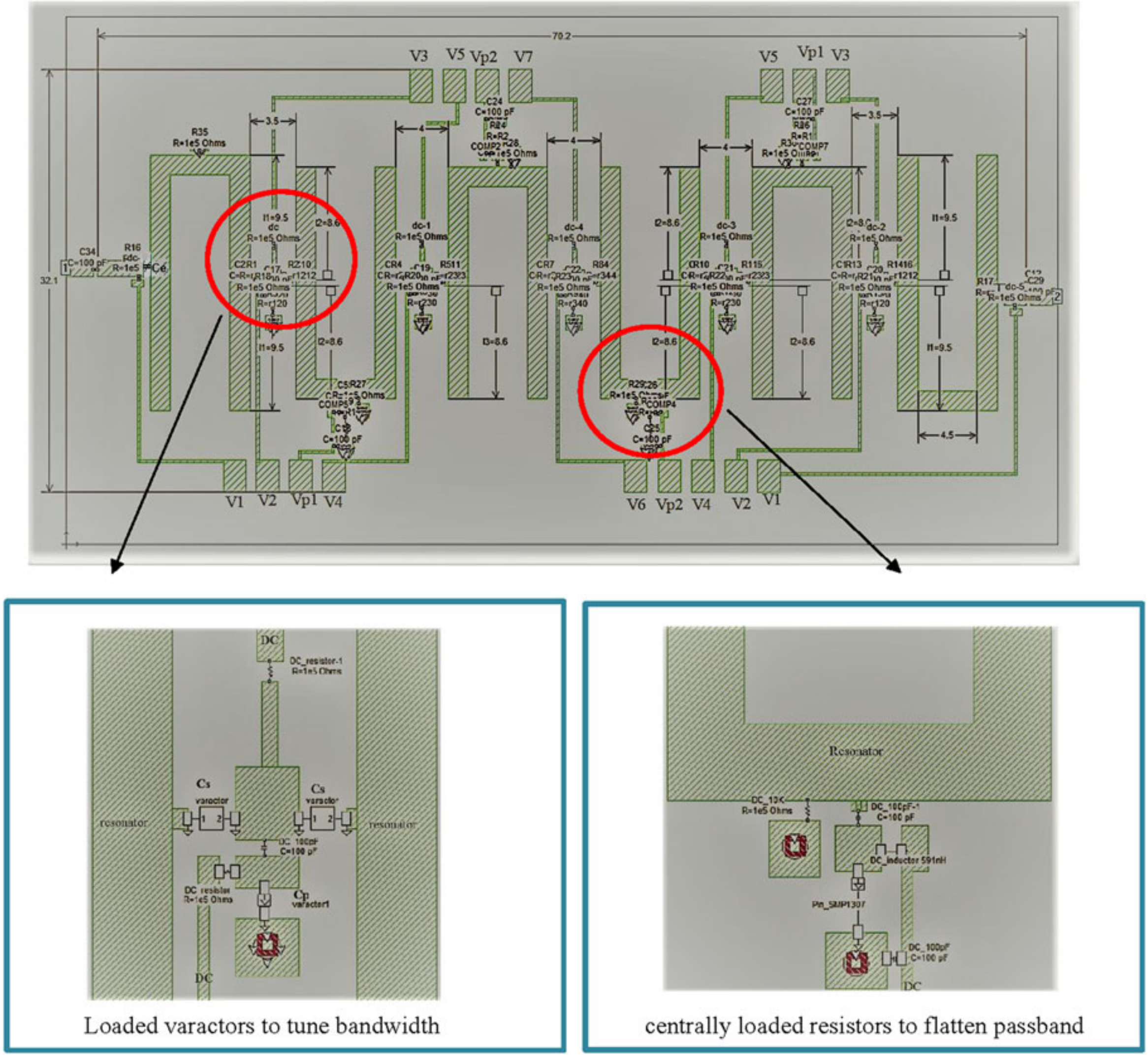
The tuning mechanism of the proposed filter

For our investigation, firstly a pair of resonators with the proposed tuning network is demonstrated and examined in Fig. 2, where the software Microwave Office (AWR) [25] is used for simulation. As we all know, for the conventional case, i.e. without shunted varactor *Cp*, if we tune the varactor *Cs*, only the lower resonance peak is shifted accordingly, as shown in Fig. 3(a). In order to tune the bandwidth while maintaining the center frequency unchanged, most of the reported work, like the design described in [4, 5], usually adopted additional varactors to adjust the frequencies of resonators, leading to the increased complexity of DC bias circuits. However, for our proposed tuning network, it is interesting to see if we kept $Cs = 3.4$ pF, when tuning *Cp* from 5 to 23.9 pF, the upper frequency peak is successfully shifted. While if we kept $Cp = 5$ pF, when tuning *Cs* from 1 to 3.4 pF, both frequency peaks are shifted together, but the lower one is shifted more significantly than the upper one. These features can be easily understood by using even/odd mode theory [26, chapter 7] and not be repeated here. Apparently, the proposed tuning network offers a possibility to adjust bandwidth without a need to tune the electrical length of resonators anymore. Furthermore, varactors *Cs* and *Cp* could be treated to have an independent effect on bandwidth tuning. In other words, by tuning *Cp*, the upper side of the passband could be controlled; by tuning *Cs*, the lower side of the passband could be mostly controlled. For better demonstration, Fig. 4(a) describes an example of a three-pole filter model based on the proposed tuning network. A set of tunable responses are given in Figs 4(b) and 4(c). Inspecting the responses given in Fig. 4(b), it is clear to see that individually tuning varactor *Cp*/*Cs* results in the upper/lower bandedge shifted, while has little effect on the opposite one. In this way, Fig. 4(c) depicts the simulated S_{21} of such a three-pole filter, with bandwidth varying from 300 to 70 MHz. Moreover, it should be highlighted that in comparison to the three-pole reconfigurable filter proposed in [4, with 4 DC voltage], the proposed one requires less DC bias (3 DC voltage) due to its simpler bandwidth tuning mechanism.

Lossy circuit technique

In order to achieve the desired insertion loss variation in the passband at each tuning state, this study adopts a lossy circuit technique by centrally loading resistors at the middle four resonators (see Fig. 1). Indeed, such a lossy technique was firstly presented in [21] and further discussed in [22] as research outcomes of the author's group. In general, centrally loading resistors at resonators produces more insertion losses at the middle of passband by power absorption, which compensates rounded-off passband edges and thus improves the insertion loss variation. In comparison to other lossy circuit techniques [16, 17], this one offers an almost unchanged in-band performance until-over flatten. Hence, there is no need to re-adjust the parameters of the reference filter, which means the synthesis processes of filter design and lossy circuit technique can be independently performed. Such characteristics are very promising and convenient to design a tunable lossy filter. As an illustration, Fig. 5 plots simulated responses of the proposed tunable filter at one tuning state, with and without the lossy circuit technique applied. Obviously, by centrally loading resistors of 50 Ohm at 3rd and 4th resonators, the insertion loss variation and return loss in the passband are enhanced, at the cost of an increased absolute insertion loss.

The associated challenge to design tunable loss filter is ideally the required loaded resistors at different tuning states should be different, since the rounded-off bandedge effect is varied against reconfigurable bandwidth. To this aim, the Pin attenuator SMP1307 from Skyworks is employed in the fabrication, whose obtainable series resistance could be continuously tuned from 10 to 80 Ohm by changing forward current from 100 to 1 mA (see in Fig. 6).



Loaded varactors to tune bandwidth

centrally loaded resistors to flatten passband

Fig. 1. Proposed six-pole microstrip filter with reconfigurable bandwidth and equivalent high-*Q* performance.

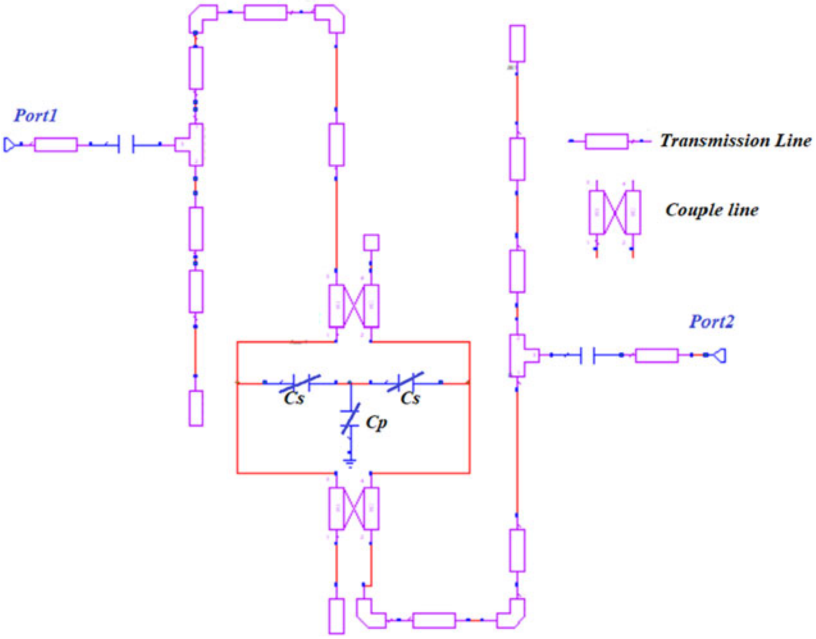
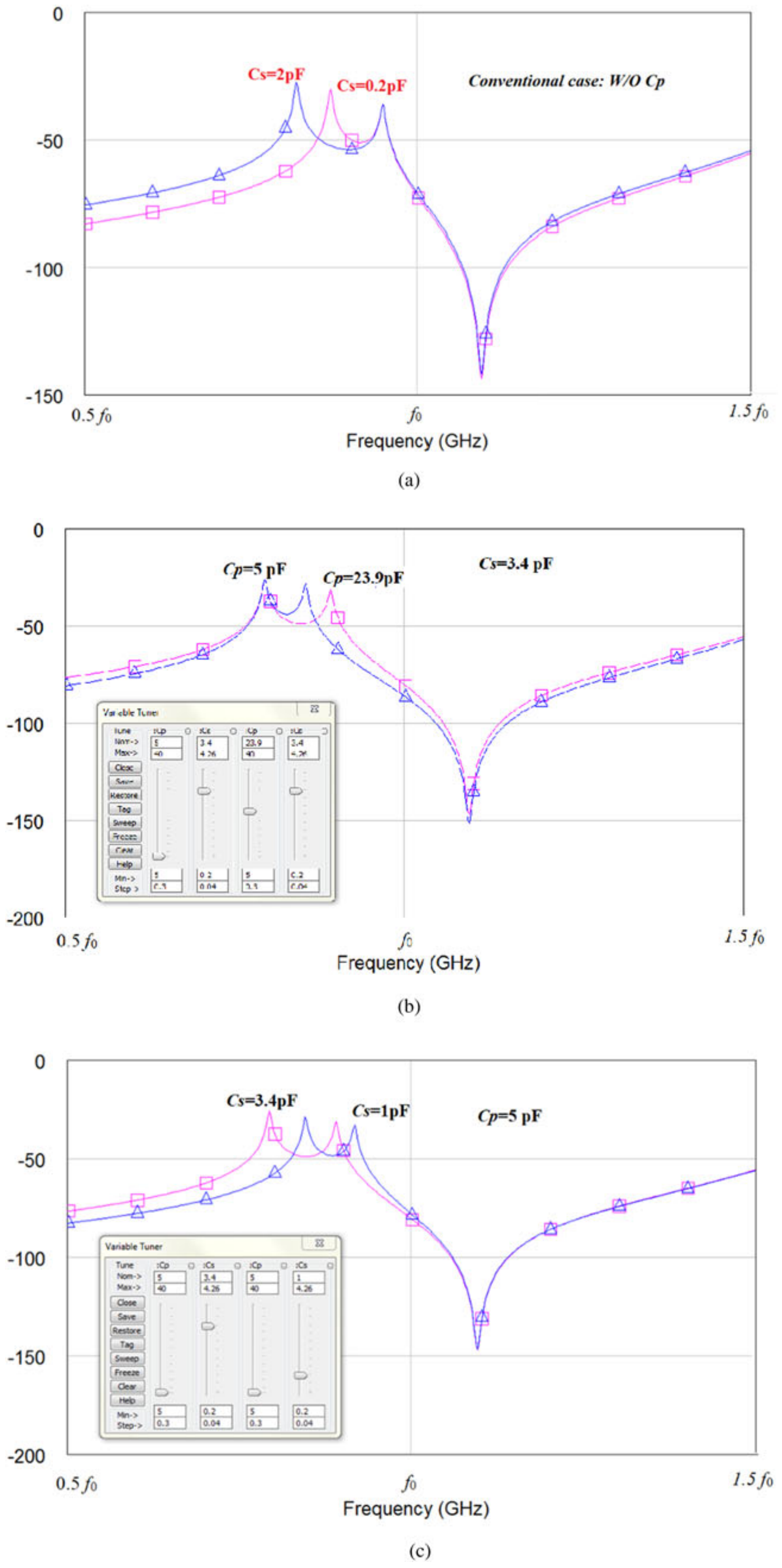


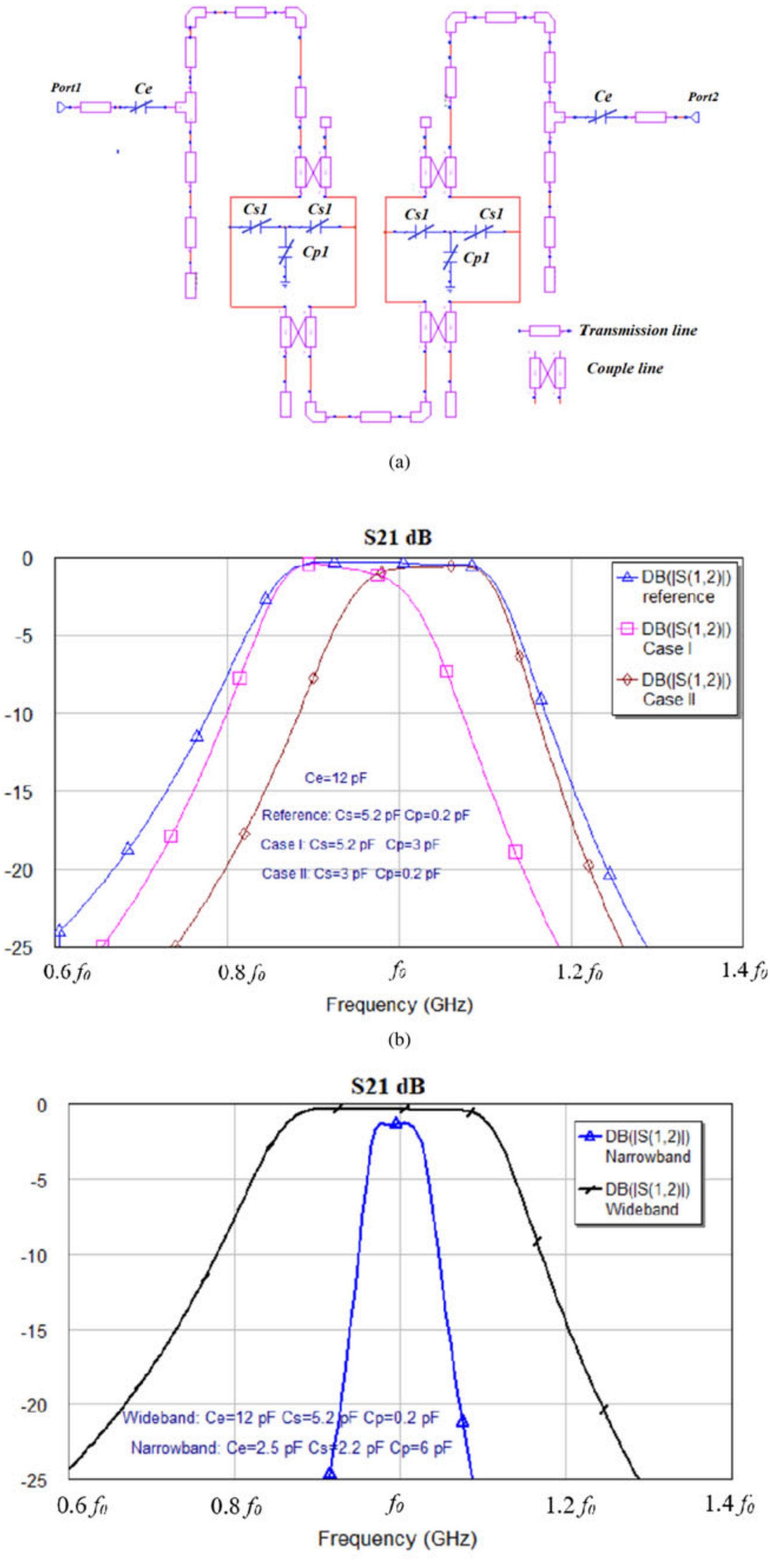
Fig. 2. The proposed configuration for controlling the internal coupling of the filter.



Tune	:Cp	:Cs	:Cp	:Cs
Nom->	5	3.4	23.9	3.4
Max->	40	4.26	40	4.26
Min->	5	0.2	5	0.2
Step->	0.3	0.04	0.3	0.04

Tune	:Cp	:Cs	:Cp	:Cs
Nom->	5	3.4	5	1
Max->	40	4.26	40	4.26
Min->	5	0.2	5	0.2
Step->	0.3	0.04	0.3	0.04

Fig. 3. S21 of (a) conventional case by only tuning *Cs*. (b) Proposed case by tuning *Cp*, with *Cs* kept fixed. (c) Proposed case by tuning *Cs*, with *Cp* kept fixed.



(a)

(b)

(c)

Fig. 4. (a) Ideal model of three-pole tunable filter based on the proposed tuning method. (b) Frequency responses by individually tuning varactors *Cs* and *Cp*. (c) The proposed three-pole filter with a wide bandwidth tuning ratio.

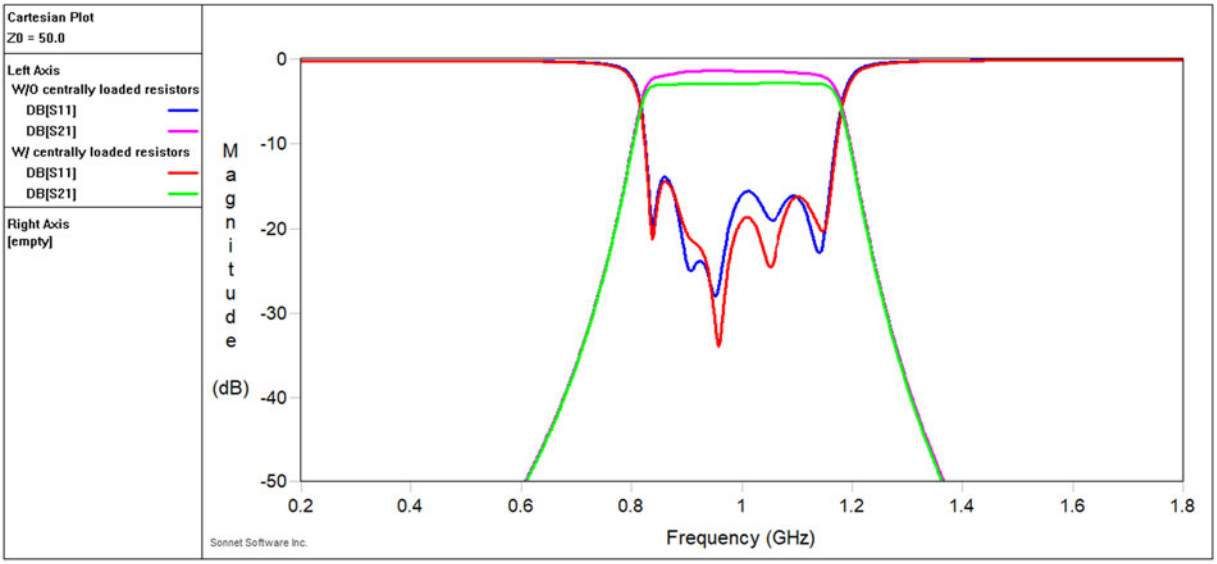


Fig. 5. The impact of centrally loaded resistors on improving passband flatness of the proposed tunable filter.

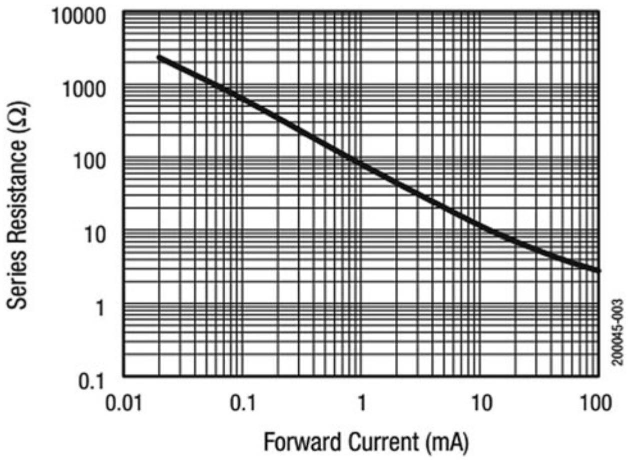


Fig. 6. Series resistance of SMP1307 versus current at 100 MHz [27].

Table 2. The detailed information about components used for fabrication

External coupling control	Internal coupling control		Loading resistors
Ce(pF)	*Cs1/Cs2/Cs3(pF)*	*Cp1/Cp2/Cp3(pF)*	Pin attenuator
MA46H204	MA46H203	MA46H203&MA46H204	SMP1307
Coilcraft 0402HP 591nH inductors, Mura GRM 100pF capacitor and TE connectivity 100 K resistor are employed for DC bias circuits			

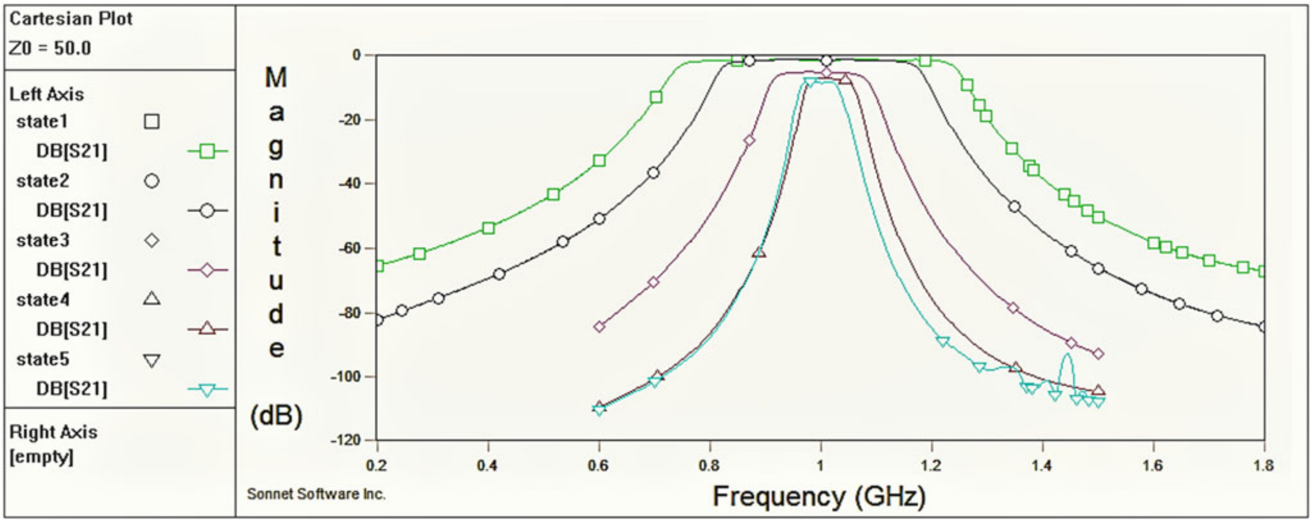
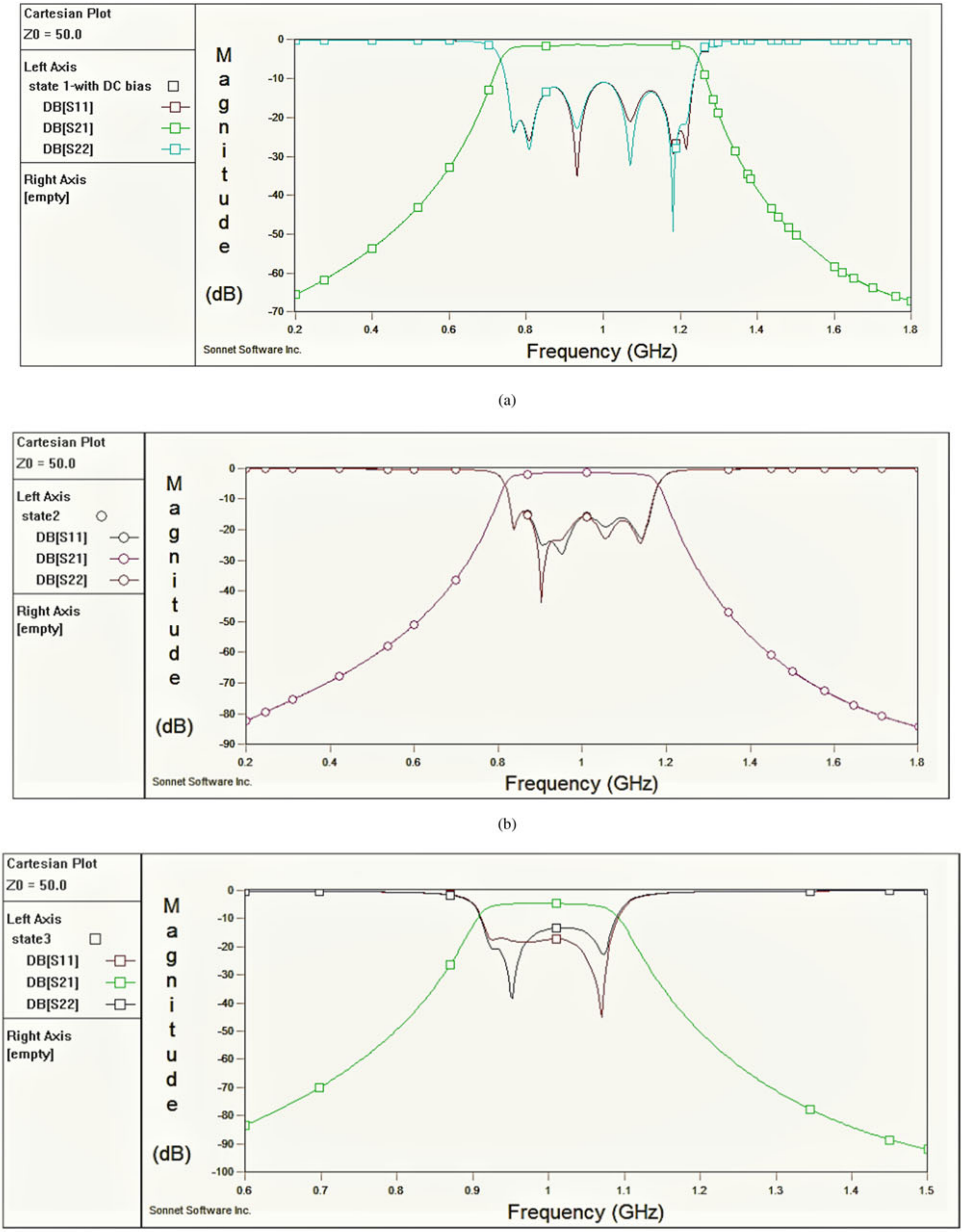


Fig. 7. Simulated results for required bandwidth tuning states from 60 to 466 MHz.

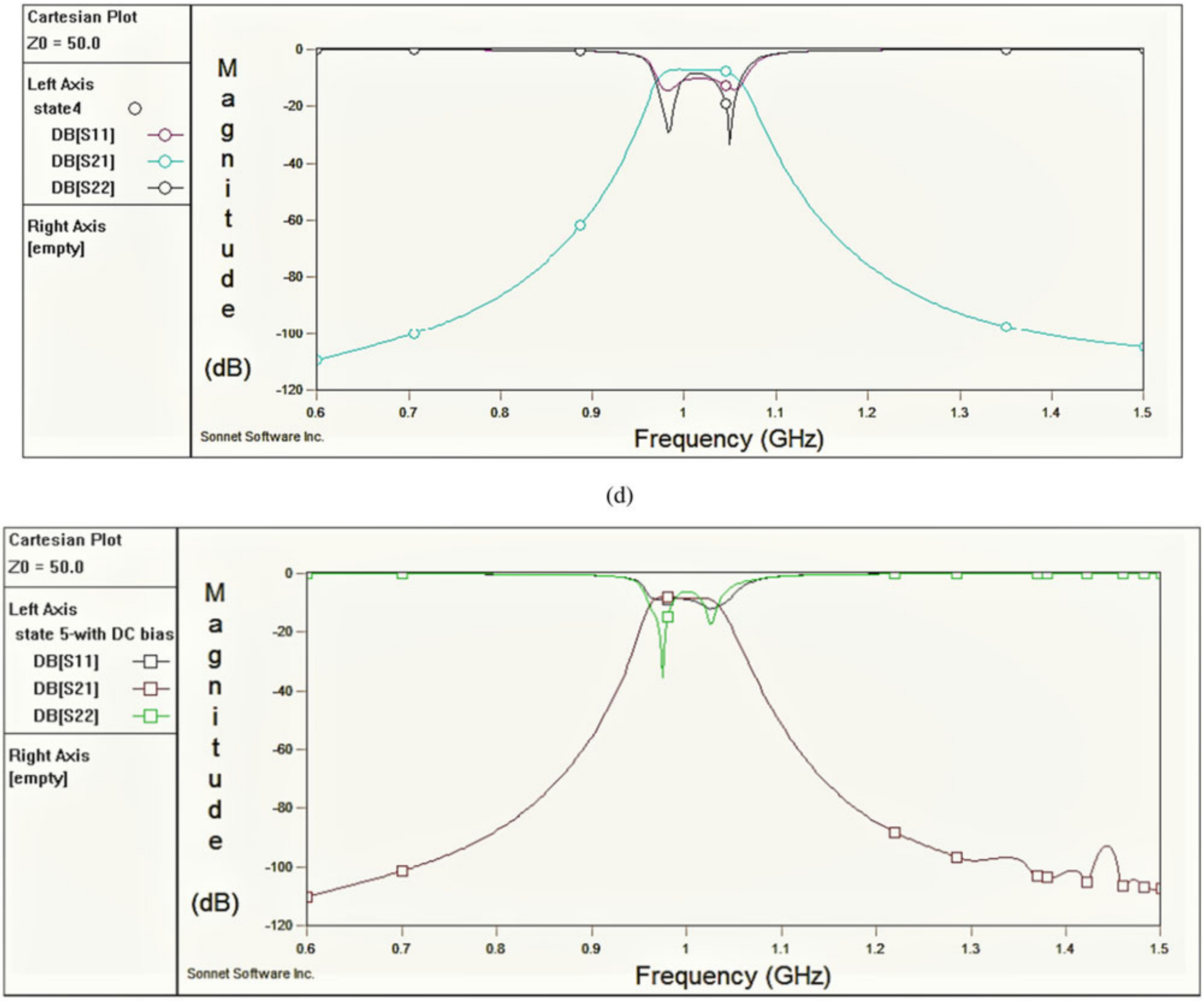


(a)

(b)

(c)

Fig. 8. Simulated full *S*-parameters of (a) state 1. (b) State 2. (c) State3. (d) State 4. (e) State 5.



(d)

(e)

Fig. 8. Continued.

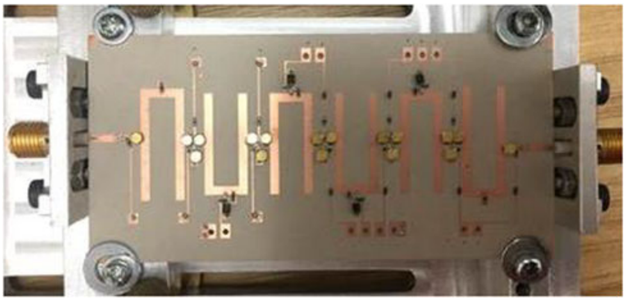


Fig. 9. Fabricated six-pole tunable filter with equivalent high-Q performance.

Simulated and measured results

To validate the circuit concept proposed in the above section, a six-order tunable microstrip filter presented in Fig. 1 is demonstrated through both EM simulation and experimentally measured results, where the substrate RT/Duriod 6010 with a relative dielectric constant $\varepsilon_r = 10.2$ and thickness $h = 1.27$ mm is used. All the EM simulations are performed using a commercially available tool SONNET [28]. Detailed information about the components used for fabrication can be found in Table 2.

Figure 7 depicts the simulated results of the proposed filter with five selected bandwidth tuning states, where the proposed design can obtain the desired channel bandwidth from 60 to 466 MHz in a continuous way, with center frequency almost unchanged. In general, by loading resistors, each state accomplishes a flat passband. The detailed frequency responses of each state can be found in Fig. 8.

For the experimental demonstration, Fig. 9 illustrates the photo of the fabricated tunable filter with enhanced performance. Figure 10 clearly demonstrated a set of measured frequency responses of this fabricated sample, where the lossy circuit technique has been applied. The detailed information about DC bias setting for each state can be found in Table 3. Firstly, it is promising to see this fabricated sample addresses a wide 1 dB-bandwidth tuning range, covering from 49 to 478 MHz, with a tuning ratio around 10:1. Secondly, resulting from different

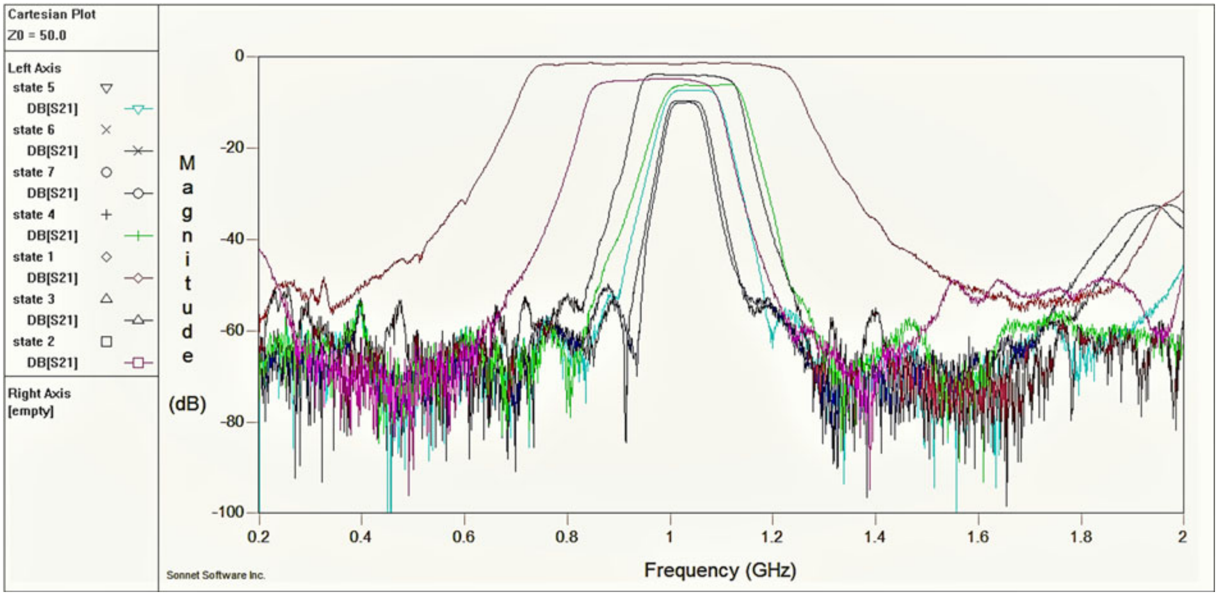


Fig. 10. The measurement results of the proposed six-pole tunable lossy filter.

Table 3. The detailed information about DC bias for each state

Voltage (V)	External coupling	Internal coupling		Centrally loaded resistors
States	MA46H204	MA46H702	MA46H203&MA46H204	SMP1307 PIN attenuator
State 1	2.7	0/0.08/0.61	20.2/22.6/21.1	n/a
State 2	6.2	2.7/2.9/3.3	4.7/11.8/8.5	R2 = 10 mA
State 3	9.0	18.22/3.68/17.8	7.3/10.0/10.0	R1 = R2 = 4 mA
State 4	8.3	7.66/6.07/16.51	7.7/9.9/10	R1 = 10 mA R2 = 10 mA
State 5	11.27	10.81/6.87/17.5	5.6/8.0/7.44	R1 = 40 mA R2 = 10 mA
State 6	12.12	14.39/8.16/17.61	4.3/6.5/6.10	predistortion
State 7	14.24	17.43/9.09/17.68	3.9/6.4/5.62	

resistors loaded at different tuning states, the filter generally obtains a flat passband within the tuning range. Moreover, it can be noted that the center frequency shift is visible at some states, which can be compensated by improving the resolution of DC supplier. Figure 11 displays the full *S*-parameters of three selected states, with bandwidth covering from wideband to narrowband. It should be highlighted that for the narrowband states of 49 and 59 MHz, the passband flatness is achieved by detuning resonators (predistortion technique) instead of centrally loading resistors, which is different from the simulated case because the fabricated dispassion losses are much higher than simulation. During the measurement, at the above narrowband states, the fabricated sample showed greater losses (due to tolerance of fabrication tolerance and SPICE models of varactors) than that of the simulated one, under the condition of no techniques to flatten the passband applied. Therefore, in the step to flatten the passband, the required values of centrally loaded resistors are out of range. Instead, it is found that at these narrowband states, the predistortion technique can help to achieve good passband flatness.

Conclusion

In this paper, a novel six-pole tunable IF lossy filter has been presented, analyzed, and experimentally verified, which addressed diverse advantages, including large bandwidth tuning ratio close to 10:1, low insertion loss variation at each tuning state, high selectivity, and simple DC control circuits. Table 4 summarized the detailed normalized performance of the proposed filter at three selected states, in comparison to the desired mask. In general, the proposed design almost successfully meets the required specifications, except for the normalized narrowband isolation achieved at the bandwidth of 49 MHz. To the authors' knowledge, this is the first time to present a tunable lossy filter with such attractive performance, which will find applications in demanding sub-systems including reconfigurable converters for satellite communications.

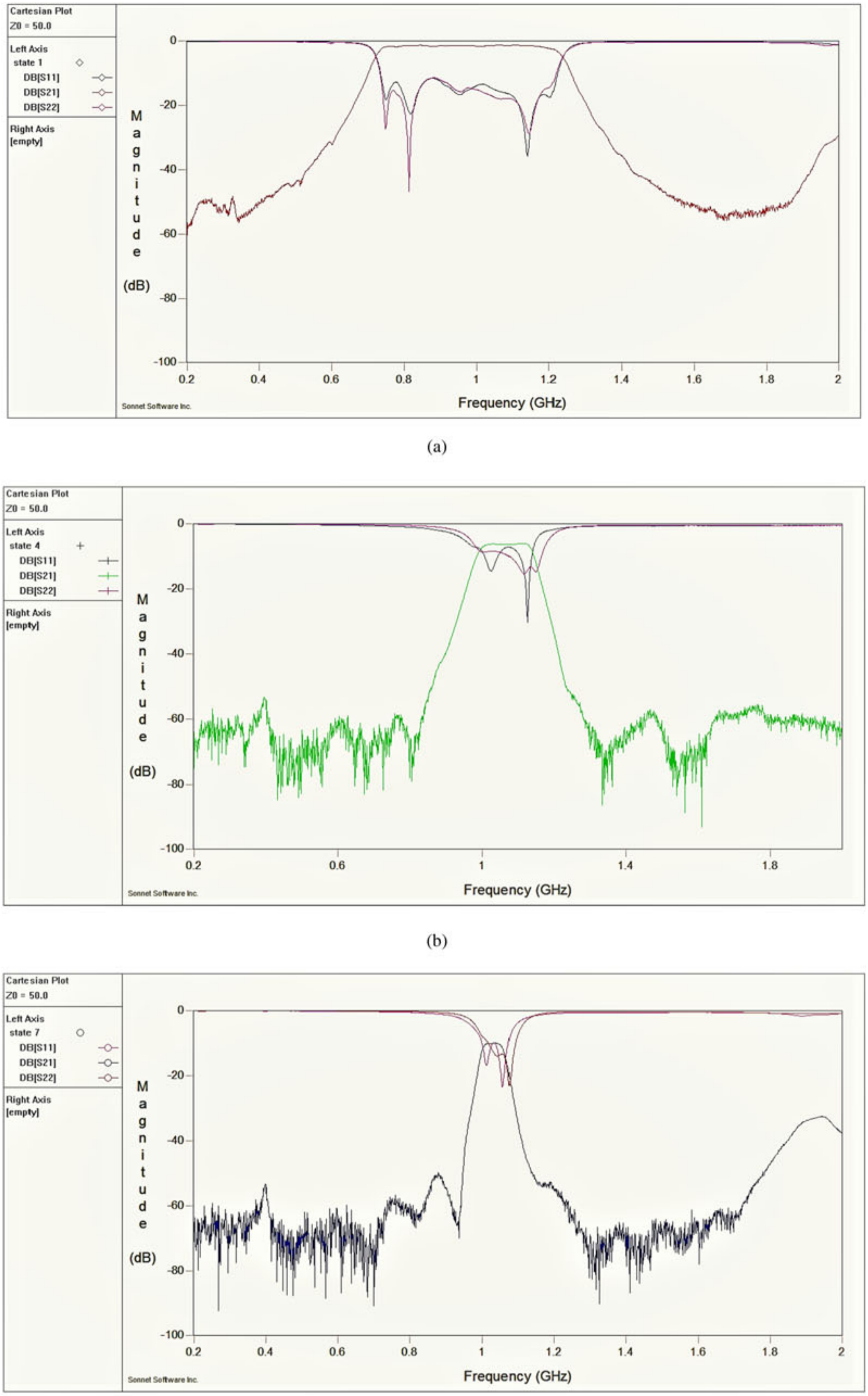


Fig. 11. Full *S*-parameters of (a) State 1_478 MHz. (b) State 4_125 MHz. (c) State 7_49 MHz.

Table 4. Detailed comparisons among the measured and desired masks

			Loss variation in passband (dB)			Narrowband isolation (dB)	
States measured	C_IF (GHz)	IL (dB)	C_IF+/−30%BW	C_IF+/−40%BW	CIF+/−50%BW	C_IF+/−80%BW	C_IF+/−160%BW
478 MHz	0.9713	1.4	<0.26	<0.45	≤1	30 (−) 26(+)	51(−) 51(+)
125 MHz	0.99	6	<0.28	<0.38	≤1	10 (−) 16(+)	42.5(−) 51(+)
49 MHz	0.99	9.9	<0.15	<0.4	≤1	6 (−) 6(+)	31(−) 30(+)
Mask	1	TBA	<0.4	<0.6	≤1	<−20	<−40

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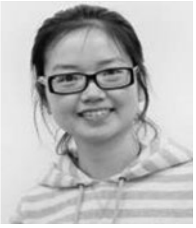

Jia Ni received the B.Eng. degree in electrical engineering from the Nanjing University of Science and Technology, Nanjing, China, in 2008, and the Ph.D. degree from Heriot-Watt University, Edinburgh, UK, in 2014. From 2014 to 2019, she has been a Post-Doctoral Research Fellow with the Microwave and Antenna Engineering Group, Heriot-Watt University, involved with research on reconfigurable microwave filters, microwave lossy filter, multilayer circuit design, and antenna (array) design. Since 2020, she works as a senior antenna system engineer in CelestiaUK Ltd.

Jiasheng Hong received the D.Phil. degree in engineering science from the University of Oxford, UK, in 1994. He then joined the University of Birmingham, UK, until 2001 when he moved up to Edinburgh to join Heriot-Watt University, UK, and is currently a Professor leading a team for research into advanced RF/microwave device technologies. He has authored and co-authored over 200 journal and conference papers in this field and has published four relevant books – Microstrip Filters for RF/Microwave Applications (Wiley, 1st ed., 2001, 2nd ed., 2011), RF and Microwave Coupled-Line Circuits (Artech House, 2nd ed., 2007), Balanced Microwave Filters (Wiley, 2018), and Advances in Planar Filters Design (IET, 2019). He is a Fellow of IEEE, a member of the IEEE MTT Technical Committees, the Subject Editor (Microwave) for Electronics Letters, an Associate Editor of *IET Microwaves, Antennas & Propagation* and *International Journal of RF and Microwave Computer Aided Engineering*.

Petronilo Martin Iglesias (M'12) was born in Caceres, Spain, on April 23, 1980. He received the Telecommunication Engineering degree from the Polytechnic University of Madrid, Madrid, Spain, in 2002, and the Master degree from the University of Leeds, Leeds, UK, in 2012. He has been working in the industry for over 10 years as a Microwave Engineer involved with active (high-power amplifiers for radar applications) and passive (filters, multiplexers, couplers, etc.) RF hardware design, including 2 years as a Radar System Engineer with Indra Sistemas, ISDEFE S.A., and Thales Alenia Space Spain. Since Summer 2012, he has been involved with research and development and project support activities related to RF passive hardware developments for the European Space Agency. His research interests are filter synthesis theory, electromagnetic (EM) design, and high-power prediction, as well as advanced manufacturing techniques for RF passive hardware. From January 2021, he is part of the Microwave Instruments Section at ESA-ESTEC.