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Emerging Trends in Techniques and Technology as Applied to Filter Design

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ABSTRACT In the last decade, the filter community has innovated both design techniques and the technology used for practical implementation. In design, the philosophy has become "if you can't avoid it, use it", a very practical engineering approach. Modes previously deemed spurious are intentionally used to create in-line networks incorporating real or imaginary transmission zeros and also reduce the number of components and thus further miniaturize; spurious responses are re-routed to increase the passband width or stopband width, frequency variation in couplings is used to create complex transfer functions, with all of these developments using what was previously avoided. Clever implementations of baluns into passive and active networks is resulting in a new generation of noise-immune filters for 5G and beyond. Finally, the use of a diakoptic approach to synthesis has appeared an evolving approach in which small blocks ("singlets", "doublets", etc.) are cascaded to implement larger networks, (reducing the need for very complex synthesis), with this new approach promising a large impact on the implementation of practical structures. Filter technology has migrated towards "observe it and then adapt it", pragmatically repurposing tools not specifically originally intended for the applications. Combinations of surface wave and bulk wave resonators with L-C networks are improving the loss characteristics of filters in the region below 2 GHz. Lightweight alloys and other materials designed for spacecraft are being used in filters intended for space, to provide temperature stability without the use of heavy alloys such as Invar. Fully-enclosed waveguide is being replaced in some cases by planar and quasiplanar structures propagating quasi-waveguide modes. This is generically referred to as SIW (Substrate Integrated Waveguide). Active filters trade noise figure for insertion loss but perhaps will offer advantage in terms of size and chip-level implementation. Finally, the era of reconfiguration might be approaching, as the basic networks are evolving, perhaps lacking only the appearance of lower-loss, higher-IP solid-state tuning elements.

INDEX TERMS Active filter, additive manufacturing (AM), BAW, balun, bypass, cascade, coupling, diplexer, doublet, E-M filter, extracted-pole, gyromagnetic, J-inverter, K-inverter, NRM, NRN, singlet, doublet, SLM, triplet, waveguide.

I. INTRODUCTION

To estimate where we are going, it is important to know where we have been, where we are today, and to understand the process used to move forward. Breakthroughs are not predictable, and certainly add a "non-linear" contribution to the slope of progress. Nonetheless, it is hoped that this paper will at least provide a glimpse of the future. Rather than focusing on today's applications (e.g., 5G, satellites, and similar), the emphasis will be on those techniques and technologies that improve design accuracy, enhance time-to-market, and reduce the need for time-consuming design iterations. For example, 5G could easily morph into 6G, 7G, NG; satellite requirements change into moon or Mars environment requirements, etc. The approach taken in this paper should result in systematic design improvements independent of highly touted systems, in vogue today but disappearing tomorrow.

A. HISTORICAL PERSPECTIVE

In the days of Guillemin [1] Darlington, Skwirzinski, [2] Van Valkenburg [3], and a host of very creative others (just naming a few) [4]–[7], mathematical rigor dominated design of all networks, including filters. Reactive transfer functions were expressed as polynomial ratios in a single variable. Required to be positive real, such polynomials were used in both numerator and denominator of the fractional ratio (network functions), which was then decomposed using continued fraction expansion. The process extracted the discrete reactive elements of a network realizing the desired transfer function to within a specified limit. Along came Paul Richards [8], and showed how reactances in lumped circuits could be exactly represented by open and short circuited one eighth wavelength transmission lines. Series stubs could then be replaced by shunt stubs using Kuroda and Levy transformations. Cohn, in a seminal work [9], showed that resonators could be combined with inverters to form direct coupled networks, both lumped and distributed. He also showed the equivalence between lumped and distributed circuit over a wide band of frequencies. Much of this work was performed at the Stanford Research Institute (SRI) in the early 1960's, leading to the famous MYJ Black Bible" [10], derived from work at Fort Monmouth, New Jersey in the late 1950's, produced by the famous trio of "workers"", G.Matthaei, L.Young and E.M.T.Jones. Cohn's work led to moving from a synthesized lumped reactive network to a distributed equivalent at microwave frequencies, work that was extended by Levy [11]. It was found that unless the transmission lines were the same length ("commensurate"), the synthesis was not exact, but it was also found that using lines of varying lengths enabled realization of networks with real and imaginary transmission zeros. Combining non-commensurate lines with lumped elements and below-cutoff ("evanescent") elements also became common, and attempts were made in the 1960-1970 period [12]–[16] to develop some synthesis methods that could make possible incorporation of the different forms of reactance versus frequency that pertained to each of the constituent elements (lumped, evanescent and propagating waveguide). In particular, Malherbe [17] developed the p-transformation, essentially paralleling two transmission lines of different lengths. This realized an equivalent circuit with two parallel Foster sections, resulting in a circuit with predetermined TZs, requiring much less optimization. However, two factors contributed to the present condition of stagnation in multi-variate synthesis: First, there was much progress in optimization methods, and it became possible to bypass exact synthesis and get practical results in the circuit domain, on a PC. Second, the availability of electromagnetic analysis and optimization in the E-M domain allowed consideration of radiation, actual losses (both undesired as in reactive components and desired, including resistors or specified values of Q), including real geometries and physical connections without using exact circuit models at all.

In 1972, Atia and Williams [18] introduced the use of a coupling matrix as a method for synthesizing both direct and cross coupled filters, also single and dual mode types.

C. Bell formalized the rotations [20], using the Given's rotation procedure, derived from the Householder transformation. These were steps leading to development of smaller and more "manufacturable" filters for primarily space applications.

R. Cameron essentially revolutionized the approach to synthesis [19] when he introduced the concepts of the transversal network prototype, followed by matrix rotations to eliminate unwanted or unrealizable couplings, into cross-coupled filters

In the early 2000's Amari [21] developed a technique for combining blocks (called singlets) using Non-Resonating Nodes (NRN). In this work and others [22]–[24], it was shown that the use of NRNs enabled realization of N transmission zeros, rather than the N/2 as in direct cascade of more complex connections known as doublets, triplets, quadruplets, etc.

The use of dielectric resonators in filters was pioneered by S. Cohn [25], realized as direct-couple resonators, but the use of the technology depended on availability of adequate resonator material, and it did not become available until the 1970-1980 period, when commercial ceramics were developed with low loss and high dielectric constant. Dual- and even higher mode order versions were developed by contributors such as J. Fiedziuszko [26]. Using reflected image theory, half wave and even quarter-cut versions were developed by Mernarian and Mansour [27], Nishiikawa, Wakino [28] et al. and others with combinations, dual mode and more.

Tunable filters, both mechanically and electronically tuned, were common and formed important components used in radios. Mechanically tuned helical resonators, as well as coaxial and waveguide cavities used to implement multi-section filters, reached a peak and stimulated the filter company start-ups of the 1960-1980 period. Mechanically tuned filters displayed low loss and high power capability, but of course were relatively slow, using stepper motors for precise tuning. Electronically tuned filters provided fast tuning, using either varactors or arrays of capacitors selected by PIN diodes. The varactor-tuned devices provided full analog tuning at the price of limited dynamic range (IP3 was no more than perhaps +10 dBm), whereas the switched capacitor arrays tuned discrete channels, but with greater dynamic range. Substitution of MEMS varactors improved dynamic range (much higher threshold of non-linearity than junction varactors), but at 3 orders of magnitude reduction in tuning speed and with less reliability. Another very important tunable filter category utilized resonant spheres of YIG (Yttrium Iron Garnet) displaying very high unloaded Q and also able to change effective permeability over a wide range, with the application of an external magnetic field. Due to the high Q, matching was difficult and bandwidth small, driving current large, but even with restriction to a low order ladder-type topology, the YIG filters realized both bandpass and bandstop filters able to tune more than a decade, above 1 GHz. YIG and other magnetically tunable filters today still are a rewarding and commercially important area of development, and readily available from companies such as [29]. The electronically tunable/switchable networks have today become more sophisticated, as used in reconfigurable circuits, able to be dynamically programmed to provide either bandpass or bandstop transfer functions. There are new magnetically tuned media being developed, including structures built on graphene and as deposited ferromagnetic films on substrates [30], so this is an active area of development and will be so in the future.

In the 1970-1980 period, active filters [31]–[34] were explored for microwave and RF applications. Active solid-state devices used internal feedback to achieve equivalent inductance values, with very high Q and of course small size, something not possible with purely passive inductors. The goal was to achieve very low loss narrow band tunable filters, trading size against DC power, but stability and noise figure proved almost insurmountable obstacles, with devices available at the time.

Manufacturing technology comprised parts machined with standard, manually-operated equipment, planar circuits (stripline, microstrip, various co-planar) etched using photographic methods or machined in air-slab line format, sophisticated plating and electroforming techniques, with digitally programmed machines coming into use, and layered circuits (without good models) also developed for the cell-phone applications. Bulk acoustic wave and Surface acoustic wave filters were also introduced, again without comprehensive modeling but with good performance.

B. CURRENT DEVELOPMENTS

Sections II and III of this paper will cover the latest synthesis techniques, from both mathematical and practical perspectives. A brief overview of that material is presented in the next 5 paragraphs:

Even with optimization and E-M analysis readily available, the synthesis and realization of filters is a long process, unless the frequency variation of the couplings between resonant elements is taken into account and used advantageously.

The idea of resonant couplings in the form of irises in waveguide structures goes back to Marcuvitz [35], Lewin [36], Snyder [37], Levy [38] and others [39], [40]. The idea of using the resonances to provide transmission zeros, both real and imaginary, is common today, but can suffer from loss issues due to the limited unloaded Q values presented by the resonant couplings. Coupling matrices used in synthesis today typically have not taken into account variation with frequency, and indeed the matrix entries can be considered constant for narrow band filters, i.e., with bandwidths of perhaps 20% maximum. However, when one synthesizes a filter with a much larger bandwidth, the variation of coupling across the passband is significant, and although optimization can modify dimensions to take this into account, a much better solution, resulting in a reduction in development time, takes this variation into account in the initial design phase. If a good circuit equivalent is used to model the coupling variation, initial optimization is possible in the circuit domain, with fine-tuning in the E-M domain. This variation also can be used effectively to provide real or imaginary transmission zeros or at least to reduce the required filter order, thus minimizing size and insertion loss.

Much development in this current period is attributed to G. Macchiarella [23], and in an also seminal paper by S. Tamiazzo and G. Macchiarella [24] in 2015, generalizing the use of coupling coefficients, using NRN, inverters and frequency-invariant couplings and showing the mathematical equivalence of synthesis using extracted poles to synthesize using NRNs. This work also demonstrated the coupling matrix synthesis with frequency invariant entries was inadequate for realizations with NRNs. The NRN approach is particularly useful in implementation of in-line filters, usually the physical configuration of choice for system applications. The use of NRNs also was shown to present some restrictions on the use of the coupling matrix approach, and the inclusion of dispersion into the inverters, resonator-NRN and resonator-to-resonator coupling is ongoing and promising, due to the work of Y. Yang, M. Yu et al, P. Zhao, K.L. Wu and others [41], [42]. Many details will be presented in Section II of this paper.

The use of non-resonating modes (NRM) as resonator bypassing elements for TM dual-mode configurations was pioneered by R. Sorrentino and S. Bastioli [43], and then extended to various microwave filter technologies by Bastioli and Snyder [101], [44], [45], and in conjunction with NRN techniques, provides new levels of miniaturization and efficiency in both waveguide and coaxial filter and multiplexer design.

Recent work on dielectric resonator filter development by C. Tomassoni and S. Bastioli [46], Bastioli, Tomassoni and Snyder [47], [48] now incorporates the use of both NRM and NRN techniques, achieving once again small size, fewer required resonators (a cost issue as well as a size issue), combined with low loss and enhanced stopband width. This work will be discussed in Section III of this paper.

Surface Integrated Waveguide (SIW) has become the planar or near-planar medium of choice, because of the ease with which it can be integrated with mounted components or interfaced into the rest of a system. Originally developed by K. Wu and his team, as well as many others in the last 10 years, it is used for many filter configurations including dual resonance, and in various air-supported or dielectric material supported varieties. Many applications of this technology are covered in Section III of this paper.

Also recently, the concept of using to advantage that which has been intentionally eliminated in the past has been the subject of much new research. The ideas of using dispersion and bypass are the core elements. Dispersion, when included in couplings, is both difficult and desirable, as discussed in the next few paragraphs. Bypassing energy before it gets to circuit elements generating spurious responses, and then recombining at the output, has been shown to extend the passband width of highpass filters and bandstop filters [49]. This latter will be discussed in Section IV of this paper

In common with filters discussed in previous sections, varactor tuned and PIN diode switched networks have today become more complex, and in conjunction with accurate synthesis, are the basis for fully bandpass, bandstop or multiplexed, and in some cases non-reflective, reconfigurable filter networks. The limitations on losses, tuning range and tuning speed previously noted as issues with the tuning elements still provide fundamental limitations at present. As previous limitations still exist due to tuning elements, no further discussion will be contained in this paper.

Active filters: Over the last 15 months, there has been some additional research on active filters. The work has progressed from the use of vacuum tubes (sic), through the latest new solid-state devices, with the hope of realizing low loss narrow band filters, with very high Q inductors, no stability issues, high power capability (improved IP3 threshold), and low noise figure. Spoiler alert: only partially successful so far (noise figure is still a major issue), but an overview of this work will be presented in Section V of this paper. Still being researched, it appears that in certain configurations, noise figure might remain essentially constant as filter bandwidth changes, leaving open the possibility that very narrow filters can be achieved, with low loss and without substituting increased noise figure for increased insertion loss. The subject will be discussed in Section IV of this paper.

Filter-Antennas: Characterizing the impedance of a radiating element (antenna) and synthesizing a matching network as part of a filter preceding the antenna has become popular. In principle, this avoids superfluous elements in the filter used to match to a 50 ohms interface, only to be later matched to the antenna. This is important technology for the wireless community, in which many bands are used, and it would be best to minimize the number of antennas required. The subject of matching into a radiating element will be discussed in Section VI of this paper. The Fano-Bode relations (also discussed in Section VI of this paper) limit the degree of match over a given bandwidth, and this fundamental limit is something not currently considered by practitioners probably because of confidence in their software to always provide an answer.

BAW/SAW (filters based on acoustic wave resonators): Technological advances enable generation of interdigital transducers of small pitch, and thus the upper frequency range for these devices has increased. Combining BAW/SAW high-Q resonators with passive low-Q components is a new and apparently fruitful development area [50], and if combined with appropriate tuning elements might result in development of small, low loss tunable filters. No further discussion in this paper.

Balanced filters: Combining filters with the baluns designed for use in low frequency couplers enables pairs of filters to be used in configurations intended to eliminate common-mode noise. The original baluns were designed to be broad band, and exhibited considerable insertion loss. More recently, the phase-inversion provided by baluns has been directly synthesized as part of the filter pairs, decreasing the loss and thus not negatively impacting the overall dynamic range. It seems likely that this technology will be extended well into the high microwave frequency range, and will be discussed in Section VII of this paper.

Additive Manufacturing: This will be covered in detail, in Section V of this paper. Section V will also discuss some other possible emerging techniques and/or technologies

C. THE FUTURE

…to be determined, but discussed in the Conclusions, Section VI of this paper.

II. EMERGING TECHNIQUE: SIMPLIFYING AND FORMALIZING FILTER DESIGN

The design of microwave filters requires first the assignment of the electrical specifications (typically represented by the so called ‘filter mask’), accompanied by various constraints regarding the physical size (layout, dimensions, weight, etc.), the environment (stability of the response vs. temperature, pressure, humidity, etc.) and still others, dictated by the specific filter application concerned.

The first choice the designer is required to make is the fabrication technology to be employed. Actually, this choice is strongly dependent upon the electrical requirements, the maximum insertion loss in the passband above all. This in fact imposes the required unloaded Q of the resonators, which finally determines the choice of the suitable technologies. Once the fabrication technology is selected, a good approach to the design of a microwave filter with narrow or moderate bandwidth comprises the following phases [51]:

1. *Approximation*. Here a suitable mathematical representation of the ideal filter response (disregarding losses) must be defined. This consists generally of a polynomial model reproducing the scattering parameters in a normalized frequency domain [52]. The transfer (S_{21}) and reflection (S_{11}) parameters are expressed as ratio of polynomials. The polynomial in the denominator is the same for all the parameters and its order represents the number of resonators used in the filter. The greater the order (also referred to as filter order), the higher is the attenuation produced by the filter at infinite frequency (but also higher are the insertion losses in the passband). The order of polynomial at numerator of the transfer parameter S_{21} defines the number of *transmission zeros*. These represent the frequencies where the attenuation goes to infinite in the ideal response (i.e., $S_{21}=0$). The roots of polynomial in the numerator of S_{11} are called *reflection zeros* and are the frequencies (inside the filter passband) where the reflection is zero. Usually, the polynomials are computed by assigning arbitrarily the transmission zeros and imposing $|S_{11}|$ equi-ripple in the passband (*Chebycheff approximation* [53])
2. *Choice of layout and synthesis of an equivalent circuit*. In this phase, the designer must decide the filter layout and synthesize a lumped-element equivalent circuit of the filter using the polynomial model previously

defined. From the synthesized circuit, useful parameters for the following phase are then derived (e.g., resonating frequencies of the resonators and coupling coefficients [52])

3. *Initial dimensioning*. The synthesized equivalent circuit must then be 'translated' into the physical structure realizing the filter. This is generally carried out by means of the extracted parameters from the synthesized circuit and produces the initial assignment of the geometrical dimensions of the structure
4. *Optimization*. The final phase consists in the refinements of the initial dimensioning so that all the electrical requirements are satisfied. In the past, this was done experimentally and required the fabrication of several prototypes and a long work, mainly based on a cut-and-try approach. Today, the use of general-purpose electromagnetic simulators avoids the experimental adjustments of the design and drastically shortens the overall required time.

As for the first phase, it should be noted that today, unlike in the past, more and more transmission zeros are required in the filter response. This is due not only to increasingly stringent requirements on the stopband attenuation, but also to the very low limits imposed to the linear distortion produced by the filters. The flatness of the group delay and attenuation is the primary requirement controlling the linear distortion; it could be improved by introducing complex transmission zeros in the response [54]. This however reduces the filter selectivity and makes the filter design more involved. A more effective approach is to increase the filters bandwidth (maintaining the stopbands position unchanged). In this way the linear distortion is reduced because the signal spectrum is concentrated in the central part of the filter passband, where both the group delay and attenuation are flatter. On the other hand, the increase of the bandwidth with the stopbands position unchanged implies a narrower transition from passband to stopbands, i.e., higher selectivity. Since the filter order cannot be changed so as not to increase the overall losses and size, the increase of the selectivity is achieved by introducing transmission zeros closer and closer to the passband.

In the second phase, the filter topology must be selected. Until recently, the most common choice for filters with transmission zeros was the cross-coupled configuration, for which well-established design procedures have been developed and a wide variety of literature is available [55]–[59]. Cross-coupled configurations can be classified into *canonical* and *cascaded-block* forms (Fig. 1).

Canonical filters have a fixed layout allowing the maximum number of transmission zeros (equal to the order of the filter). Fig. 1(a) shows the topology of the *transversal* canonical form [19]. This configuration is generally the starting point for the synthesis of many other topologies (both canonical and non-canonical), which can be obtained by means of suitable transformations (matrix rotations or Given's transform [19]). The transversal topology is also the form of recently proposed configurations that will be discussed in Section III. Fig. 1(b) shows the *folded* canonical form [58], another topology often used in practical applications (note that vertical and oblique couplings actually present depend on the number and type of transmission zeros). *Cascaded-block* filters (Fig. 1(c)) are composed of basic blocks connected in cascade, each introducing a specific number of transmission zeros [60], [61]. Among the possible blocks, the most popular are the *triplet* (three poles and one transmission zero) and the *quadruplet* (four poles and two transmission zeros, either a complex pair or both imaginary). The advantage of the cascaded-block configuration is the controllability of the transmission zeros, each depending only on few parameters of the block by means of which is introduced (in the canonical topologies each transmission zero may depend on several parameters of the whole configuration). On the other hand, the maximum number of transmission zeros in the cascaded-block configuration is not as high as in canonical configurations (it is typically lower than the filter order divided by two).

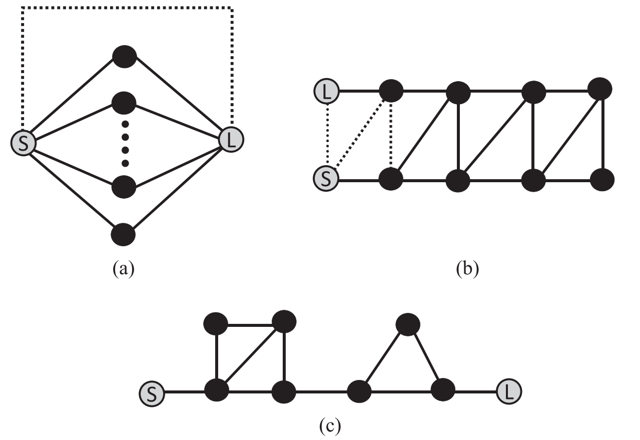


FIGURE 1. Routing schemes of cross-coupled configurations. Black circles: resonators, black lines: couplings (impedance/admittance inverters). a) Transversal canonical form (the source-load coupling is required for fully canonical characteristic). b) Folded canonical form. c) Cascaded-block form (quadruplet + triplet)

A relevant drawback of both the mentioned class of cross-coupled configurations is the relatively large volume required by the structure implementing this type of filters. As pointed out in the Introduction, miniaturization is a keyword characterizing today many applications of microwave filters. Consequently, new topological solutions have been developed for such applications, capable of satisfying both miniaturization and high selectivity, overcoming the mentioned limitations of cross-coupled configurations (including the difficulties of placing transmission zeros very close to the passband).

A. EXTRACTED-POLE CONFIGURATION

In-line topology is the simplest and more compact configuration for a microwave filter with no transmission zeros [52]. It is then a very good candidate for miniaturization, provided that a solution can be devised for introducing transmission zeros. A possible solution is represented by the extracted-pole topology where, in addition to the resonator, an additional

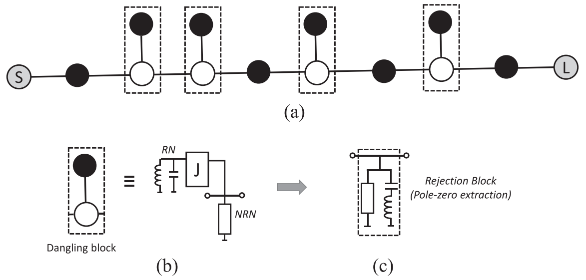


FIGURE 2. **a) Routing scheme of an extracted pole filter. Black circles: Resonant nodes (RN). White circles: Non-resonant nodes (NRN). Black lines: couplings (inverters). b) Explicit equivalent circuit of a dangling block (NRN is a frequency-invariant reactance). c) Transformation of the dangling block in a rejection block (both extract a pole-zero pair).**

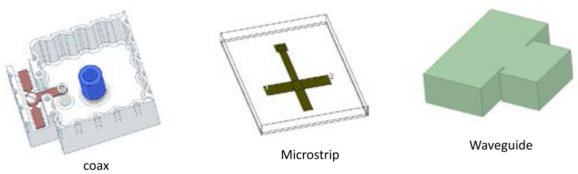


FIGURE 3. **Examples of practical implementation of pole-zero blocks.**

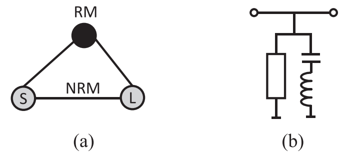


FIGURE 4. **a) Routing scheme of a singlet. b) Equivalent circuit of the singlet (rejection block), derived by a suitable transformation of the triplet configuration.**

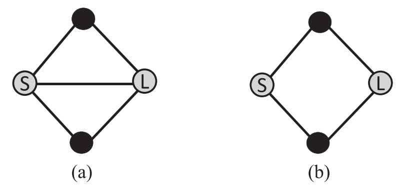


FIGURE 5. **Routing schemes of doublets. a) 2-pole and 2-zero. b) 2-pole and 1-zero**

element is used, capable of extracting a pole-zero pair (the pole is a root of the polynomial at denominator of the scattering parameters. It is also used to identify a reflection zero). Extracted-pole microwave filters were originally proposed by Rhodes [62], but their use was initially limited to special applications in waveguide technology. Things changed drastically in 2004 when Amari introduced the concept of non-resonating node (NRN) [63]. Based on this concept, a new quasi-inline topology was proposed, composed of three types of cascaded blocks ('dangling' blocks, resonators, couplings), implemented in many different technologies [64]. The routing scheme for this configuration is shown in Fig. 2(a), where it is also shown how the 'dangling' block (including the NRN) can be transformed into a cascade-connected block including a rejection resonator (identified in the following as *rejection block*).

Practical examples of physical structures extracting a pole-zero pair are shown in Fig. 3. The first (coax) implements a 'dangling' block while the other two (microstrip and waveguide) constitute rejection blocks.

Techniques have also been developed for the synthesis of extracted-pole band-stop filters [65].

For helping the 'translation' of the equivalent circuit into the physical structure, new universal parameters have been introduced (namely the *generalized coupling coefficients* [23]), which characterize the coupling between arbitrary nodes (both resonant and non-resonant). Recently, various procedure for dimensioning extracted-pole filters (represented as cascaded-block configurations) have been published [66], [67].

B. CASCADING SINGLETS AND DOUBLETS

In addition to the classical implementation of pole-zero blocks seen above, other solutions have been devised exploiting the concept of *non-resonating mode* (NRM) [68]. The simplest proposed structures is the *singlet,* composed by a cavity resonating on a selected mode and coupled to source and load. The cavity is also bypassed by another mode that cannot resonate, but propagates from source to load. The singlet is then equivalent to the triplet in Fig. 4(a), whose input and output nodes are non-resonating (source and load).

As a consequence, it is a network of order 1 (one pole), also producing one transmission zero in the response. Note that, with simple circuit manipulations, the singlet can be transformed into the rejection block shown in Fig. 4(b). It can then be used as a pole-zero block in extracted-pole filters [67].

Exploiting NRMs, another block (the *doublet*) has been proposed [69], [48], capable of extracting two poles and one or two zeros (examples of practical implementation of doublets will be illustrated in the following Section). The routing schemes of two doublet types are shown in Fig. 5. It can be observed that the doublets constitute a transverse canonical form (Fig. 1(a)) of order 2 (the one in Fig. 5(a) allows the fully canonical repose (i.e., two poles and two zeros) due to the presence of the source-load coupling).

Transversal forms of order higher than 2 exploiting NRMs have been also introduced (they will be discussed in the following Section).

Blocks exploiting NRMs, other than realizing standalone filters, can also be used in cascaded-block configurations implemented by compact structures, and exhibiting several transmission zeros, which can be controlled separately by each block [21]. Being this the target of many filters' applications today, design techniques for these new configurations are currently under investigation. When singlets or doublets are cascaded, the input and output nodes must be non-resonant (NRN), so the proposed configuration are represented by the schemes in Fig. 6. It can be noticed that such configurations belong neither to the cross-coupled topology nor to the extracted-pole one, consequently new design solutions are required.

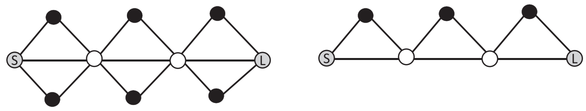


FIGURE 6. New cascaded-block topologies. a) Cascaded doublets. b). Cascaded singlet. Note that the cascaded blocks can also be separated by inverters (i.e., the shared NRNs between adjacent blocks are replaced with two NRNs coupled with an inverter). All the shown topologies are fully canonical (same number or poles and zeros).

Concerning the synthesis of the equivalent circuits of these new configurations, most of the published works resort to optimization techniques [69], [48], [70]. However, a synthesis procedure for the topology in Fig. 6(b) has been published recently [71], exploiting the mentioned equivalence of the singlet with the rejection block. Very recently, also a procedure for the synthesis of the topology in Fig. 6(a) has been developed [72], based on suitable transformations applied to the extracted-pole equivalent circuit of the filter.

The new dimensioning approaches for these new configurations (also suitable for extracted-pole filters) exploit the cascaded-block nature of the structure [67], [71]. In fact, each block can be dimensioned separately, by imposing the same response of the corresponding circuit block in the synthesized equivalent circuit. This "Divide and Conquer" technique makes easier the dimensioning of the filter structure because the solution of a multivariate complex problem (the design of the whole filter), is obtained by solving many reduced-order problems (the dimensioning of the blocks), each depending on few variables.

C. FREQUENCY-DEPENDENT COUPLINGS

As previously observed, the inline topology is the reference configuration for realizing compact and easily realizable filters. In addition to the previously mentioned solutions, another technique is currently gaining particular interest for introducing transmission zeros in the inline configuration. It consists in introducing the transmission zeros by means of the coupling elements [73]. The couplings in all-pole inline filters are represented with ideal impedance (or admittance) inverters, which are frequency-independent components, characterized by a constant parameter K (or J). To introduce a transmission zero in the response, a frequency dependent inverter can be used, with $K(f)$ (or $J(f)$) equal to zero at the frequency f_z of the transmission zero and equal to a suitable value at the center of the passband, so that the required return loss in the passband is preserved. Note that if one inverter of the inline configuration is equal to zero, the incident signal is completely reflected back, so producing infinite attenuation (which is the same behavior of a rejection block). To practically implement this idea, various structures have been devised, whose frequency characteristic approximates the frequency-dependent inverter just described. Practical solutions have been implemented in waveguide (partial height post and resonant irises [74], [75]) and coaxial [76] technologies. Initially, the filter designs were carried out by means of empirical approaches, mainly resorting to the numerical optimization of the physical structure. More recently, rigorous synthesis methods have been developed, based on suitable transformations of the coupling and capacitance matrices of canonical cross-coupled configurations [77], [78]. Using the mentioned methods, it is possible to synthesize the equivalent circuit of an inline filter with up to N-1 transmission zeros (with N order of the filter) [78].

A new structure (the *stopband singlet*) for implementing FDC has been recently proposed [79], which exploits NRMs in rectangular waveguide for creating a resonant coupling. This structure allows the transmission zeros placement very close to the passband without degrading too much the unloaded Q of the adjacent cavities (as it happens with the previously mentioned discontinuities implementing FDC in waveguide technology). To this regard, it must be observed that resonant couplings strongly interact with the adjacent resonators, modifying both the slope parameter and the unloaded Q of these resonators [80]. Consequently, the filter design may become very difficult (if not impossible) when the parameters produced by the synthesis of the filter equivalent circuit are not compatible with the constraints imposed by the resonators' technology and the electrical requirements (e.g., the transmission zeros position).

FDC have been introduced also in cross-coupled topologies, both canonical [81] and cascaded-block [82], [83]. In the last case, they allow increasing the number of transmission zeros generated by the considered block with constant couplings. For instance, a triplet and a quadruplet with one FDC between input and output generates two and three transmission zeros respectively [82].

D. CONCERNING THE EQUIVALENT CIRCUIT OF THE FILTERS

We have seen that the second phase of the usual design approach for microwave filters consists in the synthesis of a lumped-element equivalent circuit, which is then suitably 'translated' into a physical structure in the third phase. Consequently, the response of the real filter is only an approximation of the ideal synthesized response, because the synthesis is carried out in the lumped-element world while the physical structure belongs to the distributed-element world. As well-known, the accuracy of such an approach is generally acceptable for cross-coupled filters with narrow and moderate bandwidth. Filters with NRN or NRM also include frequency-independent reactances (or susceptances) in the synthesized equivalent circuit, which, in the real structure, become unavoidably frequency-dependent. The result is an increase of the discrepancies between the synthesized response and the real one (for the same filter bandwidth).

Today this accuracy problem is generally faced (and solved) in the last phase of the design approach, which consists of the final optimization of the dimensioned structure, represented with a full-wave electromagnetic model (topic that will be discusses in the next paragraph).

Nevertheless, special design techniques have been developed to improve the initial design accuracy of filters with relatively wide passband, based on the synthesis of more accurate equivalent circuits. As mentioned in the Introduction, the very first solution proposed for wideband filters design is due to Richards, who introduced the concept of commensurate unit element and moved the synthesis of the prototype into the distributed-element world [8]. Although very important conceptually, the practical convenience of this method is limited to very special cases. More recently, it has observed that, in many cases, the reason for the poor design results of relatively large bandwidth filters (10%-50%) was due to the frequency dependence of the physical structure implementing the couplings (represented as frequency-independent inverters during the synthesis). Design procedures have then been developed, using frequency-dependent model for the couplings between the resonators [84]–[86]. Note that the goal in this case has been to improve the modeling accuracy and not to introduce transmission zeros (as discussed in the previous paragraph). Design techniques for improving the accuracy of filters including NRNs have been also investigated. The solution proposed in [87] is based on the synthesis of the filter directly in the bandpass domain (instead of the normalized lowpass domain, where synthesis is usually carried out). In this way NRNs can be represented as inductors or capacitors (representation not allowed in the normalized domain). This approach may be affected by numerical accuracy issues in case of high order filters, due to the high degree of the polynomials involved in the synthesis.

E. REFINEMENT OF THE DESIGN WITH FULL-WAVE SIMULATORS

Refinement of the initial dimensioning is the last step of the design, which today is carried out exploiting the accuracy of the commercially available electromagnetic full-wave simulators. However, although the full-wave simulators allow the effective representation of the filter structure, the time required for the simulation (and, above all, for the optimization) of a complete filter is still very relevant (even using the latest generation PCs). For this reason, alternative methods to brute-force optimization have been devised, especially advisable when the results of the initial design of the filter are not very good. Direct optimization remains in any case an option for the separate dimensioning of the blocks composing the cascaded configurations discussed before.

The most popular technique for the efficient optimization of filters structures is the so-called *space mapping* [88]. It is based on two representations of the structure to be optimized, one very fast to simulate but not very accurate (e.g., the filter equivalent circuit) and the other very accurate but very demanding in term of the simulation time (it is generally based on full-wave modeling). The space mapping performs the optimization in the space of the coarse model, using the fine model to correct the results obtained. In this way the final accuracy of the optimization is mainly determined by the full-wave modeling, which is however used only to 'drive' the optimization performed with the coarse model. The overall requested time with this technique is orders of magnitude lower than that required by brute-force optimization with full-wave modeling of the filter. Several implementations of the space mapping techniques may be found in the literature, some of which specifically developed for filters optimization [89].

Another 'smart' use of full-wave simulators in the filters design is represented by the *port tuning* [90], [91]. Suitable locations are identified in the filter structure, where observation ports for the full-wave simulation are placed. At the selected locations, the resonance of the cavities composing the filter must be observed. We can then 'tune' the equivalent resonators by means of lumped reactances connected to these ports (this operation is generally carried out in a circuit simulator, where the computed N-port scattering matrix obtained by the full wave simulation of the filter has been imported).

A variant of the classic port-tuning method that avoids the use of an external circuit simulator is presented in [44], where the observation ports are placed at the end of an open-circuited (or short-circuited) transmission line (the ports replace the open-circuit or the short-circuit). Observing that the resonance frequencies of the cavities depend on the length of the transmission lines, the reference impedance of the ports is renormalized to a short-circuit (or an open-circuit) so that the tuning is carried out by moving the position of the ports reference section. As this operation is performed in post-processing (i.e., does not require the full-wave re-simulation of the structure), the tuning of the filter can be carried out in real time directly in the full-wave simulator. Moreover, using the derivative estimation of the response with respect to the geometrical parameters of the structure (available in some commercial full-wave simulators) a very fast estimation of the coupling coefficients between the cavities can be computed (always in post processing), allowing the real time tuning of also the coupling coefficients. These new implementations of the port-tuning method have been successfully applied in recently published works [92], [93].

III. EMERGING TECHNIQUE PSEUDO-ELLIPTIC REALIZATIONS

The increasing need for very steep filtering functions having extreme close-in rejection characteristics provides the reason as to why filter designers have been focusing more and more on the implementations of basic building blocks capable of generating transmission zeros. On the other hand, the need for size reduction and miniaturization pushed the filter community to find advanced realizations capable of providing the maximum number of functionalities within a single building block. The result is the one formally modelled in the previous section: a set of rather complex and high-functionality building blocks are combined in a simple way so as to obtain extreme filtering function characteristics. What is meant with the term "high-functionality" is that a single building block is responsible for the generation of multiple poles and multiple zeros. This is certainly advantageous in the world of narrowband filters, where the primary concern is to make sure we are wasting the least amount of frequency spectrum between adjacent channels or a closely-adjacent interference that has to be rejected. The size reduction, as well as the mass reduction for that matter, comes from the fact that less building blocks will be needed to obtain a certain characteristic. In other words, since the available volume is more efficiently exploited, the same function can be realized within a much smaller volume. When these advanced techniques are combined with advanced technologies, the quest for the miniaturization of very high-performance filters can undoubtedly become much more viable.

As the need for size reduction varies among different technologies (while certainly being proportional to the operating frequency), it is no mystery that cavity filters are generally the ones demanding most of the attention. Waveguide cavities, evanescent mode resonators, as well as dielectric loaded or coaxial based cavities are generally rather bulky, or at least significantly larger than any other component within the RF system (the antenna might be the exception). It is always important to keep in mind that the benefit of extreme close-in rejection does get nullified if the insertion loss at the passband edges exceeds a certain specified value. For this reason, besides the number of poles and zeros provided by a certain building block, another essential aspect that needs to be considered is the quality factor of the employed cavities/resonators. To this regard, the waveguide technology is the one providing the highest performance in terms of Q-factor, thus leading to the lowest possible passband insertion losses. At the same time, the waveguide is also the most cumbersome technology. It should therefore not come as a surprise that most of size reduction techniques have been originally developed for this particular technology.

The waveguide is also the perfect specimen to exemplify the concept of high-functionality building blocks. A standard waveguide cavity can be seen as a basic building block which generates a single pole, and higher order filters are obtained by employing multiple cavities. Since the physical reduction of the structure would require the presence of some form of capacitive loading inside the cavities (which would significantly decrease the resulting Q-factor), the most efficient way to reduce the size of the overall filter is by increasing the number of poles provided by each cavity; even better is if each cavity can also provide one or more independent transmission zeros. Such high-functionality waveguide cavities can be obtained nowadays by adopting advanced configurations of the classic multi-mode techniques, and/or by exploiting the more recent concept of nonresonating modes.

The multi-mode technique originally pioneered in [94], consists of using multiple resonant modes inside the same physical cavity. As a result, such cavities will be able to provide multiple poles readily available to increase the order of the filtering function. Depending on the internal coupling and routing scheme of these resonant modes, the cavity may also be able to generate finite frequency transmission zeros,

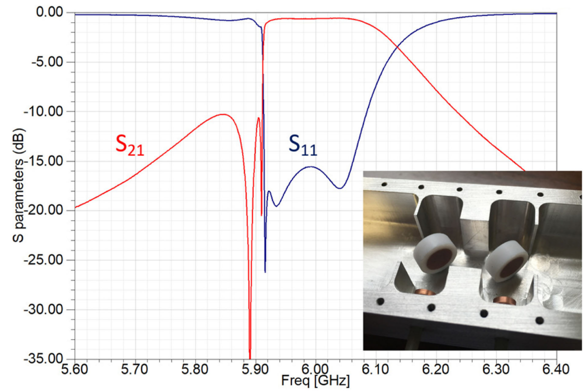


FIGURE 7. Pseudo-elliptic filter using two cascaded mixed-mode cavities.

the latter statement being especially true for cavities implementing transversal topologies [19]. A very proper example is the dual-mode cavity proposed in [95], where the two modes are connected at same time to both input and output so as to obtain a doublet topology (Fig. 5[b]) generating two poles and one transmission zero.

Along the same conceptual line, i.e., multi-mode configurations with transversal topologies, several contributions have been appeared and continue to be reported in the literature for the most various technologies. The same doublet topology as [95] is implemented in [96] by using a mixed-mode cavity. Such a cavity effectively behaves as a dual-mode structure where one mode is the TE_{101} mode of the cavity, while the other one is the $TE_{01\delta}$ mode of a dielectric resonator properly arranged within the cavity. The mixed-mode cavity represents an interesting emerging concept where modes belonging to different technologies are properly combined to attain unique characteristics. The filter proposed in [48] is indeed one of the first contributions capable of exploiting dielectric resonators (typically limited to much less than 1% bandwidth filters) for the realization of moderate bandwidth filters up to 3%, while providing the added benefit of realizing transmission zeros extremely close to the passband edges. Fig. 7 shows the experimental results and the structure of the filter, which comprises two mixed-mode cavities. Each cavity represents a building block generating an independent transmission zero in addition to the two poles, and the design procedure reported in [48] is indeed inline with the modular design concept previously discussed for cascaded-block topologies.

More complex triple-mode configurations are reported in [97] and [98], the latter employing a ceramic cavity. These works rely on building blocks implementing third order transversal topologies (three resonant modes connected in parallel between input and output). Even more extreme is the architecture presented in [99], where two triple-mode spherical cavities are connected in parallel so as to double the order of the transversal topology (up to six resonant modes connected in parallel). The structure of this filter is shown in Fig. 8. Observe that single-mode resonators (based on half-wavelength coaxial lines) are embedded as first and last resonators to

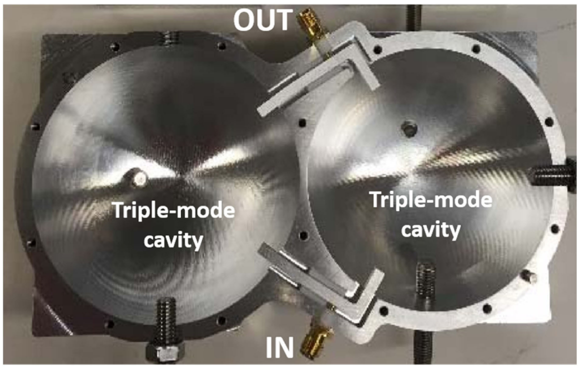


FIGURE 8. Triple-mode cavity filter (one disassembled half) using two spherical cavities connected in parallel (From [99]).

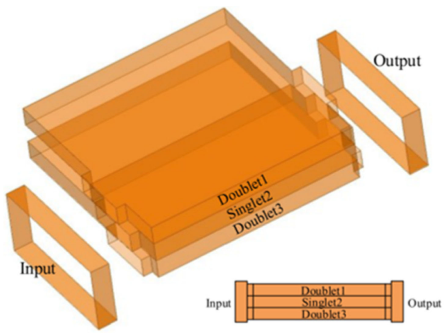


FIGURE 9. Conceptual structure of a filter where single- and dual-mode reduced-height cavities are stacked and connected in parallel between standard input and output waveguide interfaces (From [100]).

feed the two spherical cavities. The fact that two multi-mode building blocks are connected in parallel (instead of being cascaded in series) makes the structure of Fig. 8 a truly unique realization.

Another original realization following the same concept is the one very recently reported in [100], where again multiple blocks are combined in parallel for the realization of very compact pseudo-elliptic structures. The realizations in [100] are based on a set of reduced-height stacked cavities that are excited at both input and output by a standard rectangular waveguide as depicted in Fig. 9. Depending on the configuration of the stacked cavities, which themselves implement singlets or doublets, various location of the transmission zeros can be obtained. As an example, the structure depicted in Fig. 9 with two doublets and one singlet implements a fifth order transversal topology having five poles and three transmission zeros. Although somewhat different than the modular approach discussed in the previous Section, it is worth noting that the authors in [100] spent a significant effort to explain a simple design approach based on the individual full-wave design of the various sub-parts of the structure, thus confirming the emerging preference for structures and design techniques which comply with some form of modularity.

Although still exploiting the multi-mode nature of a distributed microwave structure, a completely different technique is the one based on the exploitation of the nonresonating modes [101]. Mostly developed within the last decade, the nonresonating mode technique has paved the way for the advent of a new class of microwave filters: parasitic modes and spurious resonances (historically avoided, suppressed, or compensated for) become crucial design elements allowing the designer to attain unique structures with unique filtering function characteristics and performance. Instead of increasing the number of resonant modes (either connected in parallel or series), the objective of enhancing the functionalities of a single building block is attained by mostly increasing the number of transmission zeros generated by a cavity/resonator. The latter task is accomplished by properly engaging specific parasitic modes so as to realize additional nonresonating paths which bypass the main resonant path (as depicted in the singlet topology in Fig. 4[a]). As a result, the nonresonating mode technique generally consists of rather simple low order blocks (typically singlets and doublets) which are always connected/cascaded in series. Besides the obvious advantage of realizing pseudo-elliptic filtering functions within an inline structure, the manufacturing complexity of this type of filters typically remains as simple as the one required by conventional all-pole Chebyshev structures. From the filtering function perspective, this technique proved to be especially effective when realizing transmission zeros extremely close to the passband edges.

Since the earlier works exclusively based on waveguide technology (summarized in [68]), the non-resonating mode technique has invaded all the main microwave filter technologies, including dielectric resonator filters [46], [102]–[105], planar configurations [106], [107], [70], as well as the coaxial resonator technology [108]–[112], [92], [93]. At the same time, waveguide implementations based on nonresonating modes keep on appearing in the literature. As an example, the family of TM cavity filters [113]–[115], [69] has been recently extended in [116] with the introduction of a new over-moded cavity which is especially suitable for very narrowband high frequency applications. Waveguide implementations manufactured with advanced micromachining techniques are indeed very popular for millimeter wave applications, and structures making use of nonresonating modes have been recently reported in [117] and [118].

In contrast with most nonresonating mode technologies where the engaged parasitic modes are already existing within the structure, some coaxial implementations have the unique feature of exploiting parasitic modes that are purposely generated by design. These implementations are based on the strongly-coupled resonators concept. Such a concept consists of clustering two or more resonators (very closely located one to each other) in order to use the resulting in-band resonances as filter poles, while exploiting the far away out-of-band resonance (pushed away because of the strong mutual coupling) as a nonresonating mode providing bypass coupling. The first coaxial structure based on this concept is the strongly-coupled resonator pair (SCRP) introduced in [110], where two resonators are properly arranged so that the odd mode of the

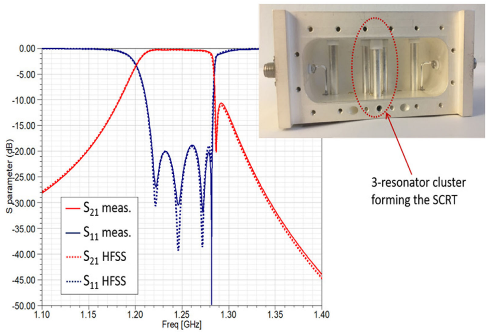


FIGURE 10. Coaxial filter with a strongly-coupled resonator triplet (SCRT).

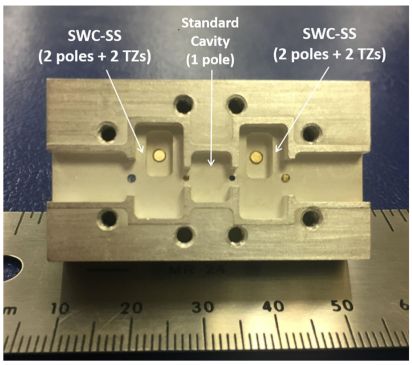


FIGURE 11. Waveguide filter using two stubbed waveguide cavities (SWC) in single-stub configuration (SS) connected by a standard waveguide cavity.

pair is the resonant mode while the even mode serves as a nonresonating mode. The SCRP can therefore generate a pole and a transmission zero (not counting the contribution of additional adjacent resonators used to feed the pair).

The SCRP has been recently supplemented by the strongly-coupled resonator triplet (SCRT). Proposed in [112] with the purpose of extending the functionalities provided by a single building block, the SCRT is capable of generating two poles and a transmission zero. The structure and response of a filter employing a SCRT between two standard coaxial resonators is shown in Fig. 10. Coaxial comb-line filters using SCRPs and/or SCRTs can realize inline filters with independent transmission zeros (located above and below the passband) without needing capacitive probes or any other form of negative coupling. Systematic design procedures for this class of filters have been recently formalized in [92] and [93].

High-functionality blocks with the largest number of poles and zeros can be obtained when the multi-mode and the nonresonating mode techniques are jointly applied, as it is the case for the very recent stubbed waveguide cavity (SWC) proposed in [119] and [120]. Proposed in both single- and double-stub configurations (indicated as SS or DS, respectively), a SWC embodies a basic building block that can generate up to three poles and three transmission zeros. The filter structure showed in Fig. 11 employs two SWC in SS configuration (each cavity is configured to provide two poles and two transmission zeros) that are cascaded by a standard

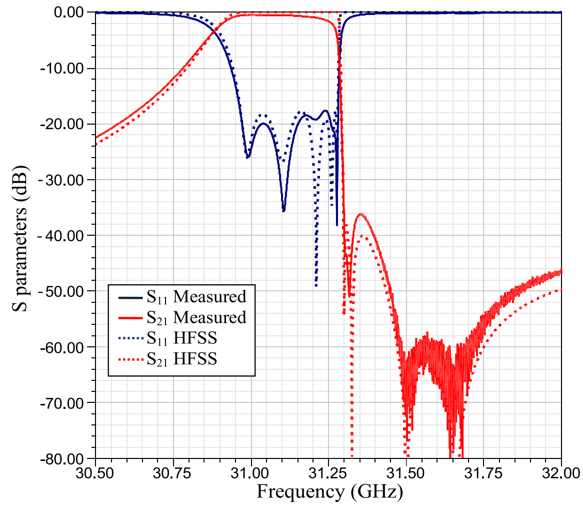


FIGURE 12. Experimental results of the filter in Fig. 11 (From [120]).

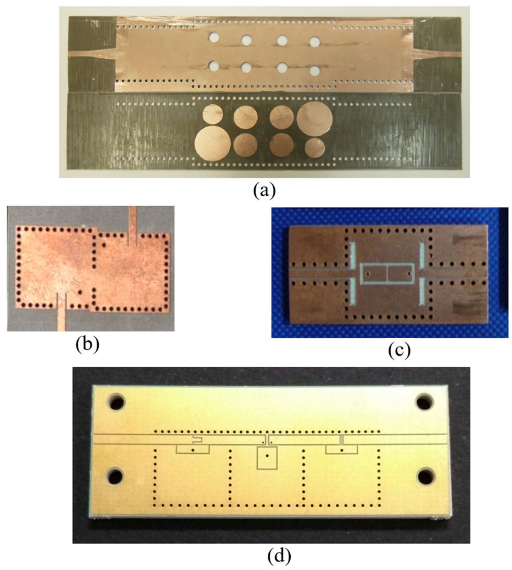


FIGURE 13. Advanced pseudo-elliptic SIW implementations: (a) filter using four pairs of mushroom-shaped resonators (From [107]); (b) filter using dual-mode cavities (From [121]); (c) coaxial SIW dual-mode cavity (From [122]); (d) filter using three cascaded coaxial SIW singlets (From [70]).

waveguide cavity. The resulting filtering function shown in Fig. 12 includes five poles and four transmission zeros. This example clearly demonstrates the effectiveness of a modular design based on high-functionality building blocks when it comes to attain extreme performance while occupying a very limited volume.

The trend of using multiple modes and/or nonresonating modes has also manifested itself in planar filters, the latter statement being particularly evident when considering the various advanced substrate integrated waveguide (SIW) based structures that have appeared in the literature in the last five years [107], [70], [121]–[124]. Fig. 13 shows a collection of some the structures proposed in those references.

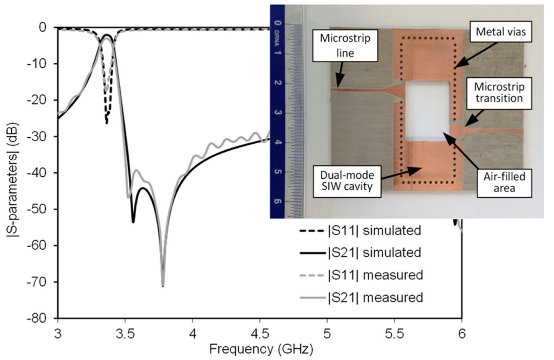


FIGURE 14. **Air-filled SIW cavity for doublet implementations (From [123]).**

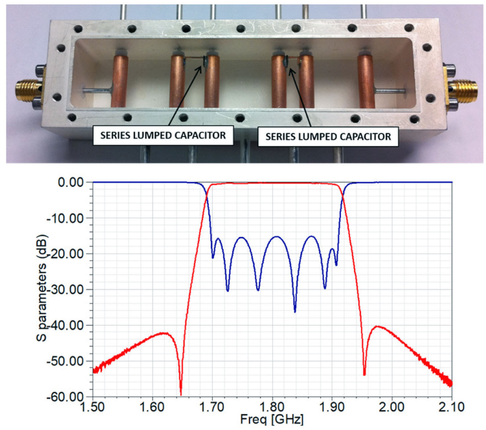


FIGURE 15. **Coaxial filter using two mixed lumped-distributed resonant couplings for the generation of two transmission zeros (From [76]).**

The high performance SIW filters and diplexers reported in [121] make use of dual-mode cavities implementing transversal doublet topologies. Each doublet exploits a lower order nonresonating mode whose contribution is modelled by means of a nonresonating node connecting input to output.

More complex are the SIW structures proposed in [107] and [122], where a pair of capacitively loaded posts are used as embedded TEM resonators to exploit the even and odd modes of the pair. Specifically, the structure in [107] (referred to as mushroom resonators) implements a singlet, as it follows the same logic applied for a SCRP where the even mode is not resonating; on the other hand, the structure in [122] (referred to as coaxial SIW cavity) implements a doublet where both even and odd modes are resonating (dual-mode behaviour). As far as coaxial SIW structures are concerned, particularly interesting is the recent contribution appeared in [70], where various coaxial SIW structures (including singlets, doublets, as well as various cascaded topologies) are presented for both bandpass and dual-band applications. Analogously to what previously discussed, the work in [70] exemplifies the effectiveness of the modular approach extended to planar structures.

Other interesting implementations of doublet topologies are those recently reported in [123] and [124], where air-filled SIW cavities are employed. Fig. 14 shows one of the doublets realized in [123]. These air-filled cavities behave as dual-mode cavities exploiting the parallel connection of the transversal topology as well as taking advantage of the bypass coupling provided by nonresonating modes.

Third order topologies are also possible by embedding additional resonant elements into a dual-mode SIW cavity, as very recently reported in [125] and [126]: the structure reported in [125] implements a third order transversal topology thanks to the presence of a capacitively loaded partial-height post located at the center of the cavity; on the other hand, the structure proposed in [126] utilizes the combination of a dual-mode cavity with a stripline resonator that can be modelled with a topology where the central resonator is extracted and connected to the main line (between the other two resonators) by means of a nonresonanting node.

Aside from the multi-mode and the nonresonating mode techniques, a different trend has also emerged in recent years with the aim of realizing pseudo-elliptic filters. Such a trend is the one including all the works devoted to the exploitation of frequency-dependent couplings. In contrast with the previously discussed realizations, whose main objective is to more efficiently exploit the available volume while generating more poles and/or more transmission zeros in each building block, for the frequency-dependent coupling technique the focus has shifted from the cavities/resonators to the coupling elements. The frequency-dependent coupling technique consists of using standard cavities/resonators that are coupled by means of more complex coupling structures. Such coupling structures effectively behave as frequency-selective elements that are capable of generating a finite frequency transmission zero (in the stopband) while providing the required coupling coefficient in the passband region.

The realization of inline filters with finite frequency transmission zeros represents the original objective that fuelled the frequency-dependent coupling method. One of the earliest works for evanescent mode filters was presented in [76], where the usage of lumped elements capacitors connected in series between two adjacent coaxial resonators was demonstrated. Fig. 15 shows the structure and experimental results of the filter proposed in [76]. The purpose of the series lumped element capacitor is to resonate the series distributed inductance of the evanescent-mode waveguide. At the resonant frequency of such a mixed lumped-distributed LC resonator, the coupling between the adjacent coaxial resonators is null, thus making it possible to generate a finite frequency transmission zero. Since two resonant couplings are used in the filter of Fig. 15, two corresponding transmission zeros are generated in the filtering function. Although completely different than the nonresonating mode technique, this example confirms again the nowadays tendency to take advantage somehow of the parasitic elements inside a filter (in this case the series distributed inductance of the evanescent-mode waveguide).

The usage of frequency-dependent couplings has been and continues to be applied to the most various microwave filter technologies, and some of the most recent contributions are

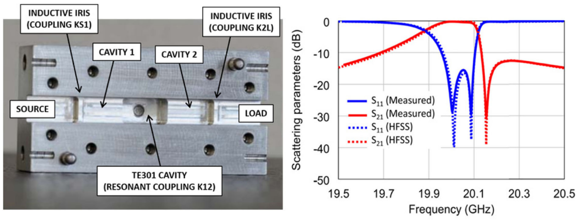


FIGURE 16. Stopband singlet (From [79]).

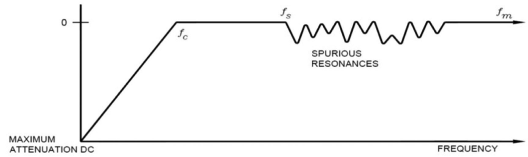


FIGURE 17. High Pass Problem Definition. f_c is the defined cut off frequency, f_s is the frequency of the first spurious resonance, f_m is the desired maximum passband frequency (From [49]).

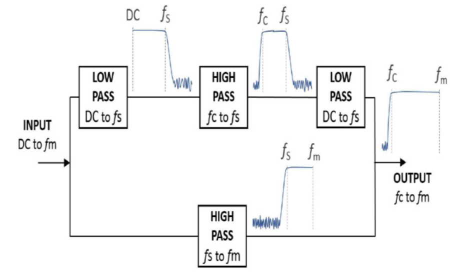


FIGURE 18. Block Diagram of the proposed method for bypassing spurious producing components and then recombining all frequencies (From [49]).

reported in [77]–[79], [81], [87]. Some recent realizations also involve the SIW technology [127], [128]. Very common for this technique are rectangular waveguide realizations, where a frequency-selective coupling can be easily realized as a stub, partial height post, or some form of resonant discontinuity. In this regard a very recent work focused on the dimensional synthesis of this kind of waveguide filters has been published in [87].

Independently of the realization technology, frequency-dependent couplings can become practically unfeasible as the transmission zero location tends to be too close to the passband edge thus contributing additional insertion loss to the passband. However, such a problem does not impact one of the latest additions to the family of filters using frequency-dependent couplings, that is the novel stopband singlet introduced in [79]. The stopband singlet consists of a TE_{301} mode cavity which is used to generate a transmission zero between two adjacent waveguide cavities. Fig. 16 shows the structure (disassembled half) and frequency response of such a configuration. Since the transmission zero is actually generated from the destructive interference created by a strong bypass coupling through the fundamental nonresonating mode, the stopband singlet be defined as the first structure capable of integrating the nonresonating mode technique into the frequency-dependent couplings method.

On a final note, it is worth noting that advanced pseudo-elliptic realizations based on more classical cross-coupled topologies continue to appear in the literature for various technologies. Innovative folded waveguide realizations based on quadruplet topologies have been recently proposed in [129] and [130] for both bandpass and dual-band applications, while a new coupling structure for the realization of cross-coupled topologies within an inline waveguide has been introduced in [131]. Moreover, SIW cross-coupled filters (including multilayer realizations) have been recently reported in [132] and [133]. Interestingly the structure reported in [133] makes use of higher order nonresonating modes to bypass a box-like topology. Finally, some cross-coupled implementations for coaxial SIW (triplets and quadruplets) are summarized in [134].

IV. OTHER EMERGING TECHNIQUES

A. BYPASSING SPURIOUS RESONANCES

One problem common to most filter networks is the presence of unwanted resonances in the components comprising the filter. For example, in a highpass filter, the series elements are primarily capacitors, but the parasitic inductance in the connections to the capacitors means that at some frequency above the highpass cutoff, energy will encounter resonances due to the interaction of the capacitor and parasitic inductance, and be delayed (meaning extra passband insertion loss will occur). Similarly, the shunt elements, primarily inductors, have parasitic capacitance associated and cause similar resonances at some point in the passband. To avoid these undesirable "glitches" (called spurious resonances) in the passband, it has been found possible to prevent the frequencies that would encounter resonance around the highpass network, re-routing them to the output, for recombination with the rest of the passband [49]. Fig. 17 shows the basic problem and defines the terms. Fig. 18 illustrates the basic solution, essentially a double-diplexer (extendable to a double multiplexer). Thus, the frequencies that would show "glitches" do not pass through the elements with parasitics, and a much wider passband is achieved. A similar approach might be possible for enhancing the passband width for bandstop ("notch") filters. It is expected that re-routing frequencies subject to unwanted resonances will be a fundamental philosophic change in filter design strategy, and in general shows that treating filter design problems as system design problems is a potentially useful strategy.

Fig. 19 is a photo of a 30 to 6000 MHz High Pass constructed using the described technique [49].

B. ACTIVE FILTERS

The use of external positive feedback in vacuum tube amplifiers has been around since the 1950's, used for implementing what was termed "Q-multipliers" [135]. This technique was used to artificially decrease the bandwidth of receivers, for enhanced selectivity, with some cost in stability. In the 1970's,

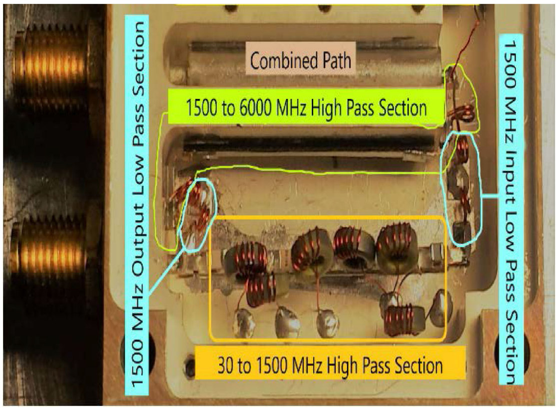


FIGURE 19. Implemented 30-6000 MHz highpass filter (From [49]).

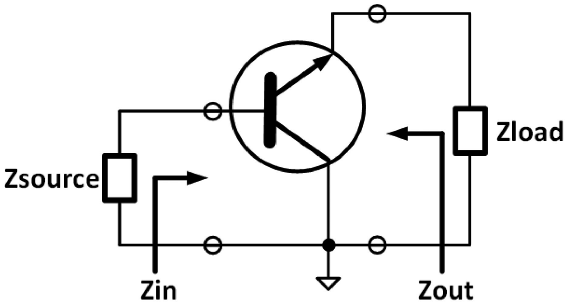


FIGURE 20. The "inverted common-collector" configuration with a BJT (Bipolar Junction Transistor)

the circuit, termed "inverted common collector" (ICC), shown in Fig. 20 was proposed by D. Adams and R.Ho and further developed by R. Snyder and D. Bozarth. [31], [32]. Considerable work has been accomplished by Sussman-Fort [33] and Chang [34] and many others, but battery drain as well as linearity, noise figure, and stability have proved challenging. The original circuit used feedback within a bipolar junction transistor (BJT) to simulate inductance in series with a negative resistor, thus implementing a high-Q inductance.

When a capacitor was placed in parallel, a very high Q tank circuit was achieved. Coupling such high Q tanks together into simple filters essentially traded DC power for Q (same way as with Q-multipliers), and pointed the way towards small filters with low loss.

Using a Z-parameter description of the network, the impedance Zin can be calculated as:

$$Zin = Z_{11} - \frac{Z_{12}Z_{21}}{Z_{22} + \ Z_{\text{load}}} \tag{5-1}$$

Similarly, for the impedance Zout in Fig. 20:

$$Zout = Z_{22} - \frac{Z_{12}Z_{21}}{Z_{11} + \ Z_{\text{source}}} \tag{5-2}$$

So, in accordance with (5-2), for $Zsource = R + j\omega L$, the generated Zout can be described by a series circuit of negative resistor and an inductor (Fig. 21(a)). [136].

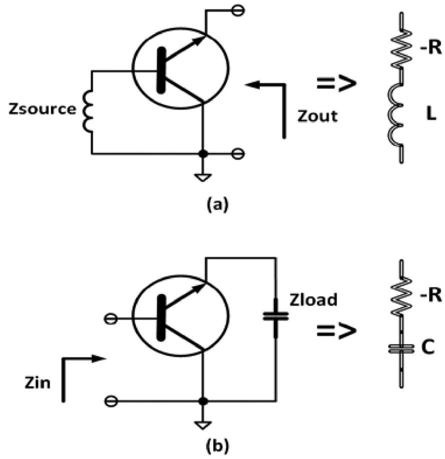


FIGURE 21. BJT negative resistance circuit topologies. (a) Inverted common-collector circuit with inductive source, (b) inverted common-collector circuit with capacitive load.

In the configuration shown in Fig. 21(a), the choice of R in series with an inductor forming the source impedance inserted into the base of the BJT is selected for a compromise between Q and stability of the equivalent output inductor.

Although very promising, the technique suffered from stability, linearity (low IP3) and noise figure problems. Very low insertion loss did not translate into very low noise figure, and so system dynamic range was determined by the effective noise figure and the IP3 point.

More recently, work has been started on using small vacuum tubes [136], not for small size or low DC power, but for enhancing the IP3 performance. Vacuum tubes used in configurations analogous to the ICC have been found to be superior not only in IP3, but in noise performance, as compared to BJT, FET and even GaN devices. Given some availability (not so available presently) of very small vacuum triodes, this work shows promise for the future, particularly in systems not limited in DC power, such as vehicles, aircraft or ships.

C. SYNTHESIZING FILTERS INTRINSICALLY MATCHED TO VARIOUS LOADS

Of recent interest has been the idea of synthesizing matching structures directly into filter transfer functions, to match a variety of sources and loads, including antennas and amplifiers. It is sometimes overlooked by designers that Bode and Fano provided limits on the degree of match possible between a given source and load, each with both resistive and reactive components, as a function of the bandwidth over which match is to be provided. This work was well-described in the famous "Black Bible" of filters [10], in the first chapter, Eq. 1.03-1 to 1.03-4.

Matching to amplifiers or other broadband components is not difficult, and because the filter and matching are usually in close physical proximity (on the same substrate), and as the broadband device impedance characteristics do not change drastically over the required matching bandwidth, this requires only that the designer ignore 50Ω to 50Ω thinking at the interface, and simply use the device impedance as a load for the filter synthesis procedure.

However, matching into an antenna [137]–[139] presents a greater difficulty, and that is due to the nature of the antenna impedance as a radiating device and the typical feedline length, between the filter and the antenna, typically due to the physical location of the antenna relative to the filter. As well, it is necessary that all reflection zeros of the antenna be located in the left half plane, possibly making it difficult to match active antennas directly.

Space limitations prevent presentation of the mathematical formalism pertaining to antenna impedance at resonance and anti-resonance (the difference between these two in the frequency domain usually defines the antenna bandwidth), but at resonance the imaginary part of the impedance dominates, must be tuned out (or conjugately matched), leaving the antenna real part as the remaining impedance to be matched. Antennas with high directivity tend to have steep slopes of reactance versus frequency, and are thus more likely to encounter the restrictions set by the Bode-Fano equations. To date, only simple, ladder-derived filter topologies have been employed (at least in published work), but using some of the design techniques discussed in Sections II and III of this paper might result from good conversations between filter and antenna designers. This might be an ongoing and productive area of development for future systems.

D. BALANCED FILTERS

Electromagnetic Interference, or EMI, has two components: conducted and radiated. Both have two sub types, common mode and differential mode. Communication systems frequently suffer "common mode" noise, a conducted interference caused by stray coupling between a circuit element and ground, typically passing back through the power supply and into another part of the system. The noise current in this case travels in the same direction on the positive and negative sides of the power supply. Common-mode noise is at the heart of conducted electromagnetic interference issues, i.e., "conducted EMI". When a noise source appears across the power supply lines and is in series with the power supply lines, the noise current flows in opposite directions on the positive and negative sides of the power supply, thus being termed conducted "differential mode noise" [140].

When radiating elements are involved, common mode interference can occur due to coupling between radiating elements, and what was defined as due to the power supply can now be considered as due to the RF source, with analogous same- or opposite- directed current flow. Such interference is termed "radiated EMI", with the common mode component the most important.

Using multiple coupled lines supporting both common mode and differential modes, it is possible to use odd/even mode analysis to design filter networks that can suppress the unwanted common mode noise in the microwave portion of a system. These designs can be implemented using split-ring resonators of various configurations, and do not require balanced to unbalanced transformer feeds ("baluns"), which are lossy elements. Thus, microwave equivalent circuits can be used to design filters that act to suppress common-mode noise in the microwave portion of the system, and thus reduce radiated EMI [141], [142].

As radiated EMI generates fields approximately 100 times higher than fields due to conducted EMI, suppressing common-mode radiated EMI is clearly quite important. As systems move to higher and higher frequency operation, it is anticipated that low-loss balanced filter networks enhancing common-mode noise immunity will become increasingly important for maximizing system dynamic range.

V. EMERGING TECHNOLOGIES

A. ADDITIVE MANUFACTURING (AM)

Also known as 3D printing, AM is a very interesting manufacturing technology whose popularity is exponentially increasing. In contrast to a milling technique that works by subtracting material, AM works by adding material. Generally, with this technology, the object is manufactured layer by layer.

According to the International Organization for Standardization (ISO/ASTM 52900:2015), AM processes are classified in 7 groups:

1. **binder jetting powder**: materials is joined by deposition of liquid bonding agent.
2. **directed energy deposition**: deposited material is melt by focused energy.
3. **material extrusion**: material is dispensed through a nozzle.
4. **material jetting:** deposition of droplets of material
5. **powder bed fusion:** a powder bed is selectively melted and fused by thermal energy.
6. **sheet lamination**: sheet of cut material are bonded to form the object.
7. **vat photopolymerization**: material contained in a vat of liquid is solidified by a laser.

In the last years the electromagnetic community started using this technology for the manufacturing of EM components [143]. The use of AM for filters [144] is particularly challenging because of their resonant nature that makes them very sensitive to losses. However, the use of AM, potentially provides several advantages. Contrasted to the new trends in design that are oriented toward a "Divide and Conquer" philosophy, from the point of view of the fabrication manufacturing in a single block, thus avoiding parts to be assembled, is preferable. Indeed, flanges and screws for assembling make the component bulky and heavy. AM offers this possibility, as well as the possibility of manufacturing lattice or honeycomb structures, thus allowing lighter components. Another important feature of the AM is the high flexibility that allows for fabrication of objects with non-conventional geometries that cannot be manufactured with traditional machinery. Rapid prototyping, immediate design revisions, low cost and custom design are other advantages. However it is difficult to exploit all that advantages, as they depends on many factors, including the

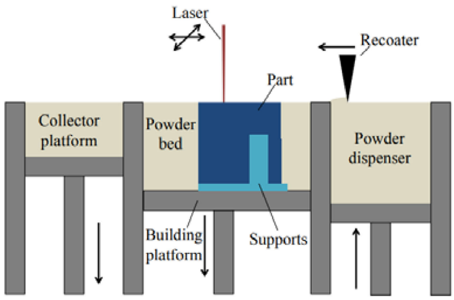


FIGURE 22. Schematic diagram of a selective laser melting system [145].

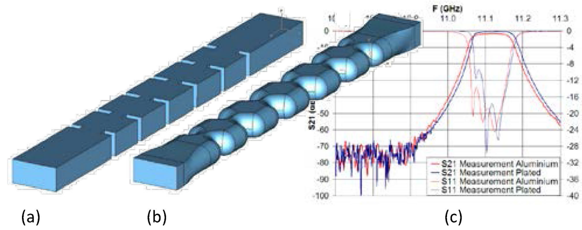


FIGURE 23. Filters manufactured in [146]. (a) Regular inductive 5th order iris filter. (b) Modified 5th order filter with smooth surfaces. (b) Comparison between simulated and measured results for the polished silverplated filter.

AM technology used, the selection of suitable materials, the specialization of the process for EM components etc. From this point of view, research is still playing an important role.

A large number of materials can be used in AM. Among them, three materials particularly useful in the fabrication of filters are: metals, plastics, and ceramics.

1) AM OF METAL FILTERS

The most popular technology for the metal additive manufacturing of filters is the Selective Laser Melting (SLM). SLM falls into the category of powder bed fusion processes. The working principle is illustrated in Fig. 22. A recoater takes the metal powder from the dispenser and spreads a thin layer of powder (20-60 μm) in the powder bed. A high power laser melts selectively the powder of that layer. After that, the building platform is moved down for allowing the recoater to spread another powder layer to be selectively melted [145]. The object is manufactured layer by layer. Supporting structures manufactured along with the component are sometimes needed for avoiding collapses of overhanging structures like horizontal (or small tilted) planes. Supporting structures, represented in cyan in Fig. 2, are removed after the printing process.

Several different metals can be used with SLM: Titanium, aluminium, stainless steel etc.

The first experiments on filters manufactured with this technology started more than 10 years ago. In 2009 Lorente [146] presented a couple of 5th order pass-band filters in X-band manufactured by SLM. One filter was a regular inductive iris filter, the other one was a filter with smooth surfaces (see Fig. 23). Both filters were manufactured with different materials: aluminium alloy and titanium. The measured manufacturing tolerances were about 0.05 mm in XY plane and about 0.15 mm along z-axis. Smooth shapes allowed an increase of Q-factor of about 15%. However, because of the roughness, (an order of magnitude higher than that of a machined surface), the Q-factor obtained was lower than that attainable by traditional manufacturing techniques. As often happens with AM, a postprocessing is necessary to obtain better performance. In that case surface chemical polishing plus silver plating allowed for a Q-factor similar to that of the milling techniques.

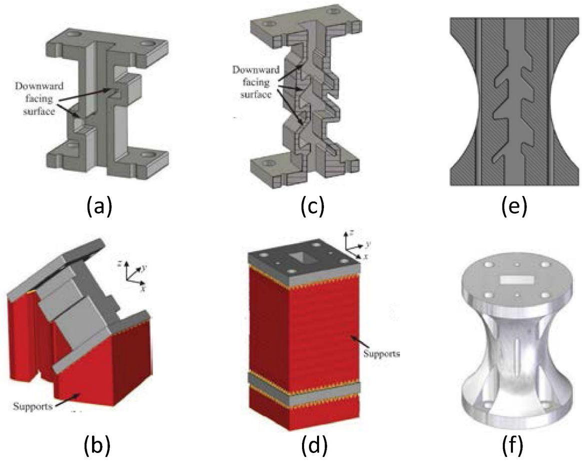


FIGURE 24. Filters manufactured in [C5]. (a) Traditional design. (b) Traditional design and supports. (c) AM oriented stub design. (d) AM oriented stub design with supports. (e) 2D view of AM oriented stub and external shape design. (f) 3D view of AM oriented stub and external shape design. In this case no supporting structure are needed.

Other postprocessing treatments such as thermal stress relieving can help in increasing the manufacturing accuracy. In [147] a comparison among Ku/K-band low-pass filters manufactured in SLM with different metals (maraging steel, titanium alloy and aluminium alloy) shows that the titanium prototype is the least accurate. Titanium strength is higher than that of aluminium and steel. This in theory should correspond to a higher printing resolution. Unfortunately higher strength leads to a higher melting temperature that results in higher thermal stress capable of deforming the structure when detached from the building platform. For that reason a stress relieving postprocessing in an oven at high temperature before the structure is detached from the building platform is advisable. In case of titanium objects a temperature up to 700 °C is used.

Another important aspect for obtaining performant components is the use of an AM oriented design. With this approach, the design takes in consideration the AM features. An example of this approach is shown in [148] where a project developed in [149] has been modified for increasing the manufacturing accuracy. In [149] a low-pass filter of Fig. 24(a) has been designed, and, in order to avoid internal supporting

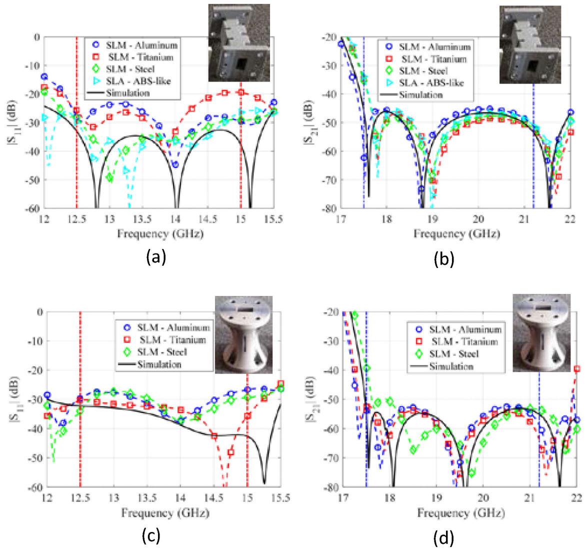


FIGURE 25. Comparison among responses of 6th order low-pass filter manufactured with different materials [147]. (a) Pass-band of the filter with traditional design. (b) Stop-band of the filter with traditional design.]. (c) Pass-band of the filter with AM oriented design. (b) Stop-band of the filter with AM oriented design.

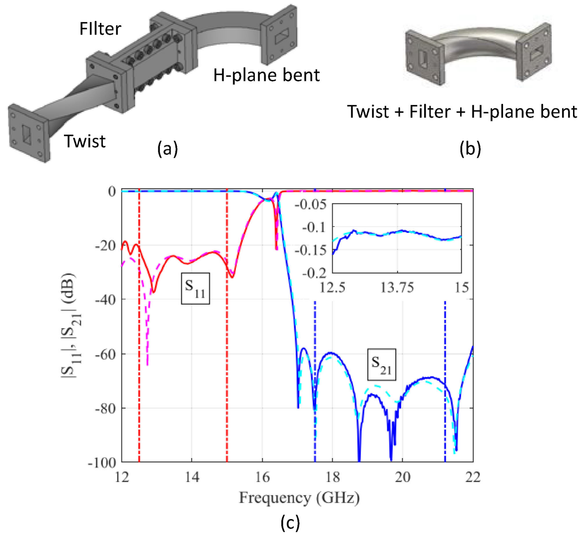


FIGURE 26. Low-pass filters [150]. (a) Assembled structures composed by three components: a twist a filter and an H-plane bent. (b) AM structure with the functionality of a twist a filter and and H-plane in a single piece. (c) Comparison between measured (solid lines) and simulated (dashed lines) scattering parameters

structures that cannot be removed, the filter has been manufactured with a tilt angle of 45 deg. In Fig. 24(b) the tilted filter is shown along with supporting structures (in red). The tilted position, however, decreases the accuracy. Indeed, the resolution along XY-plane depends on the beam-spot size that is lower than the layer thickness (about 30 microns) that determines the resolution along the Z-axis. The result of the tilt is a staircase discretization along the waveguide profile that can be avoided by positioning the structure vertically. Vertical position however requires the modification of the stub shapes for avoiding internal supporting structures. In other word an AM oriented design is needed. The resulting filter with modified stub shapes is shown in Fig. 24(c), whereas the same filter with the external supporting structures is shown in Fig. 24(d).

A further step forward in AM oriented design has been done in [147] where the external profile of the filter has been redesigned in order to maximize the heat transfer for reducing the thermal gradient and the thermal stress during the manufacturing. As can be seen, the response of the filters with AM oriented design (Fig. 25(c) and Fig. 25(d)) has higher performance than that of the filter with traditional design (Fig. 5(a) and Fig. 5(b)). The estimated dimensional accuracy for such components is in the range of 40-70 μm.

The high flexibility of AM has been cleverly exploited in [150], where the assembled structure of Fig. 26(a) composed by three components: a twist, a low-pass filter and an H-plane bent has been realized in the single compact part shown in Fig. 26(b) by using a non-conventional geometry that couldn't be manufactured with traditional techniques. Its response is shown in Fig. 26(c).

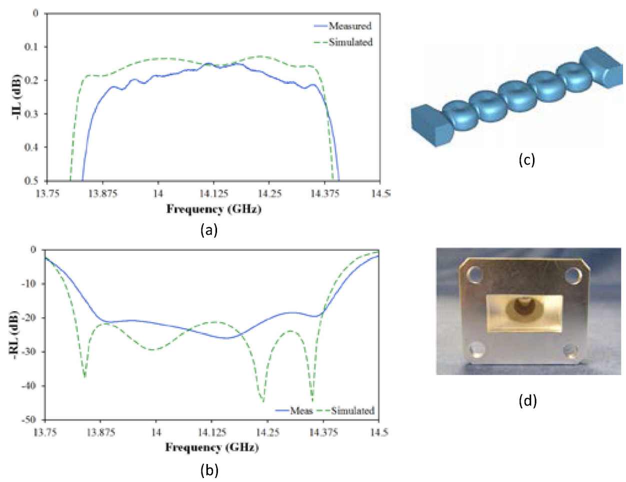


FIGURE 27. Measured and simulated performance of the breadboard filter [152]. (a) Insertion loss. (b) Return Loss. (c) Filter sketch. (d) Photo of the filter.

In [151] a sort of combline C/X-band bandpass filter with non-conventional post shapes has been manufactured. Posts have a shape of mushrooms with spherical caps. Authors called them lollypop-shaped resonators.

Researchers from Airbus developed a waveguide filter with depressed super-ellipsoid cavity [152], [153]. This shape has been used in order to decrease losses and to increase the spurious free band (see Fig. 27). Furthermore, authors noted that losses were less than expected considering the obtained roughness. Their conclusion was that the SLM uses a powder whose grains tend to be spherical and that probably this leads to more rounded peaks and troughs compared to conventionally manufactured components. They made the hypothesis

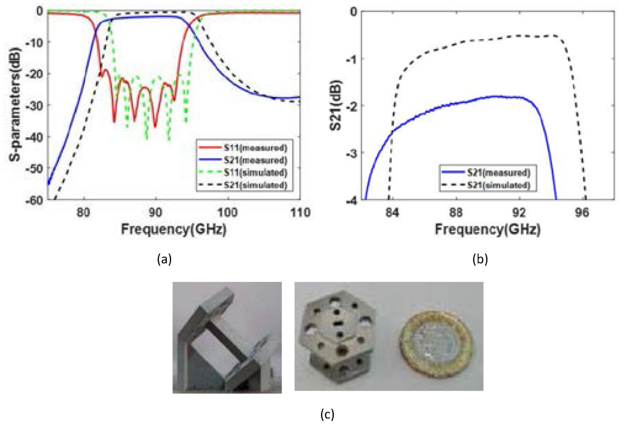


FIGURE 28. 5th order filter [155]. Comparison between Measured and simulated responses. (a) Filter response. (b) Insertion loss. (c) Photos of the filter.

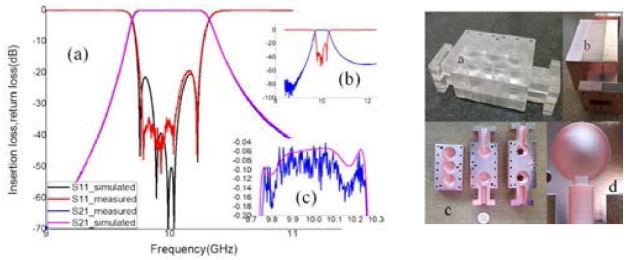


FIGURE 29. Comparison between measured and simulated result for the 5th order filter in [166]. (left) Filter response and manufactured filter. (right) Photo of manufactured filter.

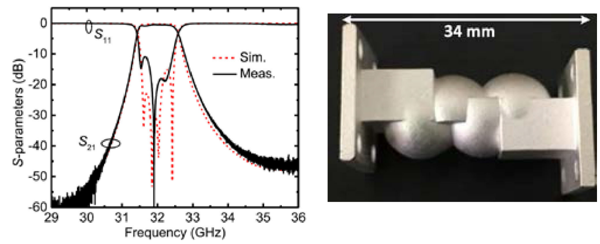


FIGURE 30. Comparison between measured and simulated result for the 5th order filter in [170]. (left) Filter response and manufactured filter. (right) Photo of manufactured filter.

that this could form an easier path for the currents with less localized concentration. Furthermore, a very interesting aspect of this filter is that it successfully passed all the space qualification tests, thus demonstrating the SLM suitability for the manufacturing of satellites components.

With the manufacturing tolerances of SLM the increasing of operational frequency can be a problem as shown in [154] where filters working around 70 and 80 GHz (E-band) have been manufacturing. However, impressive results in W-band have been obtained in [155] by using Micro Laser Sintering. With this high resolution technique a stainless steel band-pass filter of 5^{th} order at 90 GHz with fractional bandwidth 11% has been manufactured and results are shown in Fig. 28.

2) AM OF PLASTIC FILTERS

In contrast to AM of metal, plastic AM may be very inexpensive. Some 3D printers for plastic materials cost only a few hundred dollars. Of course cheaper 3D printers suffer with high manufacturing tolerance. However, it is possible to reach very high precision even with printers that cost a few thousand dollars. There is a wide scientific literature about plastic AM of filters that covers several AM technologies. Herein we will present only few examples.

A filter realized in plastic must be metallized. The easiest way to do this is by using silver paint [156]–[158]. Paint can be spread by a brush or sprayed. It can be heat-cured. The surface conductivity is not very high (10^5-10^6 S/m;). This results in filters with poor Q-factor. Another possibility is the electroless plating [159], [160]. This method allow the metallization of internal parts without the needs of dividing the filter in two or more pieces. A third possibility is the electroplating. Electroplating is a very efficient metallization process that allow high surface conductivity, however it only works on conductive surfaces. This means that the surface shall be made conductive. In these cases, silver paint [161] or electroless plating can be used.

One of the lowest cost and popular AM technology is the Fused Deposition Modelling (FDM). This technology falls into the category of material extrusion processes. In this case a filament of plastic material is dispensed through a nozzle. The nozzle (usually 0.25–0.4 mm) determines the mechanical accuracy (that it is not very high). This technology has been used to demonstrate the possibility of using the infill percentage to modulate the dielectric constant of the plastic in dielectric filters [162]–[164], however it is not very suitable for the manufacturing of filters [157], [158], [165].

Stereolithography (SLA) falls into the category of vat photopolymerization processes. In this technology, a laser selectively solidifies a liquid resin contained in a vat. The plastic structure is manufactured layer by layer. After a layer is completed the platform where the plastic structure is attached shifts a little bit to allow the next layer to be manufactured. This technology allows good resolutions. Resolution is determined in the XY-plane by the laser spot diameter (50–100 μm) while the resolution along the Z-axis is determined by the layer thickness (25–200 μm). The roughness is on the order of few microns. This technology has been widely used for filter manufacturing as it allows very good results.

Filters based on spherical resonators represent a good test for this technology because of their high Q-factor [166]–[170]. In [166] a 5th order filter centered at 10 GHz with 5% of fractional bandwidth has been manufactured. The measured passband insertion loss is 0.107 dB on average, while the simulated value is 0.072 dB. Results are shown in Fig. 29. In [170] half-spherical resonators have been employed in order to obtain a more compact structure. Results are shown in Fig. 30.

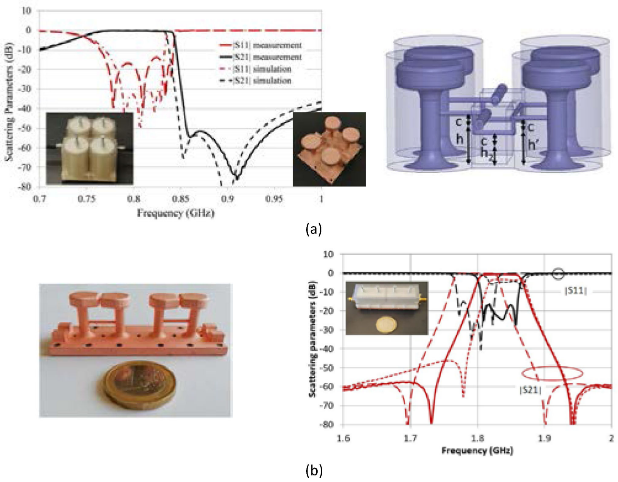


FIGURE 31. Comparison between measured and simulated response of four pole filters. (a) Filter in [173]. (b) filter in [174].

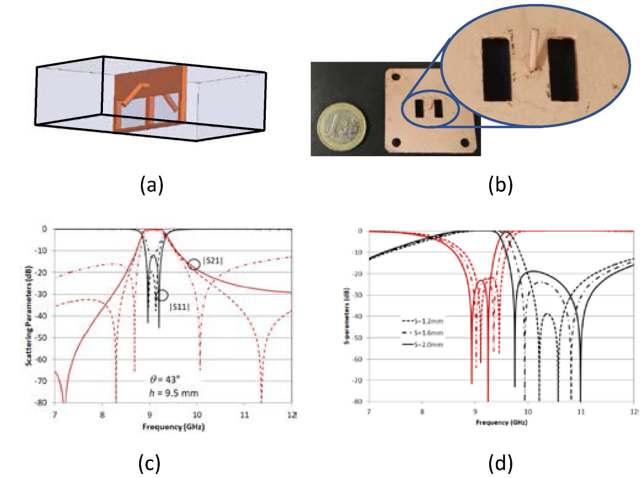


FIGURE 32. Two pole filter with two posts mounted on a thin septum. (a) Septum filter inserted in a waveguide. (b) Photo of the septum filter. (c) Response with a TZ in the lower and a TZ in the upper stop-band. (d) Two transmission zeros in the upper stop-band.

The high flexibility of AM has been exploited for the manufacturing of filters with non-conventional shapes that cannot be manufactured (or would be very difficult to manufacture) by using traditional manufacturing techniques [171]–[177]. In [172]–[174] filters based on post resonators are shown. In Fig. 31(a) mushroom shaped posts are connected through a sort of wire [172], [173]. Use of a mushroom shape guarantees very compact structures and wide spurious free stopbands. Position and shape of the connecting wire controls the position of transmission zeros (TZs). The whole structure, including wires, is manufactured with a 3D printer. In that filter a pair of posts transversally positioned implements a doublet. The design of the 4 pole 4 TZs (2 double zeros) filter has been obtained by cascading two identical doublets. The filter designed in [174] exploits frequency depending couplings obtained by a mix of inductive and capacitive coupling. Inductive coupling is obtained by a straight wire connecting the stalks of adjacent mushroom shaped posts, whereas electric coupling is obtained by reshaping the cap of the two adjacent posts so as to create a capacitive effect. Filter response is shown in Fig. 31(b).

In [175], [176] an extremely compact class of filter is presented. The filter consists of 2 bent post mounted on a thin septum (0.5 mm). The thin septum is connected to the waveguide through the flange. The septum with the two bent posts realizes a doublet capable of two poles and two TZs. As shown in Fig. 32, there is a high flexibility in terms of TZs positioning.

In [177] several wide spurious free band coaxial filters have been manufactured with SLA technology. The main idea is to exploit the supports of the central conductor as impedance inverters. Several filters, along with the response of a fourth order quarter-wave resonator filter are shown in Fig. 33.

In [178] a continuously tunable filter made by SLA using a 3D spiral ribbon is presented. According to Fig. 34, the ribbon intersects the waveguide. The part of the ribbon inside the waveguide creates an E-plane filter. The ribbon width changes continuously as the ribbon rotates, thus allowing a variation of the central frequency of the filter. In Fig. 34 The variation of the response with the ribbon rotation is shown.

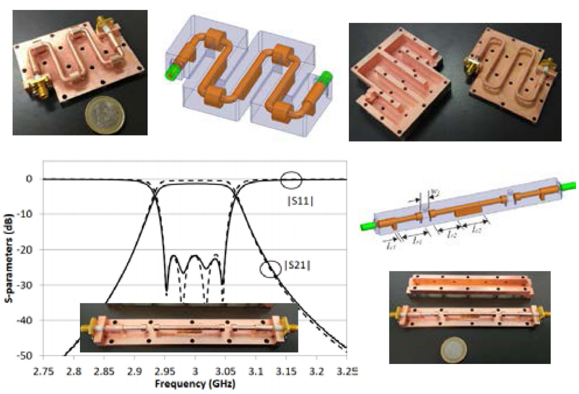


FIGURE 33. Comparison between measured and simulated response of the 4th order filter in [177]. Sketch and photos of other filters are also shown.

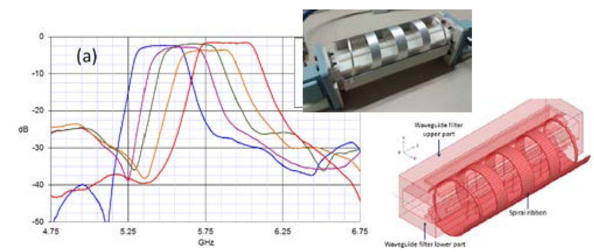


FIGURE 34. Continuously tunable filter in [178]. Measured S21 scattering parameters for different rotation angles of the ribbon.

SLA technology has been used for filters in W-band in [179]. In Fig. 35 the measurement of a 5th order filter is shown. Results are very impressive. In the same figure a photo

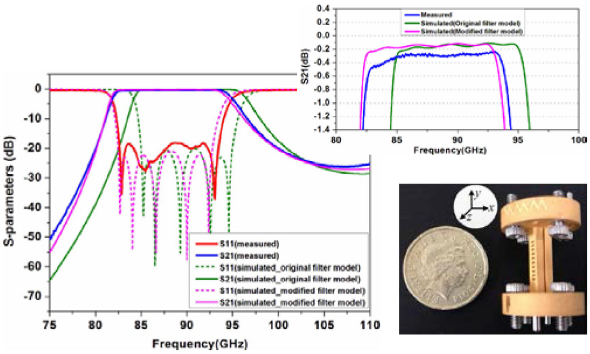


FIGURE 35. **W-band 5th order filter [179]. Comparison between simulations and measurements.**

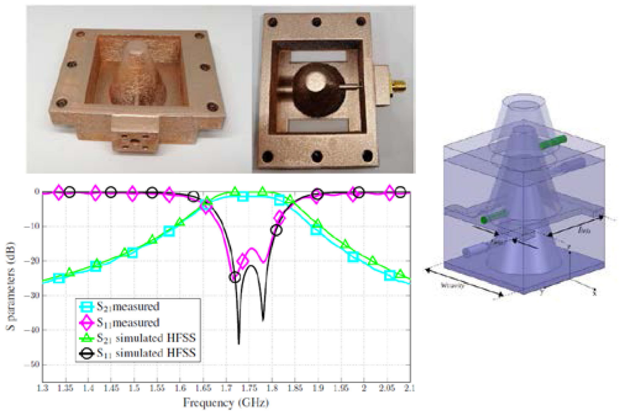


FIGURE 36. **Comparison between simulation and measurement for the filter in [180]. Sketch of the filter along with photos of some parts of the disassembled filter after the electroplating are shown.**

of the filter is also shown. The filter has been manufactured with slots for facilitating the metallization of the internal parts.

PolyJet is another interesting AM technology for the fabrication of plastic filters. PolyJet falls into the category of material jetting processes. Droplets of photopolymers are sprayed with a system similar to that of the inkjet printers. Droplets are immediately cured by UV light after their deposition. Multinozzle printer heads can be used to obtain multimaterial structures or to increase the manufacturing speed. The resolution is even better than that of the SLA (15–30 μm). The measured roughness is about 0.5 μm.

In [180] a filter based on conical post resonators working at 1.75 GHz has been manufactured by PolyJet printer. This geometry allow for cavities to be piled. This filter presents volume reduction and increased spurious free band with respect to classical combline filters. Results are shown in Fig. 36 along with the sketch of the filter and photos of some parts of the disassembled filter after the electroplating.

In [181], [182] the PolyJet printer has been used for the manufacturing of a doublet working in X-band consisting in a slotted ridge positioned into a waveguide.

In [183] a 4th order filter in groove gap waveguide technology working at around 35 GHz with fractional bandwidth

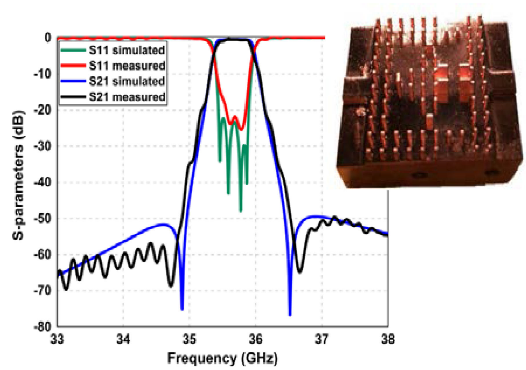


FIGURE 37. **Comparison between simulation and measurement for the filter in [183]. The photo of metallized filter without the cover is shown.**

1.4% has been manufactured using PolyJet printer. As can be seen in Fig. 37, there is an excellent agreement between simulations and measurements considering the relatively high frequency.

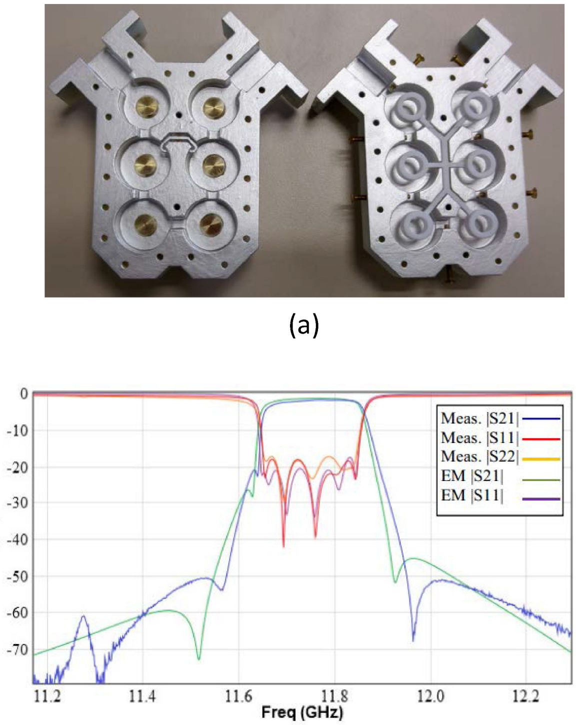
In [184] a filter working at 90 GHz and manufactured with Aerosol jet printing technology has been presented. The peculiarity of such a filter is that Aerosol jet printing technology was used to deposit both the dielectric substrate and conductive traces. Conductive traces have been manufactured by using conductive ink.

3) AM OF CERAMIC FILTERS

Additive manufacturing of ceramics is possible thanks to the Lithography-based Ceramics Manufacturing (LCM) technology that falls into the category of vat photopolymerization processes. Indeed, LCM works by polymerizing a ceramic powder suspended in a photosensitive resin. The resin is selectively cured layer by layer. The resulting part is called green body. The green body is composed of ceramic particles distributed within a photopolymer matrix. The manufactured part needs a post processing to remove the photopolymer and for sintering the ceramic particles. Post processing is a delicate phase as it needs high temperatures, and thus there is the risk of cracks. Furthermore, there is a very significant shrinkage of the green body during the post processing that shall accurately be taken into account to obtain the desired dimensions of the manufactured object.

There are very few works in literature regarding the manufacturing of filters with this technology. In [185] and [186] authors designed and manufactured a TM monolithic filter. This filter is made of two cavities that are not accessible for the metallization. The metallization is done in the external part only. From the Electromagnetic point of view the dielectric is included in the cavity. One of the advantages of using this technology however, is that the ceramic (alumina or zirconia) has excellent dielectric properties and shows a very low loss-tangent. This means that it can be used not only as a support for the metallization but also as a dielectric material itself.

Researchers from the XLim of Limoge used LCM manufactured parts as dielectric material to be inserted into metallic



(a)

(b)

FIGURE 38. Filter in [189]. (a) Photo of the disassembled filter. (b) Comparison between simulation and measurement.

enclosures [187]–[189]. In [187] a monolithic dielectric rod of zirconia shared among several adjacent cavities has been used in the design of TE01δ filters with wide bandwidth. In [188] a dielectric inserted into a cavity is used to tune the cavity resonance frequency for obtaining continuously tuned Ku-Band filters. The dielectric shape is designed so that a controlled rotation of the dielectric provokes a controlled resonance frequency shift. Finally, in [189], a skeleton-like monobloc dielectric pucks made by additive manufacturing is shown. As can be seen from Fig. 38(a) the dielectric monobloc maintains the hollowed dielectric pucks suspended in the middle of the cavities. The advantage of this arrangement is that it is not necessary to use glue for the positioning of the dielectric pucks.

LCM seems a very promising technology. Indeed AM ceramic objects present some potential advantages with respect to AM plastic objects: they are more hard and stable, they can resist very high temperatures and they can be used directly as dielectric materials. As discussed earlier, plastic can be used as dielectric material, but its loss-tangent is higher.

B. HIGH-PRECISION MILLING AND MICROMACHINING

One of the future challenges in filter technology will be increasing the operational frequency up to sub-THz and THz frequencies. In general, the manufacturing of components at those very high frequencies is challenging [190], [191] and this is particularly true for resonating structures like filters.

The manufacturing tolerance of the classical computer numerically controlled (CNC) milling technique has increased dramatically in the last years. Tolerance below 10 µm can be relatively easily obtained thus allowing the manufacturing of filters working at 100 GHz as in [192] and [193], or at 200 GHz as in [194]. Tolerance can be pushed to 2.5 µm as in [195] where filters working at 675 GHz have been successfully manufactured. In [179] a laser-based micromachining technique has been used in combination with CNC milling for the manufacturing of a filter in w-band. Laser micromachining is very accurate but it is not cost-effective when a considerable amount of material has to be removed. For this reason it can be combined with CNC milling. In the same paper a similar filter has been also manufactured by AM technology, as shown in Fig. 35.

A very interesting and promising manufacturing technique is the SU-8 Photoresist Technology. SU-8 is an epoxy-based resin that, once cured, is resistant to organic solvent. S-8 can be photolithographically patterned. This technology seems very promising for mass production, as it allows the production of several components in a single run and it has potentially lower cost than milling technique.

In [196] two different filters with the same specifications and with 287.3–295.9-GHz passband have been manufactured with two different manufacturing techniques: High Precision CNC Machining and SU-8 Photoresist Technology. Both filters perform very well, and show a similar behavior in terms of losses and stopband rejection. The SU-8 technology has been used in [197] for the manufacturing of a filter centered at 671 GHz, while in [198] for the manufacturing of a four-pole dual-band waveguide filter at 100 GHz exploiting TE_{102} and TE_{301} modes.

Another promising technology for the mass production of high frequency components is the deep-reactive ion etching (DRIE) micromachining. This technology is based on plasma etching of bulk silicon.

The high accuracy of this technology has been proved in several papers. In [199] and [200] TM dual-mode filters working at 270 GHz have been manufactured by using DRIE technique. In [201] a low loss narrow band filter (1% of FBW) working at 450 GHz has been manufactured and an unloaded Q-factor higher than 700 has been measured. Finally in [202] E-Plane and H-Plane Bandpass Filters centered at 550 and 640 GHz have been manufactured and the response of one of them is shown in Fig. 39.

C. EMERGING BITS AND PIECES OF POSSIBLES, BASED ON TECHNOLOGY

a. Light-weight alloys with temperature coefficients of expansion similar to INVAR but with much-improved thermal conductivity, again as compared to INVAR.. If issues with silver plating are resolved, such alloys will allow filters to be constructed for space applications with less than half the weight and higher average power capabilities, as compared to present designs, some of which have extended suppression of higher order modes and

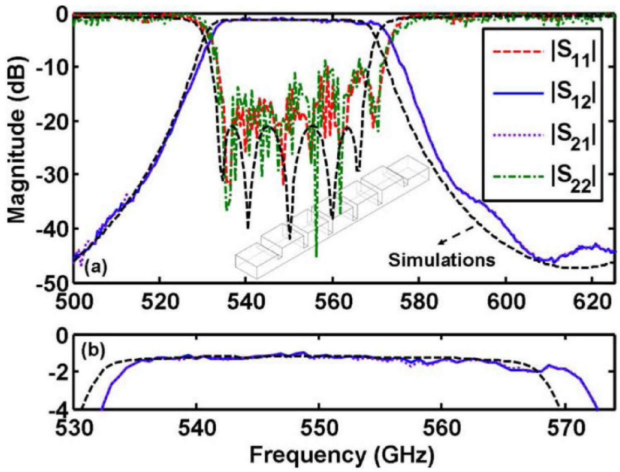


FIGURE 39. Response of a filter in [202]. Comparison between simulation and measurements.

other advanced features …but are still too heavy because of the use of INVAR, needed presently for temperature stability. Lighter weight obviously would be beneficial because the content of typical spacecraft includes many filters and other microwave hardware. However, the plating issue is critical for filters, due to insertion loss and the need to perform for long periods of time (no plating degradation permitted inside the filter, for many years) [203].

b. Dynamically reconfigurable and/or tunable filters, agile in frequency and able to dynamically move from bandpass to bandstop transfer functions [204], [205]: As mentioned in Section I, the developmental issues are not the networks, but rather the available analog tuning and digital switching elements available. Mechanical tuning is not a problem but is not considered as future technology, with the exception of tuning using MEMS varactors. Analog tuning for reconfigurable/tunable networks today depends primarily on junction varactors. Switching for digital selection is primarily based on PIN diodes. Both technologies have not changed much in the last 50 years, have relatively low IP3 thresholds and high insertion loss. Using MEMS varactors does provide high Q and good IP3, but at the expense of tuning speed [206]. Switching arrays of capacitors is a commercially available product, from several companies. There are other tuning methods available and also under development. YIG resonators provide analog tuning over a very wide bandwidth but reconfiguration has not been attempted, to the best of this author's knowledge. Other magnetically tuned elements and applications exist [207], [208] and possibly could be adapted to tuned couplings between resonators, thus providing potential reconfiguration. In summary, practical electronic tuning will require development of some new tuning mechanisms.

VI. CONCLUSIONS

In this paper we have described emerging design techniques and technologies that are applicable to new systems and design requirements that also are emergent, but not yet defined. The future of filters will depend upon the cross-disciplinary awareness of researchers and practitioners. Techniques and technology are inter-dependent. This places a burden on those wishing to be part of the future, in that a rather large breadth of knowledge is required, including expertise in synthesis, electromagnetics, materials and software. Our discipline is fortunate that many current researchers do have this broad expertise, and this has led to many of the core ingredients of progress reported herein. The idea of using previously unwanted modes for producing desired responses stems from a knowledge of electromagnetics and a realization of how to use the physics of propagation along with synthesis to implement smaller filters with better performance. The use of synthesis and a knowledge of when to best employ software has led to efficient designs, taking far less time and with first-pass success more often than not. As technology is more than just "how we make the parts", and includes new parts to make (think new dielectrics, new materials), it is too large a subject to cover in depth in this paper. There are indeed promising areas within our discipline that will affect how filters are manufactured, as well. These include additive manufacturing, materials (light weight alloys, graphene and similar layers of single atoms comprising material that can be doped or otherwise made to display unique properties) and perhaps active devices. Some areas will require other technological development, including varactors and switching diodes with improved loss, higher IP3 thresholds, perhaps sub-miniature vacuum tubes. Although we do not know the future with any certainty, it is hoped that by seeing where we have been, and where we are, that perhaps some sense of the enormous potential for filters in the future has been gained. It was once said that "All the World is a Filter" [209] and it is even more true today.

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