IEEE Journal of Microwaves

Received 5 October 2022; revised 29 November 2022; accepted 29 November 2022. Date of publication 23 December 2022; date of current version 6 January 2023.

Digital Object Identifier 10.1109/JMW.2022.3227131

Substrate Integrated Waveguide Multiband Bandpass Filters and Multiplexers: Current Status and Future Outlook

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(Invited Paper)

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This work did not involve human subjects or animals in its research.

ABSTRACT Multiband bandpass filters (BPFs) and multiplexers are essential front-end modules in the development of multifunction, multistandard, and multiband wireless communication, sensing, and positioning systems that are required in current and future intelligent electronics applications. In this paper, numerous implementation schemes and topologies of multiband BPFs and multiplexers, which have been proposed, studied, and developed so far, are holistically summarized and elaborated in terms of their merits and drawbacks. Subsequently, various technical approaches and diverse design methodologies based on substrate integrated waveguide (SIW) technology are thoroughly examined and reviewed with respect to technical features, electrical performances, and practical applications. Finally, future research and development directions and prospects of SIW multiband BPFs and multiplexers are briefly unraveled.

INDEX TERMS MTT 70th Anniversary Special Issue, implementation techniques, multiband bandpass filters, multifunction, multiplexers, substrate integrated waveguide (SIW).

I. INTRODUCTION

With the rapid development and unfolding applications of broadband and high-speed wireless systems as part of the current revolutions of information technology in the science and technology of global human society, intelligent wireless electronic systems with low profile, low latency, and low power consumption are unprecedentedly required in either military deployments or commercial products. As seen in the emerging fields and activities of 5G/6G networks [1], internet of things (IoT) [2], and artificial intelligence (AI) [3] as epitomized in Fig. 1, current and future wireless applications are advancing smoothly towards deep fusions of multitudinous demands and diverse standards. Under such circumstances, the research and development of multiband wireless systems and multifunction intelligent apparatus becomes more and more stringent, in which multiband bandpass filters (BPFs) or multiplexers are critical and indispensable constituent modules.

Multiband BPFs and multiplexers are a sort of frequency selective components that exhibit filtering characteristics in all of the multiple channels or passbands. Generally, the characters of the frequency responses, including response types, orders, center frequencies (CFs), bandwidths, and return losses (RLs), must be flexibly designated, synthesized, and designed for each channel while retaining acceptable inter-channel isolations for co-channel operations. Apart from the above-mentioned electrical properties, the circuit size is also a vital figure-of-merit that must be accounted for in most practical applications, needless to mention mechanical and thermal aspects in connection with power handling capability and other system design considerations. Fig. 2 demonstrates a few types of classical multiband wireless system architectures for radio communication links or radar sensing networks. As can be seen, whether in the duplexing transceiver architectures shown in Fig. 2(a) or in the multiband receiver architectures presented in Fig. 2(b), multiband BPFs and multiplexers are essential building blocks of these front-ends for multiband operations. Such passive components are arranged either to combine all individual channeled signals into an aggregated

FIGURE 1. **Multifunction and multistandard wireless application scenarios including 5G/6G networks [1], IoT [2], and AI [3].**

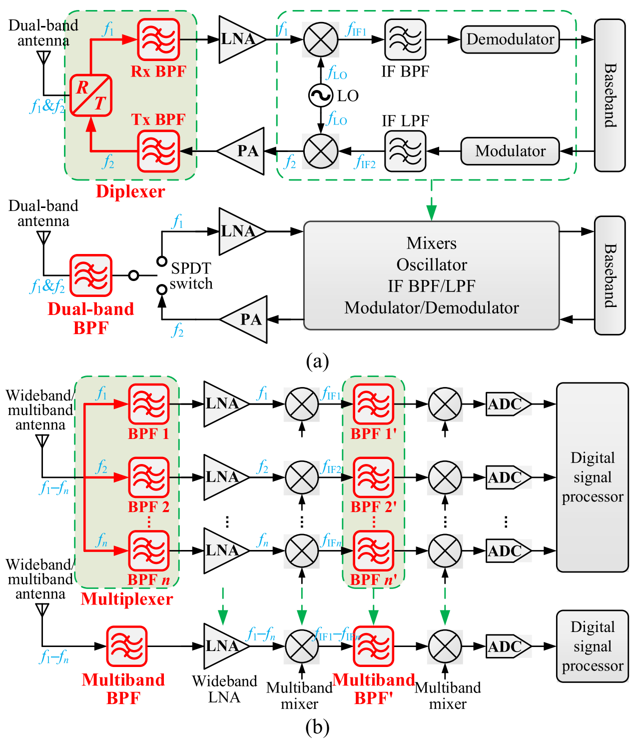

FIGURE 2. **Wireless system architectures for radio communication links or radar sensing networks using multiband BPFs and multiplexers. (a) Duplexing transceiver architectures. (b) Multiband receiver architectures.**

signal portfolio or to separate the regrouped signal portfolio into mutually and highly isolated multi-channelized signals. Therefore, they are fundamentally conditioned by the number of working channels as well as the input/output bands and sources/loads. In Fig. 2(a), the dual-band BPF and diplexer are mainly used to achieve the required filtering and isolating channelization in both transmitters and receivers connected to a shared dual-band antenna system. Whereas in Fig. 2(b), the multiband BPFs and multiplexers are basically exploited to implement the filtering functions of the illustrative multiple receiving channels linked to a wideband antenna while guaranteeing proper inter-channel isolations. To this end, it can be understood that multiband BPFs and multiplexers are indispensable and critical in the development of multifunction and multiband wireless systems for future intelligent electronics applications.

Usually characterized by various key performance indexes (KPIs) in connection with desired basic design metrics such as cost-effectiveness, dimensional compactness, integration density, bandwidth allocation, performance reliability, and power handling capability, multiband BPFs and multiplexers are often designed and developed through various technologies such as inexpensive and planar microstrip line or coplanar waveguide (CPW) technologies, costly and bulky coaxial line or metallic waveguide technologies, and so forth. As a recently established and currently popular technological platform for microwave, millimeter-wave (mmW), and terahertz (THz) applications, substrate integrated waveguide (SIW) technology has effectively regrouped the inherent advantages of both planar transmission line and non-planar metallic waveguide technologies, and has provided an attractive choice in support of the development of cost-effective, self-packaged, and high-quality multiband BPFs and multiplexers over megahertz (MHz)-thorough-THz frequencies. Driven by its superior merits of low-cost, low-loss, high-power handling capability, and high-density integration among many other properties [4], [5], [6], there have been a large volume of diversified and scattered research archives and technical reports on the development of SIW-based multiband BPFs and multiplexers over the past two decades.

As depicted in Fig. 3(a), SIW can easily support the broadband propagation of TE_{n0} modes while in the absence of TM modes. This attractiveness leads to its rapid development and global popularity in both academia and end-user communities since its synthesis and design theory can be easily and directly transplanted from the matured and classical metallic waveguide technology. As shown in Fig. 3(b), the concept and practice of substrate integration can be seen through numerous examples, which presents the three most popular non-TEM mode substrate integration schemes, including SIW, substrate integrated non-radiative dielectric (SINRD) guide, and substrate integrated image guide (SIIG) [4]. Obviously, all of them inherit the original metallic waveguide technologies but can be processed as planar transmission lines. Fig. 3(c) compares numerous impact factors among various microwave resonators, which are the leading elements for constructing

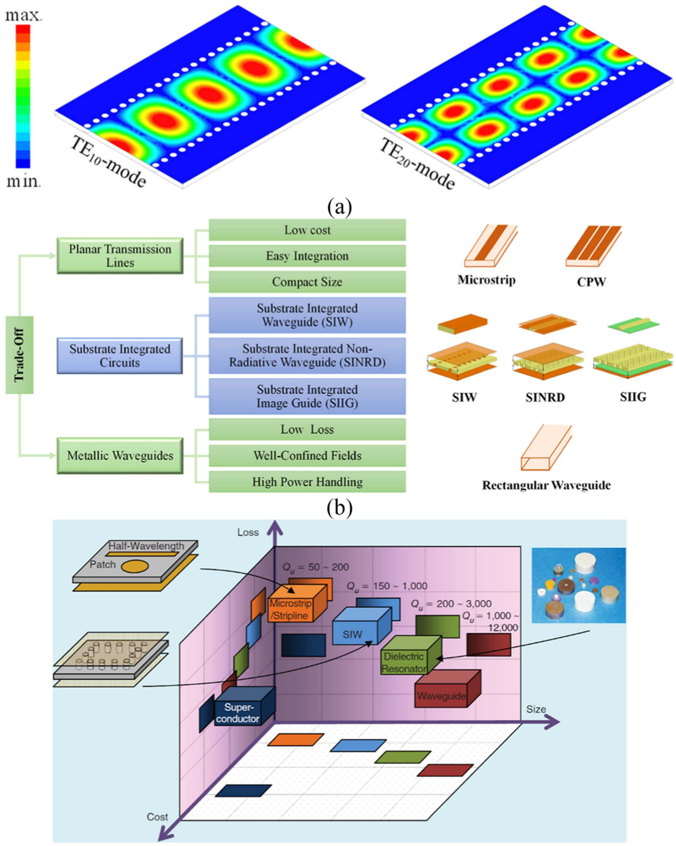

FIGURE 3. **(a) Electric field propagation of TE_{10}- and TE_{20}-mode along an SIW transmission line. (b) Three examples of substrate integrated guided-wave structures in planar form that exhibit non-TEM mode propagation as well as associated design and technology trade-offs with reference to microstrip line, CPW, and rectangular waveguide in terms of technical features, design considerations, and performance indicators [4]. (c) Relative losses, sizes, and costs of various microwave resonators [5].**

multiband BPFs and multiplexers [5]. It should be reiterated from Fig. 3(c) that SIW gathers the complementary advantages of both planar microstrip/stripline technologies and non-planar waveguide and dielectric technologies with respect to cost, size, loss, power, and processing techniques.

In this paper, the design techniques and implementation topologies of multiband BPFs and multiplexers are summarized and discussed in a comprehensive way in terms of their inherent merits and technical issues in connection with design and application requirements. This holistic review will cover a multitude of implementation schemes including shunting, coupled multimode-resonator, hybrid multimode-shunting, splitting, hybrid multimode-splitting, and single multimode-resonator solutions, which extends our prior discussions in [7] and [8]. Various technical approaches, design methodologies, and practical demonstrations using SIW techniques are examined on many aspects of importance. With the extrapolation of our current knowledge on this topic, future prospects and research orientations regarding the development of SIW-based multiband BPFs and multiplexers are also predicted and unraveled in the final section.

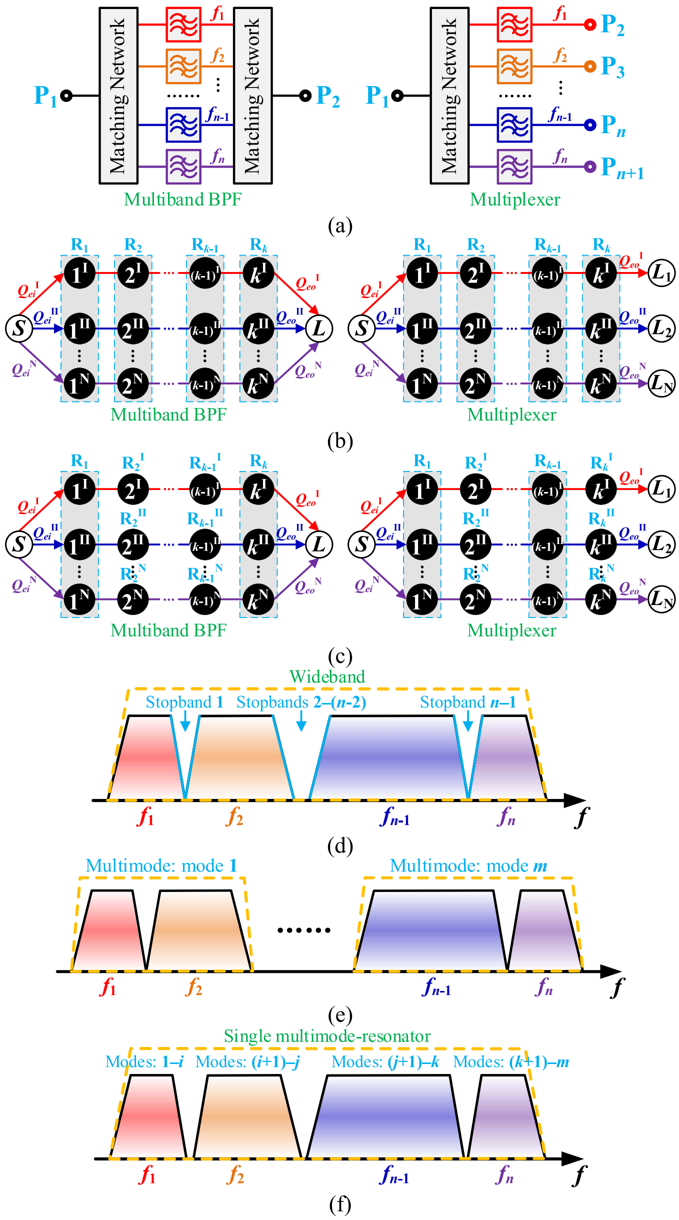

FIGURE 4. **Implementation schemes of multiband BPFs and multiplexers. (a) Shunting scheme. (b) Coupled multimode-resonator scheme. (c) Multimode-shunting hybrid scheme. (d) Splitting scheme. (e) Multimode-splitting hybrid scheme. (f) Single multimode-resonator scheme.**

II. DESIGN TECHNIQUES AND IMPLEMENTATION TOPOLOGIES OF MULTIBAND BPFS AND MULTIPLEXERS

As suggested by the conceptual illustrations shown in Fig. 4 and the comparisons of their merits and drawbacks tabulated in Table 1, the design techniques and implementation topologies of multiband BPFs and multiplexers can generally be classified into six categories according to our thorough literature review. It is worth noting that the physical implementations of these different sorts of multiband BPFs and multiplexers are completely independent of the realization or processing technologies even though each category might

TABLE 1. Comparisons of Merits and Drawbacks Among Various Schemes

Implementation Schemes	Merits	Drawbacks
Shunting	▪ Completely independent passbands ▪ Easier to realize any number of passbands ▪ Easier to design, tune, and optimize	▪ Larger sizes, higher losses ▪ Employment of matching networks and multiple individual BPFs
Coupled multimode-resonator	▪ Significantly reduced resonator number ▪ Miniaturization, low losses	▪ Relatively dependent passbands ▪ Hard to control multimode frequencies and couplings
Hybrid I: multimode-shunting	▪ Relatively independent passbands ▪ Easier to control internal couplings or bandwidths	▪ Relatively larger circuit sizes
Splitting	▪ Suitable for closely spaced passbands ▪ Small sizes, low losses	▪ Relatively dependent and inflexible passbands ▪ Difficult to synthesize, design, and optimize
Hybrid II: multimode-splitting	▪ Easier to realize more passbands ▪ Relatively easier to control internal couplings	▪ Mutually interactive passbands ▪ Difficult to synthesize, design, and optimize
Single multimode-resonator	▪ Least resonator number ▪ Smallest circuit sizes	▪ Uncontrollable filtering characteristics ▪ Limited realizable number of passbands

have a preferable technology of choice for its best achievable performances. In the following subsections, those schemes and topologies would be described and commented one by one in detail.

A. SHUNTING SCHEME

As depicted in Fig. 4(a), the most intuitive and straightforward approach to implementing multiband BPFs and multiplexers is to arrange a shunting connection of multiple individual single-band BPFs characterized using CFs of f_1–f_n via specifically designed matching networks, including multiport T-junctions, circulators, manifolds, switches, apertures, and so forth. Since each channel is composed of an independent BPF, and then all those BPFs are incorporated using the matching networks, the generated passbands are completely independent of each other. In this way, they are much easier to design, tune, and optimize compared to other schemes. Additionally, it is also easier to realize any number of channels using this scheme only if the entire passbands can be covered by the wideband matching networks. Nevertheless, the devices using this scheme usually suffer from large circuit sizes and high insertion losses (ILs) in most practical applications because of the employment of extra matching networks as well as multiple individual single-band BPFs, as described in Table 1.

B. COUPLED MULTIMODE-RESONATOR SCHEME

As elaborated in Fig. 4(b), the most commonly used scheme for the design of miniaturized multiband BPFs and multiplexers is to couple multiple multimode resonators in sequence or in other advanced topologies. In Fig. 4(b), nodes 1–k represent multimode resonators R_1–R_k, superscripts I–N denote multiple modes 1–n, S and L mean the source and load, Q_{ei} and Q_{eo} are the input and output external quality factors in the design. As explained in Table 1, much fewer resonators would be counted for this scheme compared to the shunting scheme, so this scheme highlights its distinct characteristic of miniaturization. Nevertheless, the created passbands are usually dependent on each other because of the shared resonators and coupling paths denoted by different colored curves. Therefore, it is always a challenging task to control the underlying multimode frequencies and couplings in practice, resulting in that the bandwidth of each passband cannot be allocated flexibly, so that the realizable bandwidth ratios of the multiple channels are often limited.

C. MULTIMODE-SHUNTING HYBRID SCHEME

To ease the control of the bandwidths of multiple passbands as well as their ratios, the coupled multimode-resonator scheme can be combined with the shunting scheme, leading to a typical hybrid architecture, as interpreted by the illustration of Fig. 4(c). Multiple single-mode resonators R_i^I–R_i^N operating at each different channel can be added up into the multimode multiband BPFs and multiplexers to enlarge the realizable bandwidth ratios at the expense of a small increase in circuit size. Under this circumstance, the realizable bandwidth ratios of those passbands are merely determined by the multimode Q_es since all the internal couplings become single-mode couplings due to the addition of single-mode resonators R_i^I–R_i^N. Generally, the merits of flexibly controlled passbands of the shunting scheme and small circuit sizes of the coupled multimode-resonator scheme can be preserved for this kind of hybrid scheme while circumventing their respective drawbacks.

D. SPLITTING SCHEME

As demonstrated in Fig. 4(d), another scheme to implement multiband BPFs and multiplexers is to split a broad passband into multiple sub-passbands with CFs of f_1–f_n using several inserted stopbands 1–(n-1) based on multiband coupling matrix synthesis techniques including the frequency transformations using prototype synthesis [9], [10], [11] or the optimization techniques [12] using gradient algorithm [13]. The features of closely spaced passbands as well as relatively smaller sizes and lower ILs can be characterized for the circuits using this scheme compared to the shunting scheme. However, the split multiple passbands are usually dependent on each other, so

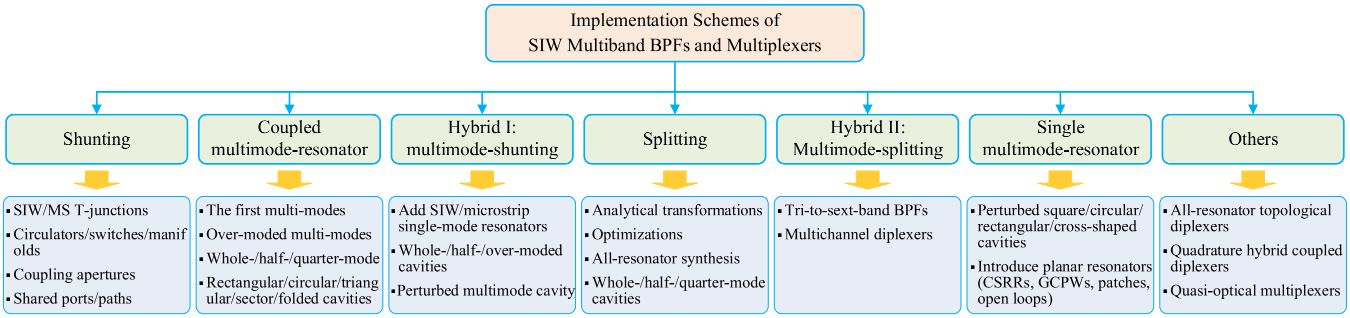

FIGURE 5. General overview of technical approaches and design highlights of SIW multiband BPFs and multiplexers.

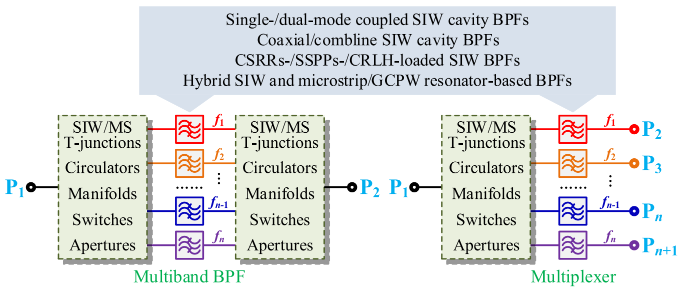

FIGURE 6. Illustration of technical approaches for developing SIW multiband BPFs and multiplexers using shunting scheme.

that they generally require strenuous efforts for tuning and optimization in simulation process, just as elaborated in Table 1.

E. MULTIMODE-SPLITTING HYBRID SCHEME

Generally, at most three to four bands can be produced and managed using the multimode-shunting hybrid scheme because of the difficulty in effectively controlling more resonant modes in the multimode resonators and the related multimode external couplings. By combining the coupled multimode-resonator scheme and the splitting scheme, more passbands can usually be generated, just as delineated in Fig. 4(e). In this case, each passband composed of each resonant mode 1–m in the multimode resonators can be split into multiple sub-bands, so that up to two or three times of the passbands denoted by CFs of f_1–f_n in Fig. 4(e) can be created compared to the coupled multimode-resonator scheme, but the split sub-bands are also dependent on each other and often limited in a close adjacency.

F. SINGLE MULTIMODE-RESONATOR SCHEME

If the circuit sizes using the aforementioned schemes are still too large in practical applications, single multimode-resonator scheme can be considered for enabling further circuit miniaturizations. As depicted in Fig. 4(f), multiple resonant modes 1–m in a single multimode resonator can be grouped into n sets to construct n passbands represented by CFs of f_1–f_n. Compared to the multiple resonators used in other schemes, the smallest footprints can be obtained and characterized for circuits using this scheme because of the employment of only one resonator, as stated in Table 1. Meanwhile, the drawbacks of this scheme are that the realizable number of passbands is rather limited, and the frequency responses of generated passbands, including CFs, bandwidths, and RLs, are generally uncontrollable and electromagnetically intercorrelated owing to the obvious difficulty in freely controlling each resonant mode in the single multimode resonator. This scheme generally requires a substantial knowledge and effort in electromagnetic modeling and simulation regarding modal behaviors.

III. RESEARCH ACTIVITIES OF MULTIBAND BPFS AND MULTIPLEXERS BASED ON SIW TECHNOLOGY

As observed and clarified from the elaborations presented in Section II and the technical comparisons listed in Table 1, each implementation scheme has its own merits and drawbacks, so that overall design considerations including footprints, number of passbands, CF ratios, bandwidth ratios, and selectivity, must be taken into account in practical applications. Focused on the evolvements and advancements of specific implementation topologies and design techniques on the basis of SIW platform, various technical approaches, design methodologies, and practical demonstrations of SIW multiband BPFs and multiplexers are examined and reviewed with elaborated technical details to appreciate their technical features in this Section. To begin with, a general overview of the already exploited approaches, methodologies, and highlights is summarized in Fig. 5, which will be discussed below in detail.

A. ACTIVITIES BASED ON SHUNTING SCHEME

The primary technical approaches and design techniques of the shunting scheme are first illustrated in Fig. 6. As can be seen, various matching networks can be exploited and combined with diverse SIW single-band BPFs to develop SIW multiband BPFs and multiplexers based on this scheme, embracing multiport wideband T-junctions based on SIW [14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35], [36], [37], [38] or microstrip [39], [40], [41], [42], [43], [44], [45], [46], [47], [48], [49], [50], [51], [52], [53] technologies, circulators [31], manifolds [32], coupling apertures [54], [55], switches [56], shared feeding ports [57], [58], [59] or coupling paths [60], [61], and so forth. Besides the feature of

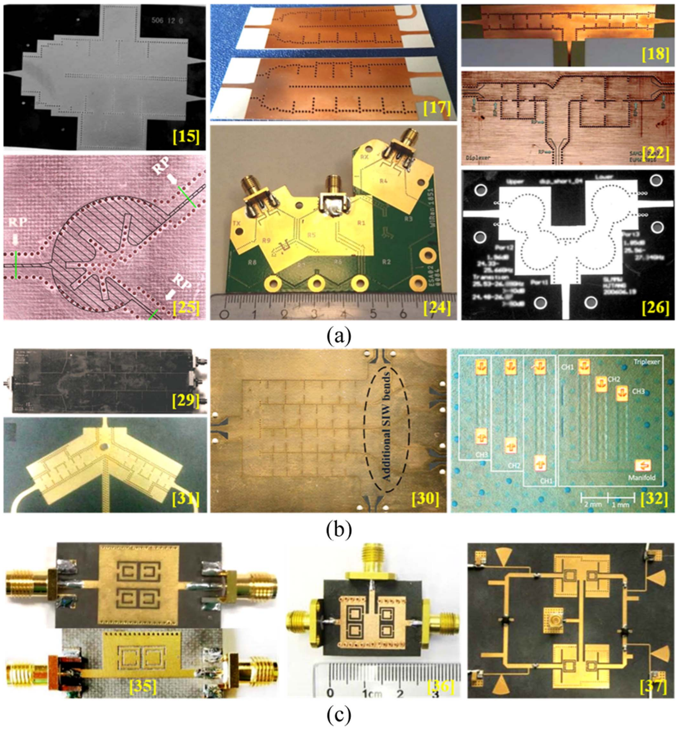

FIGURE 7. SIW T-junction-based SIW multiband BPFs and multiplexers using shunting scheme. (a) Diplexers. (b) Multiplexers based on circulator, manifold, and T-junctions. (c) CSRRs-loaded techniques.

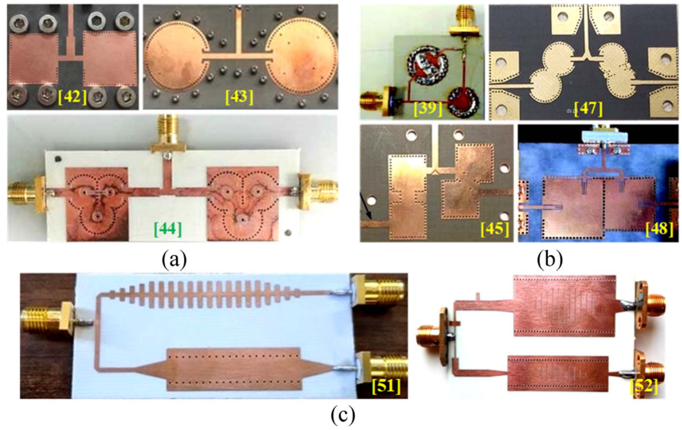

FIGURE 8. Microstrip T-junction-based SIW multiband BPFs and multiplexers using shunting scheme. (a) Based on single-mode coupled cavities. (b) Based on dual-mode or mixed-mode coupled cavities. (c) SIW loading techniques.

completely independent passbands characterized by free CFs and bandwidths, the other technical highlight of this scheme is that it can usually provide the best in-between attenuations for multiband BPFs and best inter-channel isolations for multiplexers compared to the other schemes or topologies. This is because the isolating channel between any pair of channels/passbands is the longest to sufficiently attenuate the energy of one channel to the other.

Multiport T-junctions are the most commonly used matching networks to shunt multiple branches of SIW single-band BPFs to construct SIW multiband BPFs and multiplexers. As the circuit prototypes shown in Fig. 7(a), based on three-port SIW T-junctions, diplexers can be readily developed with their two branches either established by SIW single-mode BPFs with miscellaneous coupling topologies, frequency responses, geometric configurations, and multilayered structures [14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [24], [25], or built by SIW dual-mode BPFs using dual-mode coupled circular [26] or square [27] cavities for circuit miniaturizations, or even created by SIW BPFs using mixed single-mode and dual-mode coupled cavities for generating multiple finite transmission zeros (TZs) [28]. As demonstrated in Fig. 7(b), an advanced SIW triplexer [29] and a quadruplexer [30] were developed and reported with very large-scale and high-density configurations based on multiport SIW T-junctions. Additionally, circulator and manifold were also employed to design a higher-order diplexer [31] and a THz triplexer [32], respectively, which can also be regrouped into the SIW T-junction scheme. Because of the use of extra oversized T-junctions, the circuit sizes for the above-mentioned SIW multiband BPFs and multiplexers are still too large, another kind of miniaturized solution that can be classified into the integrated SIW T-junction scheme is the SIW loading techniques including complementary split-ring resonators (CSRRs)-loaded [33], [34], [35], [36], [37] or slotline resonators-loaded [38] approaches, as demonstrated in Fig. 7(b). In this case, not only dual-to-quad band SIW BPFs were implemented [33], [34], [35], [38] but also SIW diplexers were developed [36], [37] then successfully applied to the design of a low phase noise oscillator [37]. In this kind of loading schemes, SIW not only provides the impendence matching between the input/output ports and the resonators but also supports an evanescent-mode coupling between adjacent resonators as well as the energy propagation of multiple paths. Because all the multiple passbands operate below the cut-off frequency of SIW transmission structure, miniaturization can be achieved for this kind of loading solutions. Nevertheless, it is usually difficult to realize cross-coupled topologies except conventional inline topologies, and the self-packaged characteristic of SIW structures would be destroyed due to the radiation property of CSRRs, needless to say lowering their unloaded quality factors Q_us.

Microstrip T-junctions are the other type of frequently used matching circuits in the development of SIW multiband BPFs and multiplexers [39], [40], [41], [42], [43], [44], [45], [46], [47], [48], [49], [50], [51], [52], [53] thanks to their wideband matching characteristics and significant flexibilities. The representative works using microstrip T-junctions have been described in Fig. 8. In [39], an SIW dual-band BPF using two dual-mode circular cavities was studied, designed, and connected by a pair of microstrip T-junctions. As demonstrated in Fig. 8(a), multiple types of SIW diplexers were also exploited based on microstrip T-junctions with their two branches constructed by SIW single-band BPFs either

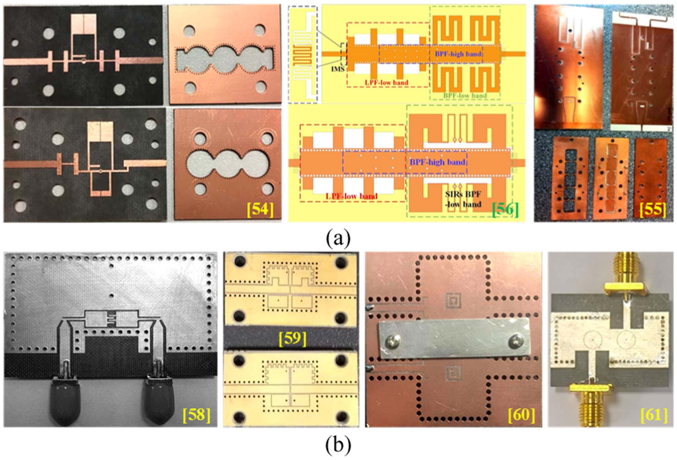

FIGURE 9. Other solutions-based SIW multiband BPFs and multiplexers using shunting scheme. (a) Based on coupling apertures or switches. (b) Based on shared feeding ports or coupling paths.

using multilayered coupled square cavities for the implementation of circuit miniaturizations [40] or for the realization of wide-stopband performances [41], [42], or using coupled circular cavities for the generation of finite TZs [43], or using circular coaxial cavities for the implementation of triplet combline BPFs [44]. To miniaturize the diplexers, the two branches can also be formed by SIW single-band BPFs using dual-mode coupled-cavity schemes [45], [46], [47] or mixed-mode coupled-resonator schemes using both SIW cavities and grounded coplanar waveguide (GCPW) resonators [48], as depicted in Fig. 8(b). For a further circuit miniaturization, SIW loading techniques including CSRRs-loaded SIW [49], composite right/left-handed (CRLH) cells-loaded SIW [50], spoof surface plasmon polariton (SSPP) [51] and SSPPs-loaded SIW [52], [53] schemes were applied to realize at least one channel of the diplexers or triplexers, as the two prototypes shown in Fig. 8(c). This kind of loading schemes are usually introduced to develop ultra-wideband (UWB) filtering components since a large quantity of resonating cells can be loaded on the top or bottom surfaces of SIW structures.

Apart from the mainstream T-junctions mentioned above, other joint interfaces have also been proposed and reported to implement SIW multiband BPFs and multiplexers using the shunting scheme. As demonstrated in Fig. 9(a), SIW dual-/triple-band BPFs and one diplexer simultaneously working at both 5G sub-6 GHz and mmW frequencies were proposed and developed in [54] based on wideband coupling apertures, with which waveguide mounted SIW technique was also proposed and covered in [55] to develop a sophisticated diplexer using a mode-matching technique. Besides the use of apertures, another scheme to realize SIW dual-band BPFs with ultra-large CF ratios operating at both microwave and mmW bands is to employ the switches, with which three experimental prototypes were developed and presented in [56]. The other approaches belonging to the shunting scheme is the shared feeding ports or coupling paths, as the design examples shown in Fig. 9(b). In [57], [58], [59], the feeding ports were shared by two channels either made of two independent SIW single-band BPFs to realize a balanced diplexer [57], or one microstrip and one SIW BPFs [58] even two coaxial SIW doublets [59] to implement SIW dual-band BPFs. In [60] and [61], balanced and single-ended SIW dual-band BPFs were demonstrated with one of the passbands dominated by fundamental SIW cavities and the other passband built by coupled CSRRs [60] or combline resonators [61]. This type of mixed-mode techniques can significantly reduce the circuit sizes while adding additional design degrees of freedom to ease the control of the CFs and bandwidths of multiple channels/passbands.

B. ACTIVITIES BASED ON COUPLED MULTIMODE-RESONATOR SCHEME

As mentioned in Section II-B, illustrated in Fig. 4(b), and tabulated in Table 1, circuit miniaturizations can generally be achieved by using the coupled multimode-resonator scheme compared to the shunting scheme thanks to significant resonator number reduction and matching network removal. The miniaturization property is obtained at the expense of reduced design degrees of freedom, so that the degrees for this scheme are often limited to effectively control the multimode frequencies and couplings in practice, and further it is hard to implement freely designated CFs and bandwidths of multiple passbands. Additionally, it is usually necessary to resort to extra finite TZs for the realization of acceptable in-between attenuations for multiband BPFs and inter-channel isolations for multiplexers due to shared resonant cavities and coupling paths. To begin with, the milestone works based on this scheme are demonstrated in Fig. 10 together with the electric field distributions in all the passbands to allow the readers intuitively understand their operating principles.

To maximally shrink the footprints, the first dual-modes of TE_{101} and TE_{201}/TE_{102} are the most commonly used resonant modes in the development of SIW dual-mode dual-band BPFs [62], [63], [64], [65], [66], [67], [68] and dual-mode diplexers [69] based on coupled SIW cavities of rectangular [62], [63], [69], half-mode rectangular [64], perturbed square [65], [66], [67], or dual-capacitively loaded square [68] shapes, as the classical design examples using coupled TE_{101}/TE_{201} dual-mode SIW rectangular cavities shown in Fig. 10(a). However, the realizable CF ratios of two passbands using the first dual-modes are usually moderate due to the limitation of the aspect ratio of a rectangular cavity. To achieve smaller CF ratios, the over-moded dual-modes of TE_{102} and TE_{201} can be adopted to implement SIW dual-mode dual-band BPFs [70], [71], [72] and dual-mode diplexers [69] with close passbands based on coupled SIW rectangular cavities [69], [70], [71] or perturbed SIW square cavities [72]. Higher-order dual-modes of TE_{201} and TE_{301} in SIW rectangular cavities were also employed in [73] to realize a Q-band SIW diplexer using low-temperature co-fired ceramic (LTCC) technology. Moreover, the TE_{102} and TE_{302} modes in SIW square cavities

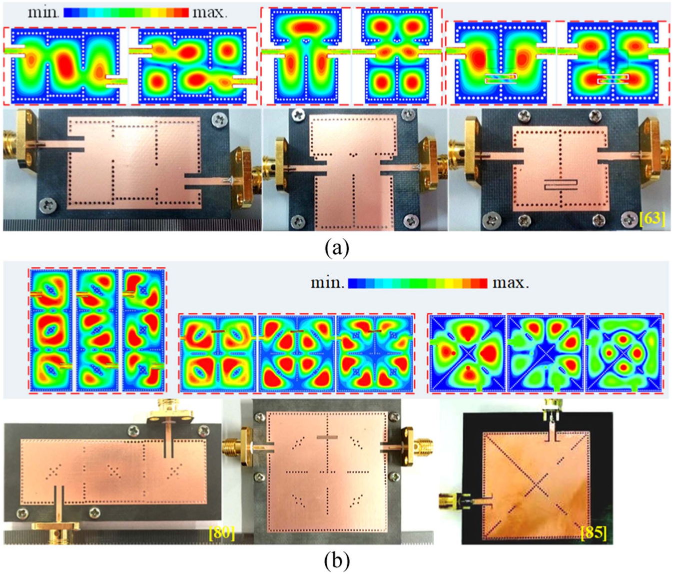

FIGURE 10. SIW multiband BPFs and multiplexers using coupled multimode-resonator scheme. (a) Dual-mode dual-band BPFs. (b) Triple-mode triple-band BPFs.

were utilized in [74] to design a balanced SIW dual-band BPF with improved common-mode suppressions. In addition to the aforementioned classical rectangular or square cavities, the first dual-modes in the folded SIW cavities [75], fan-shaped SIW cavities [76], patches-loaded SIW square cavities [77], isosceles right-angled SIW triangular cavities [78], and patches-loaded SIW resonators [79] were exploited as well to implement advanced SIW dual-mode dual-band BPFs. These techniques are usually deployed for circuit miniaturizations or other technical purposes.

Apart from the dual-mode dual-band BPFs described above, SIW triple-mode triple-band BPFs have also been developed and reported in the literature. Two synthesis and design examples are shown in Fig. 10(b). To successfully implement this kind of advanced filtering devices, the first three modes were fully exploited and utilized based on various triple-mode coupled cavities, such as perturbed SIW square [80] or circular [81] cavities, slots-loaded quarter-mode SIW circular cavities [82], fan-shaped SIW cavities [83], patches-loaded SIW evanescent-mode cavities [84], isosceles right-angled SIW triangular cavities [85], and so forth. Nevertheless, it is generally a tough task to freely control the multimode frequencies and couplings in practice, leading to inflexible CFs and bandwidths of the multiple channels/passbands. Furthermore, it is very difficult to develop more-mode more-band BPFs because of the challenges in effectively controlling the underlying multimode resonant frequencies and mutual couplings.

C. ACTIVITIES BASED ON MULTIMODE-SHUNTING HYBRID SCHEME

As pointed out in Section II-B, the drawbacks of the coupled multimode-resonator scheme are that the realizable CF ratios and bandwidth ratios of multiple passbands are limited for developed SIW multimode multiband BPFs and multiplexers because of the challenges in flexibly controlling the multimode frequencies and couplings. To mitigate this issue, the multimode-shunting hybrid scheme can be adopted to facilitate the control of the bandwidth ratios to some extent. By replacing all or alternate intermediate multimode coupled cavities with multiple single-mode cavities operating in each passband, all of the internal couplings would become single-mode couplings and then they can be controlled independently and flexibly. In this case, the bandwidth ratios of the passbands are only determined by multimode Q_es following the "Cannikin Law."[1] Although the realizable CF ratios are still limited by multimode frequencies of the common multimode resonators, the realizable bandwidth ratios are enlarged by the internal single-mode couplings. In addition, more diverse coupling topologies can be exploited in this case to realize more advanced frequency responses, and the extra TZs produced by input/output multimode cavities can be preserved as well to improve the in-between attenuations for multiband BPFs and inter-channel isolations for multiplexers.

To realize moderate CF ratios, multiple single-mode cavities were coupled into SIW dual-mode dual-band BPFs constructed by TE_{101} and TE_{201} modes in rectangular cavities based on this kind of multimode-shunting hybrid scheme [86], [87], [88]. Moreover, the single-mode SIW cavities can also be replaced by microstrip resonators to miniaturize the footprints [89]. To implement large CF ratios, half-mode dual-mode SIW rectangular cavities were systematically analyzed and successfully applied to the development of miniaturized SIW dual-band BPFs with widely separated passbands [90]. Additionally, the over-moded dual-modes of TE_{102} and TE_{201} were used in [70] to produce a quasi-elliptical SIW dual-band BPF with a small CF ratio. Some of the state-of-the-art works are demonstrated in Fig. 11(a) along with the electric field distributions in the two channels to clearly show their working mechanisms.

For SIW diplexers, dual-mode cavities operating with TE_{101} and TE_{201} modes can be considered to replace SIW T-junctions in the shunting scheme for circuit miniaturizations and loss reductions [88], [91], [92]. The first dual-modes in perturbed SIW circular cavities were also exploited in [93] to realize single-ended and balanced SIW diplexers with moderate CF ratios. Moreover, besides the use of the half-mode dual-mode SIW rectangular cavities to implement SIW diplexers with large CF ratios [94], the dual-modes of TE_{101} and TE_{301} were employed in [95] to develop an SIW diplexer with a large CF ratio as well as wide-stopband characteristic. To implement SIW diplexers with small CF ratios, the TE_{102} and TE_{201} modes in perturbed SIW square cavities [96], [97] or rectangular cavities [98], [99] are the most commonly used dual-modes to replace the T-junctions. A scheme using two dual-mode rectangular cavities operating with the TE_{102} and TE_{201} modes coupled with multiple single-mode cavities was

[1]Cannikin Law: A bucket's capacity is determined by its shortest stave.

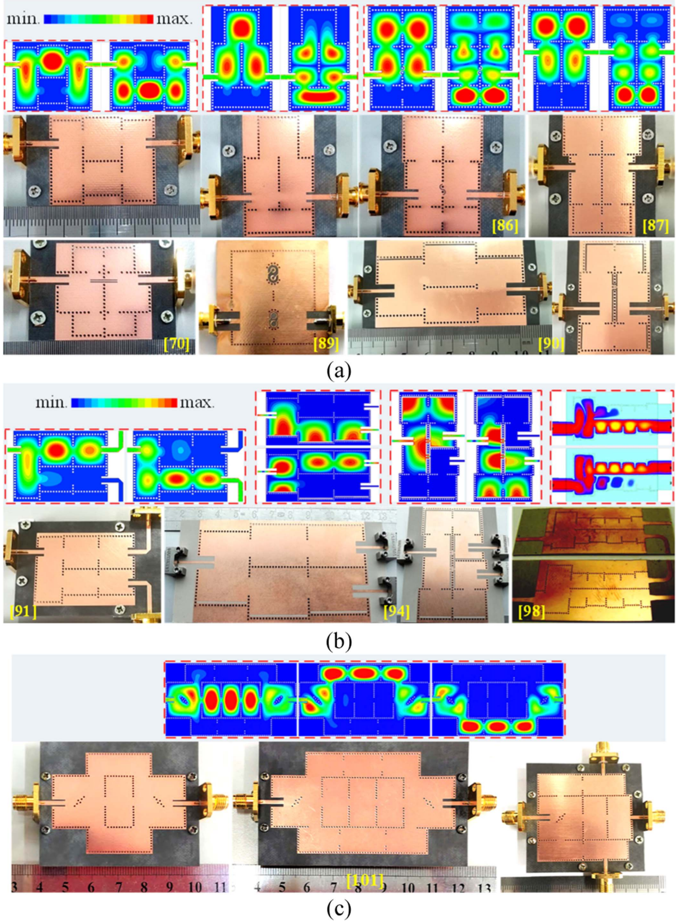

FIGURE 11. SIW multiband BPFs and multiplexers using multimode-shunting hybrid scheme. (a) Dual-band BPFs. (b) Diplexers. (c) Triple-band BPFs and triplexers.

developed and presented in [100] to generate a balanced SIW diplexer with closely spaced channels. Alternatively, patches-loaded SIW square cavities were introduced in [77] to produce an SIW diplexer with a small CF ratio. Additionally, SIW triple-band BPFs and triplexers have also been developed and reported in [101] based on this sort of multimode-shunting hybrid scheme using the perturbed SIW triple-mode cavities proposed in [80]. The experimental prototypes along with the electric field distributions in the multiple channels have been demonstrated in Fig. 11(b) and (c), respectively.

D. ACTIVITIES BASED ON SPLITTING SCHEME

Closely spaced passbands are often required for multiband BPFs and multiplexers in many practical applications [1], [2], [3]. Besides considering using over-moded dual-modes such as TE_{102} and TE_{201} to implement small CF ratios, another solution to realize SIW multiband BPFs and multiplexers with adjacent passbands is to employ the splitting scheme based on multiband coupling matrix synthesis techniques [9], [10], [11], [12]. As the experimental prototypes along with some of the coupling topologies shown in Fig. 12, SIW dual- and triple-band BPFs were thoroughly investigated and

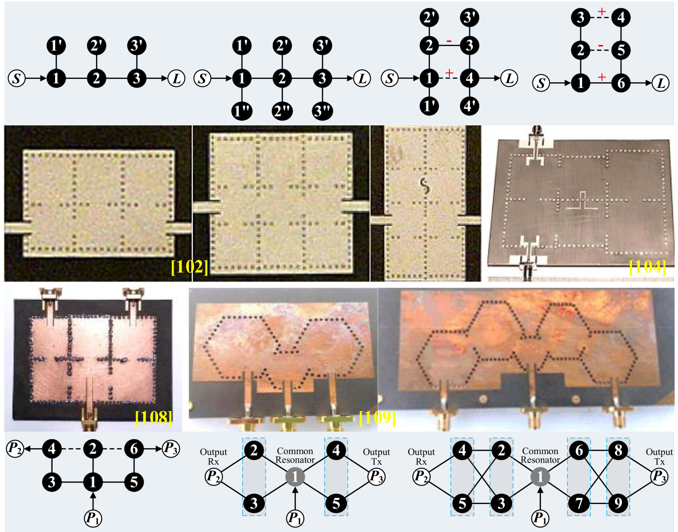

FIGURE 12. SIW multiband BPFs and multiplexers using splitting scheme.

successfully developed using this scheme based on whole-mode SIW cavities [102], [103], [104], as well as half-mode [105], [106] and quarter-/eighth-mode [107] SIW cavities for miniaturization purposes. SIW diplexers were also developed and reported with finite TZs produced in-between the two channels using single-mode [108] or dual-mode [109] coupled cavity schemes, where the diplexer synthesis is basically based on the all-resonator topological approach proposed in [110]. Since the TZs are involved in the synthesis process to split a broad passband into multiple sub-passbands, the selectivity of the channels as well as in-between attenuations for multiband BPFs and inter-channel isolations for multiplexers can be guaranteed in most of the cases. Nevertheless, the allocation flexibility of CFs and bandwidths of the passbands are usually facing great challenges limited by the synthesis theories, and the frequency responses are always difficult to tune and optimize in post-tuning processes.

E. ACTIVITIES BASED ON MULTIMODE-SPLITTING HYBRID SCHEME

Only two or three passbands can be readily produced using the splitting scheme inferred from the design examples reported in Section III-D. If more operating passbands are required, the splitting scheme can usually be incorporated with the coupled multimode-resonator scheme to double or even triple the realizable number of passbands. For instance, by splitting one of the two passbands of SIW dual-mode dual-band BPFs into two sub-bands, SIW triple-band BPFs were implemented and presented in [111], [112], [113], [114], [115]. Moreover, SIW quad-/quint-/sext-band BPFs were also developed and demonstrated in [115], [116], [117] by splitting both dual-passbands into two or three sub-bands, just as the prototypes and topologies shown in Fig. 13(a). Although much more passbands can be easily implemented, the difficulty in flexibly controlling the multimode frequencies and couplings in

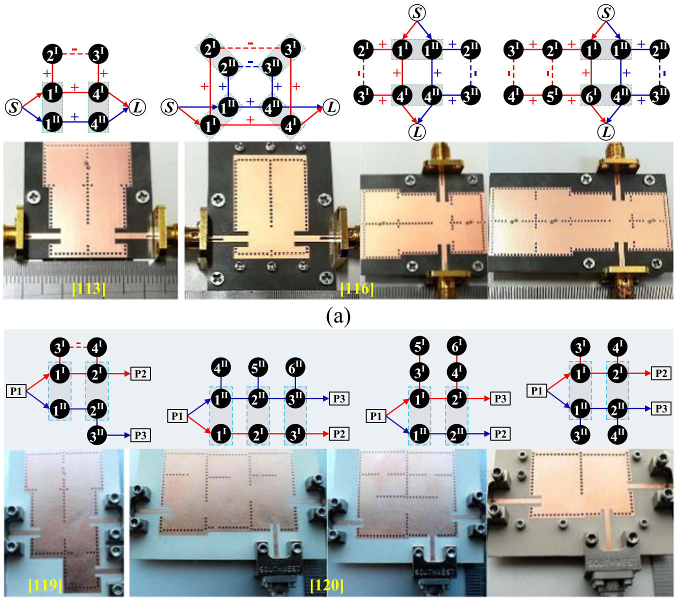

FIGURE 13. SIW multiband BPFs and multiplexers using multimode-splitting hybrid scheme. (a) Tri-/quad-/quint-band BPFs. (b) Tri-/quad-channel diplexers.

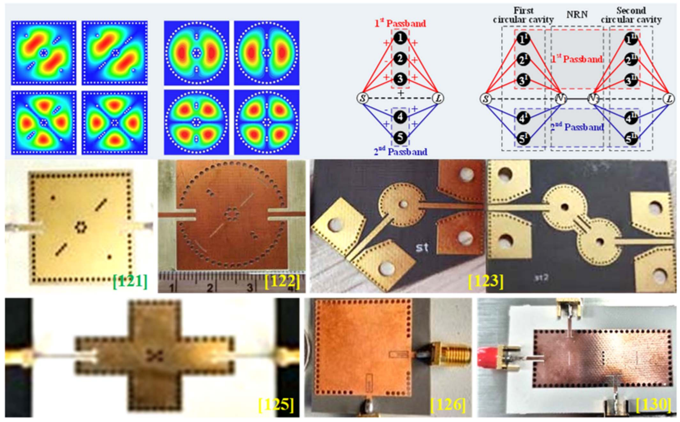

FIGURE 14. SIW multiband BPFs and multiplexers using single multimode-resonator scheme.

the coupled multimode-resonator scheme and the interactive passbands in the splitting scheme are co-existing in this hybrid scheme, leading to inflexible multiple channels.

Apparently, this sort of hybrid scheme can also be applied to implement and develop advanced multichannel SIW diplexers, which are highly desired in the developments of cost-effective and resource-saving multifunction and multiband systems. Apart from using the oversized T-junction scheme [118], SIW triple- and quad-channel diplexers were also implemented and reported in [119] and [120] by synthesizing and designing one or both of the two duplexing channels created by dual-modes in SIW cavities into two or three sub-bands, as the topologies and prototypes presented in Fig. 13(b). Although significant circuit miniaturizations can be achieved for the demonstrations using the multimode-splitting hybrid scheme [119], [120], the controllability of CFs and bandwidths of the multiple channels are less flexible compared to the T-junction scheme [118]. Additionally, since the isolation performance of the circuits using this hybrid scheme are basically conditioned by the orthogonal characteristic of dual modes, the inter-channel isolations are also much worse than those with the T-junction scheme because of shared transmission paths of the two duplexing channels.

F. ACTIVITIES BASED ON SINGLE MULTIMODE-RESONATOR SCHEME

As mentioned in Section II-F, the most compact circuit configurations can usually be implemented for multiband BPFs and multiplexers using the single multimode-resonator scheme due to the employment of merely one resonator. As the electric field distributions of multiple resonant modes illustrated in Fig. 14, single-ended or balanced SIW dual-band BPFs [121], [122], [123], [124] were successfully developed based on merely one perturbed SIW square [121] or circular [122], [123], [124] cavity by grouping those modes into two clusters. Two perturbed quintuple-mode SIW circular cavities were also cascaded in [123] to produce a high-performance dual-band BPF, and its coupling topology is shown in Fig. 14. In addition, a sext-mode SIW cross-shaped cavity was exploited in [125] to implement an SIW dual-band BPF with third-order filtering responses for both passbands. It is worthwhile mentioning that multiple TZs must be generated in the vicinity of the passbands to improve their selectivity and in-between attenuations.

As pointed out in Section II-F, it is always a challenge to freely control the multimode resonances in a single multimode cavity to realize the required CFs and bandwidths of multiple passbands owing to the limited design degrees of freedom. To ease the control of CFs and bandwidths, other types of resonators such as open loops [126], quarter-wavelength GCPWs [127], [128], capacitively-loaded patches [127] can be introduced as the extra degrees and embedded in the cavity to couple with the multiple modes in the single whole-mode [126], [127] or half-mode [128] cavity without increasing the overall footprints. Meanwhile, the issue this technique induced is that the self-packaged property of SIW structures will be destroyed due to the embedded radiating resonators, similar to the situations in the SIW loading schemes illustrated in Figs. 7(c) and 8(c).

Besides the above-mentioned dual-band BPFs, a three-state SIW diplexer with flexibly controlled CFs was proposed and reported in [129] with three input/output ports fed at specific positions of a single cavity operating with quadruple modes of $TE_{102}/TE_{201}/TE_{103}/TE_{202}$ based on this kind of scheme. Additionally, a higher-order SIW diplexer was also developed and presented in [130] based on a single slots-perturbed quadruple-mode cavity, as the last circuit prototype shown in

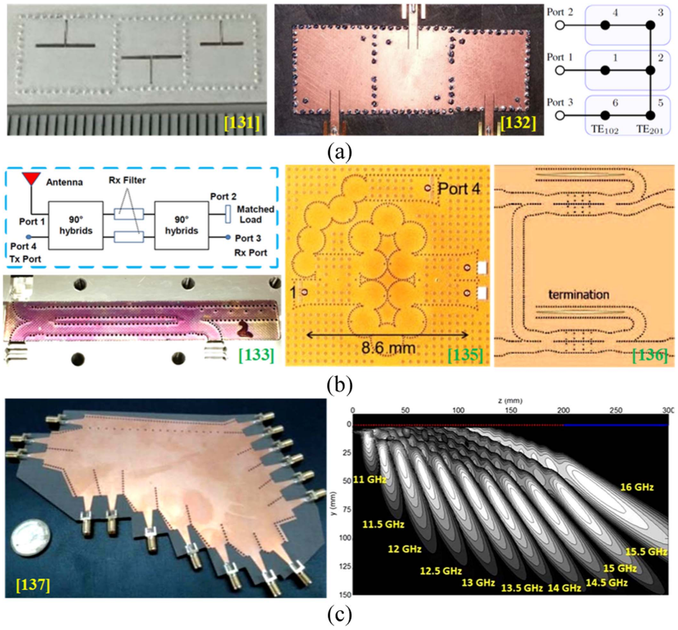

FIGURE 15. SIW multiplexers using other schemes. (a) All-resonator topological diplexers. (b) Quadrature hybrid coupled diplexers. (c) Spectral-spatial quasi-optical multiplexer.

Fig. 14. Because of sharing one resonant cavity, the inter-channel isolations are difficult to guarantee for the proposed diplexers. Additionally, it can be observed that only SIW dual-band BPFs and diplexers were implemented and developed using this scheme but there are no other multiband BPFs and multiplexers reported because of the challenges in effectively controlling more resonant modes.

G. ACTIVITIES BASED ON OTHER SCHEMES

Apart from the aforementioned implementation schemes and topologies, some other solutions have also been proposed and applied to develop sophisticated SIW multiplexers. Based on all-resonator topological diplexer synthesis technique proposed in [110], a few SIW diplexers were implemented and developed using single-mode [108], [131] or dual-mode [109], [132] coupled cavity schemes, as the two design examples shown in Fig. 15(a). No additional matching networks are needed in the synthesis process of this technique and the inter-channel isolations approximate to the levels of the shunting scheme. Similar to the splitting scheme, the CFs and bandwidths of generated passbands cannot be allocated flexibly in this approach limited by the synthesis theories, and the frequency responses are also difficult to synthesize, design, and optimize.

Another solution to achieve Tx/Rx diplexers is to employ the quadrature hybrid coupled diplexer scheme, with which several high-quality SIW diplexers were developed and reported at Ka-band [133], E-band [134], [135], and W-band [136]. The schematic diagram of this technique and three state-of-the-art works are illustrated in Fig. 15(b). Although the circuit sizes using this scheme would usually become relatively large because of the employment of two extra quadrature hybrids, the issue of the interaction between two channel BPFs is mitigated.

Moreover, a type of broadband spectral-spatial quasi-optical multiplexer providing an instantaneous spectral decomposition was proposed in [137] based on SIW platform, where an input SIW is modulated to couple the electromagnetic energy to a near-field focused surface-waves inside the hosting substrate while the focused signal can be extracted for each frequency. A fabricated prototype and the electric field distributions in some of the channels are given in Fig. 15(c). This kind of leaking-wave multiplexing technique can be used to perform broadband quasi-instantaneous mmW and THz spectral-spatial decomposition with application to the high-throughput and low-latency UWB analog signal processing.

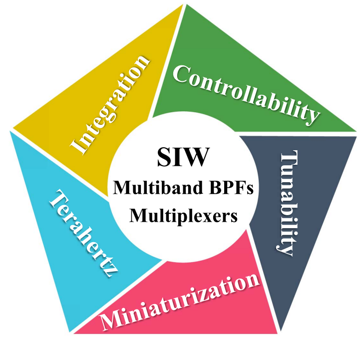

FIGURE 16. Five distinctions of future research perspectives and orientations of SIW multiband BPFs and multiplexers.

IV. FUTURE PROSPECTS AND RESEARCH ORIENTATIONS OF SIW MULTIBAND BPFS AND MULTIPLEXERS

Similar to the SIW technology developments and research outlooks presented in [4], future developments and research orientations of SIW multiband BPFs and multiplexers can also be highlighted in Fig. 16 through five distinct directions in our opinion, namely, controllability, tunability, miniaturization, terahertz, and integration. Apparently, they are closely dependent on the use of emerging and future structural innovations, advanced materials, and processing techniques. Additionally, it must be pointed out that some of these aspects are often coupled with one another, which can also be inferred from the following subsections providing a narrative discussion and future implication on each direction.

A. CONTROLLABILITY

As observed from the overall literature review in Section III, although a plenty of state-of-the-art implementation schemes, technical approaches, and design techniques have been proposed and developed to implement sophisticated SIW multiband BPFs and multiplexers, freely controlling the CF and

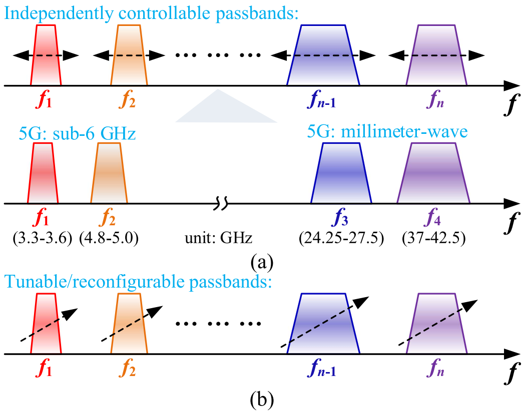

FIGURE 17. Future research and development orientations of SIW multiband BPFs and multiplexers. (a) Independent/flexible controllability of multiple channels. (b) Tunability/reconfigurability of multiple passbands.

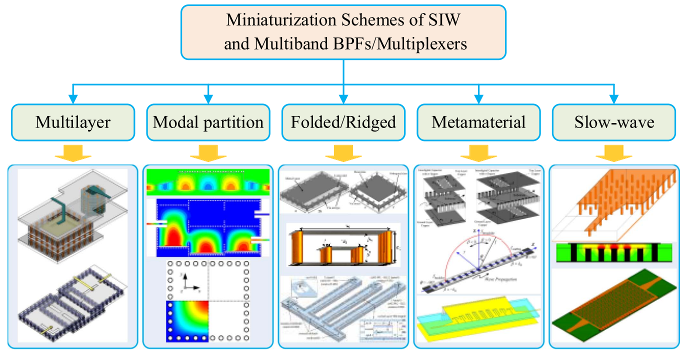

FIGURE 18. Miniaturization schemes of SIW guided-wave structures as well as SIW multiband BPFs and multiplexers.

bandwidth of each channel/passband is still challenging apart from using the oversized shunting scheme. Consequently, it is still a pressing issue to find or develop an innovative approach to implement miniaturized SIW multiband BPFs and multiplexers with all the channels/passbands independently regulated, as the conceptual illustrations shown in Fig. 17(a). Another topic outstretched from the controllability orientation is how to develop SIW multiband BPFs, multiplexers, as well as multiband antennas operating over both microwave and mmW frequency bands with ultra-large CF ratios, which is still difficult but highly desired for simultaneous 5G sub-6 GHz and mmW communications [1] as well as various applications such as IoT [2] although some attempts have already been made on this topic [54], [56], [138], [139].

B. TUNABILITY

The tunability or reconfigurability of electrical responses presents significant opportunities for developing frequency or structure-agile circuits and systems, which are usually of particular interest for current urgently required multifunction, multiband, and multimode operations. SIW technique can easily accommodate the desired tunable/reconfigurable functions through field-circuit interactions in the electric and magnetic tuning/switching using diodes or varactors [140]. Tunable/reconfigurable SIW filters or other filtering devices are also highly demanded to replace the filter banks to decrease the volume, weight, and cost of microwave and mmW electronics systems in many applications. Generally, four types of tuning schemes can be used to realize the discrete or continuous tuning, namely, mechanical tuning using screws [141], electric tuning using RF MEMS switches [142] or varactors [143], magnetic tuning using ferrites [144], and simultaneous electric and magnetic 2-D tuning using both capacitors and ferrite slabs [145] or functional materials. Since the tuning range of single-band BPFs is usually limited, combining multiple tunable channels of multiband BPFs and multiplexers into a wide tunable passband to extend the tuning range seems to be a superior approach. Several tunable SIW dual-band BPFs [64] and diplexers [23], [41], [93] have been reported so far based on some of the above-mentioned tuning mechanisms. However, tuning or reconfiguring one or all of the channels of SIW multiband BPFs and multiplexers is still tough amid the difficulty in independently tuning or controlling the frequencies and couplings of multiple modes, as illustrated in Fig. 17(b). Anyway, the shunting scheme seems to be the most viable solution for the development of tunable/reconfigurable multiband BPFs and multiplexers with freely or flexibly tuned channels/passbands up to date.

C. MINIATURIZATION

Miniaturization is always needed in the development of RF, microwave, and mmW components, devices, and systems, particularly in the design of gigahertz circuits and THz chips. Since the first invention and latter developments of SIW techniques [146], [147], [148], [149], [150], much efforts have already been invested in the miniaturization arts of SIW structures, basically embracing multilayered topologies using LTCC technology [151], modal partition techniques using half-/quarter- to $1/n^{\text{th}}$-mode SIW schemes based on modal symmetry theory [152], [153], [154], [155], folded [156], [157] and ridged [158], [159] SIW techniques, metamaterial and metasurface structures-loaded SIW solutions through left-handed and right-handed combinations [160], and slow-wave effects [161], as the few examples listed in Fig. 18. Some of these schemes have also been applied to design miniaturized SIW multiband BPFs and multiplexers, such as using LTCC-based multilayered configurations [40], [62], [69], [73], [75], [111], [131], partial-mode techniques [53], [64], [82], [90], [94], [105]–[107], [128], folded [25] and ridged [32] schemes, and metamaterial cells-based solutions [33], [34], [35], [36], [37], [49], [50], [51], [52], [53]. It is worthwhile mentioning that these miniaturization schemes would usually lead to

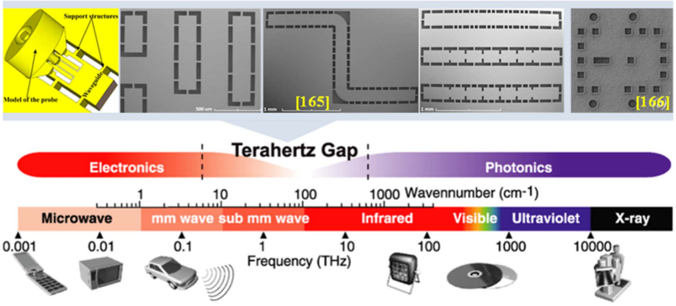

FIGURE 19. Terahertz gap for a powerful applicability of SIW techniques in the development of THz circuits, systems, and chips.

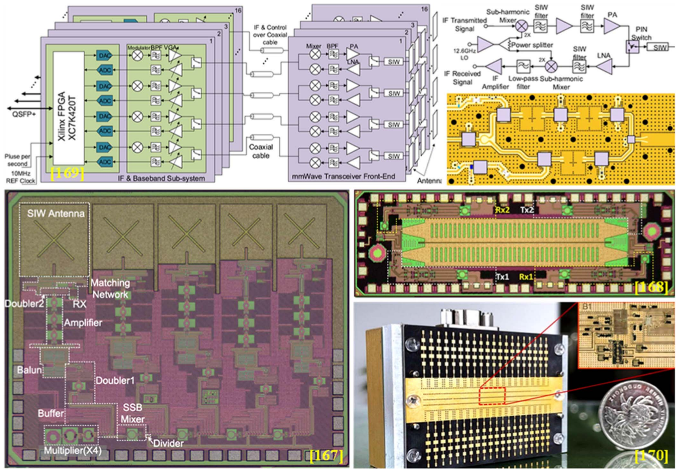

FIGURE 20. High-density integration of hybrid and monolithic microwave circuits and systems integrating SIW transimission lines, antennas, or BPFs.

the increasing of transmission loss of an SIW transmission structure or the lowering Q_u of an SIW resonant cavity. Consequently, a compromised solution through adequate choices of structures, materials, and modes must be considered altogether in most cases.

D. TERAHERTZ

Terahertz technologies have become more and more prevalent with urgent requirements for higher-throughput and lower-latency data transmissions, particularly for 6G and other wireless systems. In this case, appropriate loss-efficient and easy-to-integrate guided-wave structures become indispensable for the success of any THz circuit and system developments and deployments. Some endeavors and practices have been made on the design strategies of THz guided-wave transmission lines, transitions, and BPFs based on SIW techniques, such as using the through-silicon via (TSV) technology [162], [163], [164], the micromachined silicon-core at 220–330 GHz [165], and the cyclic etched silicon carbon (SiC) process [166], as the works illustrated in Fig. 19. A few sub-mmW and THz multiplexers have been developed based on SIW platform, such as W-band diplexers using printed circuit board process [20], [136], and 220–330 GHz manifold triplexer using semi-additive microelectronics packaging process [32]. Meanwhile, the hybrid metallic and dielectric waveguides can naturally accommodate both electrical and optical properties in a flexible manner, including the aforementioned SINRD and SIIG solutions, which will form a low-loss hybrid metal-dielectric structure for future THz applications [4].

E. INTEGRATION

As the technology roadmap of microwave circuits and systems shown in [4], the global development trend from generation to generation is fundamentally governed and navigated by the needs for higher density integration, in addition to a better integrated multifunctionality. Judging from the demands of higher frequency development and cost-effective assembling, a scalable high-density integration is always the leading specification for productivity, efficiency, applicability, and reliability. As proved by several representative wireless electronics systems demonstrated in Fig. 20, SIW techniques definitely offer a self-packaging and easy-to-integrate solution with any other planar structures to develop and implement advanced mmW and THz transceiver systems [167], [168], [169], [170], where the SIW structures are deployed not only to design Tx/Rx antennas [167], [168] but also to realize the transmissions, transitions, and BPFs [169], [170]. High-performance duplexing antenna systems have also been developed and presented in [16] and [99] based on SIW technology. In the end, the SIW-driven integration will become an ultimate design choice of hybrid and monolithic mmW and THz systems for integrating antennas, circuits, and packages altogether.

V. CONCLUSION

The design techniques and implementation schemes of multiband BPFs and multiplexers are systematically summarized and classified as six categories with their own merits and drawbacks elaborated in detail. Various technical approaches and practical demonstrations based on SIW techniques are comprehensively reviewed and elaborated in detail for each scheme or topology. The future developments and research directions are also forecasted and discussed with five distinct aspects. It can be found that SIW techniques can offer a fascinating perspective for future MHz-through-THz science and engineering as well as for the development of multifunction, multistandard, and multiband filtering devices and wireless systems.

REFERENCES

[1] W. Hong et al., "The role of millimeter-wave technologies in 5G/6G wireless communications," *IEEE J. Microwaves*, vol. 1, no. 1, pp. 101–122, Jan. 2021.

[2] W. Goddard, "History of IoT: What it is, how it works, where it's come from, and where it's going," Jun. 2019. [Online]. Available: https://itchronicles.com/iot/history-of-iot-what-it-is-how-it-works-where-its-come-from-and-where-its-going/

[3] D. Xu et al., "Edge intelligence: Architectures, challenges, and applications," Jun. 2020, *arXiv:2003.12172v2*.

[4] K. Wu, M. Bozzi, and N. J. G. Fonseca, “Substrate integrated transmission lines: Review and applications,” *IEEE J. Microwaves*, vol. 1, no. 1, pp. 345–363, Jan. 2021.

[5] X.-P. Chen and K. Wu, “Substrate integrated waveguide filter: Basic design rules and fundamental structure features,” *IEEE Microw. Mag.*, vol. 15, no. 5, pp. 108–116, Jul./Aug. 2014.

[6] M. Bozzi, A. Georgiadis, and K. Wu, “Review of substrate-integrated waveguide circuits and antennas,” *IET Microw. Antennas Propag.*, vol. 5, no. 8, pp. 909–920, Jun. 2011.

[7] K. Zhou and K. Wu, “Substrate integrated waveguide multiband bandpass filters and multiplexers,” in *Proc. IEEE MTT-S Int. Microw. Filter Workshop*, 2021, pp. 300–302.

[8] K. Zhou and K. Wu, “Overview of substrate-integrated waveguide dual-band and multiband bandpass filters,” in *Proc. 34th Gen. Assem. Sci. Symp. Int. Union Radio Sci.*, 2021, pp. 1–4.

[9] G. Macchiarella and S. Tamiazzo, “Design techniques for dual-passband filters,” *IEEE Trans. Microw. Theory Techn.*, vol. 53, no. 11, pp. 3265–3271, Nov. 2005.

[10] J. Lee and K. Sarabandi, “A synthesis method for dual-passband microwave filters,” *IEEE Trans. Microw. Theory Techn.*, vol. 55, no. 6, pp. 1163–1170, Jun. 2007.

[11] J. Lee and K. Sarabandi, “Design of triple-passband microwave filters using frequency transformations,” *IEEE Trans. Microw. Theory Techn.*, vol. 56, no. 1, pp. 187–193, Jan. 2008.

[12] M. Mokhtaari, J. Bornemann, K. Rambabu, and S. Amari, “Coupling-matrix design of dual and triple passband filters,” *IEEE Trans. Microw. Theory Techn.*, vol. 54, no. 11, pp. 3940–3946, Nov. 2006.

[13] S. Amari, “Synthesis of cross-coupled resonator filters using an analytical gradient-based optimization technique,” *IEEE Trans. Microw. Theory Techn.*, vol. 48, no. 9, pp. 1559–1564, Sep. 2000.

[14] Z. C. Hao, W. Hong, J. X. Chen, X. P. Chen, and K. Wu, “Planar diplexer for microwave integrated circuits,” *Inst. Elect. Eng. Proc., Microw., Antennas Propag.*, vol. 152, no. 6, pp. 455–459, Dec. 2005.

[15] S. H. Han, X. L. Wang, Y. Fan, Z. Q. Yang, and Z. N. He, “The generalized Chebyshev substrate integrated waveguide diplexer,” *Prog. Electromagn. Res.*, vol. 73, pp. 29–38, 2007.

[16] N. Athanasopoulos, D. Makris, and K. Voudouris, “Millimeter-wave passive front-end based on substrate integrated waveguide technology,” in *Proc. Loughborough Antennas Propag. Conf.*, 2012, pp. 1–4.

[17] Z. Kordiboroujeni and J. Bornemann, “Mode matching design of substrate integrated waveguide diplexers,” in *IEEE MTT-S Int. Microw. Symp. Dig.*, 2013, pp. 1–3.

[18] Z. Kordiboroujeni, J. Bornemann, and T. Sieverding, “K-band substrate integrated waveguide T-junction diplexer design by mode-matching techniques,” in *Proc. Asia-Pacific Microw. Conf.*, 2014, pp. 1297–1299.

[19] Z. Kordiboroujeni and J. Bornemann, “K-band backward diplexer in substrate integrated waveguide technology,” *Electron. Lett.*, vol. 51, no. 18, pp. 1428–1429, Sep. 2015.

[20] M.-H. Chen, H.-S. Cheng, P.-J. Chou, and C.-Y. Chang, “W-band T-junction and bifurcated substrate integrated waveguide diplexers,” in *Proc. Int. Workshop Electromagn., Appl. Student Innov. Competition*, 2015, pp. 1–2.

[21] C. Zhao, C. Fumeaux, and C.-C. Lim, “Substrate-integrated waveguide diplexers with improved Y-junctions,” *Microw. Opt. Technol. Lett.*, vol. 58, no. 6, pp. 1384–1388, Jun. 2016.

[22] T. Jaschke, B. Rohrdantz, J.-P. Mohncke, and A. F. Jacob, “A Ka-band substrate-integrated waveguide diplexer with wide frequency spread,” in *Proc. 46th Eur. Microw. Conf.*, 2016, pp. 779–782.

[23] M. A. Khater, Y.-C. Wu, and D. Peroulis, “Tunable cavity-based diplexer with spectrum-aware automatic tuning,” *IEEE Trans. Microw. Theory Techn.*, vol. 65, no. 3, pp. 934–944, Mar. 2017.

[24] R. Stefanski, M. Krol, and P. Jankovic, “Compact high isolation SIW X-band diplexer for Cubesat nano-satellites,” in *Proc. 1st Eur. Microw. Conf. Central Eur.*, 2019, pp. 461–465.

[25] A. Sieganschin, B. Tegowski, T. Jaschke, and A. F. Jacob, “Compact diplexers with folded circular SIW cavity filters,” *IEEE Trans. Microw. Theory Techn.*, vol. 69, no. 1, pp. 111–118, Jan. 2021.

[26] H. J. Tang, W. Hong, J.-X. Chen, G. Q. Luo, and K. Wu, “Development of millimeter-wave planar diplexers based on complementary characters of dual-mode substrate integrated waveguide filters with circular and elliptic cavities,” *IEEE Trans. Microw. Theory Techn.*, vol. 55, no. 4, pp. 776–782, Apr. 2007.

[27] A. A. Khan and M. K. Mandal, “Design of planar diplexers with improved isolation using the tunable transmission zeros of a dual-mode cavity filter,” *IET Microw. Antennas Propag.*, vol. 11, no. 11, pp. 1587–1593, Sep. 2017.

[28] X. Chen, W. Hong, T. Cui, and K. Wu, “Substrate integrated waveguide (SIW) asymmetric dual-mode filter and diplexer,” *Int. J. Electron.*, vol. 92, no. 12, pp. 743–753, Dec. 2005.

[29] D. Hou, W. Hong, L. Tian, J. Liu, and H. Tang, “A planar triplexer based on substrate integrated waveguide technology for TD-SCDMA applications,” in *Proc. Asia-Pacific Microw. Conf.*, 2009, pp. 2584–2587.

[30] Z.-C. Hao, X.-P. Huo, W.-Q. Ding, and W. Hong, “Efficient design of compact contiguous-channel SIW multiplexers using the space-mapping method,” *IEEE Trans. Microw. Theory Techn.*, vol. 63, no. 11, pp. 3651–3662, Nov. 2015.

[31] J. He, K. Gao, and Z. Shao, “A novel compact Ka-band high-rejection diplexer based on substrate integrated waveguide,” in *Proc. IEEE Int. Conf. Comput. Prob. Solving*, 2012, pp. 193–197.

[32] J. W. Holloway, G. C. Dogiamis, S. Shin, and R. Han, “220-to-330-GHz manifold triplexer with wide stopband utilizing ridged substrate integrated waveguides,” *IEEE Trans. Microw. Theory Techn.*, vol. 68, no. 8, pp. 3428–3438, Aug. 2020.

[33] Y. Dong, C.-T. M. Wu, and T. Itoh, “Miniaturised multi-band substrate integrated waveguide filters using complementary split-ring resonators,” *IET Microw. Antennas Propag.*, vol. 6, no. 6, pp. 611–620, Apr. 2012.

[34] S. Xu, K. Ma, F. Meng, and K. S. Yeo, “Novel defected ground structure and two-side loading scheme for miniaturized dual-band SIW bandpass filter designs,” *IEEE Microw. Wireless Compon. Lett.*, vol. 25, no. 4, pp. 217–219, Apr. 2015.

[35] W. Fu, Z. Li, P. Liu, J. Cheng, and X. Qiu, “Modeling and analysis of novel CSRRs-loaded dual-band bandpass SIW filters,” *IEEE Trans. Circuits Syst. II, Exp. Briefs*, vol. 68, no. 7, pp. 2352–2356, Jul. 2021.

[36] Y. Dong and T. Itoh, “Substrate integrated waveguide loaded by complementary split-ring resonators for miniaturized diplexer design,” *IEEE Microw. Wireless Compon. Lett.*, vol. 21, no. 1, pp. 10–12, Jan. 2011.

[37] Z. Yang, J. Dong, B. Luo, T. Yang, and Y. Liu, “Low phase noise concurrent dual-band oscillator using compact diplexer,” *IEEE Microw. Wireless Compon. Lett.*, vol. 25, no. 10, pp. 672–674, Oct. 2015.

[38] H. Zhang, W. Kang, and W. Wu, “Miniaturized dual-band SIW filters using E-shaped slotlines with controllable center frequencies,” *IEEE Microw. Wireless Compon. Lett.*, vol. 28, no. 4, pp. 311–313, Apr. 2018.

[39] K. Dhwaj, X. Li, Z. Shen, and S. Qin, “Cavity resonators do the trick: A packaged substrate integrated waveguide dual-band filter,” *IEEE Microw. Mag.*, vol. 17, no. 1, pp. 58–64, Jan. 2016.

[40] J.-H. Lee, N. Kidera, G. DeJean, S. Pinel, J. Laskar, and M. M. Tentzeris, “A V-band front-end with 3-D integrated cavity filters/duplexers and antenna in LTCC technologies,” *IEEE Trans. Microw. Theory Techn.*, vol. 54, no. 7, pp. 2925–2936, Jul. 2006.

[41] A. Iqbal, J. J. Tiang, C. K. Lee, and B. M. Lee, “Tunable substrate integrated waveguide diplexer with high isolation and wide stopband,” *IEEE Microw. Wireless Compon. Lett.*, vol. 29, no. 7, pp. 456–458, Jul. 2019.

[42] Z. L. Su, B. W. Xu, S. Y. Zheng, H. W. Liu, and Y. L. Long, “High-isolation and wide-stopband SIW diplexer using mixed electric and magnetic coupling,” *IEEE Trans. Circuits Syst. II, Exp. Briefs*, vol. 67, no. 1, pp. 32–36, Jan. 2020.

[43] F. Cheng, C. Gu, B. Zhang, Y. Yang, and K. Huang, “High isolation substrate integrated waveguide diplexer with flexible transmission zeros,” *IEEE Microw. Wireless Compon. Lett.*, vol. 30, no. 11, pp. 1029–1032, Nov. 2020.

[44] S. Sirci, J. D. Martinez, J. Vague, and V. E. Boria, “Substrate integrated waveguide diplexer based on circular triplet combline filters,” *IEEE Microw. Wireless Compon. Lett.*, vol. 25, no. 7, pp. 430–432, Jul. 2015.

[45] P. Chu et al., “Dual-mode substrate integrated waveguide filter with flexible response,” *IEEE Trans. Microw. Theory Techn.*, vol. 65, no. 3, pp. 824–830, Mar. 2017.

[46] K. Song, Y. Zhou, Y. Chen, A. M. Iman, S. R. Patience, and Y. Fan, "High-isolation diplexer with high frequency selectivity using substrate integrated waveguide dual-mode resonator," *IEEE Access*, vol. 7, pp. 116676–116683, Jul. 2019.

[47] X.-L. Yang, X.-W. Zhu, X. Wang, and C. Ge, "Q-band dual-mode substrate integrated waveguide filter and diplexer with circular cavity," *Int. J. RF Microw. Comput.-Aided Eng.*, vol. 31, no. 7, Jul. 2020, Art. no. e22691.

[48] P. Chu, K.-L. Zheng, and F. Xu, "A planar diplexer using hybrid substrate integrated waveguide and coplanar waveguide," in *Proc. IEEE 17th Int. Conf. Ubiquitous Wireless Broadband*, 2017, pp. 1–4.

[49] M. Adhikary, P. Chongder, and A. Biswas, "Planar miniaturized substrate integrated waveguide triplexer with radial symmetry," in *Proc. Asia-Pacific Microw. Conf.*, 2016, pp. 1–4.

[50] A. Corona-Chavez and T. Itoh, "Novel miniaturized triplexer using substrate integrated technology," in *Proc. Asia-Pacific Microw. Conf.*, 2010, pp. 678–681.

[51] E. M. Eldesouki, K. M. Ibrahim, and A. M. Attiya, "Analysis and design of a diplexer for satellite communication system," *Appl. Comput. Electromagn. Soc. J.*, vol. 35, no. 10, pp. 1236–1241, Oct. 2020.

[52] S. Soleimani, S. Mirhadi, and N. Komjani, "Design of a broadband diplexer based on substrate integrated plasmonic waveguide," *Int. J. RF Microw. Comput.-Aided Eng.*, vol. 31, no. 11, Nov. 2021, Art. no. e22854.

[53] Y. Cui, K.-D. Xu, Y.-J. Guo, and Q. Chen, "Half-mode substrate integrated plasmonic waveguide for filter and diplexer designs," *J. Phys. D, Appl. Phys.*, vol. 55, no. 12, Jan. 2022, Art. no. 125104.

[54] S. Y. Zheng, Z. L. Su, Y. M. Pan, Z. Qamar, and D. Ho, "New dual-/tri-band bandpass filters and diplexer with large frequency ratio," *IEEE Trans. Microw. Theory Techn.*, vol. 66, no. 6, pp. 2978–2992, Jun. 2018.

[55] J. Schorer, J. Bornemann, and U. Rosenberg, "Mode-matching design of substrate mounted waveguide (SMW) components," *IEEE Trans. Microw. Theory Techn.*, vol. 64, no. 8, pp. 2401–2408, Aug. 2016.

[56] Y. Su, Y. Fan, X. Q. Lin, and K. Wu, "Single-layer mode composite coplanar waveguide dual-band filter with large frequency ratio," *IEEE Trans. Microw. Theory Techn.*, vol. 68, no. 8, pp. 2320–2330, Jun. 2020.

[57] J.-C. Li, M. Mimsyad, C.-Y. Hou, C.-I.-G. Hsu, and M.-H. Ho, "Balanced diplexer design using multi-layered substrate integrated waveguide cavities," in *Proc. 48th Eur. Microw. Conf.*, 2018, pp. 707–710.

[58] L.-S. Wu, J.-F. Mao, W.-Y. Yin, and Y.-X. Guo, "A dual-band filter using stepped-impedance resonator (SIR) embedded into substrate integrated waveguide (SIW)," in *Proc. IEEE Elect. Des. Adv. Package Syst. Symp.*, 2010, pp. 1–4.

[59] S. Sirci, M. A. Sanchez-Soriano, J. D. Martinez, and V. E. Boria, "Advanced filtering solutions in coaxial SIW technology based on singlets, cascaded singlets, and doublets," *IEEE Access*, vol. 7, pp. 29901–29915, 2019.

[60] H. Zhang, W. Kang, and W. Wu, "Miniaturized dual-band differential filter based on CSRR-loaded dual-mode SIW cavity," *IEEE Microw. Wireless Compon. Lett.*, vol. 28, no. 10, pp. 897–899, Oct. 2018.

[61] Y. Zheng, Z. Wang, and Y. Dong, "Compact, dual-band, and hybrid filter based on combline and substrate integrated waveguide resonators," *Int. J. RF Microw. Comput.-Aided Eng.*, vol. 32, no. 1, Jan. 2022, Art. no. e22919.

[62] B.-J. Chen, T.-M. Shen, and R.-B. Wu, "Dual-band vertically stacked laminated waveguide filter design in LTCC technology," *IEEE Trans. Microw. Theory Techn.*, vol. 57, no. 6, pp. 1554–1562, Jun. 2009.

[63] K. Zhou, C.-X. Zhou, and W. Wu, "Substrate-integrated waveguide dual-mode dual-band bandpass filters with widely controllable bandwidth ratios," *IEEE Trans. Microw. Theory Techn.*, vol. 65, no. 10, pp. 3801–3812, Oct. 2017.

[64] A. Iqbal, J. J. Tiang, C. K. Lee, N. K. Mallat, and S. W. Wong, "Dual-band half mode substrate integrated waveguide filter with independently tunable bands," *IEEE Trans. Circuits Syst. II, Exp. Briefs*, vol. 67, no. 2, pp. 285–289, Feb. 2020.

[65] H.-W. Xie, K. Zhou, C.-X. Zhou, and W. Wu, "Compact wide-stopband SIW dual-band filter with closely spaced passbands," *Electron. Lett.*, vol. 56, no. 16, pp. 822–825, Aug. 2020.

[66] Y. Shen, H. Wang, W. Kang, and W. Wu, "Dual-band SIW differential bandpass filter with improved common-mode suppression," *IEEE Microw. Wireless Compon. Lett.*, vol. 25, no. 2, pp. 100–102, Feb. 2015.

[67] A. R. Azad and A. Mohan, "Substrate integrated waveguide dual-band and wide-stopband bandpass filters," *IEEE Microw. Wireless Compon. Lett.*, vol. 28, no. 8, pp. 660–662, Aug. 2018.

[68] M. Li, C. Chen, and W. Chen, "Miniaturized dual-band filter using dual-capacitively loaded SIW cavities," *IEEE Microw. Wireless Compon. Lett.*, vol. 27, no. 4, pp. 344–346, Apr. 2017.

[69] W.-L. Tsai, T.-M. Shen, B.-J. Chen, T.-Y. Huang, and R.-B. Wu, "Design of single-branch laminated waveguide diplexers using modal orthogonality," *IEEE Trans. Microw. Theory Techn.*, vol. 61, no. 12, pp. 4079–4089, Dec. 2013.

[70] K. Zhou, C.-X. Zhou, and W. Wu, "Substrate-integrated waveguide dual-band filters with closely spaced passbands and flexibly allocated bandwidths," *IEEE Trans. Compon. Packag. Manuf. Technol.*, vol. 8, no. 3, pp. 465–472, Mar. 2018.

[71] H. Chu and J.-X. Chen, "Dual-band substrate integrated waveguide balun bandpass filter with high selectivity," *IEEE Microw. Wireless Compon. Lett.*, vol. 24, no. 6, pp. 379–381, Jun. 2014.

[72] M. Rezaee and A. R. Attari, "A novel dual mode dual band SIW filter," in *Proc. 44th Eur. Microw. Conf.*, 2014, pp. 853–856.

[73] H. Chu, Y. X. Guo, Y. L. Song, and Z. L. Wang, "40/50 GHz diplexer design in LTCC technology," *Electron. Lett.*, vol. 47, no. 4, pp. 260–262, Feb. 2011.

[74] P. Li, H. Chu, D. Zhao, and R. S. Chen, "Compact dual-band balanced SIW bandpass filter with improved common-mode suppression," *IEEE Microw. Wireless Compon. Lett.*, vol. 27, no. 4, pp. 347–349, Apr. 2017.

[75] W. Shen, W.-Y. Yin, and X.-W. Sun, "Miniaturized dual-band substrate integrated waveguide filter with controllable bandwidths," *IEEE Microw. Wireless Compon. Lett.*, vol. 21, no. 8, pp. 418–420, Aug. 2011.

[76] S. Zhang, J.-Y. Rao, J.-S. Hong, and F.-L. Liu, "A novel dual-band controllable bandpass filter based on fan-shaped substrate integrated waveguide," *IEEE Microw. Wireless Compon. Lett.*, vol. 28, no. 4, pp. 308–310, Apr. 2018.

[77] Y.-L. Shen, J.-T. Hung, M.-H. Ho, and C.-I. G. Hsu, "Miniaturised substrate integrated waveguide cavities in dual-band filter and diplexer design," *IET Microw. Antennas Propag.*, vol. 14, no. 5, pp. 428–434, May 2020.

[78] T. Zhou, T. Liu, S. Wu, J. Xie, Y. Ye, and G. Xu, "Isosceles triangular cavity based dual-band SIW filters for 5G millimeter-wave systems," in *Proc. Int. Conf. Microw. Millimeter Wave Technol.*, 2021, pp. 1–3.

[79] Q. Zhang, C. Chen, W. Chen, J. Ding, and H. Zhang, "Novel cross-coupled dual-band bandpass filters with compact size based on dual-mode isosceles right-angled triangular resonators," *IEEE Trans. Microw. Theory Techn.*, vol. 69, no. 6, pp. 3037–3047, Jun. 2021.

[80] H.-W. Xie, K. Zhou, C.-X. Zhou, and W. Wu, "Substrate-integrated waveguide triple-band bandpass filters using triple-mode cavities," *IEEE Trans. Microw. Theory Techn.*, vol. 66, no. 6, pp. 2967–2977, Jun. 2018.

[81] M. Mehrabi, A. Arsanjani, K. Afrooz, and M. Tayarani, "Compact reconfigurable triple-mode triple-band substrate integrated waveguide bandpass filter," *Int. J. RF Microw. Comput.-Aided Eng.*, vol. 30, no. 3, Mar. 2020, Art. no. e22099.

[82] A. Iqbal, J. J. Tiang, S. W. Wong, and N. K. Mallat, "QMSIW-based single and triple-band bandpass filters," *IEEE Trans. Circuits Syst. II, Exp. Briefs*, vol. 68, no. 7, pp. 2443–2447, Jul. 2021.

[83] S. Zhang, Y. Guo, Y.-Y. Zhou, and J.-S. Hong, "Two miniaturized triple-band filters based on 90 sector substrate integrated waveguide," *Microw. Opt. Technol. Lett.*, vol. 62, no. 12, pp. 3820–3828, Dec. 2020.

[84] M.-H. Ho and K.-H. Tang, "Miniaturized SIW cavity tri-band filter design," *IEEE Microw. Wireless Compon. Lett.*, vol. 30, no. 6, pp. 589–592, Jun. 2020.

[85] J. Zhang, Q. Liu, D. Zhou, and D. Zhang, "Single-and triple-band bandpass filters using novel perturbed isosceles right-angled triangular SIW cavities," *IET Microw. Antennas Propag.*, vol. 15, pp. 241–252, 2021.

[86] K. Zhou, C.-X. Zhou, and W. Wu, "Resonance characteristics of substrate-integrated rectangular cavity and their applications to dual-band and wide-stopband bandpass filters design," *IEEE Trans. Microw. Theory Techn.*, vol. 65, no. 5, pp. 1511–1524, May 2017.

[87] K. Zhou, C.-X. Zhou, and W. Wu, "Substrate integrated waveguide dual-band filter with wide-stopband performance," *Electron. Lett.*, vol. 53, no. 16, pp. 1121–1123, Aug. 2017.

[88] H.-W. Xie, K. Zhou, C.-X. Zhou, and W. Wu, "Compact SIW diplexers and dual-band bandpass filter with wide-stopband performances," *IEEE Trans. Circuits Syst. II, Exp. Briefs*, vol. 67, no. 12, pp. 2933–2937, Dec. 2020.

[89] Y. Zhu and Y. Dong, "A compact dual-band quasi-elliptic filter based on hybrid SIW and microstrip technologies," *IEEE Trans. Circuits Syst. II, Exp. Briefs*, vol. 69, no. 3, pp. 719–723, Mar. 2022.

[90] K. Zhou, C.-X. Zhou, and W. Wu, "Dual-mode characteristics of half-mode SIW rectangular cavity and applications to dual-band filters with widely separated passbands," *IEEE Trans. Microw. Theory Techn.*, vol. 66, no. 11, pp. 4820–4829, Nov. 2018.

[91] K. Zhou, C.-X. Zhou, and W. Wu, "Compact SIW diplexer with flexibly allocated bandwidths using common dual-mode cavities," *IEEE Microw. Wireless Compon. Lett.*, vol. 28, no. 4, pp. 317–319, Apr. 2018.

[92] K. Zhou, C. Zhou, and W. Wu, "Compact planar substrate-integrated waveguide diplexers with wide-stopband characteristics," *Int. J. RF Microw. Comput.-Aided Eng.*, vol. 30, no. 6, Jun. 2020, Art. no. e22179.

[93] M. F. Hagag, M. A. Khater, M. D. Hickle, and D. Peroulis, "Tunable SIW cavity-based dual-mode diplexers with various single-ended and balanced ports," *IEEE Trans. Microw. Theory Techn.*, vol. 66, no. 3, pp. 1238–1248, Mar. 2018.

[94] K. Zhou and K. Wu, "Miniaturized diplexers with large frequency ratios based on common half-mode dual-mode SIW junction-cavities," *IEEE Trans. Microw. Theory Techn.*, vol. 69, no. 12, pp. 5343–5350, Dec. 2021.

[95] X. Liu, Z. Zhu, Y. Liu, Q. Lu, X. Yin, and Y. Yang, "Compact bandpass filter and diplexer with wide-stopband suppression based on balanced substrate-integrated waveguide," *IEEE Trans. Microw. Theory Techn.*, vol. 69, no. 1, pp. 54–64, Jan. 2021.

[96] F. Cheng, X. Lin, K. Song, Y. Jiang, and Y. Fan, "Compact diplexer with high isolation using the dual-mode substrate integrated waveguide resonator," *IEEE Microw. Wireless Compon. Lett.*, vol. 23, no. 9, pp. 459–461, Sep. 2013.

[97] M. Rezaee and A. R. Attari, "A compact substrate integrated waveguide diplexer using dual mode resonator as a junction for system in package applications," *Electromagnetics*, vol. 37, no. 2, pp. 92–105, Feb. 2017.

[98] Z. Kordiboroujeni and J. Bornemann, "Substrate integrated waveguide diplexer with dual-mode junction cavity," in *Proc. 45th Eur. Microw. Conf.*, 2015, pp. 753–756.

[99] Z. Kordiboroujeni, L. Locke, and J. Bornemann, "A diplexing antenna system in substrate integrated waveguide technology," in *Proc. IEEE Int. Symp. Antennas Propag. USNC/URSI Nat. Radio Sci. Meeting*, 2015, pp. 1042–1043.

[100] K. Song, J. Yao, Y. Chen, Y. Zhou, Y. Zhu, and Y. Fan, "Balanced diplexer based on substrate integrated waveguide dual-mode resonator," *IEEE Trans. Microw. Theory Techn.*, vol. 68, no. 12, pp. 5279–5287, Dec. 2020.

[101] H.-W. Xie, K. Zhou, C.-X. Zhou, and W. Wu, "Stopband-improved SIW triplexer and triple-band filters using alternately cascaded triple- and single-mode cavities," *IEEE Access*, vol. 7, pp. 56745–56752, 2019.

[102] X.-P. Chen, K. Wu, and Z.-L. Li, "Dual-band and triple-band substrate integrated waveguide filters with Chebyshev and quasi-elliptic responses," *IEEE Trans. Microw. Theory Techn.*, vol. 55, no. 12, pp. 2569–2578, Dec. 2007.

[103] M. Esmaeili and J. Bornemann, "Substrate integrated waveguide triple-passband dual-stopband filter using six cascaded singlets," *IEEE Microw. Wireless Compon. Lett.*, vol. 24, no. 7, pp. 439–441, Jul. 2014.

[104] K. S. K. Yeo, "A novel canonical triband substrate integrated waveguide bandpass filter," in *Proc. Asia-Pacific Microw. Conf.*, 2019, pp. 354–356.

[105] V. Sekar and K. Entesari, "A novel compact dual-band half-mode substrate integrated waveguide bandpass filter," in *Proc. IEEE MTT-S Int. Microw. Symp.*, 2011, pp. 1–4.

[106] S. A. Shakib, V. Sekar, and K. Entesari, "A compact triple-band bandpass filter based on half-mode substrate integrated waveguides," in *Proc. 42nd Eur. Microw. Conf.*, 2012, pp. 116–119.

[107] P. Li, H. Chu, and R.-S. Chen, "Design of compact bandpass filters using quarter-mode and eighth-mode SIW cavities," *IEEE Trans. Compon., Packag. Manuf. Technol.*, vol. 7, no. 6, pp. 956–963, Jun. 2017.

[108] A. Garcia-Lamperez, M. Salazar-Palma, and S. H. Yeung, "SIW compact diplexer," in *Proc. IEEE MTT-S Int. Microw. Symp.*, 2014, pp. 1–4.

[109] P. Chongder and A. Biswas, "Flexible design procedure for realisation of dual-mode substrate integrated hexagonal-cavity-based diplexer," *IET Microw. Antennas Propag.*, vol. 11, no. 14, pp. 2083–2090, Oct. 2017.

[110] X. Shang, Y. Wang, W. Xia, and M. J. Lancaster, "Novel multiplexer topologies based on all-resonator structures," *IEEE Trans. Microw. Theory Techn.*, vol. 61, no. 11, pp. 3838–3845, Nov. 2013.

[111] W.-L. Tsai, T.-M. Shen, B.-J. Chen, T.-Y. Huang, and R.-B. Wu, "Triband filter design using laminated waveguide cavity in LTCC," *IEEE Trans. Compon., Packag. Manuf. Technol.*, vol. 4, no. 6, pp. 957–966, Jun. 2014.

[112] S. Zhang, J. Y. Rao, J. J. Cheng, J. S. Hong, and F. L. Liu, "A novel triple-band bandpass filter based on equilateral triangle substrate integrated waveguide," *Microw. Opt. Technol. Lett.*, vol. 60, no. 3, pp. 575–578, Mar. 2018.

[113] K. Zhou, C. Zhou, and W. Wu, "Substrate-integrated waveguide triple-band filter with improved frequency and bandwidth allocations," *Electron. Lett.*, vol. 54, no. 19, pp. 1132–1134, Sep. 2018.

[114] Z. Yang, B. You, and G. Luo, "Dual-/tri-band bandpass filter using multimode rectangular SIW cavity," *Microw. Opt. Technol. Lett.*, vol. 62, no. 3, pp. 1098–1102, Mar. 2020.

[115] X. Guo, L. Zhu, and W. Wu, "Design method for multi-band filters with compact configuration in substrate integrated waveguide," *IEEE Trans. Microw. Theory Techn.*, vol. 66, no. 6, pp. 3011–3018, Jun. 2018.

[116] K. Zhou, C.-X. Zhou, H.-W. Xie, and W. Wu, "Synthesis design of SIW multiband bandpass filters based on dual-mode resonances and split-type dual- and triple-band responses," *IEEE Trans. Microw. Theory Techn.*, vol. 67, no. 1, pp. 151–161, Jan. 2019.

[117] K. Zhou, C. Zhou, and W. Wu, "SIW sext-band bandpass filter based on split-type triple-band symmetrical frequency responses," *Int. J. RF Microw. Comput.-Aided Eng.*, vol. 28, no. 9, Nov. 2018, Art. no. e21594.

[118] P.-L. Chi, H.-T. Shih, and T. Yang, "5G millimeter-wave substrate integrated waveguide quad-channel diplexer with high in-band and wideband isolation," *IEEE Microw. Wireless Compon. Lett.*, vol. 31, no. 6, pp. 650–653, Jun. 2021.

[119] K. Zhou and K. Wu, "Multichannel substrate integrated waveguide diplexer made of dual-mode cavities and split-type dual-band response," in *Proc. IEEE MTT-S Int. Microw. Symp.*, 2021, pp. 685–688.

[120] K. Zhou and K. Wu, "Multichannel substrate integrated waveguide diplexers based on orthogonal dual modes and split-type multiband responses," *IEEE Trans. Microw. Theory Techn.*, vol. 70, no. 1, pp. 356–366, Jan. 2022.

[121] M. Li, C. Chen, W. Chen, and H. Zhang, "A novel dual-band bandpass filter using a single perturbed substrate integrated waveguide cavity," in *Proc. IEEE MTT-S Int. Microw. Symp.*, 2017, pp. 1076–1079.

[122] A. R. Azad and A. Mohan, "Single- and dual-band bandpass filters using a single perturbed SIW circular cavity," *IEEE Microw. Wireless Compon. Lett.*, vol. 29, no. 3, pp. 201–203, Mar. 2019.

[123] X.-L. Yang, X.-W. Zhu, and X. Wang, "Dual-band substrate integrated waveguide filters with perturbed circular cavity," *IEEE Microw. Wireless Compon. Lett.*, vol. 32, no. 4, pp. 293–296, Apr. 2022.

[124] Y.-K. Han, H.-W. Deng, J.-M. Zhu, S.-B. Xing, and W. Han, "Compact dual-band dual-mode SIW balanced BPF with intrinsic common-mode suppression," *IEEE Microw. Wireless Compon. Lett.*, vol. 31, no. 2, pp. 101–104, Feb. 2021.

[125] C. Chen and Q. Ji, "Triple-mode dual-band bandpass filter based on cross-shaped substrate integrated waveguide," *Electron. Lett.*, vol. 55, no. 3, pp. 138–140, Feb. 2019.

[126] Y.-D. Wu, G.-H. Li, W. Yang, and T. Mou, "A novel dual-band SIW filter with high selectivity," *Prog. Electromagn. Res. Lett.*, vol. 60, pp. 81–88, 2016.

[127] J. Li, G. Li, Z. Wei, G. Xu, Z. Ju, and J. Huang, "Compact dual-band bandpass filter based on substrate integrated waveguide cavity with high selectivity," *Prog. Electromagn. Res. M*, vol. 61, pp. 147–158, 2017.

[128] B.-G. Liu, Y.-P. Lyu, L. Zhu, and C.-H. Cheng, "Compact single- and dual-band filters on hexa-modes half-mode substrate integrated waveguide resonator with loaded H-shaped slot," *IEEE Microw. Wireless Compon. Lett.*, vol. 30, no. 12, pp. 1129–1132, Dec. 2020.

[129] L. Qu, Y. Zhang, J. Liu, and Y. Fan, "Three-state SIW diplexer with independently controllable centre frequencies," *Electron. Lett.*, vol. 55, no. 9, pp. 548–550, May 2019.

[130] L. Qu, Y. Zhang, J. Liu, X. Bo, H. Jing, and Y. Fan, "Design of filtering crossover and diplexer on SIW quadruple-mode resonators in a single cavity," *IEEE Access*, vol. 8, pp. 176789–176796, 2020.

[131] I. Llamas-Garro, F. Mira, P. Zheng, Z. Liu, L.-S. Wu, and Y. Wang, "All-resonator based LTCC diplexer using substrate-integrated waveguides," *Electron. Lett.*, vol. 53, no. 21, pp. 1410–1412, Oct. 2017.

[132] A. Garcia-Lamperez, M. Salazar-Palma, and S. H. Yeung, "Compact diplexer with dual-mode SIW resonators," in *Proc. 44th Eur. Microw. Conf.*, 2014, pp. 857–860.

[133] J. R. Aitken, J. Hong, and Z.-C. Hao, "Millimetre wave SIW diplexer circuits with relaxed fabrication tolerances," *IET Microw. Antennas Propag.*, vol. 11, no. 8, pp. 1133–1138, May 2017.

[134] Y. Uemichi et al., "An E-band hybrid-coupled diplexer built of silica-based post-wall waveguide," in *Proc. 47th Eur. Microw. Conf.*, 2017, pp. 819–822.

[135] Y. Uemichi, O. Nukaga, X. Han, S. Amakawa, and N. Guan, "Highly configurable cylindrical-resonator-based bandpass filter built of silica-based post-wall waveguide and its application to compact E-band hybrid-coupled diplexer," in *Proc. IEEE MTT-S Int. Microw. Symp.*, 2019, pp. 726–729.

[136] Y.-L. Cheng, H.-W. Chen, P.-D. Huang, and C.-Y. Chang, "A W-band quadrature hybrid coupled substrate integrated waveguide diplexer," in *Proc. Asia-Pacific Microw. Conf.*, 2015, pp. 1–3.

[137] J. L. Gomez-Tornero, A. J. Martinez-Ros, S. Mercader-Pellicer, and G. Goussetis, "Simple broadband quasi-optical spatial multiplexer in substrate integrated technology," *IEEE Trans. Microw. Theory Techn.*, vol. 63, no. 5, pp. 1609–1620, May 2015.

[138] B. J. Xiang, S. Y. Zheng, H. Wong, Y. M. Pan, K. X. Wang, and M. H. Xia, "A flexible dual-band antenna with large frequency ratio and different radiation properties over the two bands," *IEEE Trans. Antennas Propag.*, vol. 66, no. 2, pp. 657–667, Feb. 2018.

[139] J. F. Zhang, Y. J. Cheng, Y. R. Ding, and C. X. Bai, "A dual-band shared-aperture antenna with large frequency ratio, high aperture reuse efficiency, and high channel isolation," *IEEE Trans. Antennas Propag.*, vol. 67, no. 2, pp. 853–860, Feb. 2019.

[140] K. Entesari, A. P. Saghati, V. Sekar, and M. Armendariz, "Tunable SIW structures: Antennas, VCOs, and filters," *IEEE Microw. Mag.*, vol. 16, no. 5, pp. 34–54, Jun. 2015.

[141] F. Mira, J. Mateu, and C. Collado, "Mechanical tuning of substrate integrated waveguide filters," *IEEE Trans. Microw. Theory Techn.*, vol. 63, no. 12, pp. 3939–3946, Dec. 2015.

[142] V. Sekar, M. Armendariz, and K. Entesari, "A 1.2–1.6-GHz substrate-integrated-waveguide RF MEMS tunable filter," *IEEE Trans. Microw. Theory Techn.*, vol. 59, no. 4, pp. 866–876, Apr. 2011.

[143] A. Anand, J. Small, D. Peroulis, and X. Liu, "Theory and design of octave tunable filters with lumped tuning elements," *IEEE Trans. Microw. Theory Techn.*, vol. 61, no. 12, pp. 4353–4364, Dec. 2013.

[144] S. Adhikari, Y.-J. Ban, and K. Wu, "Magnetically tunable ferrite loaded substrate integrated waveguide cavity resonator," *IEEE Microw. Wireless Compon. Lett.*, vol. 21, no. 3, pp. 139–141, Mar. 2011.

[145] S. Adhikari, A. Ghiotto, and K. Wu, "Simultaneous electric and magnetic two-dimensionally tuned parameter-agile SIW devices," *IEEE Trans. Microw. Theory Techn.*, vol. 61, no. 1, pp. 423–435, Jan. 2013.

[146] H. Uchimura, T. Takenoshita, and M. Fujii, "Development of a laminated waveguide," *IEEE Trans. Microw. Theory Techn.*, vol. 46, no. 12, pp. 2438–2443, Dec. 1998.

[147] J. Hirokawa and M. Ando, "Single-layer feed waveguide consisting of posts for plane TEM wave excitation in parallel plates," *IEEE Trans. Antennas Propag.*, vol. 46, no. 5, pp. 625–630, May 1998.

[148] D. Deslandes and K. Wu, "Integrated microstrip and rectangular waveguide in planar form," *IEEE Microw. Wireless Compon. Lett.*, vol. 11, no. 2, pp. 68–70, Feb. 2001.

[149] D. Deslandes and K. Wu, "Single-substrate integration technique of planar circuits and waveguide filters," *IEEE Trans. Microw. Theory Techn.*, vol. 51, no. 2, pp. 593–596, Feb. 2003.

[150] F. Xu and K. Wu, "Guided-wave and leakage characteristics of substrate integrated waveguide," *IEEE Trans. Microw. Theory Techn.*, vol. 53, no. 1, pp. 66–73, Jan. 2005.

[151] T.-M. Shen, C.-F. Chen, T.-Y. Huang, and R.-B. Wu, "Design of vertically stacked waveguide filters in LTCC," *IEEE Trans. Microw. Theory Techn.*, vol. 55, no. 8, pp. 1771–1779, Aug. 2007.

[152] W. Hong et al., "Half mode substrate integrated waveguide: A new guided wave structure for microwave and millimeter wave application," in *Proc. Joint 31st Int. Conf. Infrared Millimeter Waves 14th Int. Conf. THz Electron.*, 2006, pp. 219–219.

[153] Q. Lai, C. Fumeaux, W. Hong, and R. Vahldieck, "Characterization of the propagation properties of the half-mode substrate integrated waveguide," *IEEE Trans. Microw. Theory Techn.*, vol. 57, no. 8, pp. 1996–2004, Aug. 2009.

[154] S. Moscato, C. Tomassoni, M. Bozzi, and L. Perregrini, "Quarter-mode cavity filters in substrate integrated waveguide technology," *IEEE Trans. Microw. Theory Techn.*, vol. 64, no. 8, pp. 2538–2547, Aug. 2016.

[155] A. P. Saghati, A. P. Saghati, and K. Entesari, "Ultra-miniature SIW cavity resonators and filters," *IEEE Trans. Microw. Theory Techn.*, vol. 63, no. 12, pp. 4329–4340, Dec. 2015.

[156] N. Grigoropoulos, B. Sanz-Izquierdo, and P. R. Young, "Substrate integrated folded waveguides (SIFW) and filters," *IEEE Microw. Wireless Compon. Lett.*, vol. 15, no. 12, pp. 829–831, Dec. 2005.

[157] H.-Y. Chien, T.-M. Shen, T.-Y. Huang, W.-H. Wang, and R.-B. Wu, "Miniaturized bandpass filters with double-folded substrate integrated waveguide resonators in LTCC," *IEEE Trans. Microw. Theory Techn.*, vol. 57, no. 7, pp. 1774–1782, Jul. 2009.

[158] W. Che, C. Li, D. Zhang, and Y. L. Chow, "Investigations on propagation and the band broadening effect of ridged rectangular waveguide integrated in a multilayer dielectric substrate," *IET Microw. Antennas Propag.*, vol. 4, no. 6, pp. 674–684, Jun. 2010.

[159] M. Bozzi, S. A. Winkler, and K. Wu, "Broadband and compact ridge substrate-integrated waveguides," *IET Microw. Antennas Propag.*, vol. 4, no. 11, pp. 1965–1973, Nov. 2010.

[160] Y. Dong and T. Itoh, "Composite right/left-handed substrate integrated waveguide and half mode substrate integrated waveguide leaky wave structures," *IEEE Trans. Antennas Propag.*, vol. 59, no. 3, pp. 767–775, Mar. 2011.

[161] A. Niembro-Martin et al., "Slow-wave substrate integrated waveguide," *IEEE Trans. Microw. Theory Techn.*, vol. 62, no. 8, pp. 1625–1633, Aug. 2014.

[162] M. S. Mahani and G. W. Roberts, "A mmWave folded substrate integrated waveguide in a 130-nm CMOS process," *IEEE Trans. Microw. Theory Techn.*, vol. 65, no. 8, pp. 2775–2788, Aug. 2017.

[163] X. Liu, Z. Zhu, Y. Liu, Q. Lu, X. Yin, and Y. Yang, "Wideband substrate integrated waveguide bandpass filter based on 3-D ICs," *IEEE Trans. Compon., Packag. Manuf. Technol.*, vol. 9, no. 4, pp. 728–735, Apr. 2019.

[164] F. Wang, V. F. Pavlidis, and N. Yu, "Miniaturized SIW bandpass filter based on TSV technology for THz applications," *IEEE Trans. THz Sci. Technol.*, vol. 10, no. 4, pp. 423–426, Jul. 2020.

[165] A. Krivovitca, U. Shah, O. Glubokov, and J. Oberhammer, "Micromachined silicon-core substrate-integrated waveguides at 220–330 GHz," *IEEE Trans. Microw. Theory Techn.*, vol. 68, no. 12, pp. 5123–5131, Dec. 2020.

[166] Y.-C. Liu et al., "Terahertz monolithic integrated cavity filter based on cyclic etched SiC via-holes," *IEEE Trans. Electron Devices*, vol. 68, no. 1, pp. 311–317, Jan. 2021.

[167] X. Yi, C. Wang, X. Chen, J. Wang, J. Grajal, and R. Han, "A 220-to-320-GHz FMCW radar in 65-nm CMOS using a frequency-comb architecture," *IEEE J. Solid-State Circuits*, vol. 56, no. 2, pp. 327–339, Feb. 2021.

[168] H. Saeidi, S. Venkatesh, X. Lu, and K. Sengupta, "THz prism: One-shot simultaneous localization of multiple wireless nodes with leaky-wave THz antennas and transceivers in CMOS," *IEEE J. Solid-State Circuits*, vol. 56, no. 12, pp. 3840–3854, Dec. 2021.

[169] B. Yang, Z. Yu, J. Lan, R. Zhang, J. Zhou, and W. Hong, "Digital beamforming-based massive MIMO transceiver for 5G millimeter-wave communications," *IEEE Trans. Microw. Theory Techn.*, vol. 66, no. 7, pp. 3403–3418, Jul. 2018.

[170] X. Yang et al., "Low-loss heterogeneous integrations with high output power radar applications at W-band," *IEEE J. Solid-State Circuits*, vol. 57, no. 6, pp. 1563–1577, Jun. 2022.

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