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A dual-band filtering push-pull power amplifier with a large frequency ratio employing a hybrid-mode bandpass response balun

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Abstract: A dual-band filtering push-pull power amplifier (PA) with a large frequency ratio is presented in this paper. The developed filtering power dividing/combining network is based on microstrip line (MSL) and substrate integrated waveguide (SIW) hybrid-mode filtering balun. The MSL filtering balun works at S-band with an operational frequency range of 2.6-2.86 GHz. Meanwhile, the SIW filtering balun is designed for Ku-band operation, covering a frequency range of 13-13.65 GHz. Under these conditions, this prototype is capable of attaining a frequency ratio as high as five times the original value. Attributing to the inherent differential characteristic of the hybrid-mode filtering balun with a large frequency ratio, the proposed push-pull PA can not only realize the filtering functionality but also achieve second-harmonic suppression. To validate the designed concept, the proposed prototype has been designed, fabricated, and measured. Measurement results demonstrate that the proposed PA achieves a 7-dB small-signal gain while maintaining out-of-band spurious rejection during active testing. The developed dual-band filtering push-pull PA has achieved an excellent performance of a peak output power of 36.8 dBm at low frequencies and 36 dBm at high frequencies. Meanwhile, by employing dual-band filtering baluns, the PA inherently suppresses even-order harmonics while simultaneously providing filtering characteristics in both operational bands, which effectively suppresses near-band spurious signals.

Key words: Large frequency ratio, dual-band filtering balun, harmonic suppression, push-pull power amplifier

1 Introduction

With the rapid advancement of 5G communication and radar technologies, the demand for high-power microwave components has grown substantially, spurring extensive research in this field. However, constrained by the limitations of semiconductor technology, the output power of individual devices remains inherently constrained. To settle this challenge, push-pull power amplifiers (PAs) have attracted extensive research attention (Tiwari et al., 2020; Dong et al., 2022; Fahmi et al., 2025; Koh et al., 2025; Liu et al., 2025; Jobs et al., 2018; Zhou et al., 2025; Chen et al., 2024; Chen et al., 2020). These systems manipulate the superposition of electromagnetic waves to combine multiple low-power signals into a single high-power output.

For instance, a broadband power combiner based on a ridge waveguide was introduced in Dang et al. (2020), operating across 18–40 GHz and ultimately achieving a peak output power of 3.9 W by combining outputs from 16 GaAs monolithic microwave integrated circuit (MMIC) PAs. Similarly, a push-pull PA presented in Feng et al. (2019) utilizes two back-to-back filtering baluns to perform power combining while achieving a power-added efficiency (PAE) of 48.7% and effectively suppressing the second harmonic signals. As a device capable of providing differential signals, a balun is particularly suitable for application in push-pull power combining scenarios where

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harmonic suppression is required (Shi et al., 2024; Huang et al., 2019; Wang et al., 2016; Feng et al., 2017; Steele et al., 2024; Naeini et al., 2020; Guo et al., 2025; Stameroff et al., 2013; Chiu et al., 2006; Geng et al., 2016).

The push-pull PA has been designed and implemented across various transmission lines. Alternatively, the hybrid-mode transmission line has been widely adopted in multiple microwave devices owing to its high integration, compact size, and multifunctionality (Guo et al., 2018; Zhang et al., 2021; Ning et al., 2025; Tang et al., 2019). By utilizing two microwave devices with distinct transmission line structures but similar functionalities, the hybrid-mode transmission line enables multiple functions while maintaining a compact form factor. For instance, the design in Tang et al. (2019) integrates two filters based on microstrip line (MSL) and waveguide technologies, respectively, allowing operation in two distinct frequency bands without increasing the overall footprint and with minimal mutual interference.

This paper presents a dual-band filtering push-pull PA with a large frequency ratio, designed using a hybrid configuration that combines an MSL and a substrate integrated waveguide (SIW)-based filtering balun. The low-frequency MSL filtering balun features a symmetric output topology, where a 180° phase difference between the output signals is achieved by adjusting the relative position of the input terminal, while filtering characteristics are realized through stepped impedance resonators (SIRs). In addition, the high-frequency SIW filtering balun generates phase-inverted output signals by exciting the vertical TM_{110} higher-order mode within the SIW cavity. Two types of filtering baluns are integrated and coupled via slots etched on the surface of the middle conductor between two dielectric substrates. Through the adoption of a back-to-back architecture to amplify and combine the differential signals generated by the filtering baluns, the proposed prototype achieves high output power with a large frequency ratio dual-passband filtering response and effective even-order harmonic suppression, which is further validated by experimental results.

2 Design architecture

Fig. 1 illustrates architectures of various push-pull PAs.

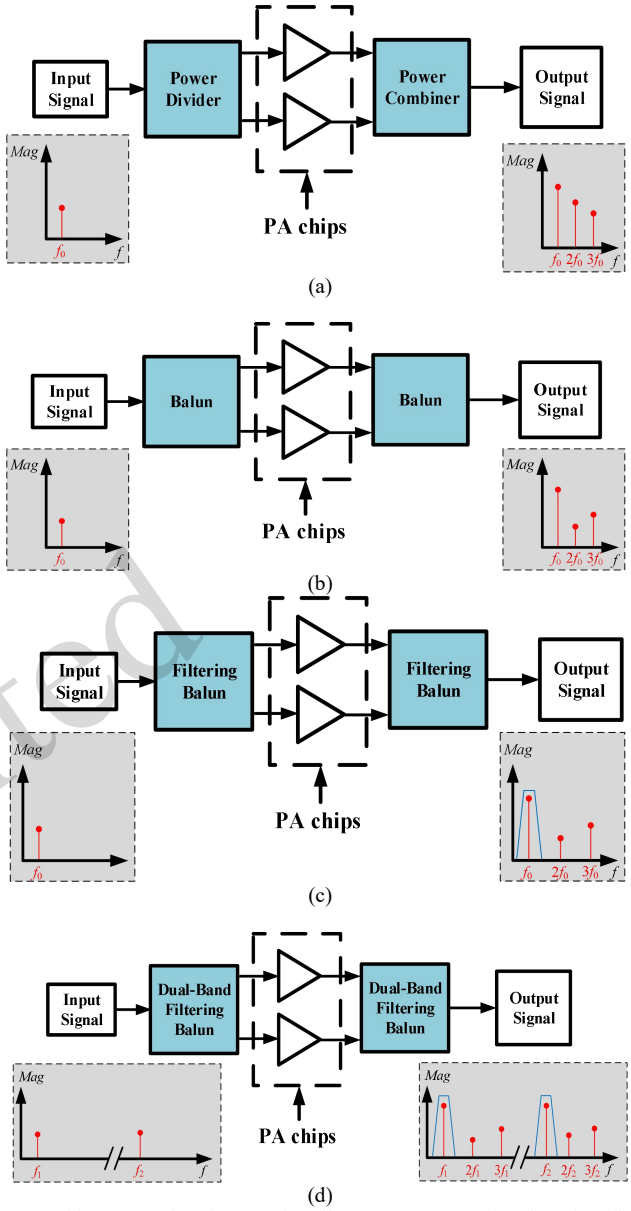

Fig. 1. Architectures of various push-pull PAs. (a) Conventional push-pull PAs. (b) Push-pull PAs employing baluns. (c) Filtering push-pull PAs network. (d) Dual-band filtering push-pull PAs.

Specifically, the conventional push-pull PA architecture is presented in Fig. 1(a). A conventional push-pull PA comprises three stages: power division, power amplification, and power combining. First, the power divider splits the input signal into multiple paths of in-phase signals with equal amplitude, which are then amplified by PAs and finally combined in the power combining stage, thereby generating an output signal with significantly higher power than the achievable limit of a single amplifier. Fig. 1(b) depicts the architecture of a push-pull PA implemented with balun-based power dividers. Distinguished from conventional push-pull PAs, this configuration specifically employs baluns instead of standard power dividers for both the power splitting and combining functions. Fig. 1(c) presents the

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architecture of a push-pull PA based on filtering baluns. Building upon the push-pull structure shown in Fig. 1(b), this design replaces conventional baluns with filtering baluns, thereby incorporating filtering characteristics into the push-pull PA. Consequently, Fig. 1(d) demonstrates the design of a dual-band filtering push-pull PA based on hybrid-mode transmission lines. Evolving from the architecture in Fig. 1(c), this design incorporates dual-band filtering baluns for power division and power combining, enabling dual-band operation while maintaining the functionalities of the original filtering push-pull network within both operational bands.

Owing to its inherent differential-output architecture, a balun intrinsically delivers odd harmonics (including the fundamental tone) as differential-mode signals, while even harmonics manifest as common-mode signals. Once the differential signals output from the balun are amplified, the two PAs exhibit strong nonlinearity, delivering outputs with identical amplitude, opposite phase, and high saturated power. This nonlinear behavior can be mathematically represented as follows:

$$i_1 = a_1 v + a_2 v^2 + a_3 v^3 + \ldots \quad (1)$$

$$i_2 = a_1 v e^{-j\pi} + a_2 (v e^{-j\pi})^2 + a_3 (v e^{-j\pi})^3 + \ldots \quad (2)$$

In the above equations, v denotes the input voltage, i_1 and i_2 represent the output currents, and parameter an governs the transfer function of the PAs. The two signals amplified by the PAs are combined by a balun, which merges the two out-of-phase input signals into one combined signal. Synthesizing Equations (1) and (2) yields Equation (3), revealing that the composite output current reinforces the fundamental component while suppressing even-order harmonics, a key benefit of the push-pull architecture. The total current synthesized from the two paths can be expressed as

$$i = i_1 + i_2 e^{-j\pi} = 2a_1 v + 2a_3 v^3 + \ldots \quad (3)$$

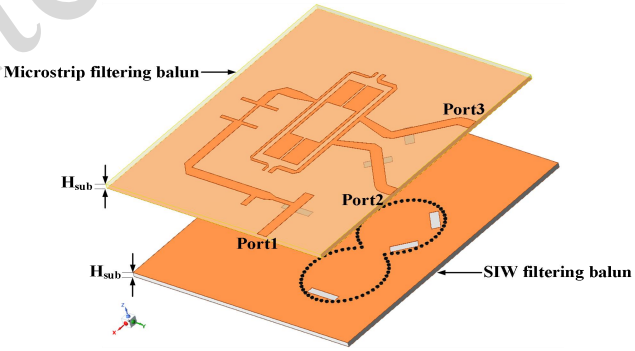
The proposed dual-band filtering push-pull PA, utilizing dual-band filtering baluns and operating at a large frequency ratio, demonstrates a significant enhancement in output power comparable to conventional architectures. Furthermore, it effectively suppresses even-order harmonics and their associated spurious components. Moreover, the adoption of filtering baluns for power combining enables effective rejection of near-band spurious responses in both operating bands. This approach achieves dual-band filtering characteristics while avoiding the size penalty associated with cascaded external filters.

3 Dual-band filtering balun and filtering push-pull PA with large frequency ratio

A. Large frequency ratio dual-band filtering balun

Fig. 2(a) illustrates a 3D view of the proposed dual-band filtering balun with a large frequency ratio. The designed prototype comprises two types of filtering baluns: an MSL filtering balun and an SIW filtering balun.

The MSL filtering balun is designed based on a Marchand balun architecture (Geng et al., 2016; Lin et al., 2015). It is composed of a section of impedance-transforming line, a stepped-impedance low-pass filter (LPF), two $\lambda/2$ uniform-impedance resonators (UIRs), and two $\lambda/2$ SIRs. The low-frequency signal is introduced into the MSL filtering balun from the unbalanced port 1 and is guided through the impedance-transforming line. Subsequently, the input signal is fed into the LPF, which is designed to isolate the two response bands, thus preventing the low-frequency signal from interfering with the high-frequency filtering balun. The configuration employs two UIRs and two SIRs, primarily in a combined configuration. Under differential-mode excitation, the odd-mode half-circuit is formed by four quarter-wavelength resonators. With mixed differential-mode coupling between the UIR and SIR, the coupling between the two SIRs is predominantly electric.



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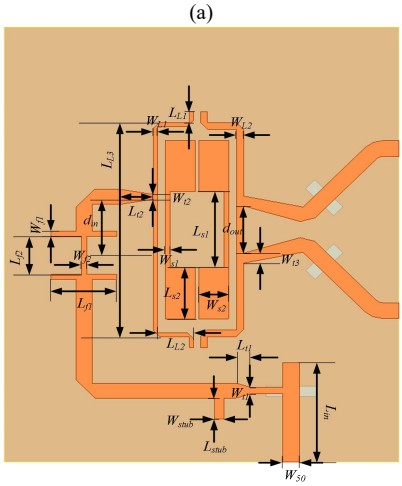

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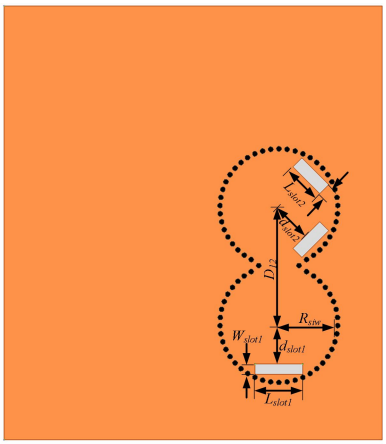

(c)

Fig. 2. (a) 3-D view of the proposed bandpass filtering balun. (b) Top view of the upper substrate. (c) Top view of the lower substrate.

The design methodology of the MSL filtering balun is outlined as follows:

Step 1: Topology selection and initial sizing. The balun is based on a modified Marchand topology, chosen for its inherent wideband differential performance. The $\lambda/2$ UIRs and SIRs were initially dimensioned using standard transmission-line equations at the center frequency. The SIRs were employed primarily to introduce an additional transmission zero for improved out-of-band rejection and to provide an extra degree of freedom for bandwidth control.

Step 2: Bandwidth matching. The target bandwidth was achieved by controlling the coupling coefficients between the resonators and the feeding lines. The coupling was tuned by adjusting the gaps between adjacent resonators and the length/width of the coupling sections.

Step 3: Phase and amplitude imbalance optimization. As for the phase characteristic, the fundamental 180° phase difference is structurally enforced by the laterally offset input feed line, and fine-tuning of the phase balance was achieved by slightly adjusting the electrical lengths of the two output paths, specifically by optimizing the meandered output lines. As for the amplitude characteristic, amplitude balance between the two output ports was optimized by ensuring symmetrical geometry and by carefully adjusting the impedance transformer at the input to provide equal excitation to both signal paths.

Figs 2(b) and (c) present the detailed layout and dimensional parameters of the MSL filtering balun and SIW filtering balun, respectively. A Rogers 4003 (ε_r = 3.55, h = 0.813 mm, tanδ_D = 0.0027) substrate is utilized for this design. The corresponding parameters are summarized in Table 1.

Table 1 Geometrical parameters of filtering design (unit: mm)

Structure	Parameter
MSL filtering balun (Fig. 2(b))	W_{50} = 1.88, L_{in} = 11.8, L_{t1} = 1.6, W_{t1} = 0.8, L_{stub} = 2.5, W_{stub} = 1.1, L_{f1} = 7.5, W_{f1} = 0.6, L_{f2} = 4.5, W_{f2} = 0.6, d_{in} = 3.6, L_{t2} = 3.8, W_{t2} = 0.58, L_{L1} = 1.3, L_{L2} = 4.1, L_{L3} = 25.4, W_{L1} = 0.45, W_{L2} = 0.8, L_{s1} = 9, W_{s1} = 0.55, L_{s2} = 6.1, W_{s2} = 3.4, d_{out} = 5.6, W_{t3} = 1.18.
SIW filtering balun (Fig. 2(c))	R_{siw} = 7, D_{12} = 13.8, d_{slot1} = 4.8, W_{slot1} = 1.2, L_{slot1} = 5.7, d_{slot2} = 4.6, W_{slot2} = 1.5, L_{slot2} = 4.5.

Fig. 2(c) depicts the top view of the lower substrate. The high-frequency signal entering the same port 1 is directly coupled into the SIW filtering balun through the rectangular slot etched at the bottom of the upper substrate. It should be mentioned that the low-pass filter cascaded with the MSL filtering balun prevents this upper branch from interfering with the high-frequency response.

As two orthogonal degenerate modes of the circular SIW resonator, the vertical TM_{110} mode and the horizontal TM_{110} mode exhibit electric field distributions oriented 90° apart (Li et al., 2019; Li et al., 2015). The field distribution of the vertical TM_{110} mode in the circular cavity demonstrates odd symmetry, characterized by equal magnitude but opposite phase on either side of the cavity center. In contrast, the horizontal TM_{110} mode exhibits even symmetry, with the field being identical in both magnitude and phase across the two symmetric halves. Consequently, the proposed two-order SIW filtering balun is designed based on the vertical TM_{110} mode of the circular SIW cavity.

The design methodology of the SIW filtering balun is outlined as follows:

Step 1: Mode selection and cavity design. The balun operation is based on exciting the vertical TM_{110} mode in a circular SIW cavity. The dimension of the cavity was first calculated to resonate at the desired center frequency for this mode, using the relationship equation (4) for a circular cavity, with effective permittivity accounting for the SIW substrate.

$$f_{mnp}^{TM} = \frac{c}{2\pi\sqrt{\xi_r}}\sqrt{\left(\frac{\chi_{mn}}{a}\right)^2 + \left(\frac{p\pi}{d}\right)^2} \tag{4}$$

In the above equations, f_{mnp}^{TM} represents the resonant frequency of the TM mode, c denotes the speed of light in a vacuum, ε_r represents the relative permittivity of the substrate, a is the effective radius of the SIW cavity, d is the thickness of the substrate, m, n, and p are the mode indices, and χ_{mn} denotes the n-th root of the m-th order Bessel function $J_m(x) = 0$, corresponding to the boundary conditions for the TM mode.

Step 2: Bandwidth matching. A second-order bandpass response was implemented using two coupled cavities. The bandwidth is determined by the inter-cavity coupling, controlled

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by the coupling aperture between the cavities, and the input/output coupling, controlled by the dimensions of the coupling aperture.

Step 3: Phase and amplitude imbalance optimization. The 180° phase difference is an inherent property of the selected vertical TM_{110} mode, which exhibits odd symmetry. The phase balance across the band was ensured by symmetrically positioning the two output coupling slots on opposite sides of the cavity center. The exact slot positions were fine-tuned to compensate for any parasitic phase shifts introduced by the microstrip feeding lines. The amplitude balance is achieved by the geometrical symmetry of the output slots. Their identical dimensions and symmetrical placement relative to the field maximum of the TM_{110} mode guarantee equal coupling to the two output ports.

Fig. 3 demonstrates the simulated electric-field distribution within the SIW cavity at 13.5 GHz. The plot confirms the excitation of the vertical TM_{110} mode, characterized by two anti-phase field distributions coexisting within the cavity. Two output coupling slots are positioned to efficiently extract these differential signals into the output MSLs, thereby realizing the balun function. The signal is coupled from port 1 of the microstrip feeding line through an aperture into the first circular SIW cavity, and the vertical TM_{110} mode is then excited within the two cavities. When the signals are coupled to port 2 and port 3 of the MSL filtering balun, they exhibit equal amplitude and opposite phase. The corresponding geometrical parameters are provided in Table 1.

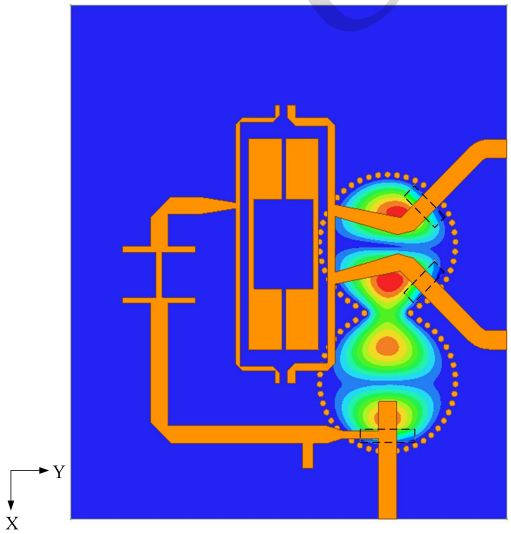

Fig. 3. The simulated electric-field distribution within the SIW cavity at 13.5 GHz

Following the individual design and optimization of the MSL and SIW filtering baluns, the co-design and integration considerations are considered as follows:

First, the LPF placed before the MSL balun was crucial for band isolation. Its cutoff frequency was designed to be between the working band of MSL and SIW filtering baluns, preventing the low-frequency signal from interfering with the SIW cavity's operation. Second, the final optimization of the entire hybrid structure was performed in a combined EM simulation, allowing for the fine-tuning of all parameters to account for any unintended cross-coupling between the MSL and SIW sections, ensuring that the bandwidth matching targets and phase/amplitude balance were satisfied simultaneously for both bands. The design flowchart of the proposed dual-band filtering balun is shown in Fig. 4.

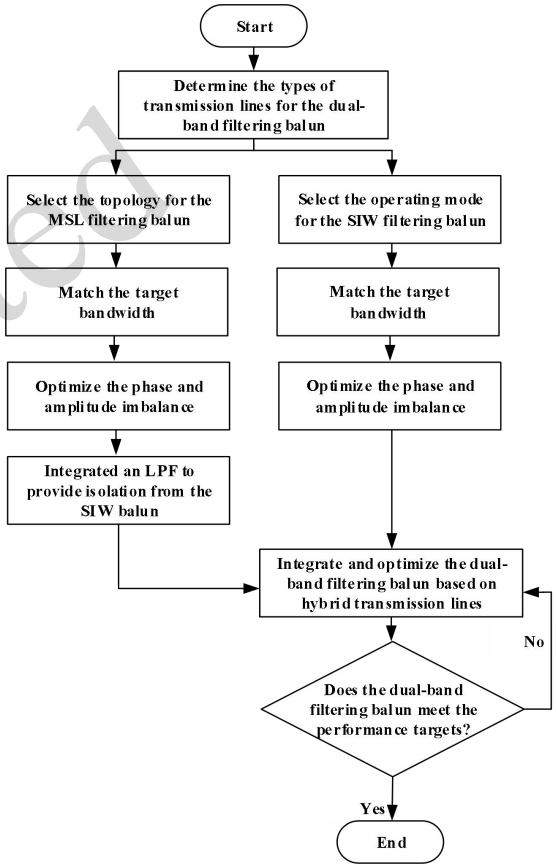

Fig. 4. The design flowchart of the proposed dual-band filtering balun.

The final dual-band filtering balun achieves a fivefold frequency ratio. In this design, the attainable frequency ratio is constrained by both physical layout considerations and substrate performance limitations. First, the physical layout dictates that the frequency cannot be too high or too low. If the frequency ratio is too low, the physical size of the SIW cavity will become significantly larger than that of the MSL structure, leading to layout conflicts and potential unwanted coupling between the resonators. Moreover, the coupling aperture at the SIW input will be positioned far from the MSL input port. To enable port reuse

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at the input of the dual-band filtering balun, a long, curving MSL feed line will be needed to connect them, thereby introducing excessive loss into the low-frequency filtering balun. Conversely, an extremely large frequency ratio would lead to a tiny SIW cavity. The proper operation of the SIW balun depends on exciting the TM_{110} mode, whose field symmetry dictates that the output coupling slots must be placed symmetrically to generate differential signals. For port reuse, these slots must also cover the MSL output feed lines. A small R_{siw} makes it difficult to satisfy both the mode symmetry requirement and the port reuse constraint simultaneously without significant performance degradation.

Second, for the SIW balun, the substrate thickness must satisfy $h < \lambda_g/4$ to minimize radiation loss and suppress higher-order vertical modes. For the MSL balun, conversely, its power handling capability and quality factor generally benefit from a thicker substrate. Therefore, selecting a substrate involves a trade-off that defines the range of the ratio between the pair of low and high working frequencies.

Our design, with a fivefold frequency ratio, successfully balances these opposing constraints, providing ample space for the MSL structure to wrap around the SIW cavity without a significant loss penalty.

As a design trade-off, the relatively large footprint of the proposed hybrid MSL and SIW structure can be considered as a consequence of integrating two distinct transmission-line technologies to achieve the large frequency ratio and dual-band filtering functionality within a single module. Because the MSL filtering balun operates at relatively low frequencies, primarily in the S-band, and employs $\lambda/2$ UIRs and SIRs to achieve its filtering response, it inherently results in a larger footprint. In addition, to enable coupling with the microstrip filtering balun at both the input and output ports, the size of the SIW filtering balun cannot be designed excessively compact.

B. Large frequency ratio dual-band filtering push-pull PA

The proposed dual-band filtering balun with a large frequency ratio is employed to implement a back-to-back active dual-band filtering push-pull PA architecture.

Fig. 5 demonstrates a physical configuration of the proposed active dual-band hybrid filtering push-pull PA with a large frequency ratio. A low-pass filter is incorporated prior to the MSL filtering balun to prevent any adverse effects on the performance of the SIW filtering balun. The input signal is first processed by the LPF and then fed into the MSL filtering balun, which outputs two differential signals of equal amplitude. These two signals are subsequently amplified by separate wideband PA chips and finally combined, exploiting an identical filtering balun configuration. For the high-frequency path, the input signal is directly coupled into the SIW cavity. After processing, the output signal is coupled into the output microstrip feeding line. This configuration enables the high-frequency and low-frequency sections to share common input and output ports, significantly enhancing the overall integration level and practical applicability of the design.

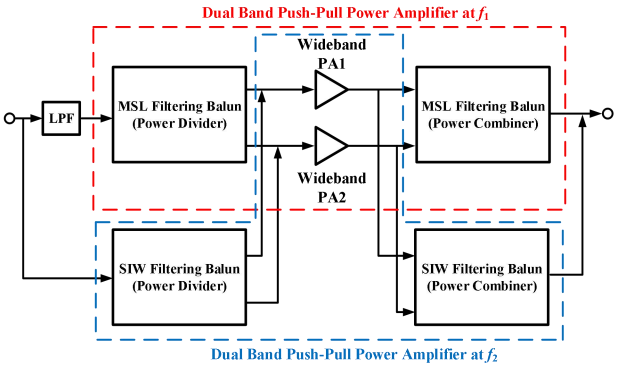

Fig. 5. Architecture of the proposed hybrid-mode dual-band filtering push-pull PA with a large frequency ratio.

The filtering push-pull PA functions by dividing an input low-power signal, separately amplifying the resulting signals, and synthesizing them to achieve an output power greater than that available from a single PA chip. As outlined in section II, amplifying the differential-mode signals prior to synthesis provides the dual advantage of fundamental wave amplification and second harmonic suppression. Leveraging this principle, the proposed filtering dual-band PA employs a back-to-back structure incorporating the designed dual-band hybrid-mode filtering baluns. This configuration not only preserves the inherent dual-band filtering characteristics of the baluns but also simultaneously provides both signal amplification and second-harmonic suppression.

4 Implementation and measurement

For a practical demonstration, the dual-band filtering push-pull PA with a large frequency ratio designed in the previous section has been manufactured and characterized. The proposed filtering balun at low frequency employing MS resonators is designed on the top substrate. Meanwhile, the filtering balun at high frequency, exploiting SIW resonators, is manufactured on the bottom substrate. The determined parameters are listed in Table 1.

The assembly layouts of the dual-band large-frequency-ratio filtering balun are displayed in Fig. 6. The MSL and SIW filtering balun are fabricated on two dielectric substrates with identical substrates, respectively. To facilitate the experiment and the minimize performance impact on the dual-band filtering balun, the low- and high-frequency baluns are arranged in a stacked configuration as depicted in Fig. 2(a) and secured with nylon screws.

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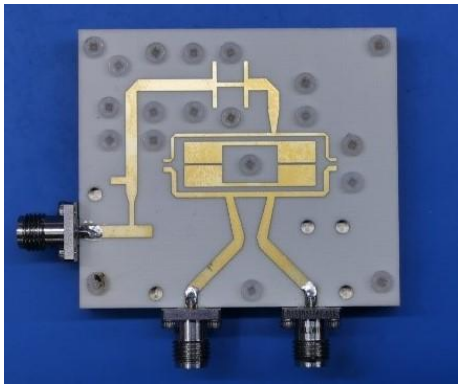
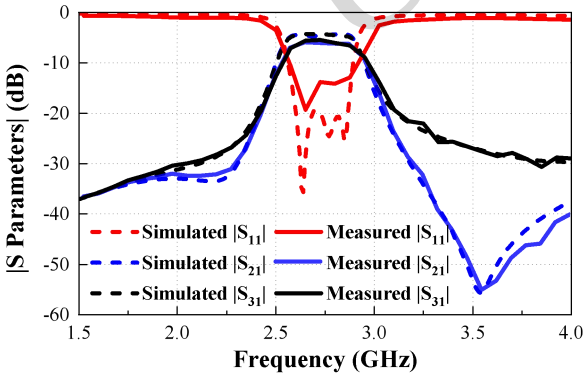


Fig. 6. The assembly layouts of the proposed dual-band large-frequency-ratio filtering balun.

Fig. 7 demonstrates the simulated and measured performance of the dual-band filtering balun. For the low-frequency filtering balun, the measured results indicate a return loss better than 19 dB over the 2.6-2.86 GHz band and an insertion loss of 1.3 dB after excluding the contributions from SMA connectors and microwave cables, whereas the measurement of the high-frequency SIW filtering balun indicates a return loss better than 13.5 dB and an insertion loss of 2.3 dB in the 13-13.65 GHz range, with the effects of SMA connectors and microwave cables de-embedded. Furthermore, both simulation and measurement indicate that the phase difference between the two output ports is maintained at 180° with a deviation of less than ±5° throughout their operational bands, demonstrating excellent phase balance.



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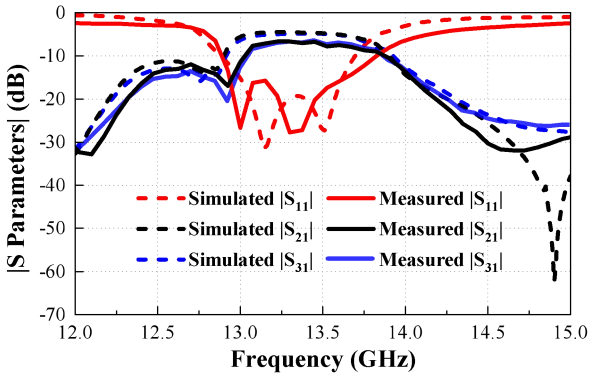

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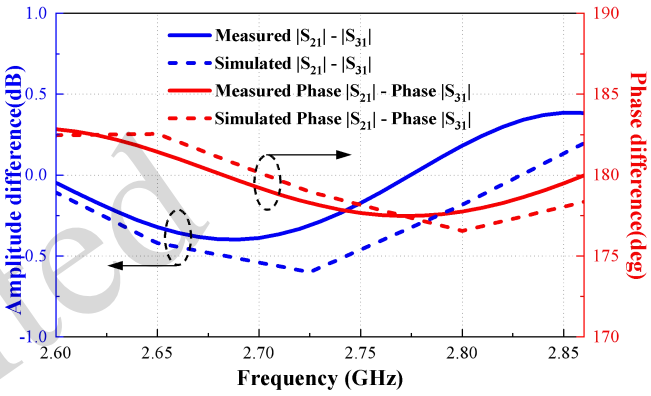

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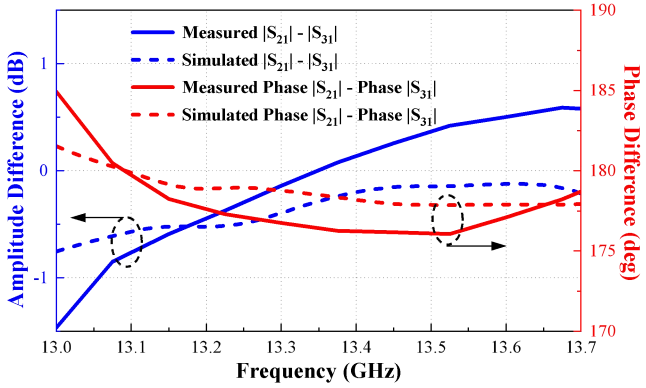

(d)

Fig. 7. Simulated and measured results of the proposed dual-band hybrid filtering balun: (a) Low-frequency response. (b) High-frequency response. (c) Phase imbalance in the low-frequency band. (d) Phase imbalance in the high-frequency band.

Fig. 8 exhibits the assembly layouts and experiment configuration for the proposed devices. Specifically, Fig. 8(a) presents the detailed assembly layouts of the large-frequency-ratio dual-band filtering push-pull PA. Two of the developed dual-band filtering baluns function as the input power divider and output power combiner, respectively. Between them, two broadband GaN MMIC PA modules are integrated to amplify the signals, thereby enabling experimental validation of the complete active push-pull PA. To achieve a higher saturated output power,

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an identical PA module is placed in front of the input filtering balun to drive the entire push-pull PA.

To characterize the proposed concept, a test setup based on the large frequency ratio dual-band filtering push-pull PA is implemented; the schematic illustration and photograph of the test environment are depicted in Fig. 8(b) and Fig. 8(c), respectively. The input signal from an Agilent E8267D signal generator is first amplified by the external PA module to compensate for its limited output power and then further amplified by the specifically designed dual-band filtering push-pull PA. All PAs utilized in the design are biased by a DC power supply, and the final output is measured by a Keysight N9030B spectrum analyzer via a 30-dB attenuator. The PA chips are biased at -1.8 V gate voltage, +28 V drain voltage, and operate with a quiescent current of 440 mA.

The measured small-signal gain and dual-band spectral responses are presented in Figs 9 and 10, respectively. As shown in Fig. 9, the implemented filtering push-pull PA maintains a consistent 7-dB small-signal gain across both operational bands, with bandwidths aligning closely with passive measurement results. Due to inherent gain flatness variations in the employed MMIC PA chips, the designed PA exhibits some in-band gain fluctuations. Furthermore, the system maintains excellent filtering performance during active testing, demonstrating effective suppression of out-of-band spurious components.

The spectral response of the dual-band filtering push-pull PA operating at its low-frequency band under a 2.75 GHz input signal is presented in Fig. 10(a). The low-frequency saturated output power of the PA is 36.8 dBm, while the second harmonic at 5.5 GHz is effectively suppressed, with its output power measured at only −54.7 dBm. Furthermore, under a 13.5 GHz input signal, Fig. 10(b) displays the spectral response of the dual-band filtering push-pull PA operating at its high-frequency band. A saturated output power of 36 dBm is observed in the high-frequency band. Additionally, the second harmonic at 27 GHz is strongly suppressed, with its output power measured at −53 dBm. The slight difference in peak output power between the bands is attributed to the frequency-dependent gain variation of the broadband PA chips.

Table 2 summarizes and compares the performance of previously demonstrated state-of-the-art and the proposed design. Utilizing the radial waveguide power combining technique, Koh et al. (2025) achieved a 0.5 W output in the W-band, whereas this work achieves a peak output power superior by 10 dB. Although the broadband 24-way radial power-combining network in Liu et al. (2025) demonstrates improved isolation and the highest output power reported, it does not incorporate any filtering capabilities. An ultra-wideband RIWG power-combining method is presented in Dang et al. (2020). It features a bandwidth covering the K to Ka bands, while harmonic suppression capability is relatively limited. Feng et al. (2019) presents an SIW-based filtering push-pull PA that provides harmonic suppression. In contrast, this work extends this concept to dual-band operation through the use of hybrid transmission lines, enabling filtering and harmonic suppression in two frequency bands. Li et al. (2023) presents a diplexer-like dual-band filtering PA, which operates at 2.1/3.5 GHz, delivering output powers of 41.0 and 39.5 dBm at two frequencies, while also achieving second-harmonic suppression. Multi-functional circuits have also been employed in the design of dual-band filtering PAs (Chen et al., 2022). By allowing the power combiner and the filtering circuits to share a common resonator, the overall circuit size can be reduced. A dual-band PA based on a harmonic-controlled dual-band matching network (HCDMN) has been proposed in Kim et al. (2024). The HCDMN comprises $\lambda/4$ open stubs for suppressing second-harmonic signals, and saturated Pout values of 40.3 and 41.9 dBm at 2.3 and 3.35 GHz, respectively. However, it is generally challenging for dual-band power amplifiers to achieve a large frequency ratio by implementing a single-circuit configuration based on the same type of transmission line.

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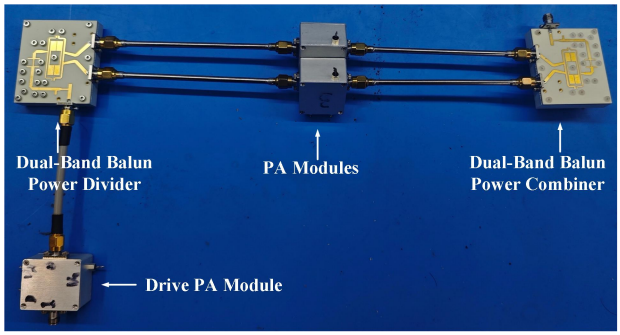
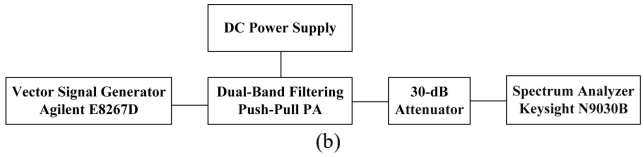
Table 2 Performance comparison between this work and prior studies

Reference	Type	Operating Band	Frequency (GHz)	R_f	Pout (dBm)	Filtering Function	N-way	Harmonic Suppression	Footprint ($\lambda_g \times \lambda_g \times \lambda_g$)
Koh et al. (2025)	Waveguide	1	93~101	N/A	26.72	No	8	No	24×26×6.5
Liu et al. (2025)	Waveguide	1	26~42	N/A	54.7	No	24	No	11×11×4.3
Dang et al. (2020)	RIWG	1	18~40	N/A	35.9	No	16	No	3.4×2.6×2.2
Feng et al. (2019)	SIW	1	5.4~5.6	N/A	38.5	Yes	2	Yes	5.6×4.7×0.03
Li et al. (2023)	MSL	2	2.1/3.5	1.7	41/39.5	Yes	1	Yes	N/A
Chen et al. (2022)	MSL	2	2.14/2.6	1.2	43.25/43.3	Yes	2	Yes	N/A
Kim et al. (2024)	MSL	2	2.2~2.25/ 3.3~3.45	1.5	40.3/41.9	Yes	1	Yes	1×0.73×0.01
This work	**MSL&SIW**	**2**	**2.6~2.86/ 13~13.65**	**5**	**36.8/36**	**Yes**	**2**	**Yes**	**0.77×0.88×0.03**

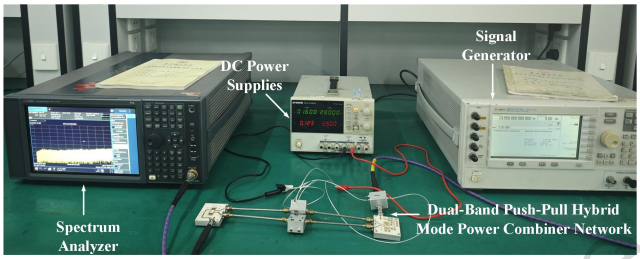
R_f represents the frequency ratio of the dual-band PAs.
λ_g represents the guided wavelength.



(a)



(b)



(c)

Fig. 8. (a) Assembly diagram of the dual-band filtering push-pull PA. (b) Test schematic illustration of the dual-band filtering push-pull PA. (c) The experimental environment of the proposed dual-band filtering push-pull PA.

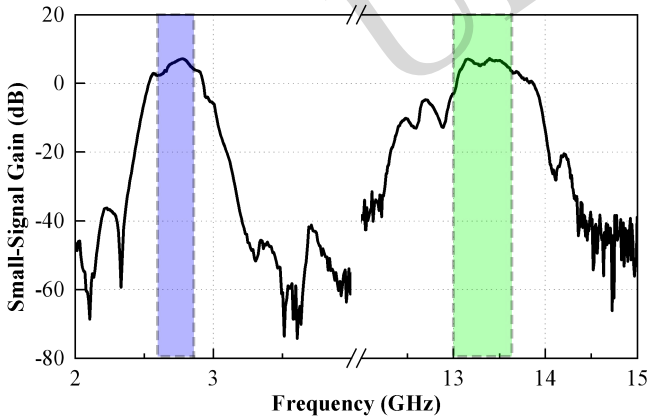
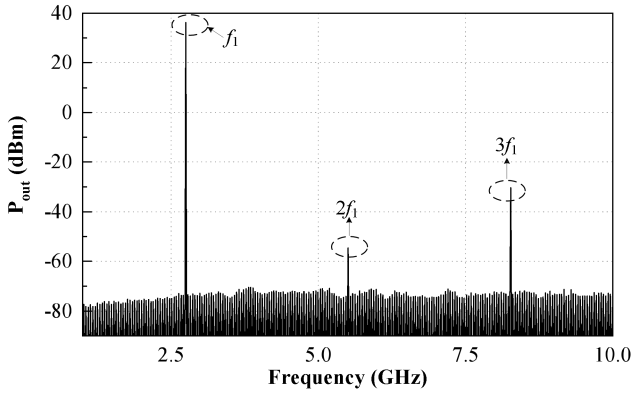
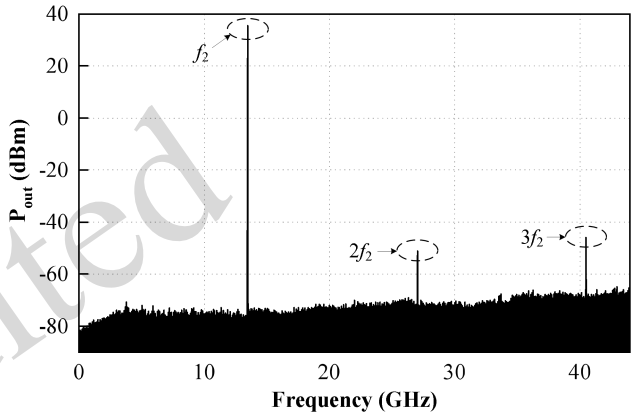


Fig. 9. The measured small-signal gain of the proposed dual-band filtering push-pull PA.



(a)



(b)

Fig. 10. The measured results of the proposed dual-band filtering push-pull PA. (a) Low-frequency measured result. (b) High-frequency measured result.

Attributing to the MSL-SIW hybrid architecture, the proposed dual-band filtering PA achieves the optimization of spatial utilization, insertion loss, and power handling capacity by combining the strengths of both technologies, compared to using a single transmission line. The SIW section of the hybrid architecture enables flexible mode selection, which achieves differential output for balun operation through mode controlling. With its high Q-factor and excellent electromagnetic shielding properties, the hybrid architecture provides steeper out-of-band suppression and superior passband selectivity, which offers an effective design pathway for high-performance, compact dual-band filtering power amplifiers.

5 Conclusion

In this paper, a dual-band filtering push-pull PA with a large frequency ratio utilizing hybrid-mode filtering baluns is designed, fabricated, and measured. Firstly, a dual-band filtering balun with a large frequency ratio is designed based on an MSL and SIW hybrid structure. Subsequently, a dual-band filtering push-pull PA is developed using a back-to-back configuration. It utilizes the proposed filtering baluns and GaN MMIC PA modules. Based on the passive measurement results, the active small-signal

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power gain and saturated output spectra are also characterized. Simulation and measurement results have reached a satisfactory agreement. It can provide effective guidance and a method for application scenarios with a large frequency ratio, such as 5G/6G base stations or user equipment.

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Author contributions

Jiyang CHU: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Writing – original draft. Xiang WANG: Conceptualization; Funding acquisition; Investigation; Project administration; Supervision; Validation; Writing – original draft. Tianxiang CHEN: Formal analysis; Investigation; Methodology; Project administration; Supervision; Visualization. Jindong ZHANG: Formal analysis; Investigation; Methodology; Project administration; Supervision; Visualization. Jun HU: Formal analysis; Investigation; Methodology; Project administration; Supervision; Visualization. Huangyan LI: Formal analysis; Investigation; Supervision; Validation. Boyu SIMA: Formal analysis; Methodology; Project administration; Validation. Wen WU: Project administration; Resources; Supervision; Validation

Ji-Yang CHU designed the research. Ji-Yang CHU, Xiang WANG and Tian-Xiang CHEN processed the data. Ji-Yang CHU drafted the manuscript. Xiang WANG helped organize the manuscript. Ji-Yang CHU, Xiang WANG, Tian-Xiang CHEN, Jin-Dong ZHANG, Jun HU, Huangyan LI, Boyu SIMA and Wen WU revised and finalized the paper.

Conflict of interest

All the authors declare that they have no conflict of interest.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declaration on the use of generative AI tools

During the preparation of this work, the authors used ChatGPT to improve language. After using this tool, the authors reviewed and edit-ed the content as needed and take full responsibility for the content of the published article.

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