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RESEARCH ARTICLE

Realization of Low in-Band Harmonic for Compact 6–18-GHz T/R Module Under TX-Mode Operation

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Abstract — Wideband high power amplifier (PA) with poor harmonic suppression will degrade the performance of the active electronically scanned array (AESA) due to its harmonic products falling into the operating bandwidth of a wideband T/R module. In view of this, a compact reconfigurable harmonic suppress circuit (HSC) is proposed to achieve low in-band harmonic for compact T/R module with multiple octaves under TX-mode operation. The HSC consists of eight microstrip resonant stubs with high impedance and multiple p-i-n switches. By controlling the p-i-n switches, the HSC can work in three states. When six of the used p-i-n switches are "ON" state, the corresponding microstrip resonant stubs are loaded onto the 50 Ω transmission line, which performs a bandstop filter (BSF). For verification, the HSC with bandwidth of 12–15 GHz/15–18 GHz is designed to apply to a 6–18 GHz T/R module. As a result, the second harmonic of 6–9 GHz transmitting signal can be suppressed below 32 dBc when compared to the PA's fundamental output. While the p-i-n switches are "OFF" state, the HSC is almost the same as a 50 Ω transmission line, which will have a little effect on the 9–18 GHz transmitting signal. The measurement results approximately agree with the calculated results and simulated results, which demonstrate the validity of the proposed HSC.
Keywords — GaN power amplifier (PA), Harmonic suppression, Low in-band harmonic, p-i-n switch, Wideband T/R module.
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I. Introduction

Gallium-nitride (GaN) power amplifier (PA) with multiple-octave operating bandwidth usually exhibits poor harmonic suppression because of its high nonlinearity [1]–[6]. For the application of wideband T/R module [1], the harmonic products of a wideband PA will fall into the operating frequency range, which can hardly be eliminated by a bandpass filter (BPF) [7], [8], as shown in Figure 1.

As for a specific T/R module with operating bandwidth of 6–18 GHz, the second harmonic will appear in the Zone II (12–18 GHz) when PA operates in Zone I (6–9 GHz). To effectively avoid the performance degradation caused by the harmonic product of a PA, a traditional method is to use a bandpass filter associated with two

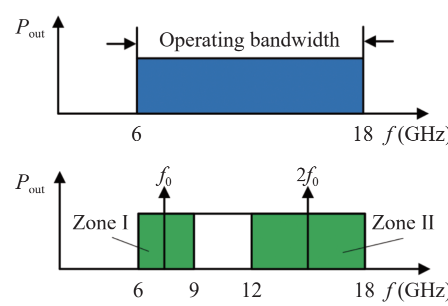

Figure 1 The operating condition of a 6–18-GHz PA.

single-pole-double-throw (SPDT) switches to enhance the harmonic suppress level within the range of operating bandwidth, as presented in Figure 2. In the TX-mode operation of a T/R module, the two SPDT switches should

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be switched to connect the BPF which can easily suppress the second harmonic of 6–9-GHz transmitting signal. When the T/R module operates in the range of 9–18 GHz, the two SPDT switches should be switched to connect 50-Ω transmission line. It can be found that such a T/R module will have larger area and higher cost. For this reason, the PA with second harmonic suppression (SHR) can achieve more compact T/R module with low in-band harmonic. Several types of PA with certain degree of SHR have been reported in [1]–[3], [9]–[12]. One useful way is to use push-pull PA [1]–[3]. By using two identical PAs with two wideband baluns placed at their input and output, respectively, the second harmonic of a push-pull PA can be suppressed to an acceptable level as compared to fundamental output [1]–[3]. However, to obtain the same output power as that of a single PA, the push-pull PA uses two PAs, which brings a great pressure on the heat dissipation for a compact T/R module in large-scale active electronically scanned array (AESA) [13]–[17].

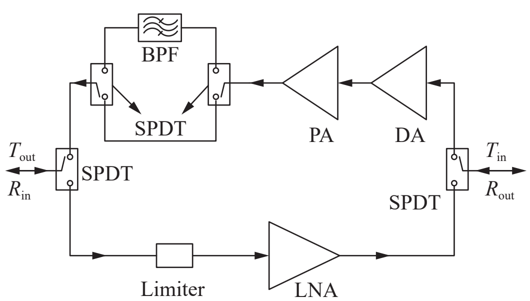

Figure 2 Block diagram of a 6–18 GHz T/R module with low in-band harmonic.

To overcome the drawbacks of the methods mentioned above, a compact reconfigurable harmonic suppress circuit (HSC) is proposed to suppress the in-band second harmonic of 6–18 GHz T/R module. The HSC is composed of one 50-Ω microstrip line and eight high impedance resonant stubs loaded with a single-pole-single-throw (SPST) switch. By changing the condition of SPSTs, the HSC can be reconfigured. With six of SPST switches being "ON" state, the HSC performs as a bandstop filter (BSF) which can achieve desired SHR for the 6–7.5/7.5–9 GHz transmitting signal. Moreover, the stopband bandwidth can be extended and flexibly controlled by using multiple resonant stubs with different resonant frequencies [18]. While all SPST switches are being "OFF" state, the HSC can be equivalent to a 50 Ω microstrip line. As a result, the 9–18 GHz transmitting signal will not be affected by the HSC. The area of the designed HSC layout is only 14.2 × 10 mm^2, which can be easily integrated into a T/R module without increasing circuit area evidently. In addition, the cost of a T/R module with over 32 dBc SHR in TX-mode is effectively reduced as compared to the scheme in Figure 2.

II. Design of Compact Reconfigurable Harmonic Suppress Circuit

1. Analysis

Figure 3 presents the topology of the proposed HSC. The HSC is constructed by using multiple microstrip resonant stubs loaded with a SPST switch. The resonant stubs are loaded onto the 50 Ω transmission line with equal spacing length l_0. To minimize the loading effect as much as possible, the characteristic impedance Z_1 of the resonant stubs is chosen as 100 Ω and the loading position l_T should be less than $\lambda_g/8$ (λ_g is the guided wavelength at 18 GHz). Then, the short stubs exhibit high impedance for 6–18 GHz signal as all of SPSTs are being "OFF " state [19], [20]. When SPST switch is being "ON " state, each stub forms a resonant pole. Then a stopband with desired bandwidth and multiple different resonant frequencies can be achieved by using given number of stubs. Based on the design method for the asynchronously-tuned filter [18], the stubs with different length can flexibly control the pole location. When SPSTs are being "OFF " state, signal transmission is hardly affected by the resonant stubs. Herein, the SPST is implemented by employing p-i-n diode APD0805-000 (C_p = 0.05 pF, R_s = 2 Ω) from Skyworks Corporation in this design. To simplify the analysis, the ideal model of SPST is utilized. So when all of SPSTs are being "ON" state, the $ABCD$-matrix of the HSC can be expressed as [20], [21]

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ \mathrm{j}Y_1 \tan\beta l_1 & 1 \end{bmatrix} \begin{bmatrix} \cos\beta l_0 & \mathrm{j}Z_0 \sin\beta l_0 \\ \mathrm{j}Y_0 \sin\beta l_0 & \cos\beta l_0 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \mathrm{j}Y_1 \tan\beta l_2 & 1 \end{bmatrix} \times \begin{bmatrix} 1 & 0 \\ \mathrm{j}Y_1 \tan\beta l_{n-1} & 1 \end{bmatrix} \begin{bmatrix} \cos\beta l_0 & \mathrm{j}Z_0 \sin\beta l_0 \\ \mathrm{j}Y_0 \sin\beta l_0 & \cos\beta l_0 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \mathrm{j}Y_1 \tan\beta l_n & 1 \end{bmatrix} \tag{1}$$

where $Y_1 = 1/Z_1$, $Y_0 = 1/Z_0$, l_0 is physical length of $\lambda_g/4$ at 12 GHz (λ_g is the guided wavelength), and $l_1, l_2, \ldots, l_n$ is physical length of the $\lambda_g/4$ resonant stub i ($i = 1, 2, \ldots, n$), respectively. Then the S_{21} and S_{11} of HSC can be computed by

$$S_{21} = \frac{2}{A + B/Z_0 + CZ_0 + D} \tag{2}$$

$$S_{11} = \frac{A + B/Z_0 - CZ_0 - D}{A + B/Z_0 + CZ_0 + D} \tag{3}$$

Based on formulas (1)–(3), the frequency responses of the HSC shown in Figure 3 can be investigated by using MATLAB software. Aiming at achieving low in-band harmonic for a 6–18 GHz T/R module, the SHR of 6–9-GHz band is set as below −30 dBc in this design. Moreover, the 6–9 GHz band is divided into two sub-bands (6–7.5/7.5–9 GHz), whose harmonic can be suppressed by changing the condition of SPSTs in the HSC. To obtain the desired SHR for 6–7.5 GHz band, the frequency responses with the different number denoted

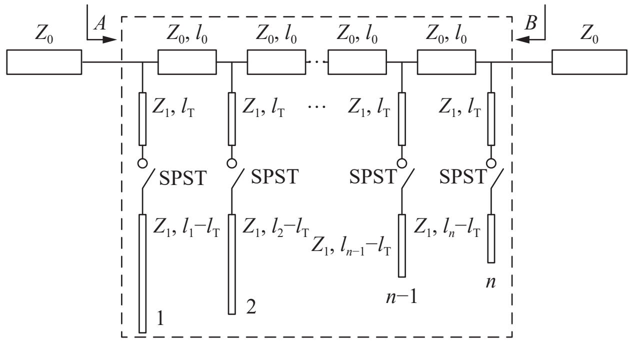

Figure 3 Schematic of the proposed reconfigurable HSC.

as n of the resonant stubs are calculated and plotted in Figure 4. The resonant frequencies of the stubs are distributed over the frequency range of 6–7.5 GHz. As can be seen, the 12–15 GHz band is suppressed below 30 dB by using six resonant stubs or more, while the return loss (RL) is kept below 12 dB in the range of 6–7.5 GHz. To make the HSC more compact, six resonant stubs are utilized for each operation mode. Then, four of them are also used to suppress the harmonic of the 7.5–9 GHz band, as exhibited in Figure 5. By adding extra two resonant stubs, the predefined suppression level can also be obtained in the range of 15–18 GHz.

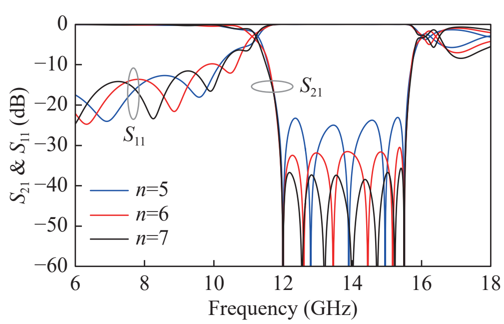

Figure 4 The calculated frequency responses under different number of resonant stub.

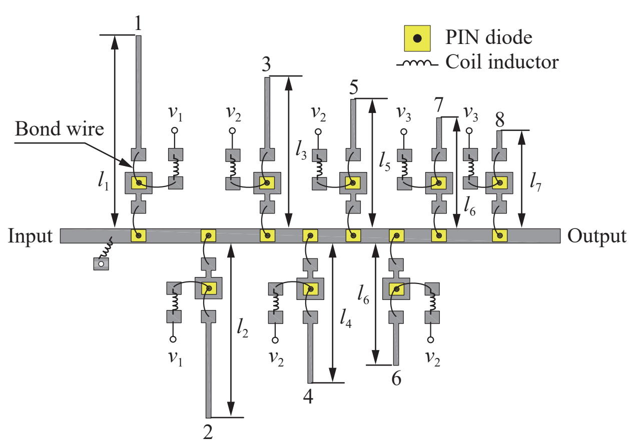

Figure 5 Layout of the proposed reconfigurable HSC.

2. Circuit implementation of HSC

The layout of the reconfigurable HSC is shown in Figure 5. Each SPST switch is realized by cascading two p-i-n diodes, which can enhance the isolation level. In this way, the loading effect will be further minimized, resulting in little influence on the transmitting signal of 9–18 GHz band. The resonant stubs 1–6 controlled by the voltages v_1 and v_2 are used to suppress the 12–16 GHz band. While the resonant stubs 3–8 controlled by the voltages v_2 and v_3 are used to suppress 16–18 GHz band. In this design, the substrate Al_2O_3 ceramic with thickness of 0.381 mm and relative dielectric constant of 9.8 is utilized. The coil inductor is used for RF choke and the bond wires for interconnecting different metal pads. Based on the calculated frequency responses, the initial dimensions of the resonant stubs that resonate in the range of 12–18 GHz can be evaluated using Agilent's software ADS2014. With the co-simulation of the commercial software HFSS15 and ADS2014, the whole layout of the harmonic suppress circuit is optimized and its overall size is 14.2 × 10 mm^2 (2.24 λ_g × 1.58 λ_g, λ_g is the guided wavelength at 18 GHz). The detailed dimensions are as follows (unit: mm): $w_1 = 0.04$, $l_1 = 2.4$, $l_2 = 2.4$, $l_3 = 2.25$, $l_4 = 2.05$, $l_5 = 1.85$, $l_6 = 1.65$, $l_7 = 1.4$, $l_8 = 1.2$.

III. Measurement Results

For demonstration, the HSC is fabricated by using thin-film technology, as presented in Figure 6(a). It is worth mentioning that the p-i-n diodes are pasted onto the metal pads by using the electrically conductive Ag epoxy. To suppress the 12–15 GHz band, the voltage v_1, v_2 and v_3 is set as 1.7, 1.7 and 0 V, respectively. As shown in Figure 6(b), over 20 dB suppression level is obtained in 12–15 GHz band while keeping the insertion loss (IL) less than 0.5 dB in 6–7.5 GHz band. When the voltage v_1, v_2 and v_3 is set as 0, 1.7 and 1.7 V, respectively, the suppression level in the 15–18 GHz band is greater than 30 dB and the IL in 7.5–9 GHz band is also less than 0.5 dB. The direct mode can be obtained by setting v_1, v_2 and v_3 to 0 V, the IL is less than 1 dB over the entire frequency range of 6–18 GHz, as shown in Figure 6(c). Due to the fabrication and micro-assembly tolerance, the preset stopband at 12–15 GHz moves towards to higher frequency as compared to the simulated results, leading to the degradation of the suppression level at 12 GHz.

Figure 7(a) presents the measurement setup for a 6–18 GHz T/R module cascaded by the HSC. In TX-mode operation, the GaN PA in T/R module can deliver an output power of 10 W and its normalized output power with fundamental and second harmonic output is plotted in Figures 7(b) and (c). When the HSC operates in the lower stopband, the SHR of the T/R module is suppressed below 32 dBc in the frequency range of 12–15 GHz. While for the upper stopband operation, the SHR achieves better than 45 dBc in the frequency range of 15–18 GHz. In contrast to the T/R module without the HSC, the SHR is improved up to at least 20 dBc. So the low in-band harmonic is achieved for the 6–18 GHz T/R

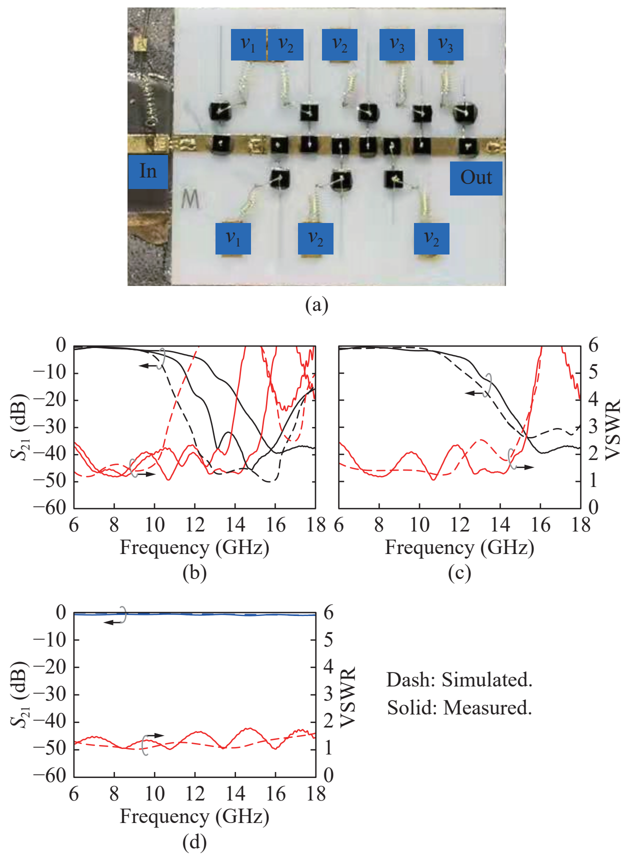

Figure 6 (a) The photograph of the proposed HSC and its frequency responses for (b) Suppressing 12–15-GHz band, (c) Suppressing 15–18-GHz band and (d) Direct mode operation (VSWR: voltage standing wave ratio).

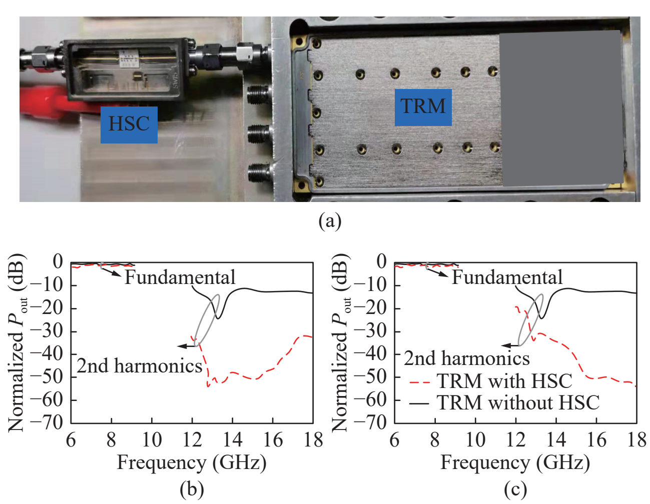

Figure 7 (a) Measurement setup for TRM with HSC; TRM output with HSC operating in (b) Lower stopband and (c) Upper stopband (TRM: T/R module).

module. The performance comparison for GaN-based PA with SHR is listed in Table 1. As observed, the GaN PA in this work delivers the highest output power while keeping high SHR. Moreover, the minimum number of PAs in this paper wins an advantage over other reported work in reducing DC power consumption.

Table 1 Performance comparisons between the reported GAN-based PAs with SHR and this work

Ref.	Tech.	BW (GHz)	P_{sat} (dBm)	SHR (dBc)	Topology	No. of PAs
[1]	PCB	6–18	31	40	Push-pull	2
[2]	PCB	4–8.5	30.5	30	Push-pull	2
[3]	0.25 μm GaAs pHEMT	4–20	30	33	Push-pull	2
This work	PCB	6–18	40	32	Single-ended	1

Note: BW is short for bandwidth.

IV. Conclusion

In this paper, a reconfigurable HSC is presented to suppress the in-band harmonic product of the wideband T/R module. The HSC can operate in three modes by controlling SPSTs. Therefore, the desired in-band harmonic suppression of a specific T/R module can be realized freely. Additionally, the achieved compact HSC is compatible with the low-cost T/R module. By placing the HSC at the output of a PA, the output SHR of 6–9 GHz band is enhanced compared with that of a standalone PA. The measurement results approximately agree with the simulated results, which proves the validity of the proposed method. In the future, the reconfigurable HSC can be further miniaturized by using MMIC technique and integrated into PA modules.

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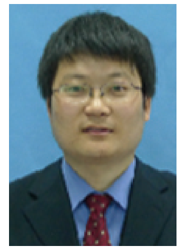

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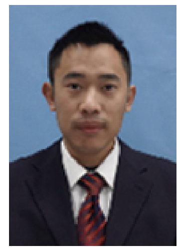

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