An Inter-Stage Filter Network for Distortion Reduction in Concurrent Dual-Band Power Amplifier Operation

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***Abstract*—This work presents a novel approach for reducing the out-of-band distortion generated in a concurrent dual-band power amplifier (PA) without penalty to output power or efficiency using a filter between a driver amplifier and final-stage PA that manipulates the driver amplifier out-of-band distortion such that the overall distortion of the cascade is minimized. The cascaded PA operates at 2.4-GHz and 3.5-GHz with peak output power and drain efficiency of 41.6/40.4 and 65.2/55.1 respectively. The filter reduces the out-of-band distortion of the cascade when excited by dual 10-MHz LTE-like signals by 10 dB while improving average drain efficiency by 5 percentage points.**

***Index Terms*—Distortion compensation techniques, power added efficiency, power amplifiers.**

I. Introduction

Traditional and novel applications of RF and microwave engineering continue to demand increasing access to limited available spectrum. This need has driven the development of dual-band PA techniques [1]. While dual-band techniques are successful in realizing good RF performance in each individual band, it is often prohibitively difficult to operate the amplifier in both bands simultaneously due to the associated output distortion [2]. Even digital predistortion (DPD) techniques, the gold standard of PA linearization, struggle with linearizing both in-band and out-of-band distortion [3].

In the analog domain, distortion reduction techniques include using a filter at the output of a dual-band PA that passes the fundamental frequencies of each band while rejecting distortion frequencies. While this technique is straightforward, particularly in cases with wide spacing in frequency between the fundamental and distortion frequencies, the pass-band loss of such a filter degrades the system's gain and efficiency and must be traded off against stop-band rejection [4].

As an alternative analog approach, we propose an interstage network between the driver amplifier and final-stage PA, as illustrated in Fig. 1. The filter's purpose is *not* simply to minimize the distortion product tones at the input of the final-stage PA. Rather, it applies an appropriate amplitude and phase shift to the distortion products generated by the broadband driver amplifier so as to minimize the *overall* distortion of the PA cascade. The required filter transfer function depends on the nonlinearities of the final-stage PA, and is determined in this work through large-signal simulation. The architecture

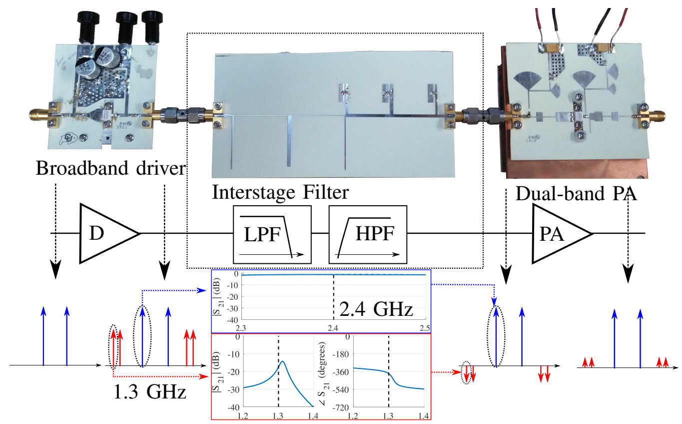

Fig. 1: Overview of the driver-filter-PA cascade architecture. The filter passes the two fundamental tones while perturbing the out-of-band distortion products of the driver such that the overall distortion of the cascade is minimized.

is demonstrated with a dual-band PA operating at 2.4 / 3.5 GHz on two concurrent 10-MHz LTE-like signals for a 10 dB reduction in the intermodulation distortion and a 5 percentage point improvement in the average modulated drain efficiency compared to the same system without the interstage filter.

II. Distortion Reduction Approach

The proposed novel interstage distortion reduction technique exploits the nonlinearity of the driver stage to generate signals at the distortion frequencies that are input to the final-stage PA. By appropriately manipulating the amplitude and phase of these signals to compensate for the PA's nonlinear response, the overall distortion of the cascaded system can be minimized. In order to design an interstage network to linearize the cascade, we must first determine what distortion products will appear and what interstage transfer function will remove them.

The distortion products generated by a dual-band PA operating at a lower frequency band f_L and upper frequency band f_U can be parameterized in terms of a center frequency between the bands f_c, band spacing f_b, and coefficients m and n (where $k = |m| + |n|$ is the order of the distortion) as:

$$\mathrm{IM}(m,n) = mf_U + nf_L = (m+n)f_c + \frac{1}{2}(m-n)f_b \quad (1)$$

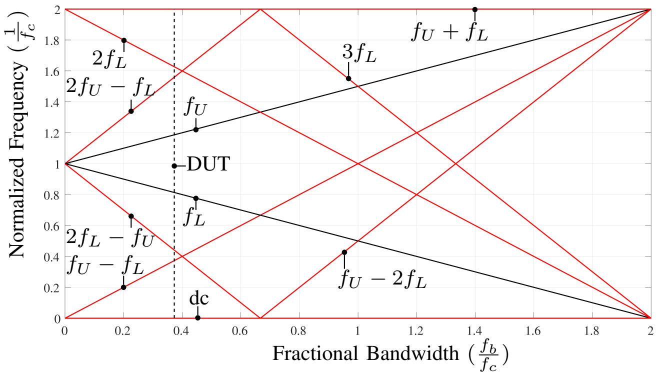

Fig. 2: Frequency locations of the fundamental (black) and third order distortion products (red), normalized to the center frequency of the dual-band PA as a function of its fractional bandwidth. The black, dashed line shows the location of third order distortion products in the dual-band PA under test.

The dominant third-order nonlinear response of the PA ($k \leq 3$) is taken to be of primary interest in this work. By normalizing (1) by the system's fractional bandwidth f_b/f_c, the resulting normalized frequency locations for all relevant values of k can be plotted as in Fig. 2, in which the fundamental frequencies are shown in black and distortion frequencies in red. Four critical values of fractional bandwidth emerge from this plot for the dual-band PA in this work: 1.1 GHz, 1.3 GHz, 4.6 GHz, and 4.8 GHz.

The overall distortion from the cascade of driver, interstage network, and dual-band PA can be found using a Volterra series approximation as (7) of [5], which can be rewritten in terms of the $2\omega_2 - \omega_1$ distortion product as:

$$V_{out}(2\omega_2 - \omega_1) = V_{in}^2(\omega_2)V_{in}^*(\omega_1)\times \\ [H_{1,A}^2(\omega_2)H_{1,A}^*(\omega_1)H_{3,B}(\omega_2,\omega_2,-\omega_1)H_{\mathrm{IN}}^2(\omega_2)H_{\mathrm{IN}}^*(\omega_1) \\ + H_{3,A}(\omega_2,\omega_2,-\omega_1)H_{1,B}(2\omega_2-\omega_1)H_{\mathrm{IN}}(2\omega_2-\omega_1)] \quad (2)$$

In (2), $H_{n,a}$ represents the Volterra nonlinear transfer function of n^{th} order for either the driver (A), interstage network (IN) or dual-band PA (B). The interstage network responses at ω_1 and ω_2 (i.e., $H_{\mathrm{IN}}(\omega_1)$ and $H_{\mathrm{IN}}(\omega_2)$) must be selected to minimize loss and therefore maximize system performance, but the interstage network response at the distortion product $H_{\mathrm{IN}}(2\omega_2 - \omega_1)$ can be selected with appropriate amplitude and phase so that the two additive terms in (2) cancel and the overall output distortion is minimized. This process is possible for all real distortion products generated in the dual-band PA.

III. Prototype Design

The demonstrator hardware is based on the CG2H40010F device for both the driver and the final-stage amplifier. The driver amplifier is designed as a wideband gain stage with a reactive matching network, and the dual-band final stage PA follows the SRFT-based design in [6]. A photograph of the amplifiers with interstage network can be seen in Fig. 1. Given the difficulty in analytically determining the nonlinear transfer functions of the driver amplifier and dual-band PA

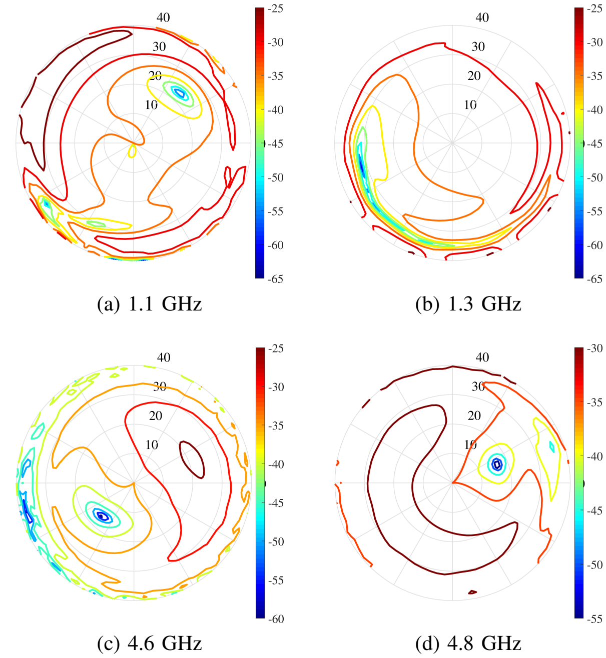

Fig. 3: Simulated IMD3 products in dBc at (a) 1.1 GHz, (b) 1.3 GHz, (c) 4.6 GHz, and (d) 4.8 GHz as a function of the transfer response in dB and degrees of an ideal interstage filter between the driver amplifier and PA.

[7] the desired interstage network transfer function H_{IN} was determined in simulation from maufacturer-provided large-signal models. The resulting cascaded system responses to variable H_{IN} at 1.1 GHz, 1.3 GHz, 4.6 GHz, and 4.8 GHz are shown in Fig. 3. These plots indicate the distortion in dBc at each frequency with an interstage network that passes the fundamental signals but applies attenuation and phase at the distortion frequency listed.

To realize the optimal transfer function values found in Fig. 3 and to minimize loss at the fundamental frequencies, a pseudo-bandpass filter comprised of a open-stub filter cascaded with a shorted-stub filter was designed as pictured in Fig. 1. The open-stub filter is designed as a low-pass filter with a corner frequency around 4 GHz and the shorted-stub filter is designed as a "high-pass" filter with a corner frequency around 1.9 GHz. The large attenuation values for the optimal transfer function found in Fig. 3 mean that it is relatively easy to design the cascade of these two filters to meet the optima.

IV. Measured Results

The cascaded amplifier system's out-of-band response is first characterized based on the standard two-tone distortion metric, IMD3, with and without the interstage filter. For all power levels the cascade with the filter present has lower IMD3, by up to 20 dB in the case of 1.1 GHz.

While the results from Fig. 4 indicate the filter reduces out-of-band distortion at all frequencies of interest, the response to concurrent modulated signals is of even greater interest.

TABLE I: Performance comparison to state-of-the-art dual-band PAs. For accurate comparison with the referenced single-stage PAs, only final stage gain and efficiency is reported.

Ref./ Year	**OMN Design**	**Freq. (GHz)**	**Gain (dB)**	**Pout (dBm)**	**Drain Eff. (%)**
[8] 2017	Dual-band RFT	2.4 / 3.5	10.6 / 11.2	40.6 / 41.2	70 / 71
[1] 2021	NPE method	0.9 / 1.75	16 / 13	40.5 / 41.0	74 / 73†
[6] 2021	Dual-band filter/SRFT	2.4 / 3.5	10.5 / 10.7	41.5 / 40.7	66 / 58
This Work	Interstage filter	2.4 / 3.5	10.5/10.8	41.6/40.4	65/55

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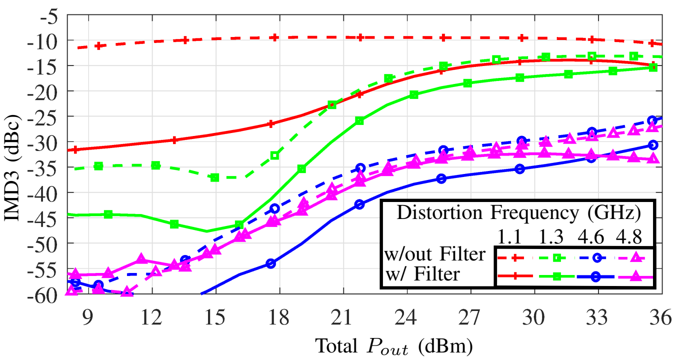

Fig. 4: Measured distortion response of driver-filter-PA and driver-PA cascades as a function of total output power when tones at 2.4 GHz and 3.5 GHz are simultaneously applied.

The driver-filter-PA cascade's response to concurrent 10-MHz LTE-like signals at an average output power of 31 dBm with and without the filter present is shown in Fig. 5. The cascade with the filter suppresses distortion at almost all distortion frequency locations, not just the four third-order distortion frequencies under consideration in this design. Comparing the power ratios of these out-of-band signals (integrated over a 10-MHz band) shows that the cascade with filter suppresses these distortion products by at least 10 dB. Additionally, the filter has the added benefit of improving the overall efficiency of the final power amplifier: the cascade with filter has 35% average drain efficiency compared to 30% without the filter. This improvement is attributed to less dc power spent on generating distortion products, as the in-band signal PAPRs are nearly identical in each case.

A comparison to other state-of-the art dual-band PAs is given in Table I, with only the final-stage performance reported for direct comparison to the other single-stage works, most of which do not report linearity metrics. In [6], concurrent operation without DPD for 10-MHz signals at 2.4 / 3.5 GHz is demonstrated with -36 / -36 dBc ACPR and 21% average drain efficiency at 30 dBm average output power. Compared to that work, the presented interstage filter technique in concurrent operation without DPD of 10-MHz signals at the same frequencies realizes -41 / -42 dBc ACPR with the reported 35% drain efficiency at 31 dBm average output power.

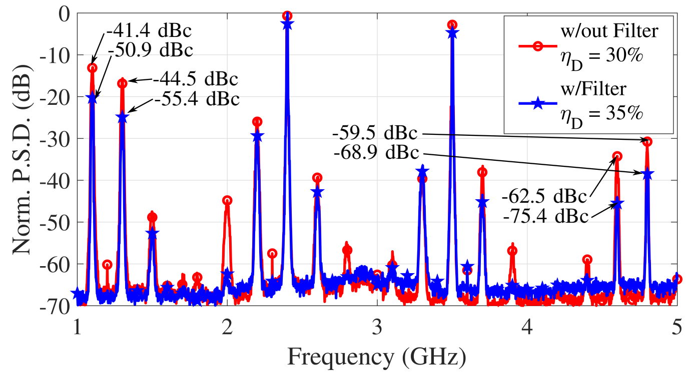

Fig. 5: Output spectrum of driver-filter-PA and driver-PA cascades when simultaneously excited by 10 MHz LTE-like signals at 2.4 and 3.5 GHz with 31 dBm average output power.

V. Conclusion

The interstage filter proposed in this work acts as an analog predistorter by manipulating the intermodulation products generated by the driver amplifier to cancel out distortion in the final RF stage. As demonstrated, it is able to improve the out-of-band power ratio by 10 dB in concurrent dual-band operation with modulated signals, while simultaneously improving the drain efficiency of the final stage by 5 percentage points. An interesting effect of this approach is that the driver is not required to operate in deep back-off; in fact, some nonlinearity in the driver is required. This implies that the driver can be operated in a relatively efficient state closer to saturation.

Acknowledgment

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