A Stand-Alone Distortion-Cancelling Cell for Microwave Amplifiers

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***Abstract*—This letter presents a standalone circuit (cell) to reduce the third-order inter-modulation distortion (IMD) produced in microwave amplifiers. The cell splits the output of the amplifier into two paths. In one path, the amplified signal and the IMD tones pass through toward the output. In the other path, an auxiliary FET device biased near pinchoff and a tunable phase shifter reproduce the amplifier's IMD tones but with the opposite phase as the original tones. When the IMD tones in the two paths are combined at the output, they cancel out and the input third-order intercept point (IIP_3) of the amplifier is improved. The cell requires only two tuning voltages: one for the auxiliary FET and another for the variable phase shifter. Experimental test results show that the cell was able to improve the IIP_3 of a commercial, off-the-shelf, microwave amplifier from $+9.5$ dBm to $+17.5$ dBm.**

***Index Terms*—Distortion cancellation, IIP3, microwave amplifiers, OIP3, third-order intermodulation distortion (IMD).**

I. INTRODUCTION

As the complexity of mobile communications standards continues to increase in order to accommodate more data flow, the linearity specifications on front-end microwave amplifiers are further tightened to keep signal distortion at sufficiently low levels. As a result, amplifier linearization is a topic of wide interest among researchers and design engineers. Classic linearization techniques to reduce amplifier distortion include, for example, pre-distortion, feedback, and feedforward [1], [2]. There is also the Doherty amplifier topology [1], where a peaking amplifier is placed in parallel with a main amplifier to boost the output power of the main amplifier, which effectively linearizes the main amplifier. Derivative superposition (DS) [3] offers another way to reduce amplifier distortion and is a more recent entrant into the family of linearization techniques. DS has been successfully applied not only to amplifiers [3]–[6] but to mixers as well [7], [8].

A benefit of the DS technique is that it generally requires less circuitry compared to the predistortion, feedforward, or feedback linearization methods. To take advantage of DS, however, it has been necessary until now to integrate the linearization circuitry into the amplifier itself so that the *composite* circuit produces less distortion compared to the baseline amplifier without DS. Yet, there are situations where it is not feasible, or convenient, to redesign an existing amplifier to incorporate the DS linearization circuitry. In those situations it is preferable to use a standalone DS circuit that can be located after the amplifier to reduce the distortion and that is independent of the inner workings of the amplifier.

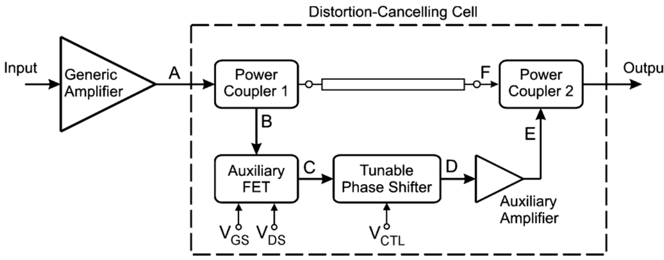

Fig. 1. Block diagram of the DCC (in the dashed box).

This letter reports the design and experimental verification of a standalone circuit, or cell, that reduces the distortion produced by a generic microwave amplifier. The distortion-cancelling cell (DCC) draws on the ideas behind DS linearization where IMD tones are generated that have the opposite phase as the IMD tones of the main amplifier and when they are combined at the output, the IMD tones cancel. To customize the DCC to function with any given amplifier, only two dc voltages need to be adjusted. Indeed, a certain amount of customization is not uncommon for standalone linearizers: in digital pre-distortion linearizers, for instance, the nonlinear amplifier response is determined beforehand and used in lookup tables.

II. DISTORTION-CANCELLING CELL

A. General Concept

The block diagram of the DCC is contained inside the dashed box in Fig. 1. The generic amplifier, hereafter "the amplifier", is a connectorized commercial amplifier whose distortion we want to cancel. Power coupler 1 is a 3 dB Wilkinson power splitter that routes the amplifier's output into two paths. In the top path, the amplified signal plus the IMD tones produced in the amplifier propagate onward on a 50 Ω transmission line. In the bottom path, an inverted replica of the amplifier's IMD tones is generated. At coupler 2, the waveform in the top path is combined with the out-of-phase IMD tones from the bottom path and the result is a distortion-free signal at the output of the system.

B. Detailed Description

Suppose that two closely spaced tones, ω_1 and ω_2, the desired signals, are incident on the amplifier in Fig. 1. The diagrams in Fig. 2 help illustrate the operation of the DCC by showing

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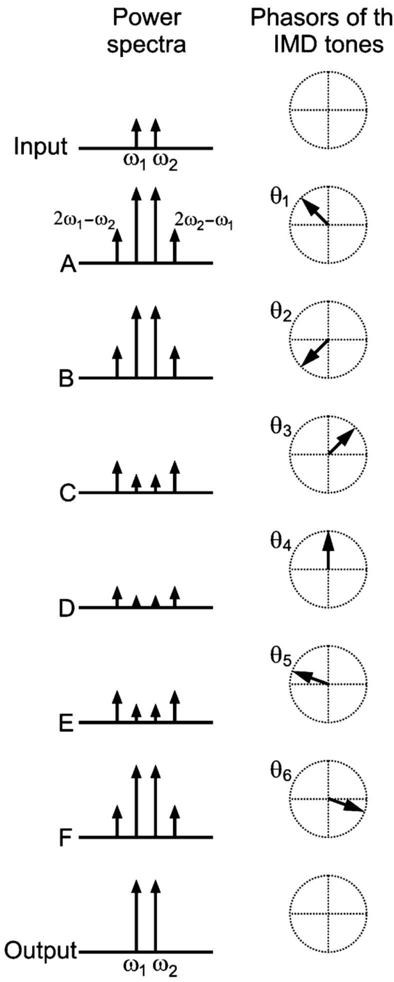

Fig. 2. Power spectra and the phasors of the IMD tones at various nodes throughout the DCC in Fig. 1.

the power spectra and the phasors of the IMD tones throughout the cell. At point A in Fig. 1 the IMD tones generated by the amplifier at $2\omega_1 - \omega_2$ and $2\omega_2 - \omega_1$ will have some phase angle θ_1, as shown in Fig. 2. The IMD tones experience a phase shift, $\Delta\theta$, as they pass through power coupler 1 and their phase angle at point B will be $\theta_2 = \theta_1 + \Delta\theta$.

The auxiliary FET does not provide signal gain but instead it is biased in a region of its I-V characteristic where its nonlinear response is accentuated. Therefore, when the tones ω_1 and ω_2 are incident on the auxiliary FET, the IMD tones will be regenerated at point C in Fig. 1 but the ω_1 and ω_2 signals will be much reduced in strength. The gate-to-source bias voltage, V_{GS}, of the auxiliary FET determines whether its g_{m3} coefficient is positive or negative [3] in the expression for its drain current

$$i_{ds} = g_m v_{gs} + g_{m2} v_{gs}^2 + g_{m3} v_{gs}^3 + \cdots \tag{1}$$

where

$$g_{mn} = \frac{\partial^n I_D}{\partial V_{GS}^n}. \tag{2}$$

Thus, the sign of g_{m3} establishes whether the third-order IMD tones at point C will have the same or the opposite phase as the IMD tones at B. Through manual tuning a V_{GS} is found that will yield IMD tones at point C whose phase is $\theta_3 = \theta_2 + 180°$ as depicted in the fourth phasor diagram in Fig. 2. Note that the optimal V_{GS} depends on the incident signal's power level but there are ways to automate the search for that V_{GS} using digital techniques [6]. Furthermore, the digital techniques can also be used to mitigate amplifier memory effects.

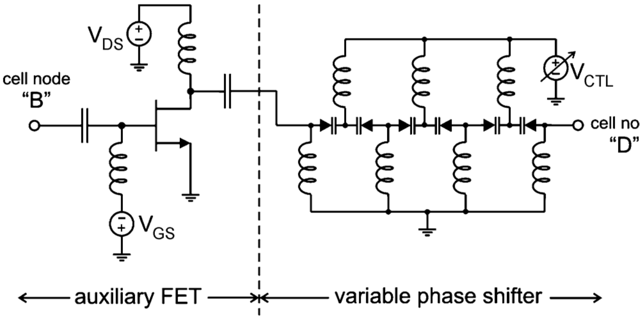

Fig. 3. Schematics of the auxiliary FET and the variable phase shifter.

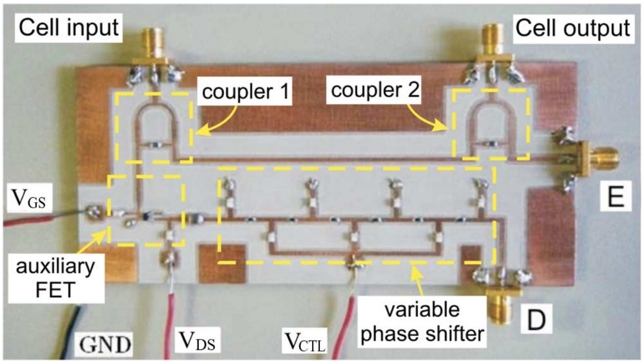

Fig. 4. Photograph of the stand-alone DCC.44Fig. 4. Photograph of the stand-alone DCC.

The variable phase shifter is used to tune the phase of the IMD tones in the bottom path so that when they reach point E, their phase angle is $\theta_5 = \theta_6 + 180°$. Thus, when the IMD tones in the upper and lower paths are combined at coupler 2 they cancel out.

The variable phase shifter implemented in this work is an L–C structure with varactor diodes serving as the capacitors. The structure has a non-zero insertion loss and, as a result, an auxiliary amplifier is used to boost the amplitude of the IMD tones in the bottom path back to the required values for cancellation with the IMD tones in the upper path. The auxiliary amplifier introduces its own phase shift on the IMD tones, but variable phase shifter can be appropriately tuned to counteract the phase shift of the auxiliary amplifier.

C. Implementation

The DCC was built on a Rogers RO3010 high-frequency laminate ($\epsilon_r = 10.2$). The 3 dB power couplers are both of the Wilkinson type. The auxiliary FET was a packaged NE34018-T1 HFET from NEC. Because the purpose of the auxiliary FET is just to produce IMD tones, not signal gain, only a pair of bias tees were needed to feed the dc bias to the gate and drain terminals of the device as shown in Fig. 3. The schematic diagram of the variable phase shifter is also shown in Fig. 3. The varactor diodes used in the phase shifter were SMV1405-079LF surface-mount abrupt junction devices from Skyworks. The auxiliary amplifier was a connectorized

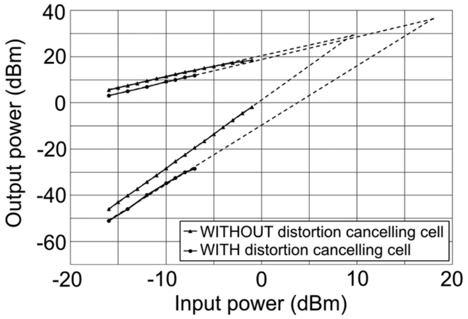

Fig. 5. IP_3 measurement of the main amplifier with and without the distortion cancelling cell.

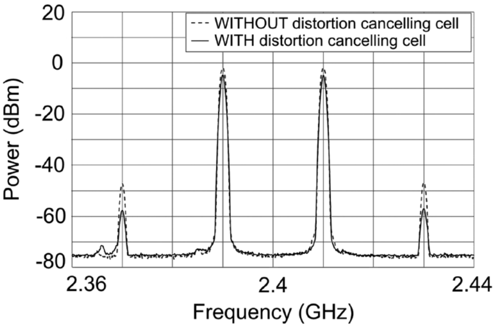

Fig. 6. Measured amplifier output spectra with (solid line) and without (dashed line) the DCC.

TABLE I

RESULTS SUMMARY

Amplifier	Without DCC	**With DCC**	Change
IIP_3	9.5 dBm	**17.5 dBm**	+8 dB
OIP_3	29.5 dBm	**37 dBm**	+7.5 dB
Power gain	21 dB	**19 dB**	-2 dB

ABP1200-01-1825 amplifier from Wenteq Corp. with a gain of 18 dB and an output $\mathrm{P}_{1\ \mathrm{dB}}$ of 25 dBm. A photograph of the assembled circuit is shown in Fig. 4. The auxiliary amplifier was attached between SMA connectors D and E in Fig. 4.

III. EXPERIMENTAL RESULTS

To verify the effectiveness of the DCC, the first step was to establish the baseline performance of the generic amplifier by itself. The generic amplifier used in the experiments was a connectorized CSA-880912 amplifier from Celeritek. A two-tone test was carried out on the amplifier to determine its IMD response and its third-order intercept point (IP_3). Using input tones at 2.39 GHz and at 2.41 GHz and sweeping their input power levels simultaneously, the IIP_3 of the amplifier alone was measured at 9.5 dBm and its OIP_3 was 29.5 dBm. The input $\mathrm{P}_{1\ \mathrm{dB}}$ of the amplifier was also measured and it was -2 dBm while the output $\mathrm{P}_{1\mathrm{dB}}$ was $+18$ dBm.

Next, the DCC was connected to the output of the amplifier and another two-tone test was done using the same input frequencies as before. With the input tones at their lowest input power setting, the gate bias voltage of the auxiliary FET device and the control voltage of the variable phase shifter in the DCC were varied until the power of the IMD tones was minimized. Once those two voltages were established, the power of the two input tones was swept to determine the new IP_3 of the amplifier plus the DCC. This second two-tone test showed that the IIP_3 increased to 17.5 dBm and the OIP_3 rose to 37 dBm. Thus, the DCC improves the IIP_3 of the amplifier by $+8$ dB and the OIP_3 improves by $+7.5$ dB. In terms of the gain, the amplifier plus cell combination has a gain of 19 dB while the amplifier by itself has a gain of 21 dB. The 2 dB drop in gain is due to the insertion loss of the back-to-back power couplers and the transmission line in the upper path of the DCC.

A plot of the two-tone test results for the amplifier alone and for the amplifier plus the DCC is shown in Fig. 5. Table I contains a summary of the measured IP_3 results for the amplifier with and without the DCC (see Fig. 6).

IV. CONCLUSION

We have shown that the distortion produced by a microwave amplifier can be reduced by placing a standalone distortion-cancelling cell after the amplifier. The cell employs the principle of derivative superposition to cancel the IMD produced by the amplifier. A key advantage of the approach presented here is that the cell can be used with a preexisting amplifier. The prototype was implemented on a printed circuit board but it is also amenable to monolithic implementation.

REFERENCES

[1] S. C. Cripps, *RF Power Amplifiers for Wireless Communications*, 2nd ed. Norwood, MA: Artech House, 2006.

[2] F. Raab, P. Asbeck, S. Cripps, P. Kenington, Z. Popovic, N. Pothecary, J. Sevic, and N. Sokal, “Power amplifiers and transmitters for RF and microwave,” *IEEE Trans. Microw. Theory Tech.*, vol. 50, no. 3, pp. 814–826, Mar. 2002.

[3] D. R. Webster and D. G. Haigh, “Low-distortion mmic power amplifier using a new form of derivative superposition,” *IEEE Trans. Microw. Theory Tech.*, vol. 49, no. 2, pp. 328–332, Feb. 2001.

[4] V. Aparin and L. Larson, “Modified derivative superposition method for linearizing fet low-noise amplifiers,” *IEEE Trans. Microw. Theory Tech.*, vol. 53, no. 2, pp. 571–581, Feb. 2005.

[5] B. R. Jackson and C. E. Saavedra, “A CMOS amplifier with third-order intermodulation distortion cancellation,” *IEEE Topical Mtg. Silicon Monolith. Integr. Circuits RF Syst.*, pp. 1–4, Jan. 2009.

[6] A. M. El-Gabaly, D. Stewart, and C. E. Saavedra, “2-Watt broadband GaN power amplifier RFIC using the f_T doubling technique and digitally-assisted distortion cancellation,” *IEEE Trans. Microw. Theory Tech.*, to be published.

[7] K.-H. Liang, C.-H. Lin, H.-Y. Chang, and Y.-J. Chan, “A new linearization technique for CMOS RF mixer using third-order transconductance cancellation,” *IEEE Microw. Wireless Compon. Lett.*, vol. 18, no. 5, pp. 350–352, May 2008.

[8] M. Wang and C. E. Saavedra, “ $+14$ dB improvement in the IIP_3 of a CMOS active mixer through distortion cancellation,” in *IEEE MTT-S Int. Dig.*, Beijing, China, Apr. 2013, to be published.