Effective Output Intercept Point (EOIP) — A Useful RF Transmitter Figure-of-Merit

This new test method expands on standard two-tone techniques, incorporating wide bandwidth signals

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Nonlinear behavior characteristics of transmitters generate energy outside of the desired signal channel. This undesired energy causes interference in adjacent and alternate channels of the system, reducing system capacity, quality of service, or both. In this article, a general purpose figure-of-merit (FOM) is proposed to relate this off-channel energy with the output power of the transmitter. This FOM is applied to the transmitter output signal, to ensure that all effects of the transmitter circuitry are taken into account.

A prevalent output signal quality specification is adjacent channel power ratio (ACPR). This specification relates the output signal power in the adjacent channel (measured through a defined filter) to the output signal power delivered to the desired channel. ACPR is thus a relative specification. By the nature of nonlinear distortion products, the output signal ACPR performance changes as the output power is varied. ACPR alone, then, is not a good means of comparing the interference-generating tendencies between different transmitter implementations.

This article proposes the use of the *effective output intercept point* (EOIP) as the desired transmitter figure-of-merit. The EOIP is based on the well-known two-tone output intercept point measurement, which is modified to account for signal spectra using arbitrary modulation techniques with random data streams.

Review of output intercept point

A conventional model for an essentially linear amplifier with small nonlinear characteristics consists of a simple power law which relates the output signal $y(t)$ to the input signal $x(t)$.

$$y(t) = a_0 + a_1 x(t) + a_3 x^3(t) + a_5 x^5(t) + \dots \quad (1)$$

where a_0 is a DC offset, a_1 is the (desired) linear gain, and a_3, a_5, … represent third-order, fifth-order, etc., small nonlinearities.

The use of output intercept points (OIP) is well established as a measure of amplifier or system linearity (dominance of coefficient a_1). Measured using two sinusoidal signals separated by a relatively small frequency difference, intercept points due to third, fifth and higher odd-orders are calculated from the relationship

$$\mathrm{OIP}_n = P_{\mathrm{out}} + \frac{R_n}{n-1}$$
$$n = 3, 5, \dots \quad (2)$$

where P_{out} is the output power corresponding to the strongest of the intended output tones, and R_n is the suppression of the distortion products relative to the reference output tone due to amplifier nonlinearity of order n. The attractiveness of the OIP is that, in theory, it remains unchanged for various output powers, and is a characteristic of the amplifier alone (for a two-tone input signal) and not of the actual input or output powers.

For example, from the amplifier output signals shown in Figure 1 where a two-tone input signal is applied, and 0 dB amplitude corresponds to +30 dBm, we calculate the third- and fifth-order output intercept points as

$\mathrm{OIP}_3 = (30 - 13) + 47/2 = 40.5$ dBm
$\mathrm{OIP}_5 = (30 - 13) + 86/4 = 38$ dBm

[See Figure 1(a).]
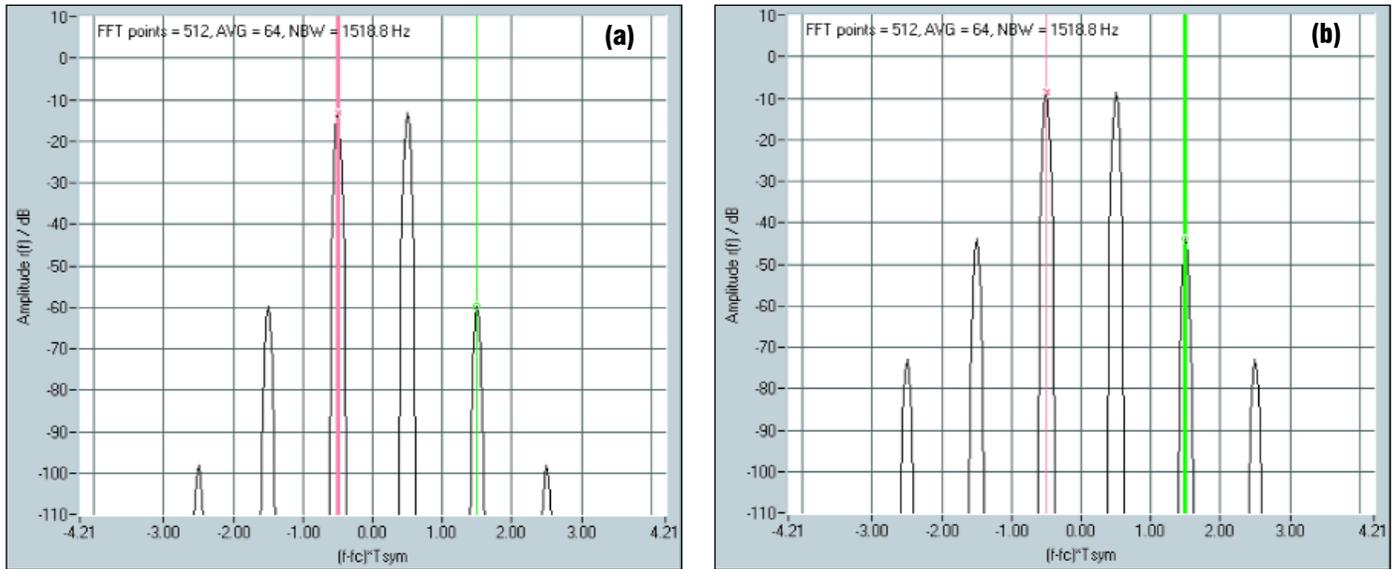
▲ **Figure 1. Amplifier output signal with a two-tone input signal showing signal distortion due to third- and fifth-order non-linearities at two different output powers: (a) 23 dBm; and (b) 27 dBm.**

$OIP3 = (30 - 9) + 34/2 = 38$ dBm
$OIP5 = (30 - 9) + 64/4 = 37$ dBm

[See Figure 1(b).]

Note that the measurement bandwidth is not critical as long as it is significantly less than the frequency separation of the two-tone input, so that the distortion products can be resolved. We can also observe that the OIP_3 for Figure 1(b) is lower than that for Figure 1(a) due to additional third-order distortion resulting from the fifth-order nonlinearity, which increases the measured third-order distortion. This demonstrates a fundamental limitation of the intercept point concept — intercept points are constants only when that particular order of distortion is present. Since distortions are only very rarely of a single order in real circuitry, intercept points are only a moderately accurate predictor of distortion signal powers.

Definition of EOIP

For a radio transmitter using arbitrary digital modulation, the two-tone OIP measurement does not apply for three reasons:

1. The modulation does not result in an output signal composed of two sinusoidal tones;
2. The internal nodes of the transmitter are not usually available to isolate and characterize the output amplifier alone;
3. The characteristics of the actual digital modulation are usually quite different from simple sine waves so that the conventional OIP may not directly correspond to (or predict) distortions on the digital signal.

The same principle can be used to evaluate the transmitter output signal directly. As the next section shows, third-order nonlinearity alone results in distortion products on both sides of the output signal, offset in frequency by the symbol rate (f_s). Similarly, fifth-order nonlinearity alone results in distortion products on both sides of the output signal offset in frequency by twice the symbol rate ($2f_s$), as well as distortion products on both sides of the output signal offset in frequency by the symbol rate. In general, the distortion present at $\pm f_s$ is larger than the distortion present at $\pm 2f_s$. This is represented in Figure 2, in which the signal modulation is $\pi/4$-DQPSK, as used in IS-136.

$EOIP_n$ is defined in a similar manner to two-tone third- and fifth-order intercepts, since third- and fifth-order nonlinearities are the primary causes of adjacent and alternate channel distortion products. However, the results of conventional OIP_n and $EOIP_n$ calculations are different for two major reasons: The signal modulation types are quite different; and The EOIP calculation is based on total output power, rather than the power in a single component of the output signal.

The calculation of the nth order effective output intercept point ($EOIP_n$) is done in a modulation-independent manner as follows:

1. Measure the total output power in dBm (P_{out}).
2. Then, using a spectrum analyzer with a resolution filter bandwidth (RBW) $\sim f_s/20$ and a narrower video bandwidth (VBW $<<$ RBW)
   (a) Measure the output power density at the carrier frequency (p_0) in dBm/RBW.
   (b) Measure the output power density at frequencies above and below the carrier of (n–1)/2 times the
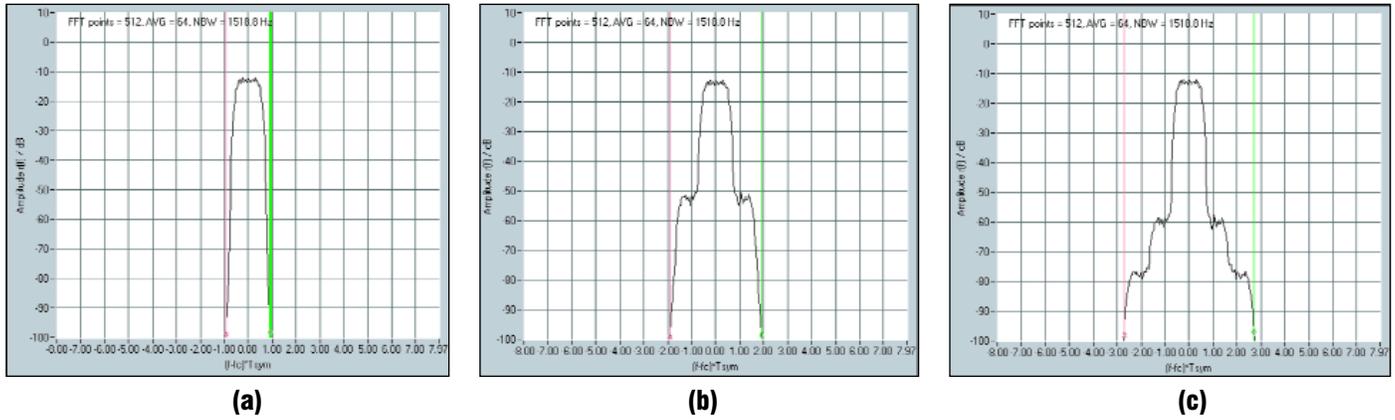
▲ **Figure 2. Transmitter output spectra for the IS-136 signal: (a) perfect transmitter; (b) only third-order nonlinearity; and (c) only fifth-order nonlinearity.**

symbol rate (fs) in dBm/RBW, keeping the largest measurement (pd).

(c) Subtract p_d from p_0 to get the distortion suppression R_n.

(d) Calculate EOIP_n using Equation (3).

$$\text{EOIP}_n = P_{\text{out}} + \frac{R_n}{n-1}$$

$$n = 3, 5, \dots$$

(3)

Note that the measurement bandwidth RBW is not critical, as long as it is significantly less than the symbol rate f_s.

Hardware EOIP calculation examples

Two examples of EOIP calculations on actual hardware are presented below. Both of these transmitters are generating the $\pi/4$-DQPSK signal defined by IS-136. The first example is from a conventional linear transmitter, which uses a class-AB output amplifier. The second example is from Tropian's new polar modulation transmitter architecture, which uses an efficient, com-
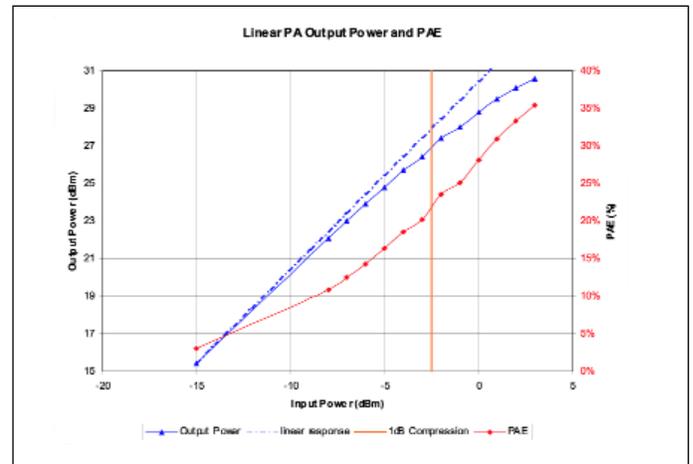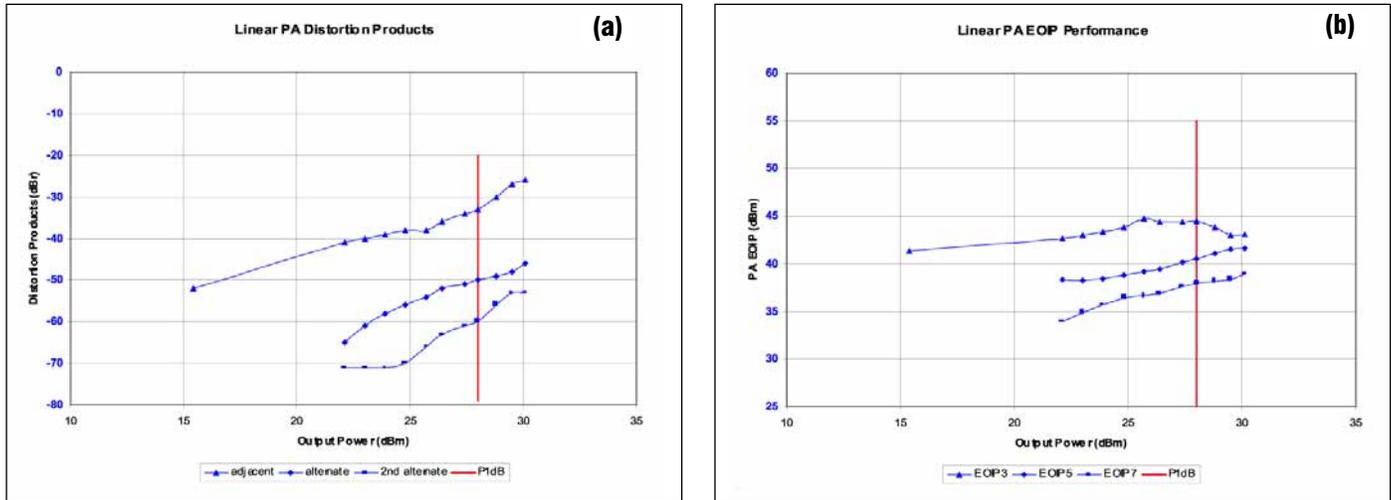

▲ **Figure 3. Linear amplifier output power and PAE characteristics.**

pressed power stage.

Example 1: Linear Transmitter — The linear transmitter for this example uses conventional quadrature
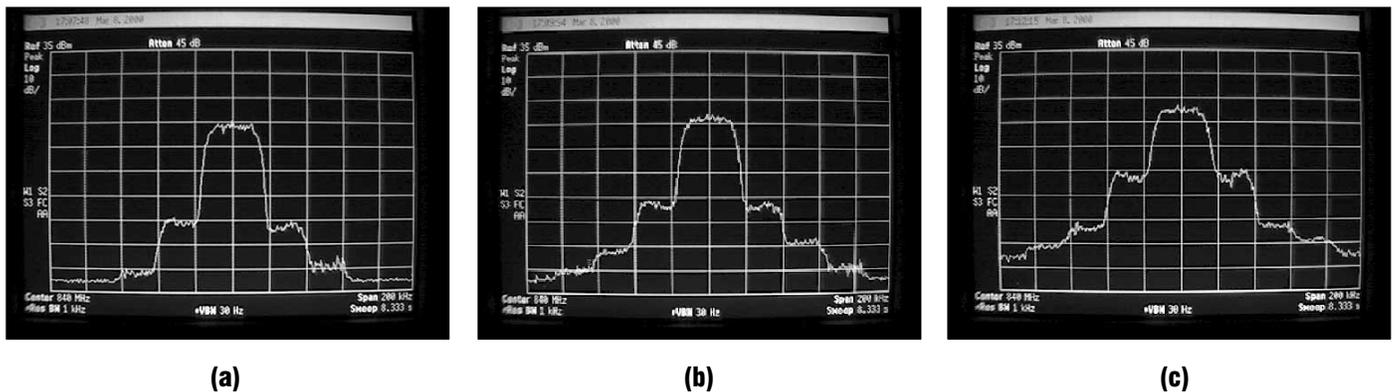
▲ **Figure 4. IS-136 output spectrum for the linear transmitter at (a) 22 dBm output power (5 dB backoff); (b) 26 dBm output power (1 dB backoff); and (c) 29.5 dBm output power (1.5 dB compression).**
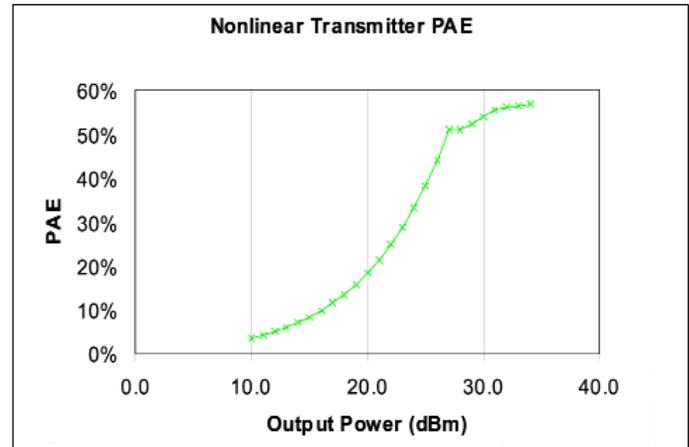
▲ Figure 5. Distortion performance of the GaAs HBT MMIC linear output amplifier: (a) R3, R5, and R7; and (b) corresponding results for EOIP$_3$, EOIP$_5$, and EOIP$_7$.

modulation and a new GaAs HBT MMIC designed for linear TDMA (IS-136) and CDMA (IS-95) handset operation. The measured output power and power-added efficiency (PAE) are shown in Figure 3.

In Figure 4, distortion products due to third- and fifth-order nonlinearities are clearly evident. Further, the spectra in Figures 4(b) and 4(c) have distortion products at $\pm 3f_s$, so the seventh-order effective output intercept point can also be calculated.

Using the technique defined above at several output powers, the values for EOIP$_3$, EOIP$_5$, and EOIP$_7$ are calculated. The results are shown in Figure 5. The values of EOIP$_3$ always exceed those of EOIP$_5$ and EOIP$_7$, and fall between 40 and 45 dBm.

Example 2: Polar Modulation Transmitter — The polar modulation transmitter used in this example does not use conventional quadrature modulation. Using a new architecture developed at Tropian, this transmitter is completely general in signal capability, including the constant envelope AMPS and GSM signals as well as the
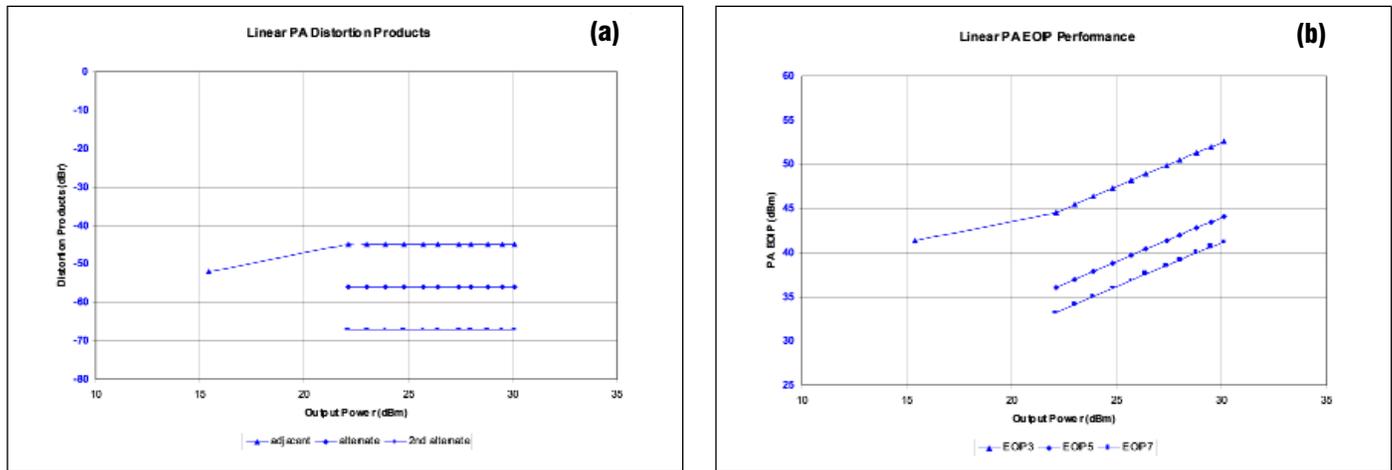

▲ Figure 6. Characteristics of the polar modulation transmitter PAE.

envelope varying EDGE, TDMA (IS-136) and CDMA (IS-95) signals. This transmitter is similarly scaled for
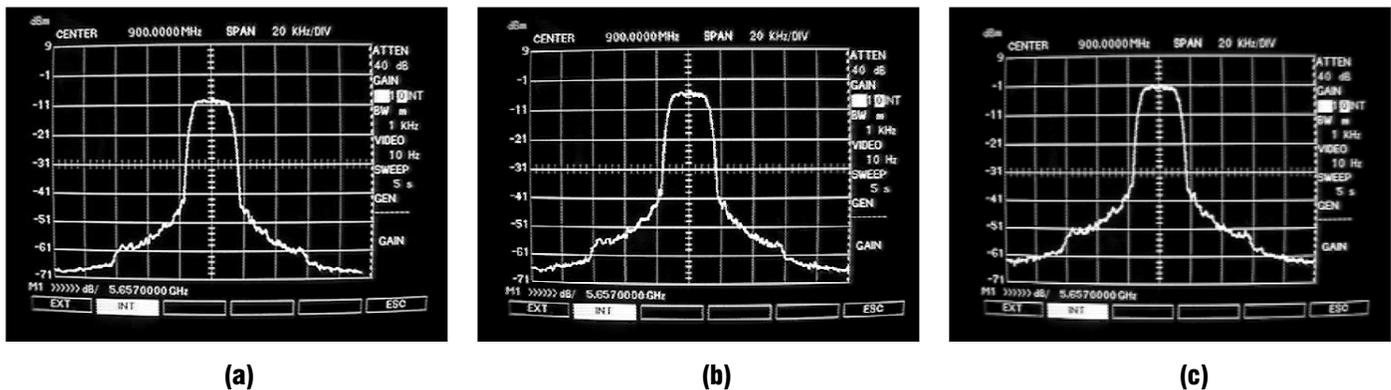
▲ Figure 7. IS-136 output spectrum for the polar modulation transmitter at (a) 23 dBm output power; (b) 27 dBm output power; and (c) 30 dBm output power.

▲ **Figure 8. Distortion performance of the Tropian IS-136 transmitter: (a) R3, R5 and R7; and (b) corresponding results for EOIP$_3$, EOIP$_5$, and EOIP$_7$.**

handset output power levels. The measured handset transmitter power-added efficiency (PAE) is shown in Figure 6.

Output spectra from the polar transmitter generating the NADC π/4-DQPSK signal are shown in Figure 7. These spectra correspond directly to those of Figure 4, except that they are taken at nominally 1 dB higher power. When compared to the linear transmitter, two characteristics of the output signal from the polar transmitter are immediately evident from Figure 7. First, the level of distortion sidebands is significantly lower than from the linear transmitter. Second, the output spectrum has an identical shape at each transmitter output power.

Using the technique defined above at several output powers, the values for EOIP$_3$, EOIP$_5$ and EOIP$_7$ are calculated. The results are shown in Figure 8. The values of EOIP$_3$ always exceed those of EOIP$_5$ and EOIP$_7$, and fall between 55 and 45 dBm. With such high values for EOIP$_3$ and EOIP$_5$, adjacent channel and alternate channel interfering energy are significantly reduced from conventional levels.

Conclusion

An effective output intercept point is a useful figure-of-merit for transmitter output signals. It is more useful than the conventional adjacent channel power rejection (ACPR) specification, because it is not a relative measurement but is an absolute number incorporating transmitter output power. A higher EOIP number cor-

responds to lower signal distortion. Thus, to improve system capacity by reducing interference levels, transmitters that have the highest possible EOIP rating are desired for these applications.

The EOIP for a transmitter is defined in a modulation-independent manner. This allows EOIP to be calculated for any transmitter and signal type, including envelope varying and constant envelope signals. For signal types that have spectra that extend beyond the symbol rate, such as GMSK, EOIP calculations can also be used to measure modulator spectral accuracy by comparing the measured EOIP to theoretical limits of the signal spectrum.

Unlike conventional linear transmit architectures, the new polar transmitter exhibits essentially constant signal spectrum shape at all output signal power levels. This characteristic does not follow the conventional power law distortion model; thus, EOIP predictions do vary with output power level. At particular output powers, EOIP can be measured and provide a meaningful comparison with conventional transmitters. For the NADC signal example shown, this results in a significantly higher EOIP figure-of-merit at maximum power than for the conventional transmitter. This transmitter also exhibits significantly higher energy efficiency due to its extremely nonlinear circuit operation. ∎

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