PA 中的 AM-PM 效应分析

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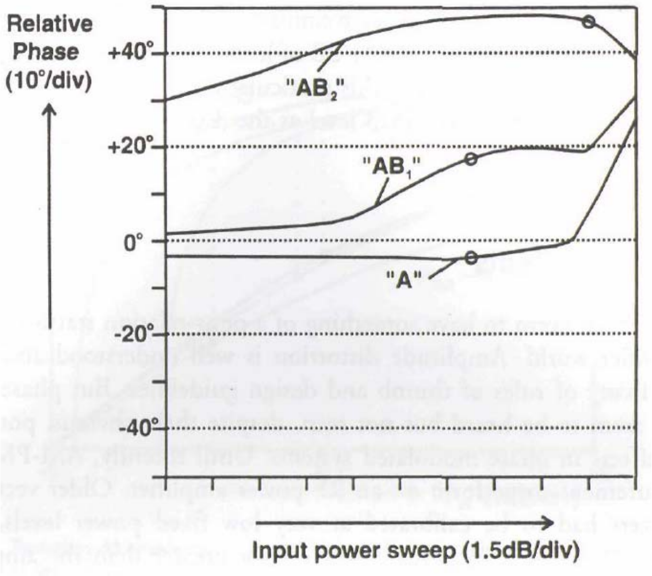
在理想的线性 PA 中，输入输出之间的相位差应该是零或者常数，即输出信号只是输入信号经过幅度放大和加入一定的延时。在实际 PA 中，由于其非线性的影响，会发生 AM-AM 失真和 AM-PM 失真。AM-AM 失真是指输出信号和输入信号幅度上的失真，比如当输入信号摆幅进入阈值电压之下或者饱和电压之上时，输出电压信号就会发生截断或削顶，即为 AM-AM 失真。AM-PM 失真是指，非线性 PA 输入信号幅度上的变化，导致了输出和输入信号之间的相位差的变化。

There is also a good deal of mystery about exactly what causes AM-PM distortion in the first place. Simple clipping on supply rails, does a reasonable job of explaining gain compression, but it is not clear where phase distortion comes from even when we are looking at well-clipped voltage and current waveforms.

下图所示为一个 1.9GHz 1W PA 的 AM-PM 测试结果：



图中可以看到，Class A 工作模式（“A”）下，在P_{in-1dB}输入功率（圆圈表示）以下，输出和输出的相位差为常数，因为此时 PA 线性良好；当输入功率大于P_{in-1dB}时，相位差开始增大，在更大的输入功率处，相位差曲线变得很陡峭。Class AB 工作模式下（“AB_1”和“AB_2”），由于 PA 的非线性，输入输出的相位差即使在很小的输入功率下，也不是常数。尤其是在深 Class AB 工作模式下（“AB_2”）：shows an almost linear phase change versus dB drive level up to the compression point (circle indicated), where it starts a more rapid reversal. So here is final twist in the reduced conduction angle PA story, it seems that deep AB operation may cause substantial AM-PM problems in the precompression zone.

PA 中 AM-PM 失真的来源：

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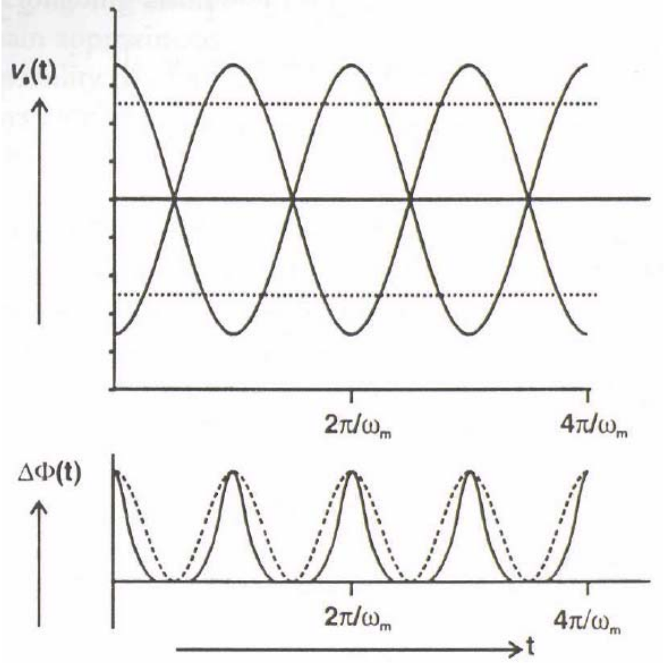
In general, AM-PM effects can be traced to the signal-level dependence of several key transistor model elements. For FETs the input capacitance and both the depletion and junction resistance of the gate-source diode can be primary culprits. It should be noted that nonlinear resistance, in the presence of linear reactance, can cause AM-PM effects, just as much as nonlinear reactance. For BJTs, the nonlinear base-collector capacitance adds an important additional source of drive-dependent phase shift. All of these effects are detailed, interactive, and highly complex in themselves, and pose great challenges for physical modeling, such as that which is more successfully employed for compression and clipping effects. So the only way that AM-PM can be treated in a concise manner is to resort to empirical describing functions fitted to physical measurements.

下图所示为 PA 在变包络信号激励（上图）下的输入输出相位差（下图）：



Even with no attempt to model the precise shape of the phase characteristic a key feature emerges. The phaseshifts which occur at envelope amplitude maxima have twice the fundamental frequency of the double sideband modulation, as indicated by the dashed sinewave.

AM-PM 效应的解析分析：

设 PA 输出信号（DSB AM）为：

$$v_s(t)=\cos(\omega_m t)\cdot\cos\{\omega t+\frac{\phi}{2}[1+\cos(2\omega_m t)]\} \tag{1.1}$$

其中：ω_m 为调制信号（即包络信号）角频率；ω 为载波信号频率（$\therefore \omega>\omega_m$）；

$\Delta\Phi=\frac{\phi}{2}\cdot[1+\cos(2\omega_m\cdot t)]$ 为 AM-PM 相位差（设 $\phi\ll 1$）。

令 AM-PM 相位差 $\Delta\Phi=\frac{\phi}{2}\cdot[1+\cos(2\omega_m\cdot t)]=0$，可解得：$\omega_m t=n\cdot\pi$ (n=0,1,2...)。

所以当 $v_s(t)$ 包络达到正、负峰值时，AM-PM 相位差达到最大值 ϕ。

公式(1.1)可以改写为：

$$v_s(t)=\cos(\omega_m t)\cdot\{\cos(\omega t)\cdot\cos\Psi-\sin(\omega t)\cdot\sin\Psi\} \tag{1.2}$$

其中：$\Psi=\frac{\phi}{2}\cdot[1+\cos(2\omega_m t)]$。因为$\phi\ll 1$，所以可以使用$\cos\Psi\approx 1,\ \sin\Psi\approx\Psi$近似来简化公式(1.2)：

$$\begin{aligned}
v_s(t)&=\cos(\omega_t t)\{\cos\omega t-\frac{\phi}{2}\cdot[1+\cos(2\omega_m t)\cdot\sin(\omega t)]\}\\
&=\cos(\omega_m t)[\cos(\omega t-\frac{\phi}{2})+\frac{\phi}{2}\cdot\cos(2\omega_m t)\cdot\sin(\omega t)]\\
&=\cos(\omega_m t)\{\cos(\omega t-\frac{\phi}{2})+\frac{\phi}{4}\cdot\sin[(\omega+2\omega_m)t]+\frac{\phi}{4}\cdot\sin[(\omega+2\omega_m)t]\}\\
&=\frac{1}{2}\cdot\{\cos[(\omega+\omega_m)t]-\frac{\phi}{2}\}+\frac{1}{2}\cdot\{\cos[(\omega-\omega_m)t]-\frac{\phi}{2}\}\\
&\quad+\frac{\phi}{8}\cdot\{\sin[(\omega+\omega_m)t]+\sin[(\omega+3\omega_m)t]+\sin[(\omega-\omega_m)t]+\sin[(\omega-3\omega_m)t]\}
\end{aligned} \tag{1.3}$$

从公式(1.3)可以看到，AM-PM 失真使得输出信号中产生了与 AM-AM 失真相同频率的三阶交调产物：$\omega\pm 3\omega_m$，其幅度为$\frac{\phi}{8}$。

AM-AM 和 AM-PM 效应引起的三阶交调失真：

统一考虑 AM-AM 和 AM-PM 失真时，PA 输出信号（DSB AM）为：

$$\begin{aligned}
v_s(t)&=[\cos(\omega_m t)+\mu_3\cdot\cos(3\omega_m t)+\mu_5\cdot\cos(5\omega_m t)+\ldots]\\
&\quad\cdot\cos\{\omega t+\frac{\phi}{2}\cdot[1+\cos(2\omega_m t)]\}
\end{aligned} \tag{1.4}$$

在这里，为了分析简便，仅考虑三阶 AM-AM 失真，即：

$$\begin{aligned}
v_s(t)&=[\cos(\omega_m t)+\mu_3\cdot\cos(3\omega_m t)]\\
&\quad\cdot\cos\{\omega t+\frac{\phi}{2}\cdot[1+\cos(2\omega_m t)]\}
\end{aligned} \tag{1.5}$$

将(1.5)式展开，得到：

$$\begin{aligned}
v_s(t)&=\frac{1}{2}\cdot\cos[(\omega+\omega_m)t-\frac{\phi}{2}]+\frac{1}{2}\cdot\cos[(\omega-\omega_m)t-\frac{\phi}{2}]\\
&\quad+\frac{\phi}{8}\cdot\{\sin[(\omega+\omega_m)t]+\sin[(\omega+3\omega_m)t)]+\sin[(\omega-\omega_m)t]+\sin[(\omega-3\omega_m)t]\}\\
&\quad+\frac{\mu_3}{2}\cdot\cos[(\omega+3\omega_m)t-\frac{\phi}{2}]+\frac{\mu_3}{2}\cdot\cos[(\omega-3\omega_m)t-\frac{\phi}{2}]\\
&\quad+\frac{\phi\mu_3}{8}\cdot\{\sin[(\omega-3\omega_m)t]+\sin[(\omega+5\omega_m)t]+\sin[(\omega-3\omega_m)t]+\sin[(\omega-5\omega_m)t]\}
\end{aligned} \tag{1.6}$$

由式(1.6)可以得到输出信号中的三阶交调产物的幅度为：

$$v_{im3} = \frac{\mu_3}{2} \cdot \cos[(\omega \pm 3\omega_m)t - \frac{\phi}{2}] + \frac{\phi}{8} \sin[(\omega \pm 3\omega_m)t] \tag{1.7}$$

This shows the principal components of the third order IM products, with representations from both amplitude and phase distortion mechanisms. Note that under the ongoing assumption of small ϕ, the phase distortion contributions will remain approximately in quadrature with the amplitude ones. So there is no possibility of significant cancellation occurring between the components generated by the two distortion mechanisms. The AM-AM and AM-PM components will always combine to produce IM3 sidebands which have a higher amplitude than either of these individual parts. Experimental measurement of the relative contributions of AM-AM and AM-PM contributions requires the measurement of the relative phase of the IM sidebands, this is not a straightforward work.

Reference

Steve C. Cripps, “*RF Power Amplifiers for Wireless Communications*” 2nd Edition, Artech House, 2006

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