5.2 Simulating memory effects

The Volterra model as introduced earlier is a good tool for recognising distortion mechanisms and memory effects, but it unfortunately has some weaknesses and limitations, because it can be used only for modulation frequency-dependent memory effects. Since it ignores nonlinearities higher than order three, it cannot be used for modelling the modulation amplitude-dependent memory effects introduced in Section 2.4. A 5th order Volterra model would be an excellent tool for both memory effects, but it would be very difficult to calculate, because the number of distortion mechanisms increases rapidly with the order of nonlinearity.

Since an analytical solution for distortion products up to order five lies beyond the scope of the present work, there is no other choice but to simulate the amplifier numerically. The harmonic balance method, which iterates solutions to Kirchhof's Law at the frequencies of the fundamental signals and nonlinear responses, is one solution for that (Kundert & Sangiovanni-Vincenteli 1990). In spite of some severe problems with HB, such as convergence, numerical noise and slowness, this is a very useful tool when used correctly (Microwave Office Users' Manual). Careful judgement should be exercised, for example, with regard to the simulation model used. Most models are inadequate at frequencies that are far away from the fundamental frequency, and therefore it is safe to use a small number of frequencies in simulations. For example, if nonlinearities up to order nine in the 2 GHz amplifier are to be taken into account, the model must be valid up to 18 GHz. Any discontinuity in derivatives or other non-physical phenomena at that frequency will exercise an effect on IM3, and consequently not too many harmonics in HB should be used unless one can be sure that the model works correctly over the entire frequency range (Maas 1991).

5.2.1 Normalization of IM3 components

The drawback of the HB method is that only a resultant of each spectral component can be obtained, and not the contributors to the nonlinearities of different orders, and amplitude sweep is needed to differentiate 5th order effects from IM3, for example. This differentation can be achieved by first simulating the amplifier without memory effects. Such a situation can be obtained by avoiding dynamic temperature variations inside the chip, i.e. by setting the chip temperature to be constant, so that the low frequency thermal memory effects vanish. The electrical memory effects can then be made to disappear by employing a two-tone test with a very narrow tone spacing, because the node impedances for all the spectral components inside the frequency bands become equal. Fifth order effects can now be separated from IM3 as follows:

$$IM3_{NORM} = \frac{IM3 - k \cdot IM5}{A_{IN}^3} \tag{66}$$

This normalization is based on knowledge derived from Section 2.4. 5th order distortion mechanisms do not generate IM5 terms alone but also IM3, and IM5 components caused by 5th order nonlinearities are exactly in-phase with the IM3 ones caused by the same nonlinearities, as long as there is no disturbance from 7th or higher order nonlinearities and no memory. Moreover, the amplitude of IM3 caused by 5th order effects is exactly five times higher than that caused by IM5, which means that the coefficient k in (66) is exactly five. In practice, however, nonlinearities not only generate other distortion products, but also modify the fundamental signals. This gain compression/expansion cannot be neglected at high amplitudes (as was done in the theoretical considerations in Chapter 2), and the factor k can deviate from five. Its correct value can easily be estimated, however, by means of an amplitude sweep with memory effects excluded.

After determining k, the tone spacing of the two-tone signal can be swept and the memory effects in the amplifier can be characterized. Since the phase difference between IM3 and IM5 caused by 5th order nonlinearities is no longer zero, memory effects in the amplifier can be recognized immediately from the normalized IM3, and the same conclusion can be reached when the amplitude ratio between the two changes. The denominator in (66) is employed for clarity, because it would be very difficult to see small deviations in normalized IM3 values if their value increased to the 3rd power of the input amplitude.

This normalization is now applied to the CLY2 common-source FET amplifier introduced in Chapter 3 is extracted up to order five by the S-parameter characterization method presented in Chapter 4. Nonlinearities in circuit elements are modelled by polynomial voltage-controlled current sources (VCCS), corresponding to the principle of Volterra analysis. A two-tone test at centre and modulation frequencies of 1.8 GHz and 1 kHz respectively is applied, and the power of the input signal is swept. The simulated amplitudes of IM3L and IM3H are presented in two ways in Fig. 55, the solid, almost linearly increasing lines representing the curves seen in most textbooks, in which the IM sidebands are presented in dBc as functions of the input or output power. The curves for the lower and upper sidebands are practically equal, and the IM3 terms increase 3 times faster than the fundamental signal. In many cases, however, it is important to know how the sidebands deviate from the 3:1 slope, and thus the dashed line in Fig. 55 represents the normalized curve and it is seen that significant deviations from straight lines (from 3:1) exist for IM3 sidebands on a linear scale. The normalization set out in (66) is now used, and IM3 is presented at a k value of 5. The normalized IM3 value is almost a straight line, which means that significant proportion of the deviations from 3:1 at moderate amplitude levels can be explained by 5th order effects. At very high amplitudes, the normalized IM3 starts to deviate, an effect that can be explained by the 7th and higher order terms and the gain compression caused by them. Normalized IM3L and IM3H are also presented in Fig. 55 at 1MHz tone spacing, and some amplitude-dependent memory is observed at high amplitudes.

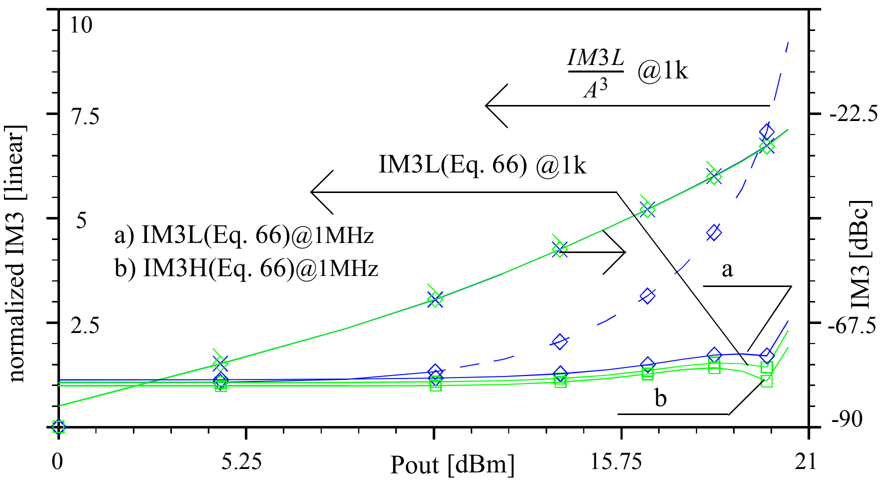

Fig. 55. 3rd order intermodulation products as a function of output power in dBc's and normalized form at 1kHz and 1MHz tone spacings.

5.2.2 2D sweep

The normalized IM3 will now be examined as a function of both modulation frequency and amplitude in order to determine the memory effects in the amplifier. As shown in Fig. 56 and 57, both modulation frequency-dependent and amplitude-dependent memory effects inevitably have a significant impact on distortion performance. Resonance is observed in the IM3 components at a modulation frequency of 500 kHz, as already noted in Chapter 3, and this is highly dependent on amplitude, as seen in Fig. 56. Large phase deviations in the phase of the normalized IM3L, as presented in Fig. 57, are observed at the resonance, and a smooth phase drift of 20 degrees is also detected with increasing signal amplitude. The observed memory effects are extremely harmful to the cancellation performance of most linearization methods. In the predistortion technique, for example, preinverse nonlinearity is needed for optimum cancellation of the distortion components, but as almost all of the predistortion circuits have no desired memory effects, optimal cancellation performance can be achieved only at a constant amplitude and constant tone spacing. This is not very practical in modern telecommunication systems, which use wideband signals with high crest factors.

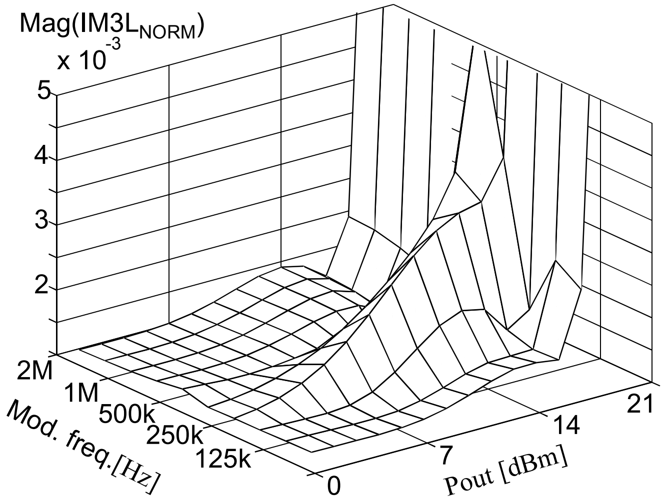

Fig. 56. Magnitude of the normalized IM3L as a function of tone spacing and amplitude.

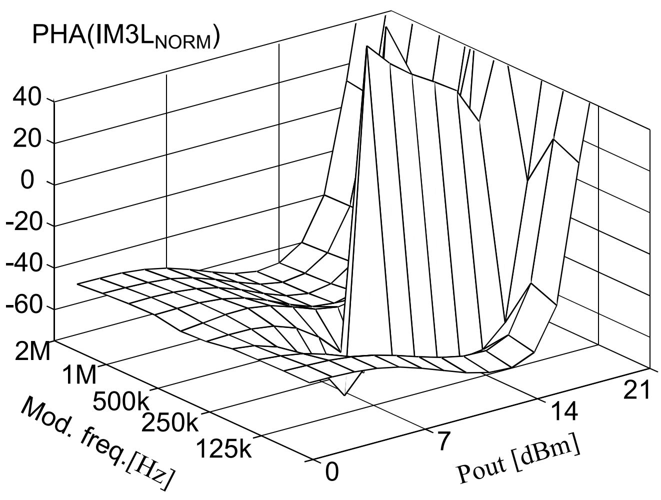

Fig. 57. Phase of the normalized IM3L as a function of tone spacing and amplitude.

There are two approaches to overcoming the problems of memory effects. First, the opposite memory effects can be constructed inside the predistortion circuit, or in a more sophisticated version, adapting linearizers can be used (although these are also more power-consuming), or second, minimization of the memory effects in the PA can be analysed. 3D surfaces give a clear picture of how easily the power amplifier can be linearized. Flat surfaces correspond to optimum linearizability, which means that optimal cancellation can be achieved over the ranges of both amplitude and modulation frequency. In many cases, poor cancellation performance on the part of a predistorter, for example, indicates a poorly designed power amplifier rather than any fault in the linearizer.

5.2.3 Conclusions

The memory effects have to be taken into consideration in linearized power amplifiers. Modulation frequency domain memory effects can easily be calculated analytically by means of a Volterra model, but amplitude domain effects need numerical simulations. Since numerical tools such as HB are only able to show the resultant of each nonlinear response, a normalization technique to is introduced in this Section to differentiate the 5th order effects from the IM3. The dynamic thermal part of the amplifier model is first disconnected, and a two-tone test with a very narrow tone spacing is employed to avoid memory effects. The ratio between the 5th order IM3 and IM5 terms is now characterized by amplitude sweep and the 5th order effects can be differentiated from the IM3 components. Next, the tone spacing and amplitude are swept, and whenever there are memory effects in the amplifier, so that the differentiation is no longer perfect, memory effects in the amplifier can be identified from the normalized value of IM3. This is very advantageous, because the amplitude and modulation frequency at which the memory effects become significant can be seen. Depending on the shapes of the surfaces, a non-flat surface can be detected on the following grounds: first, modulation frequency-dependent memory effects exist, and cancellation cannot be optimum over the whole modulation frequency range, or second, amplitude-dependent memory effects exist, and cancallation cannot be optimum over the whole amplitude range, or at least, when using a predistorter up to order five, for example, cancellation cannot be optimum for both the IM3 and IM5 terms.

5.3 Measuring the memory effects

An analytical Volterra model for calculating IM3 sidebands and memory effects was presented in Chapter 3 and simulation methods for the memory in the previous Section. Since it would nevertheless be interesting to see the memory effects in reality, a new technique for measuring the amplitude and phase of the distortion sidebands is developed in this Section.

Memory effects are rather difficult to measure. Spectrum analysers may be used to measure sideband amplitudes, but they do not provide phase information. Although a system comprising two network analyzers is capable of yielding phase information on the fundamental signals in a two-tone test, as explained by Bösch & Gatti (1989) and Cripps

(2001), the measurements only produce information on the memory effects of this signal, and can be regarded as the modulation frequency dependence of the AM-AM and AM-PM curves. Since the behaviour of IM3 components deviates from that of fundamental signals, this procedure does not provide complete information on the memory effects of the IM components, which is a point of primary interest in terms of linearization.

Some systems for measuring the phase of the harmonics have been developed (Lott 1989) and one for the IM3 relative phase (Suematsu et al. 1997). These are based on a diode that is used as a reference nonlinearity, producing a constant-phase IM3 component over a modulation band. Suematsu et al. (1997) apply a two-tone signal to the DUT and reference nonlinearity, and the output signals are combined. They then try to cancel out this sum of the constant phase reference IM3 and the measured IM3 by tuning the manual attenuators and phase shifters in order to find the phase of the IM3 component at the output. The drawback of the method is that only relative phase information with respect to amplitude can be obtained, the validity of which is dependent on the reference nonlinearity. An ideal 3rd order distorter is needed to avoid errors. Also, no tone-difference sweep was reported by Suematsu et al. (1997), and memory in the reference is liable to cause errors in the results. Finally, tuning of the manual attenuators and phase shifters at any amplitude and tone-difference value is quite a major task.

5.3.1 Test Set-up and Calibration

The system introduced in Fig. 58 can be employed for measuring both the amplitude and phase responses of IM signals in order to characterize the memory effects of the amplifier. The key idea behind the measurements is that a signal at the frequency of the IM3 is applied to the input of the amplifier together with a two-tone signal. By adjusting the amplitude and phase of the IM3 test signal, the output IM3 can be cancelled out. Furthermore, memory effects can be measured by sweeping the tone difference of the two-tone signal over a range of modulation frequencies. The test set-up presented here does not actually measure the IM3 component at the output, but instead it measures the optimum input predistortion signal that creates maximum cancellation of the output. This is a significant advantage, because it allows the measurements to be used directly as required characteristics for predistortion circuits. Since no manual attenuators or phase shifters are used, the measurement system can be designed to be fully automatic as will be seen in Section 5.3.2.

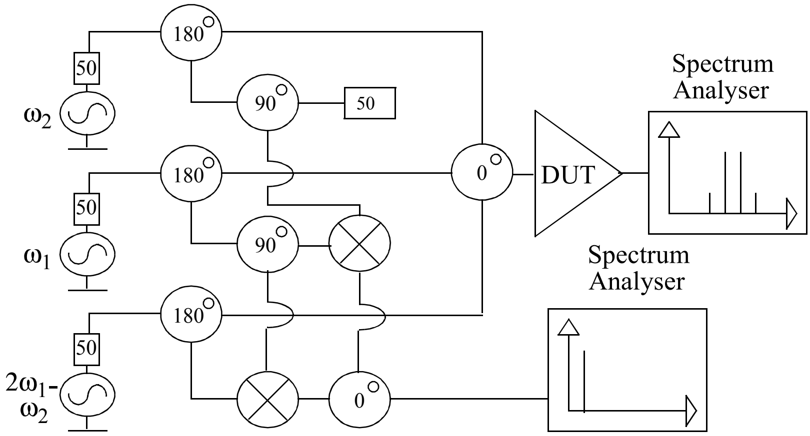

Fig. 58. System for measuring memory effects.

The actual test signal is the sum of ω_1, ω_2 and $2\omega_1$-ω_2, all locked to the same reference, and the rest of the circuit is needed for calibration. The basic idea of calibration is that two down-converted signals are compared in order to detect the phase of the IM3 signal. A two-tone input signal is mixed down to the envelope frequency, along with the lower of the two-tone signal and the IM3L signal. These two are brought to a resistive power combiner, and by adjusting the amplitude and phase of the IM3L signal, the signal at the output of the power combiner is made to vanish. The phase shift of these two equally spaced frequency components is fixed and depends only on the phase shift of the cables and power splitters, which can be easily measured and calibrated. After that, the amplitude and phase of the IM3L signal is adjusted again until the IM3L component at the output of the amplifier disappears. In this way, the phase difference between these two situations in which the signal component vanishes gives the phase of the IM3L component of the amplifier. Calibration of the cables is an important issue in phase measurements, because the electrical length of the cables is a function of the tone difference in the two-tone signal, and this effect has to be taken into account if the maximum modulation frequency is in the MHz range. The low-frequency reference part of the circuit must be calibrated, too, because its electrical length also becomes important in the MHz range.

The amplitude of the IM3L generated by the amplifier is easy to obtain, because the attenuation of the cables and power splitters/combiners can easily be taken into account and no phase comparison or calibration is needed. The IM3H of the amplifier can similarly be measured, either simultaneously or separately. A fourth signal generator for the IM3H can by employed for simultaneous measurement of both the lower and upper IM3 sidebands. The sidebands can be measured independently by changing the IM3L signal generator to the IM3H frequency and by changing the frequencies of the lower and upper two-tone signals.