ECE 4880: RF Systems

Fall 2016

Chapter 7: Architecture to Improve Linearity

Reading Assignments:

1. W. F. Eagan, *Practical RF System Design*, Wiley, 2003, Chap. 6.

Game Plan for Chap. 7: RF splitting and combining for linearity

1. Passive modules borrowed from microwave circuits: Phase shifter, directional coupler, power dividers and combiners.
2. Parallel combining: The role of phase delay
3. Feedforward for distortion cancellation
4. Other possible architectures to improve linearity

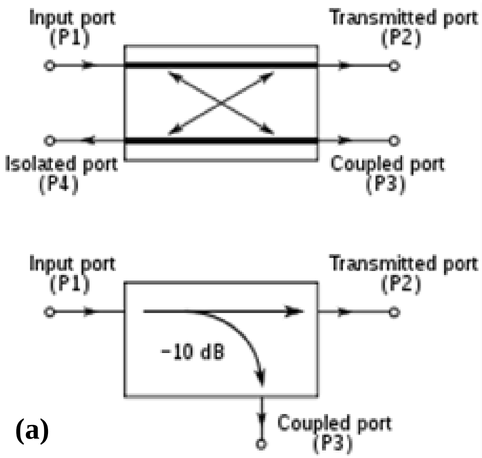
7.1 Passive modules borrowed from microwave circuits: Phase shifter, directional coupler, power dividers and combiners.

RF transceiver design has borrowed several important ideas from conventional microwave circuits, where the component size is comparable to wavelength and phase shift is an integral part of the design. A ready example is the transmission line, and the associated Smith Chart analysis. We will consider these techniques in the transceiver architecture, using microwave components such as phase shifters and directional couplers, useful in signal conditioning and splitting.

Fig. 7.1. Microwave or RF power splitter based on transmission lines.

We will define a ***phase shifter*** as a lossless transmission line. When both input and output are impedance match, the only effect of the transmission line is the phase shift of the traveling wave. This corresponds to the origin in the Smith Chart where line length only changes phase without changing magnitude. We can imagine an RF ***signal splitter*** as well, with half of the signal power splitting to two identical transmission lines (voltage will be just $1/\sqrt{2}$ smaller). At the splitting point, we can make additional structures or lumped element for impedance matching. A commercial RF power splitter is shown in Fig. 7.1, although an integrated circuit version can be done as well. Most passive power splitters by transmission lines are reciprocal, i.e., if you feed two signals to Out1 and Out2, the power will be combined to the In terminal (i.e., they are NOT directional).

Often we would like to split the power unevenly, with the main path as the signal and the side path for feedback or measurements. This is shown in Fig. 7.2a as the microwave ***directional coupler***. There is often negligible loss in the main path (say –0.5dB), and the side path has more than –10dB attenuation. The directivity is defined by the ratio of the side signals when the main signals travel forward and reverse. A common directional coupler will provide up to 45dB further attenuation if the main signal travels in the reverse direction. A commercial component is shown as an example in Fig. 7.2b. In addition to the three required terminals (In and Out as the main path, and Coupled as the side path), one more terminal for "Isolate" or "Iso", which will be connected with a 50Ω resistor to dissipate heat when mismatch or leakage current needs to be dissipated. This is needed as the unit is passive, and no path for dumping excessive or unexpected microwave energy. Iso is also convenient in conventional "screw tuning" and measurements. When the passive component was made, a post-manufacturing tuning can be done by changing an inside plate position (accessible screws outside) that minimizes the power output at "Iso".



(a)

(b)

Fig. 7.2. Microwave/RF directional coupler based on transmission lines: (a) Schematic where P1 ↔ P2 is about –0.5dB and P1 → P3 is about –10dB and P2 → P3 is about –50dB (directional coupling); (b) A commercial sample with dual bands of operations.

Another useful module is the 3dB ***quadrature hybrid coupler***, also called 90° hybrid, which may come with some variations at the termination. As shown in Fig. 7.3a, power can enter at any of the four terminals and will be equally split to the two terminals at the opposite side with 3dB attenuation. The flat-cross terminal will be in phase and the diagonal-cross terminal will have a –90° phase shift (or 90° phase delay).

(a) (b) (c)

Fig. 7.3. 3dB quadrature hybrid coupler (aka 90° hybrid) where both inputs are split equally and sent to the both outputs with in phase horizontally and with a –90° phase shift diagonally: (a) Schematic; (b) A commercial sample with directivity for In and Out; (c) A possible transmission line implementation.

7.2 Parallel combining: The role of phase delay

We will now look at the use of these passive microwave components to better condition the signal amplification with improved linearity. The first method is to combine two (later on 2^N) identical amplifier with carefully designed phase shift for adding the signal in phase and the distortion out of phase. The first example is the parallel amplifier combiner with quadrature hybrid coupler, as shown in Fig. 7.4.

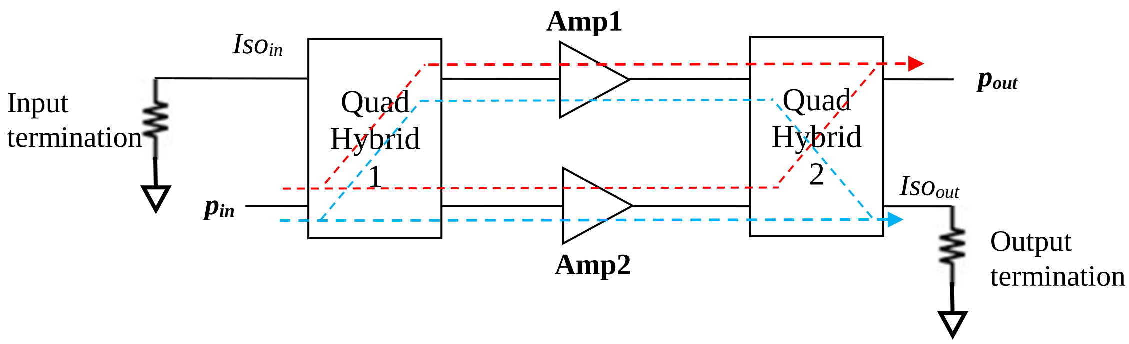


Fig. 7.4. An power amplifier using the 90º hybrid (3dB quadrature hybrid coupler) module to achieve better linearity and impedance match.

1. For path1 where p_{in} reaches p_{out} from Amp1 will have 90º phase shift for the input to Amp1 from Quad Hybrid 1, while path2 where p_{in} reaches p_{out} from Amp2 will also have 90º phase shift after the output of Amp2 from Quad Hybrid 2. Therefore, the amplified p_{in} adds up in phase (coherently) at p_{out}. These two nearly symmetric paths are shown in the red dash lines in Fig. 7.4. Notice we just achieve the **same** overall gain as the individual amplifier, as Quad Hybrid 1 has 3dB attenuation due to splitting and Quad Hybrid 2 has 3dB gain due to combining. However, each amplifier is working at an input and output power that are 3dB lower, respectively. This improves linearity!

2. For p_{in} to reach Iso_{out} , the path through Amp1 has 90º phase shift from both Quad Hybrid 1 and 2, and the path through Amp2 is in phase (0º phase shift). Therefore, on the fundamental frequency, these two paths are 180º out of phase, and will add up to zero in the ideal situation. These paths are shown in the blue dash lines in Fig. 7.4.

3. The hybrid amplifier achieves more for impedance matching. Assume if Amp1 and Amp2 are not matched well to p_{in}. In regular conditions, the signal reflected back will pollute the source (called jitter) and may cause further reflection. Here, if the reflection coefficient from Amp1 and Amp2 is *the same* (even they are not zero due to input impedance mismatch), the reflection caused by p_{in} of Amp1 will have –180º phase shift from that of Amp2, and hence cancelled. The reflection will add in phase in the Iso_{in} terminal and dissipated. The same principle applies to the output impedance as well. Even though the output impedance does not match with the transmission line, as long as Amp1 and Amp2 have the same output impedance, p_{out} will see full gain eventually. Any difference or mismatch will cause a small leakage power in Iso_{out}.

4. Just as in the directional coupler, availability of "Iso" as an external connection in quad hybrid module is useful for two purposes during mismatch and nonideal situations: relief the energy dissipation from module package and an extra terminal for debugging (you do not want to disconnect the main terminals usually!)

5. The hybrid amplifier achieves EVEN more for linearity. First Amp1 and Amp2 combine the output power, and therefore, the individual output power is 3dB further away from the OIP3 (the case in comparison is if all final output power is from one amplifier, v_{in} needs to be 3dB larger), and will thus have 6dB less IM3. We can make further observation of the nonlinear terms from Amp1 and Amp2. Remember that the signal from Amp1 to p_{out} has input with –90º phase shift,

and hence the second harmonic output will shift –180° and the third harmonic –270°. The signal from Amp2 to p_{out} has output with –90° phase shift, and hence both second and third harmonic output will shift –90°. The fundamental signals add up in phase as previously analyzed. H2 adds up in quadrature and will be $1/\sqrt{2}$ lower in power. H3 is entirely cancelled!!!

6. For intermodulation, IM2 has $1/\sqrt{2}$ lower in power. IM3 components of $2f_a + f_b$ and $f_a + 2f_b$ are cancelled. $2f_a – f_b$ and $2f_b – f_a$ will add up in phase unfortunately, although we still have the original –6dB reduction from the lower output in each amplifier.

7. We can repeat this module to achieve even better linearity. An example of combining 8 amplifiers to achieve 9dB reduction in amplifier v_{in} and v_{out} is shown in Fig. 7.5. This will have an effective reduction in IM3 by 18dB!!!

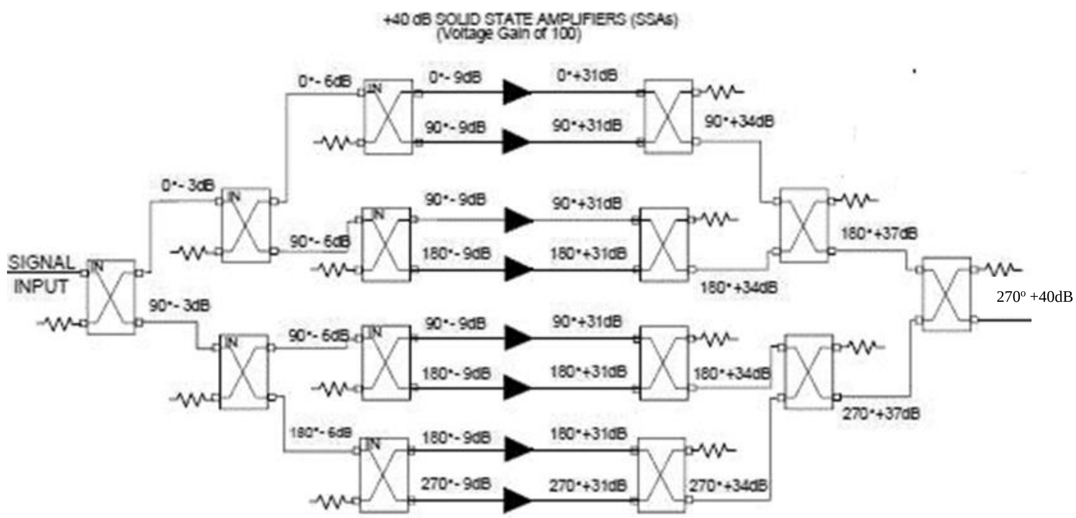


Fig. 7.5. Combiner for 8 amplifiers using the quadradure hybrid coupler.

8. With the idea of phase shift and smart combination of amplifiers, we can better cascade amplifiers to achieve higher total p_{out} as well. The level of usable p_{out} is originally limited by linearity when p_{out} is close to OIP3, but now this constraint is much more relaxed with power combiners.

9. After understanding the advantages of quadrature phase shift, we can reflect on our use of *I* (in-phase) and *Q* (quadrature) for the mixer design better. The phase shift in the mixer is NOT by the transmission line coupler, but by the phase shift in frequency generation to be applied to the mixer. Surely, generation of *I* and *Q* can still be done by feeding the LO signal to the quad hybrid, instead of relying on internal *Q* generation. In addition to the better coverage in amplitude and phase modulation (aka q-ary modulation) by using *I* and *Q*, we can also see the advantage of splitting the same signal paths but keeping 90° phase shift!

10. We should reflect that quad hybrid is more than just the power splitter and combiners (then we can use the power splitter in Fig. 7.1), as the magnitude splitting and combining are just part of the advantages. The quadrature shift also provides the impedance match and H3 cancellation that are not possible with considering phase.

Exercise: For the 180° hybrid coupler shown in Fig. 7.6, v_a is split to v_c and v_d both in phase with 3dB attenuation, and v_b is split to v_d in phase, but to v_c with 180° phase shift as indicated by the only arrow in the block. Analyze p_{out} , Iso_{in} and Iso_{out} at the fundamental frequencies, harmonics and intermodulation.

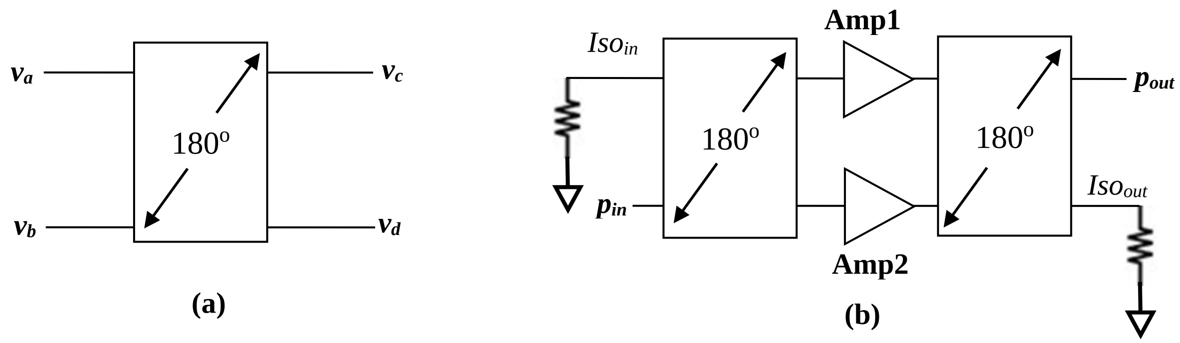


Fig. 7.6. An amplifier using the 180° hybrid coupler module.

Ans: for the fundamental frequency, the two paths to p_{out} will add up in phase, and will cancel at Iso_{out} with 180° out of phase. If there is any impedance mismatch, however, some power will be subtracted from p_{out} to Iso_{out}.

7.3 Feedforward distortion cancellation

Another way to improve linearity of an amplifier is through feedforward cancellation. The basic idea is to estimate the IM3 or jamming distortion (cannot be filtered) out of an amplifier, shifted 180° and cancel the distortion through a RF combiner. A small inconvenience exists. We have prior knowledge of the input signal, *not* the distortion to be subtracted. Therefore, we need to first produce a copy of the distortion from another subtraction to evaluate the distortion. The block diagram for this feedforward distortion cancellation is shown in Fig. 7.7.

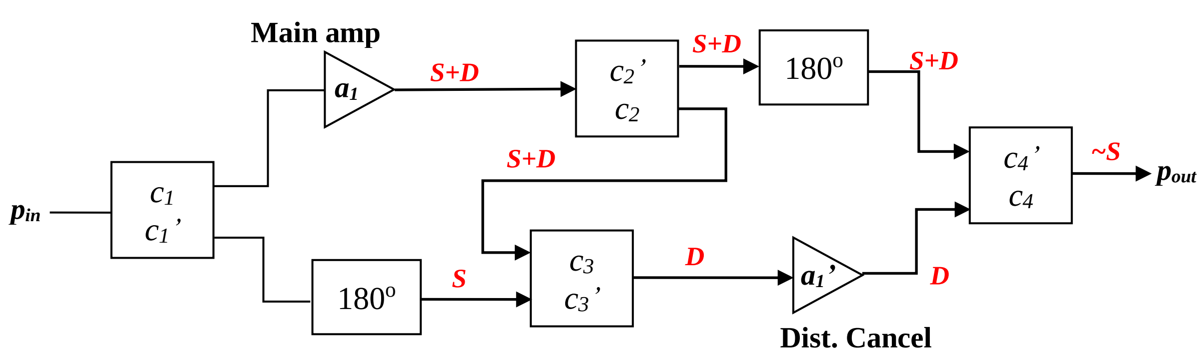


Fig. 7.7. Signal diagram for feedthrough distortion cancellation.

To achieve the purpose of distortion cancellation, two equality conditions are needed:

Main path: $c_1a_1c_2'c_4'$ = Distortion eval path: $c_1a_1c_2c_3a_1'c_4$

Distortion sample path: $c_1a_1c_2c_3$ = Signal eval path: $c_1'c_3'$

That is, for p_{out} to have no distortion of the main amplifier a_1 (but now the distortion from a_1' distortion cancellation amplifier is unavoidable, so that should be designed with less gain and less nonlinearity):

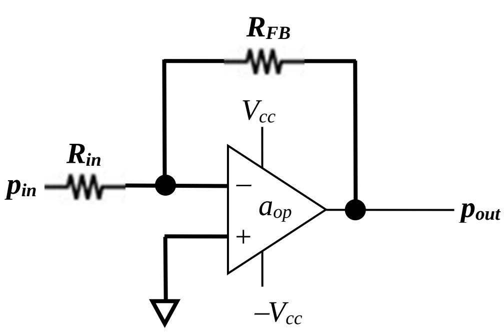
$$\begin{aligned} c_2'c_4' &= c_2c_3a_1'c_4 \\ c_1a_1c_2c_3 &= c_1'c_3' \end{aligned} \tag{7.1}$$

Notice that if the directional coupler is built by passive LC elements with minimal noises, $c_i + c_i' = 1$, for $i = 1 - 4$. Also, to keep the main path gain to be as much as possible (the initial purpose): $c_1 \cong c_2' \cong c_4' \cong 1$. Therefore, the real choices are c_3 and a_1'. We also need to make sure the subsidiary distortion cancellation amplifier a_1' will have minimum distortion (as all a_1' distortion elements will go to p_{out}). Often we design the blocks so that the distortion after c_3 coupler is much smaller (or much further away from IIP3 of a_1') than the input of a_1.

The feedforward technique can be generalized to other measure-and-compensate purposes. Although the block diagram looks a bit complicated, it is one of the popular design features in many practical systems where components can deviate significantly from their ideal specification.

7.3 Other possible architectures to improve linearity

A classical way to improve linearity of an active module is by feedback with passive elements, although this often has more stringent frequency requirements. An example can be seen from the OP AMP designs you have learned in basic circuit courses in Fig. 7.8.



When $a_{op} \to \infty$ and $R_{out} \to \infty$, gain $\cong \dfrac{R_{FB}}{R_{in}}$

Fig. 7.8. OP AMP with feedback to enhance linearity by using the passive elements.

In addition to the stringent frequency requirement (feedback loop delay is negligible), there are many other problems in this OP-AMP topology:

1. Although LC resonators can be integrated into the OP AMP, the loop delay caused by the large Miller capacitance (as the OP AMP has huge gain) will still limit the frequency range severely.

2. Huge distortion (aka nonlinearity) when output voltage is close to V_{cc} or $-V_{cc}$ of the OP AMP! Even many OP AMPs have V_{cc} from 10 – 24V, this is still just 30 dBm to 38 dBm of p_{out} on a 50Ω output resistance.

3. The linear gain depends on the output load has much larger resistance than R_{FB} so that the gain is not heavily dragged down. However, R_{out} is mostly around 50Ω, which makes R_{FB} and R_{in} to be very small and hence leaky. We will either need a matching network or other circuit blocks to stabilize the linear gain.

4. The power consumption at V_{cc} and $-V_{cc}$, and the leakage through R_{FB} and R_{in} can be serious, and the power efficiency is often very low without other resonance network.

However, this topology is meaningful to introduce the possible feedback uses (and feedback is one of the most important concepts in engineering to keep stability). So, it is “well known”, and we can let those people working in AM/FM bands, or students who have not taken our class, continue using this topology. Oh yes, I have been sarcastic here.