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Baseband I/Q Trace Mismatch Degrades Sideband Suppression of RF I/Q Modulation

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ABSTRACT

The trace mismatches between DACs and RF modulators, including I and Q paths, differential line I_P and I_N, and differential line Q_P and Q_N, cause I/Q amplitude and phase errors and result in the sideband suppression (SBS) degradation in the RF modulation. This work investigated effects of these trace mismatches to the amplitude and phase errors and to the RF modulator SBS for providing a guideline in designing the interface between DAC and RF modulator and in the PCB layout.

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1 Effects of I/Q Amplitude and Phase Errors to Sideband Suppression

In the most of applications, the Digital to Analog Converter (DAC) usually provides the baseband I/Q signals directly to RF modulators. Figure 1 shows TI's DAC348x interfaces directly with TRF3705 modulator and two low-pass filters (LPFs) along I and Q paths are used to reject the DAC sampling images.

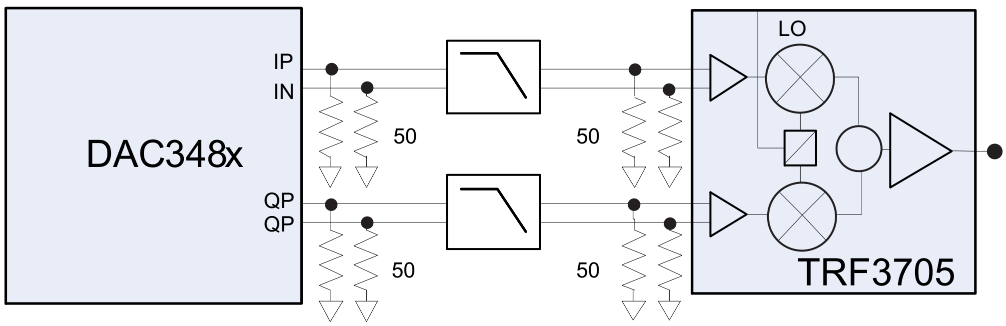


Figure 1. DAC348x Interface with the TRF3705 Modulator

The baseband inputs are comprised of the in-phase signal (I) and the Quadrature-phase signal (Q). The I and Q lines are differential lines. The RF modulator exhibits symmetry with respect to the quadrature input paths. It is recommended that the PCB layout maintain that symmetry in order to ensure that the quadrature balance of the device is not impaired. This symmetry includes the symmetry between I and Q, between I_P and I_N, and between Q_P and Q_N. The traces between I_P and I_N, and between Q_P and Q_N should be routed as differential pairs and their lengths are all kept equal. This symmetry requirement should also be applied to I and Q LPFs.

In reality, there will always be some mismatches between I and Q, between I_P and I_N, and between Q_P and Q_N. These mismatches cause I/Q phase and amplitude errors, which will result in the sideband suppression degradation at RF modulator's output. Typically the mismatches should be kept small enough so that the unadjusted SBS is less than –40 dBc.

The relationship between I/Q mismatches and the sideband rejection can be described as

$$SBS(dBc) = 10 \log_{10} \frac{1 + A^2 - 2A\cos\theta}{1 + A^2 + 2A\cos\theta} \tag{1}$$

where A is the voltage ratio of I amplitude to Q amplitude, and θ is the phase difference between I and Q. Figure 2 shows the SBS versus amplitude and phase mismatches. As shown in Figure 2, without amplitude mismatch (that is, A = 0 dB), θ must be less than 1.146° to achieve a SBS of better than –40 dBc and 0.36° for –50 dBc, which reveals that the SBS is very sensitive to the I/Q phase error.

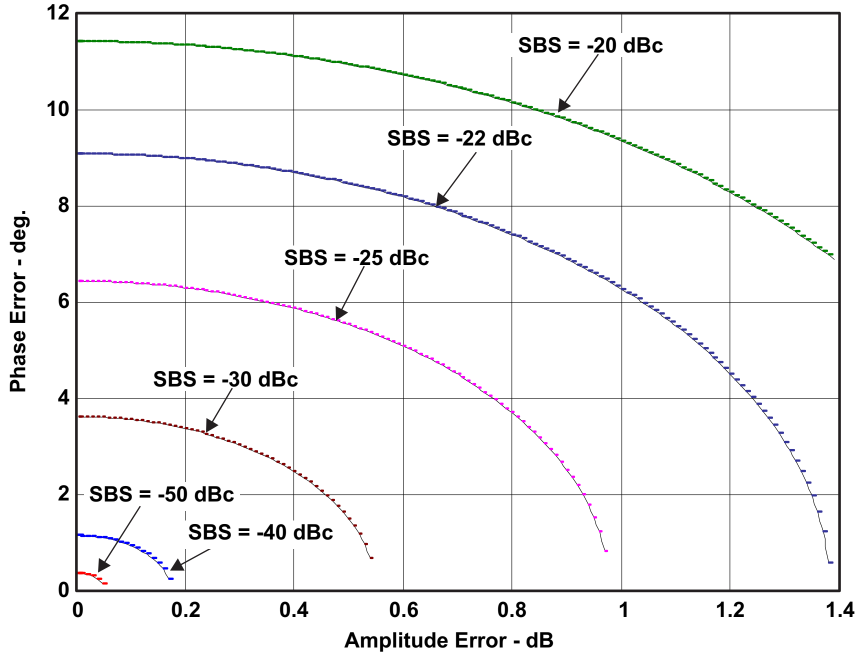


Figure 2. SBS vs I/Q Amplitude and Phase Mismatches for I/Q Modulator

2 Trace Mismatches between I and Q Channels

In this section, we will analyze the effect of the trace mismatch between I and Q channels on the SBS. Let us design a coupled microstrip line as the 100-Ω differential line on FR-4 material PCB as shown in Figure 3. The I/Q trace length mismatch causes no amplitude mismatch but only some phase mismatch. We have the phase error expressed as

$$\theta = \beta \Delta L = \frac{2\pi}{\lambda g} \Delta L = \frac{2\pi \ f_{BB}\sqrt{\varepsilon_e}}{C} \Delta L \qquad (2)$$

where ΔL is the trace length mismatch between I (I_P and I_N have the same length) and Q (Q_P and Q_N have the same length), f_{BB} the baseband signal frequency, λ_g the differential line wavelength at f_{BB}, C the light speed in the free space, and ε_e the effective dielectric constant of the coupled-microstrip line. Using Linecalc of Agilent's ADS, ε_e is calculated as 2.341.

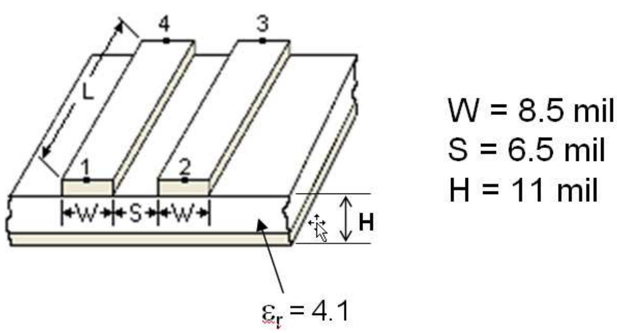
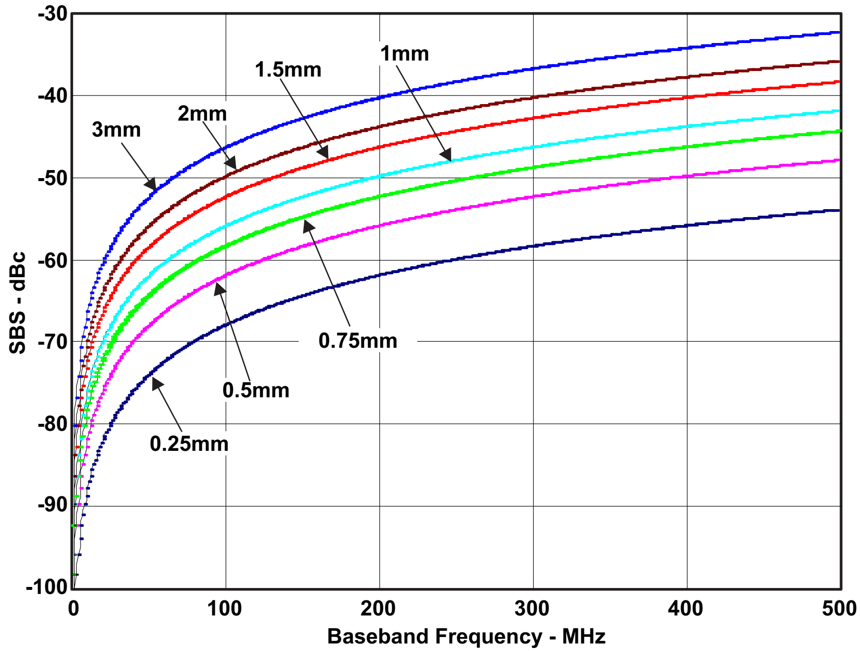


Figure 3. Coupled Microstrip Line as Differential Line for I and Q Signals

Substituting Equation 2 into Equation 1, we plot the relationship between SBS at the RF output and the baseband I/Q trace mismatch in Figure 4.



NOTE: Effective dielectric constant of 2.341 was used for the differential line in the calculation.

Figure 4. SBS vs. I/Q Trace Length Mismatch

If the unadjusted SBS at the RF modulator needs to be kept below –40 dBc for the baseband frequency at 300 MHz, the trace mismatch between I and Q paths should be less than 2 mm (78 mils).

3 Trace Mismatches between I_P and I_N and between Q_P and Q_N

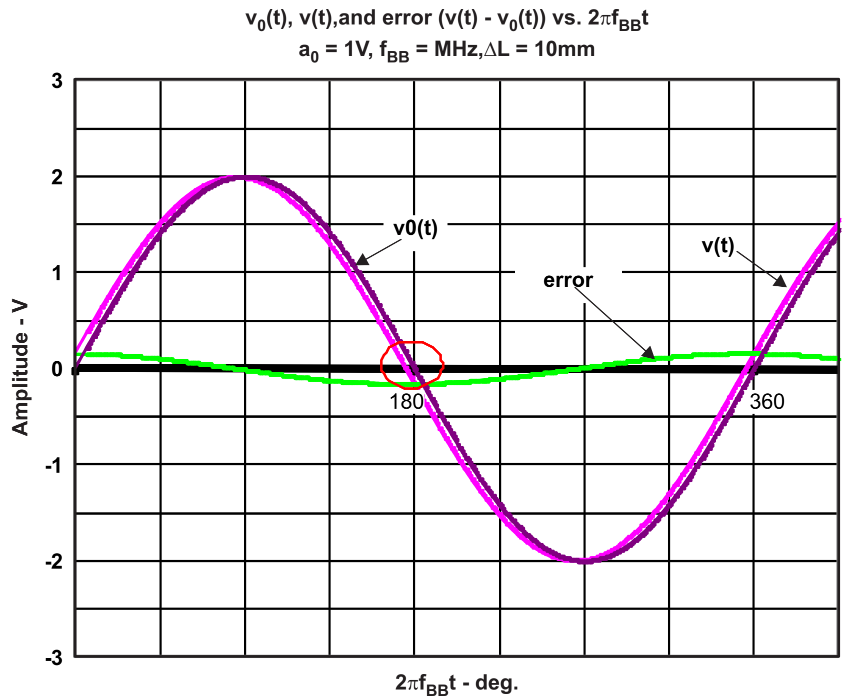
If the trace length for I_N or Q_N is ΔL longer, than the trace length for I_P or Q_N, it causes both amplitude and phase error. The ideal differential signal, $v_0(t)$, and distorted differential signal, v(t) and the error, Δv(t), could be expressed as:

$$v_0(t) = v_{P0}(t) - v_{N0}(t) = a_0\sin\left(2\pi f_{BB}t\right) - a_0\sin\left(2\pi f_{BB}t + \pi\right) = 2a_0\sin\left(2\pi f_{BB}t\right) \tag{3}$$

$$\begin{aligned} v(t) &= v_{P0}(t) - v_N(t) = a_0\sin\left(2\pi f_{BB}t\right) - a_0\sin\left(2\pi f_{BB}t + \pi - \beta\Delta L\right) \\ &= 2a_0\cos\left(\frac{\beta \times \Delta L}{2}\right)\sin\left(2\pi f_{BB}t + \frac{\beta\Delta L}{2}\right) \end{aligned} \tag{4}$$

$$\Delta v(t) = v(t) - v_0(t) \tag{5}$$

where $v_{P0}(t)$ and $v_{N0}(t)$ are the ideal differential signals, and $v_N(t)$ is the signal for I_N or Q_N with ΔL trace mismatch. Figure 5 shows that amplitude and phase errors are produced by the differential line trace mismatch. The phase error is the difference at the zero crossing between the ideal signal, $v_0(t)$, and the distorted signal, v(t).



NOTE: Effective dielectric constant of 2.341 was used for the differential line in the calculation.

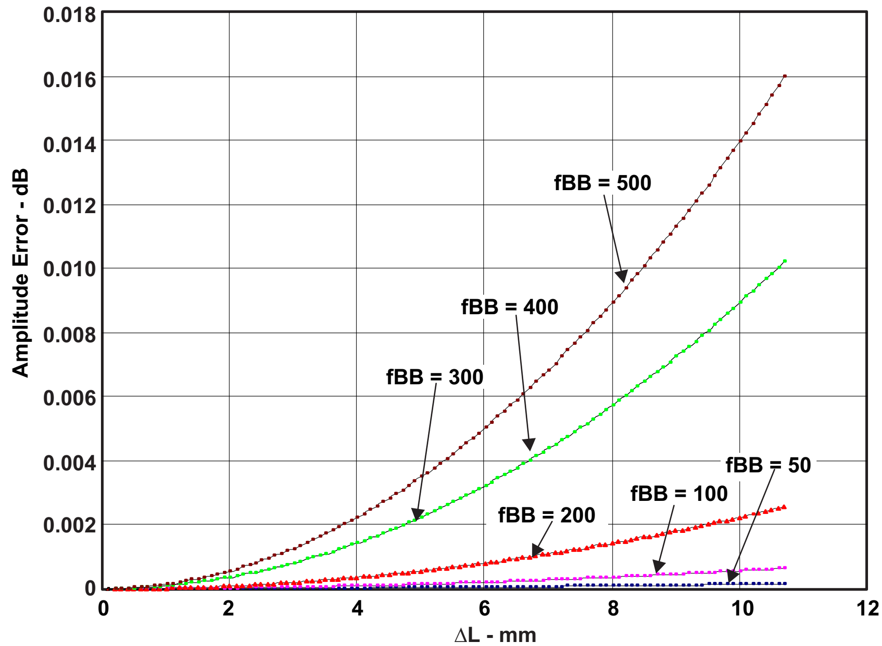
Figure 5. Amplitudes of the Ideal and Distorted Differential Signals and the Error Signal

Base on Equation 4 and Equation 5, the useer can write the amplitude and phase errors due to the differential line trace mismatch into the following equations:

$$A = -10\log_{10}\left(\cos\left(\frac{\beta \times \Delta L}{2}\right)\right) \tag{6}$$

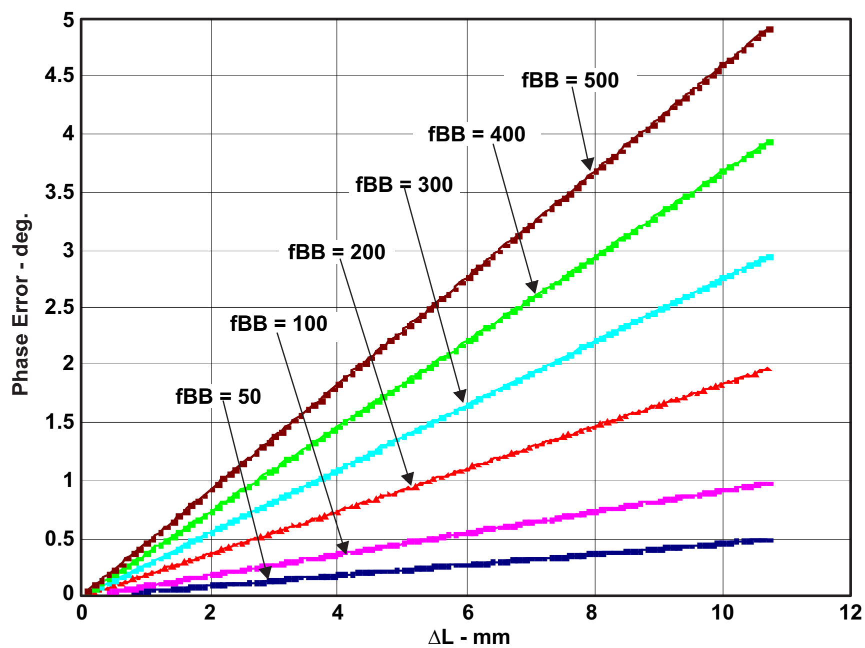
$$\theta = \frac{\beta \Delta L}{2} \tag{7}$$

Figure 6 and Figure 7 are the plots for amplitude and phase with different baseband Frequency. A trace mismatch of 1 mm (39 mils) at the baseband frequency of 500 MHz results in a phase error of 0.459 degree and an amplitude error of 0.00014 dB. According to Figure 2, this phase error is dominant in degrading the SBS due to the differential trace mismatch. Once the amplitude and phase errors are known, one should find the SBS degradation caused by the differential trace mismatch using Figure 2.



NOTE: Effective dielectric constant of 2.341 was used for the differential line in the calculation

Figure 6. Amplitude Error due to Differential Trace Mismatch at Different Baseband Frequency



NOTE: Effective dielectric constant of 2.341 was used for the differential line in the calculation

Figure 7. Phase Error due to Differential Trace Mismatch at Different Baseband Frequency

According to Figure 2, if the unadjusted SBS at the RF modulator needs to be kept below –40 dBc, the I/Q phase should be less than 1.146°. This demands the difference line trace mismatch to be less than 4 mm (156 mils) for the baseband frequency at 300 MHz.

Comparing Equation 2 and Equation 7, the user can determine that the same trace mismatch between I and Q paths causes twice the I/Q phase error as the differential line trace mismatch does between the I_P and I_N or between Q_P and Q_N.

4 Experiment

4.1 *Case 1: Trace mismatch between the differential line IP and IN*

This case is to experimentally prove the results in Section 3. The setup in Figure 8 has an adaptor with 0.773° phase length at the baseband frequency 20 MHz inserted into the IP path. The measured SBS was –49.55 dBc.

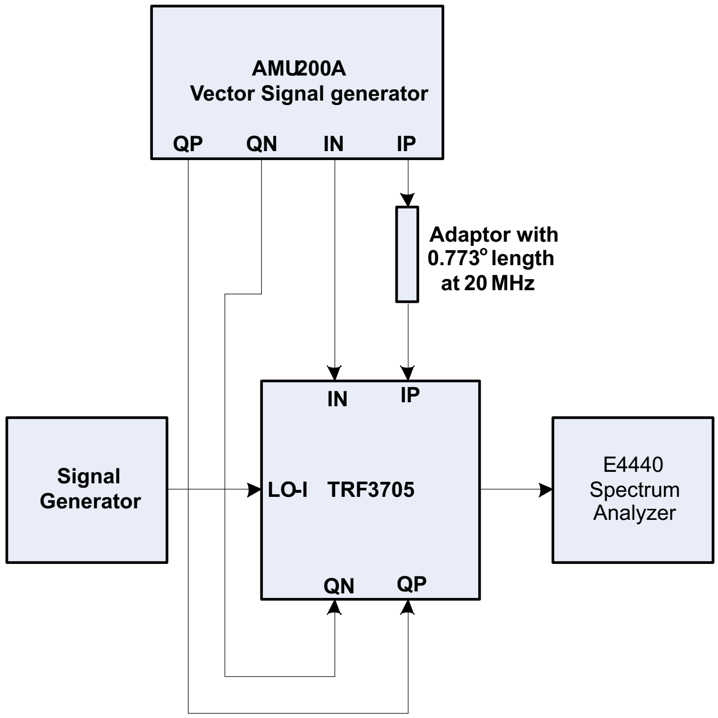


Figure 8. Set-up for Emulating Differential Line Trace Mismatch with Insertion of 0.773° Line Length in IP Path, IF Frequency = 20 MHz.

4.2 *Case 2: Trace mismatch between I and Q*

This case is to experimentally prove the results in Section 2. The setup in Figure 9 has an adaptor with 0.773° phase length at the baseband frequency 20 MHz inserted into both IP and IN paths. The measured SBS was –43.4 dBc, about 6 dB worse from the SBS in Case 1. This is corresponding to a phase mismatch of 0.773°/2 = 0.3865°.

Note that the measured SBS of –43.4 dB is very closed to calculated –43.42 dB SBS for a phase mismatch of 0.773°.

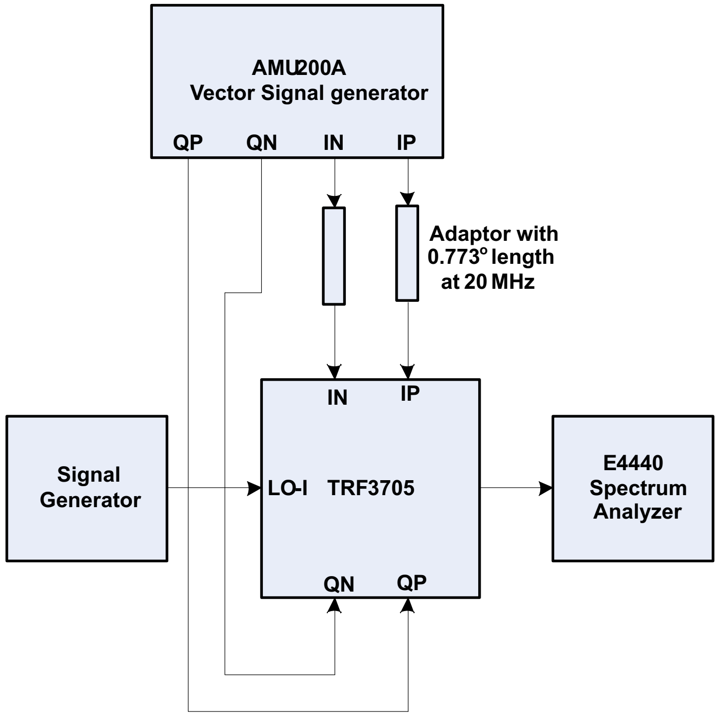


Figure 9. Set-up for Emulating I/Q Trace Mismatch with Insertion of 0.773° Line Length in IP and IN Paths, IF Frequency = 20 MHz

5 Conclusion

This work investigated effects of I/Q trace mismatches to the amplitude and phase errors and to the RF modulator SBS. The results provides the trace mismatch tolerance for designing the interface between DAC and RF modulator and in the PCB layout in order to meet the modulation SBS specification. Multiple graphics provided these relationships for easy reference. Below are a few highlights:

- The trace mismatch between I and Q paths causes only the I/Q phase error.
- The trace mismatch between the differential line I_P and I_N or between Q_P and Q_N. caused both amplitude and phase errors, but the phase error is dominant in degrading the SBS performance in RF modulation.
- The same trace mismatch between I and Q paths causes twice the I/Q phase error as the differential line trace mismatch does between I_P and I_N or between Q_P and Q_N.

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