Texas Instruments

Application Report
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Understanding CW Mode for Ultrasound AFE Devices

ABSTRACT

Ultrasound imaging is one of the most common medical imaging modalities in use today due to its safety and cost-effectiveness. There are numerous ultrasound image modes like A-mode, B-mode, Doppler ultrasound, and other variations. As opposed to A-mode and B-mode ultrasound, continuous wave (CW) Doppler ultrasound helps to identify not just the location of tissue but also the motion of fluids and organs within the body. Using the Doppler effect—where the frequency observed by a receiver changes based on the motion of the transmitter—the direction and velocity of body fluids can be determined from the CW I and Q outputs of Texas Instruments' AFE58xxxx devices.

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1 Introduction

The CW signal path of Texas Instruments™ AFE58xxxx devices consist of a low-noise amplifier (LNA), a voltage-to-current converter, two passive mixers (per channel), a pattern generator, a crosspoint switch, and shared summing amplifiers (with low pass filters), shown in Figure 1.

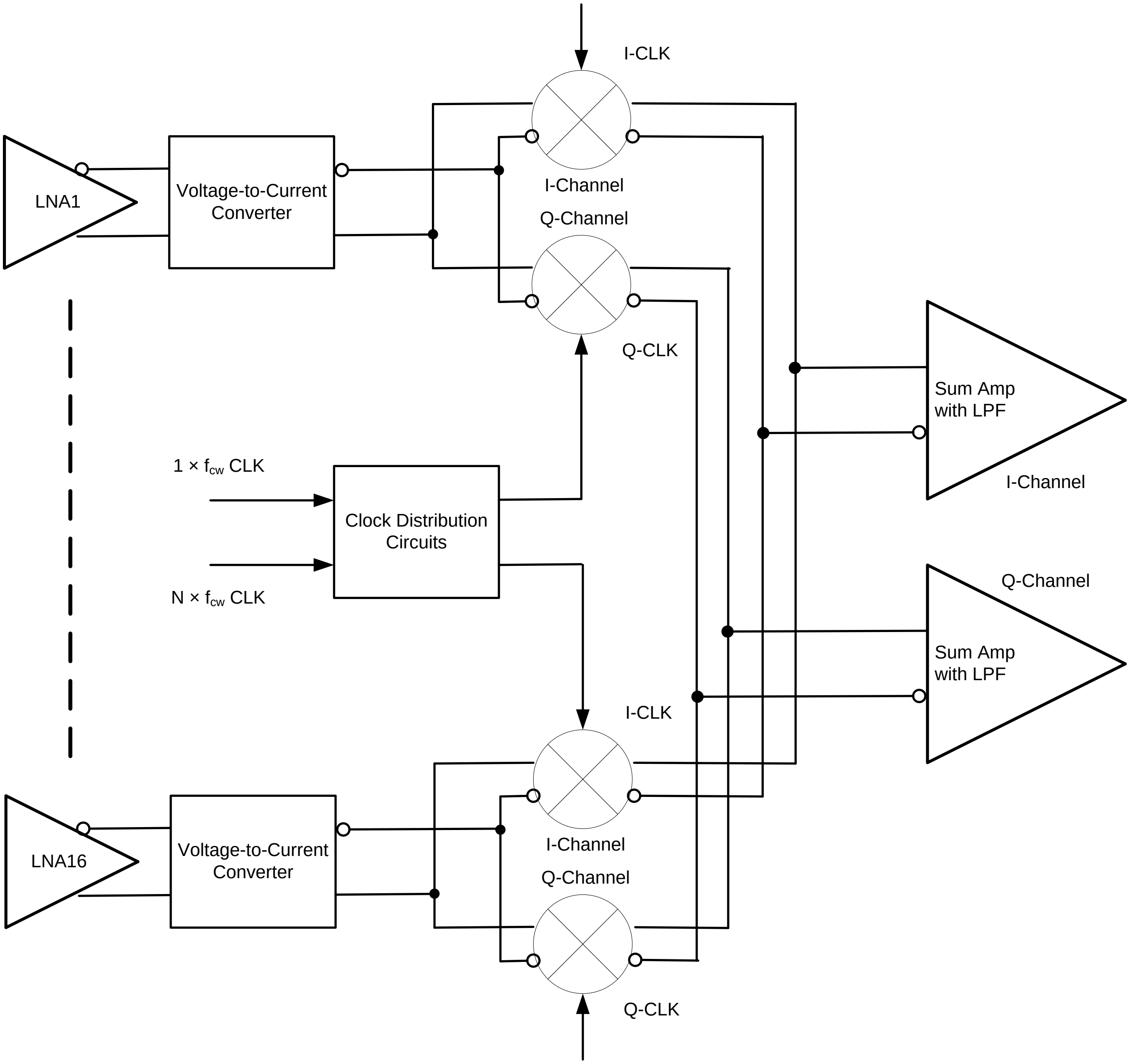

Figure 1. CW Topology in the AFE58xxx8

At a high level, the input signal is amplified by the LNA, converted to current by the voltage-to-current converter, then mixed with a local oscillator (LO) clock signal to capture the frequency difference introduced by the Doppler effect. The current outputs of all sixteen channels are then summed together and converted into an output voltage by the summing amplifier.

The data sheet for the AFE58xxx8 provides more detail on the makeup of the various components in the CW portion of the device, but these specifics are beyond the scope of this report. Instead, this report focuses on detailing the CW mixers, clock phase generation, and the expected outputs of the I and Q channels.

2 Background and Theory

2.1 CW Frequency Mixers

The 16 CW channels of the AFE58JD18 device each contain two frequency mixers. For a single channel, these two mixers help extract the frequency difference information for the in-phase and quadrature signal processing paths.

The CW frequency mixers are passive and switch based with a square wave as the local oscillator (LO) signal. The AFE58xxx8 devices also include a proprietary harmonic suppression circuit to eliminate the effects of the largest odd harmonics (third and fifth) from the square wave (from Fourier analysis, a square wave consists only of odd harmonics), approximating the operation of the square wave mixer to a single sine wave mixer.

Assuming that the received voltage signal is a cosine wave reflected off of body tissue and fluid in motion, after amplification it is converted to current and sent to the I and Q mixers (shown in Figure 1). The output of a frequency mixer, $V_0(t)$ is the multiplication of its two input signals: the LO signal, $L_O(t)$, and the received cosine wave, $V_{IN}(t)$. See Equation 1.

$$V_{IN}(t) = A \times \cos(\omega_{in} t + \varphi) \tag{1}$$

The LO signal is a cosine wave at the original transmit frequency of ω_0 for the in-phase or I-channel, and a sine wave for the quadrature phase or Q-channel of the mixer.

$$\begin{aligned} LO_I(t) &= B \times \cos(\omega_{LO} t + \gamma) \\ LO_Q(t) &= B \times \sin(\omega_{LO} t + \gamma) \\ V_{0I}(t) &= V_{IN}(t) \times LO_I(t) = A \times B \times \cos(\omega_{in} t + \varphi) \times \cos(\omega_{LO} t + \gamma) \end{aligned} \tag{2}$$

From the trigonometric identity where:

$$\begin{aligned} &\cos(x) \times \cos(y) = 0.5 \times \left[\cos(y - x) + \cos(y + x)\right] \\ &V_{0I} = \left(A \times \frac{B}{2}\right) \times \left[\cos(\omega_{LO} t + \gamma - \omega_{in} t - \varphi) + \cos(\omega_{LO} t + \omega_{in} t + \varphi + \gamma)\right] \\ &= 0.5 \times A \times B \left[\cos((\omega_{LO} - \omega_{in})t - \varphi + \gamma) + \cos((\omega_{LO} + \omega_{in})t + \varphi + \gamma)\right] \end{aligned} \tag{3}$$

Assuming $\omega_{in} t = \omega_0 t + \omega_{doppler} t$, then $\omega_0 t = \omega_{LO} t$ is the frequency of the transmitted signal.

$$V_{0I} = 0.5 \times A \times B \times \left[\cos(-\omega_{doppler} t - \varphi + \gamma) + \cos(2\omega_0 t + \omega_{doppler} t + \varphi + \gamma)\right] \tag{4}$$

With the low pass filter at the summing amplifier removing the higher frequency $2\omega_0$ term, the frequency difference introduced by the Doppler effect, $\omega_{doppler}$ can be extracted from the cosine term and subsequently, the speed of the moving tissue/fluid. Note cos(−x) = cos(x).

While the I-channel information by itself is enough to decipher the speed of tissue, the direction of motion cannot be obtained from just the cosine. For the Q-channel (see Equation 5):

$$V_{0Q}(t) = V_{IN}(t) \times LO_Q(t) = A \times B \times \cos(\omega_{in} t + \varphi) \times \sin(\omega_{LO} t + \gamma) \tag{5}$$

From the trigonometric identity, where:

$$\begin{aligned} &\sin(y) \times \cos(x) = 0.5 \times \left[\sin(y - x) + \sin(y + x)\right] \\ &V_{0Q} = \left(A \times \frac{B}{2}\right) \times \left[\sin(\omega_{LO} t + \gamma - \omega_{in} t - \varphi) + \sin(\omega_{LO} t + \omega_{in} t + \varphi + \gamma)\right] \\ &= 0.5 \times A \times B \times \left[\sin((\omega_{LO} - \omega_{in})t - \varphi + \gamma) + \sin((\omega_{LO} + \omega_{in})t + \varphi + \gamma)\right] \end{aligned} \tag{6}$$

Assuming $\omega_{in} t = \omega_0 t + \omega_{doppler} t$, $\omega_0 t = \omega_{LO} t$:

$$V_{0Q} = 0.5 \times A \times B \times \left[\sin(-\omega_{doppler} t - \varphi + \gamma) + \sin(2\omega_0 t + \omega_{doppler} t + \varphi + \gamma)\right] \tag{7}$$

Unlike the low frequency cosine term for the I-channel, the polarity of the low-frequency sine component of the Q-channel changes depending on whether it is a positive or negative frequency. If the Doppler-shifted frequency of V_I is higher than the frequency of LO (as opposed to lower for a positive sine frequency term), the low frequency sine term represents the sine of a negative frequency and the output phase of the Q-channel changes by 180° (see Equation 8).

$$\sin(-x) = -\sin(x) = \sin(x + 180°) \tag{8}$$

In other words, the Q-channel indicates whether the Doppler frequency shift is due to fluids moving towards or away from the receiving element (information on direction in addition to speed).

2.2 CW Clock Phase Generation

To accurately extract the frequency difference information at the output of the mixers, 16 equally-spaced phases (and 16 possible values for γ) of the input 1X clock are generated to closely match up with corresponding phases of the received signal. These 1X clocks with different phases are then assigned to any of the 16 channels using the SPI-controlled cross-point switch (see Figure 2).

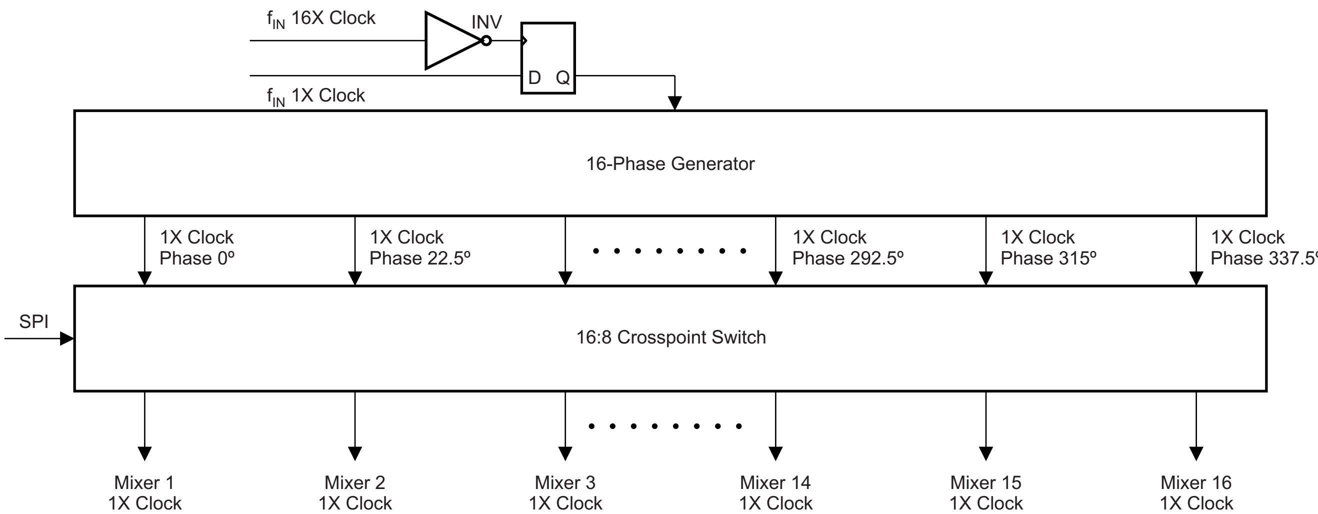

Figure 2. Phase Generation for 16× Clock Mode

The AFE58xxx8 devices have up to three different ways to generate the 16 phases required for CW beam forming:

- With a 16X clock
- With an 8X or 4X clock
- With a 1X clock

When generating 16 equal phases in 22.5° increments (360° / 16) using the 16X clock method, the 1X clock is setup as the input to a positive-edge triggered D flip-flop with an inverted 16X clock as the clock source for the flip-flop. Therefore, the output of the flip-flop changes on the negative edge of the 16X clock.

The 1X clock with the desired phase delay (γ) is output on the next 16X positive clock edge because of the required minimum hold time (time required to keep the flip-flop input steady for the output to be valid). See Figure 3.

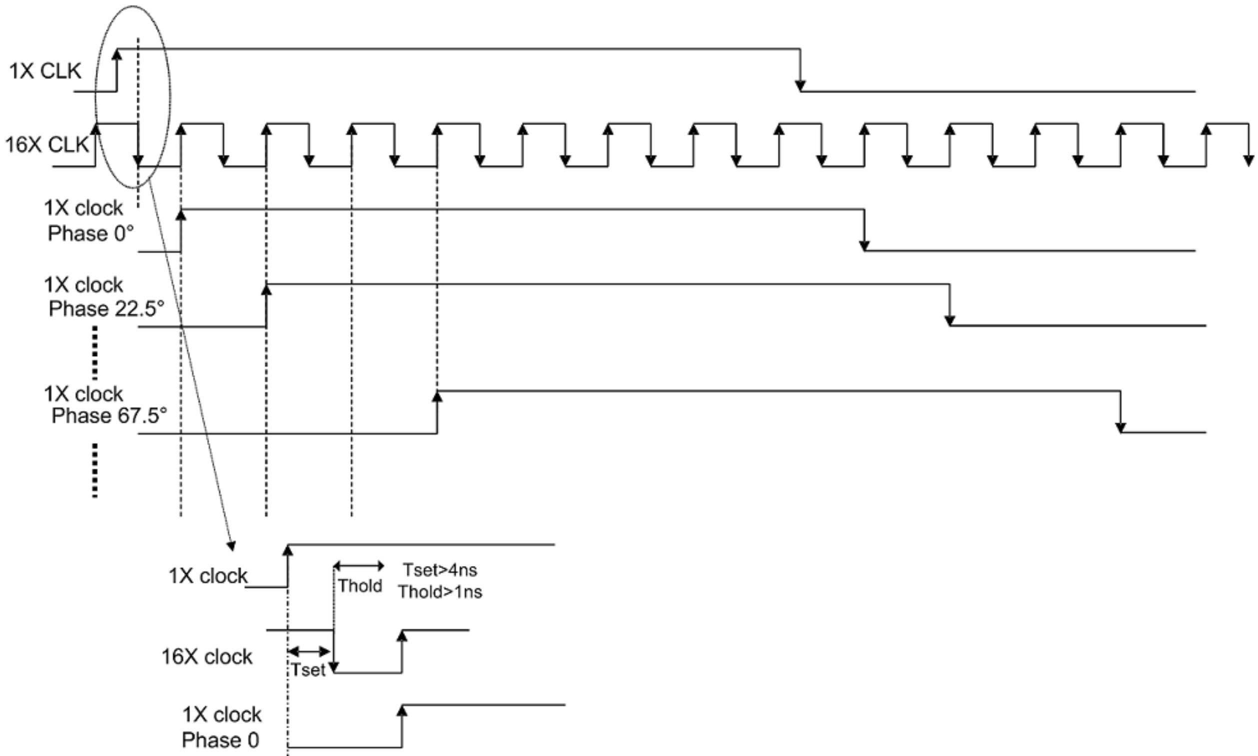

Figure 3. 16X Mode Phase Timing Diagram

When generating all 16 phases in 8X or 4X clock mode, the 4X (or 8X) clock is first used to generate 1X clocks with four equal phases of 90° (or eight equal phases of 45°) with an inverter and positive edge-triggered flip-flop. The generated 1X clocks are then fed into an I/Q CLK generator to produce the in-phase (cosine) and quadrature phase (sine) signals for the mixer at the input 1X frequency (see Figure 4).

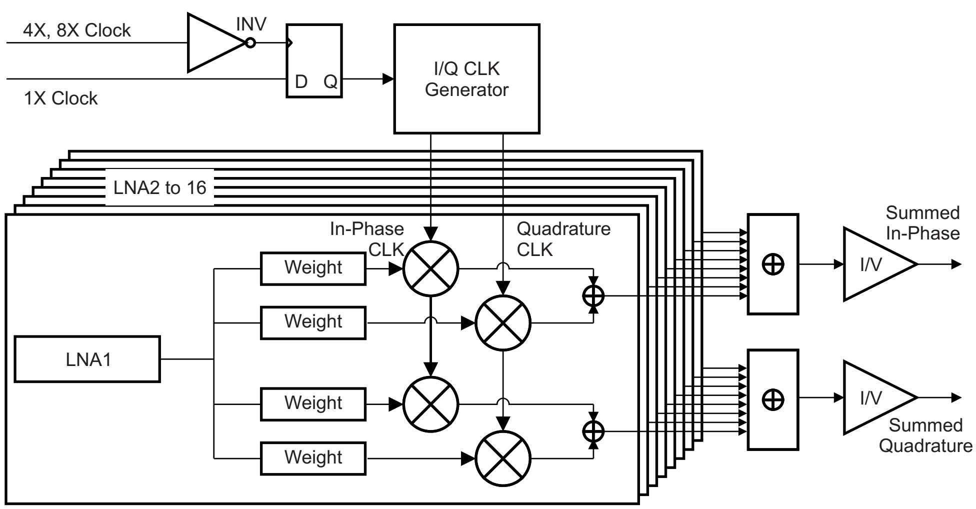

Figure 4. Phase Generation for 8X and 4X Clock Mode

Assuming a received signal frequency equal to the 1X clock frequency of ω_0, in order to generate a phase difference of x × 22.5°, or x × 2π / 16, the received cosine wave is multiplied by a weight. As an example, in order to get a phase difference of 67.5°, weights of cos(6π / 16) and sin(6π / 16) are added to the I and Q paths for the incoming cosine wave so that the mixer output (note from Figure 4 two mixers and a summation block for each I, Q path) becomes:

$$V_{0I4X}(t) = A \times B \times \left[(\cos(\omega_{in} t + \varphi) \times \cos(\omega_0 t) \times \cos\left(\frac{6\pi}{16}\right) - \cos(\omega_{in} t + \varphi) \times \sin(\omega_0 t) \times \sin\left(\frac{6\pi}{16}\right) \right]$$

$$= A \times B \times \cos(\omega_{in} t + \varphi) \times \left[(\cos(\omega_0 t) \times \cos\left(\frac{6\pi}{16}\right) - \sin(\omega_0 t) \times \sin\left(\frac{6\pi}{16}\right) \right]$$

$$\text{From } \cos(x + y) = \cos x \times \cos y - \sin x \times \sin y$$

$$(\cos(\omega_0 t) \times \cos\left(\frac{6\pi}{16}\right) - \sin(\omega_0 t) \times \sin\left(\frac{6\pi}{16}\right) = \cos\left(\omega_0 t + \frac{6\pi}{16}\right)$$

$$\text{Then } V_{0I4X}(t) = A \times B \times \cos(\omega_{in} t + \varphi) \times \cos\left(\omega_0 t + \frac{6\pi}{16}\right) \tag{9}$$

Note that this is the same as the equation for the 16X mode with $\omega_{LO} = \omega_0 t$, $\gamma = (6\pi / 16)$.

The Q-channel is set up similarly, with:

$$V_{0Q4X}(t) = A \times B \times \left[\cos(\omega_{in} t + \varphi) \times \cos(\omega_0 t) \times \sin\left(\frac{6\pi}{16}\right) + (\cos(\omega_{in} t + \varphi) \times \sin(\omega_0 t) \times \cos\left(\frac{6\pi}{16}\right) \right]$$

$$= A \times B \times \cos(\omega_{in} t + \varphi) \times \left[\cos(\omega_0 t) \times \sin\left(\frac{6\pi}{16}\right) + (\sin(\omega_0 t) \times \cos\left(\frac{6\pi}{16}\right) \right]$$

$$\text{From } \sin(x + y) = \sin x \times \cos y + \cos x \times \sin y$$

$$\cos(\omega_0 t) \times \sin\left(\frac{6\pi}{16}\right) + \sin(\omega_0 t) \times \cos\left(\frac{6\pi}{16}\right) = \sin\left(\omega_0 t + \frac{6\pi}{16}\right)$$

$$\text{Then } V_{0Q4X}(t) = A \times B \times \cos(\omega_{in} t + \varphi) \times \sin\left(\omega_0 t + \frac{6\pi}{16}\right) \tag{10}$$

For the 1X mode, synchronized clocks 90° out of phase are needed by the AFE58xxx8 devices for the phase-delayed LO signals required by the mixers. Then the sine and cosine at the 1X clock frequency are multiplied with the appropriate weights to produce the desired phase-delayed LO frequencies just like the 8X and 4X mode.

All 16 I-channel current outputs and 16 Q-channel current outputs are summed by two separate summing amplifiers at the CW beam-former output in order to improve signal-to-noise ratio (SNR). When the phase of the received signal for each of the 16 channels is perfectly matched to the phase of its corresponding LO ($\varphi = \gamma$), all 16 I-channel (or Q-channel) sinusoidal signal outputs constructively sum to a higher amplitude while their uncorrelated noise components combine by the square root of the sum of squares. Therefore, it is important to match up the input signal of each channel to the closest of the 16 possible phases to prevent destructive interference of the signal portion of the sinusoidal outputs that can lead to poor SNR performance.

3 Experiment and Data

Figure 5 represents (theoretically) how the cosine leads the sine for a positive angle.

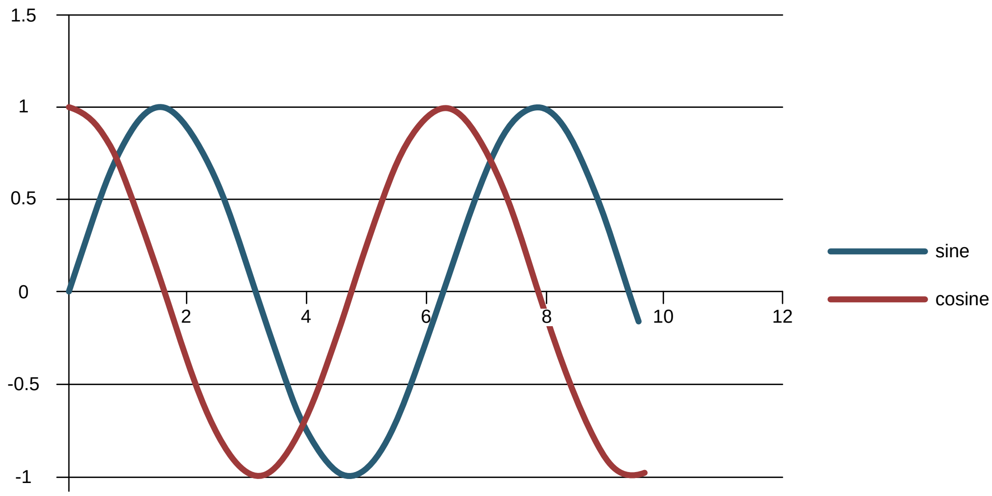

Figure 5. Sine and Cosine Phase Relationship

Therefore, it is expected that the I-channel leads the Q-channel, because the I and Q channels represent the cosine and sine of the same difference frequency, respectively (from Equation 4 and Equation 7).

The AFE58JD18EVM was then tested in the laboratory in CW mode, with a LO frequency of 1.953125 MHz and an input sinusoid of 1.943125 MHz, –15 dBm (see Figure 6 for results).

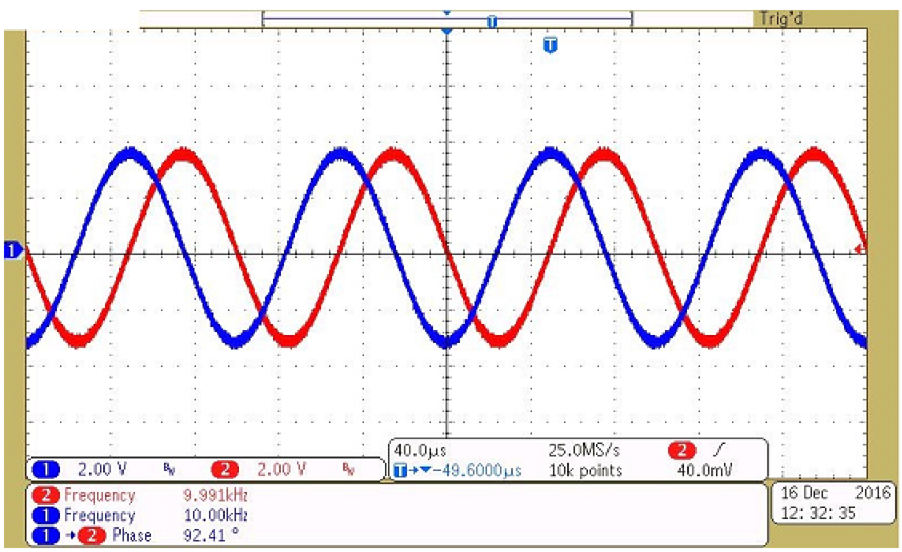

Figure 6. Filtered I and Q Outputs for Positive Delta Frequency

The channel 1 signal is the I-channel signal at 10-kHz and channel 2 represents the Q-channel signal at 10-kHz, but lagging the I-channel data by 90°. This is as expected for a positive frequency difference ($\omega_{LO} - \omega_{in}$) as the cosine leads the sine. Figure 7 shows the oscilloscope image when the frequency of the input signal was changed to 1.963125 MHz.

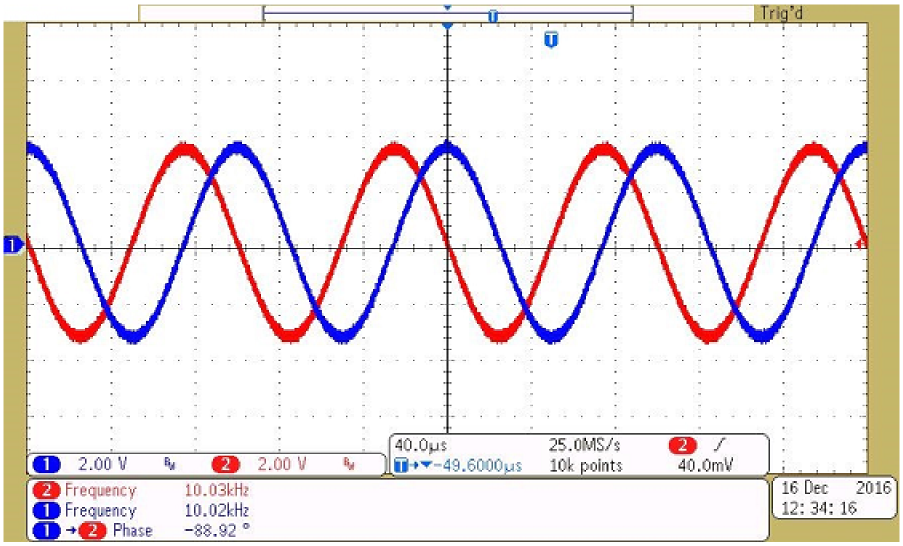

Figure 7. Filtered I and Q Outputs for Negative Delta Frequency

The Q-channel now leads the I-channel because the frequency difference turned negative and therefore, the sine shifts by 180°.

Note that on the AFE58xxx8EVMs, CW clock generation is done using the LMK0482X devices in clock divider mode. The onboard 125-MHz crystal is divided down to 31.25 MHz for the 16X clock and 1.953125 MHz for the 1X clock, respectively. By modifying the appropriate LMK0482X register mapped to the 16X clock divider controls, the 8X and 4X clocks can also be generated by the EVM. Conversely, Figure 8 shows that external clocks can also be provided to the board after configuring the CW clock selection jumpers for an external source.

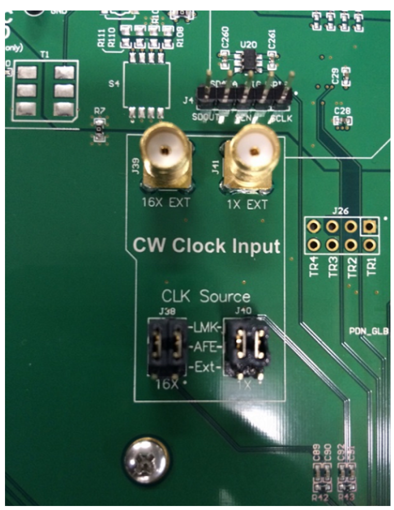

Figure 8. AFE58xxx8 Default CW Jumper Configuration

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