Single Sideband (SSB)

Modules: Audio Oscillator, Wideband True RMS Meter, Multiplier, Adder, Quadrature Utilities, Phase Shifters (2), Quadrature Phase Splitter, Tuneable LPF, Noise Generator, VCO, Speech, Headphones

0 Pre-Laboratory Reading

Single sideband (SSB) is a common analog modulation scheme for voice communications. With SSB only one sideband—either the upper or the lower—is present in the modulated carrier. That is acceptable because the two sidebands contain the same information, so the elimination of one sideband does not cause a loss of information. SSB uses radio spectrum efficiently: for a given message signal, only half as much bandwidth is occupied by the modulated carrier (compared with DSB or AM). SSB is used for amateur (ham) radio, citizens' band (CB) radio, and short-wave broadcasting.

There is more than one way to generate SSB carriers. One method is to use a DSB modulator and then eliminate one sideband (either the lower or the upper) with a filter. That method is conceptually simple but has a significant drawback. The filter can be challenging to design: it must have a quite sharp roll-off that will pass the one sideband but reject the other sideband that is just the other side of the carrier frequency. In the present experiments SSB carriers will be generated by a different method. The method employed here is known as the phasing method, and it incorporates a Hilbert transform.
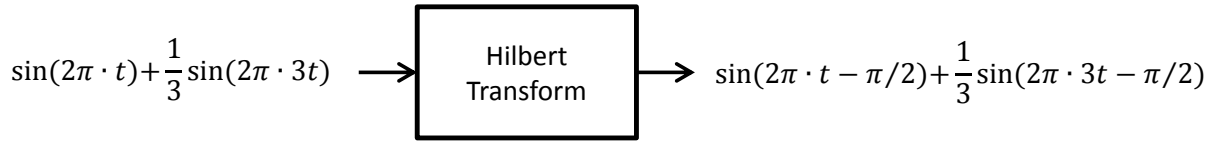
0.1 Hilbert Transform

For a Hilbert transform, both the input and the output are in the time domain. This is unlike the Fourier transform, for which the input is in the time domain and the output is the frequency domain description of the input. The Hilbert transform is a linear, time-invariant system. If the input is a sinusoid, the output is also a sinusoid of the same frequency. Here is an example:

$$\cos(2\pi \cdot 5t) \longrightarrow \boxed{\begin{array}{c}\text{Hilbert}\\\text{Transform}\end{array}} \longrightarrow \cos(2\pi \cdot 5t - \pi/2)$$

For a sinusoidal input, the output has a phase that is less than that of the input by $\pi/2$ radians. The amplitude is unchanged between input and output.

Here is a more complicated example:

$$\sin(2\pi \cdot t) + \frac{1}{3}\sin(2\pi \cdot 3t) \longrightarrow \boxed{\begin{array}{c} \text{Hilbert} \\ \text{Transform} \end{array}} \longrightarrow \sin(2\pi \cdot t - \pi/2) + \frac{1}{3}\sin(2\pi \cdot 3t - \pi/2)$$

In this example, each sinusoid on the input gives rise to a sinusoid of the same frequency on the output. Each output sinusoid has a phase that is less than that of its corresponding input by $\pi/2$ radians. The amplitude of each sinusoid is unchanged between input and output.

This is not the same as a time delay. A time delay of τ is equivalent to a phase change of $-2\pi f \tau$, where f is the frequency of the sinusoid. For example, if the input shown above were delayed by $\tau = 1/4$ second, the result would be

$$\sin\left[2\pi\left(t - \frac{1}{4}\right)\right] + \frac{1}{3}\sin\left[2\pi \cdot 3\left(t - \frac{1}{4}\right)\right] = \sin\left[2\pi \cdot t - \frac{\pi}{2}\right] + \frac{1}{3}\sin\left[2\pi \cdot 3t - \frac{3\pi}{2}\right] \quad (1)$$

This is different from the output of the Hilbert transform. A delay of $\tau = 1/4$ second corresponds to a loss in phase of $\pi/2$ radians for a sinusoid of frequency 1 Hz but a loss in phase of $3\pi/2$ radians for a sinusoid of frequency 3 Hz.

The two-sinusoid input considered above and its Hilbert transform are shown below:
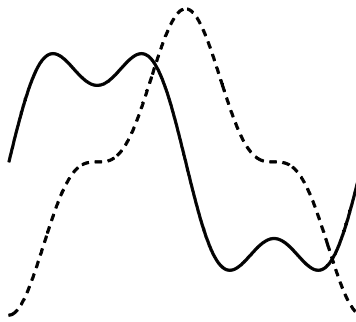
$\sin(2\pi \cdot t) + \frac{1}{3}\sin(2\pi \cdot 3t)$ (solid curve) and its Hilbert transform (dashed curve)

The Hilbert transform of a signal does not, in general, look like the original signal. (In the exceptional case of a single sinusoid, however, the Hilbert transform does look like a time-delayed version of the original.) In the above example, the input signal is the first two terms in the Fourier series expansion of a square-wave; the Hilbert transform looks quite different.

In the following analysis, a signal is considered as a weighted sum of sinusoids. A periodic signal consists of a discrete set of frequency components. An aperiodic signal (with finite energy) can be represented with a Fourier transform; therefore, such a signal consists of a set of frequency components that form a continuum on the frequency axis.

In general, a signal $x(t)$ has a Hilbert transform $\hat{x}(t)$:

$$x(t) \longrightarrow \boxed{\begin{array}{c} \text{Hilbert} \\ \text{Transform} \end{array}} \longrightarrow \hat{x}(t)$$
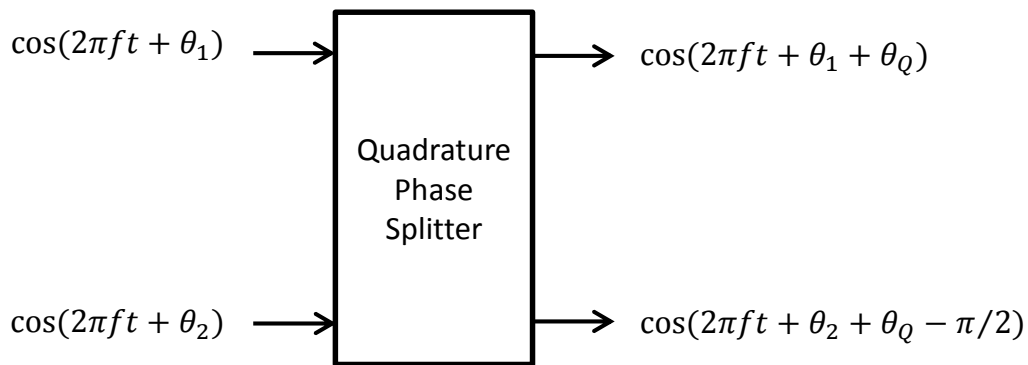
Every frequency component of $x(t)$ appears in $\hat{x}(t)$ with a phase change of $-\pi/2$ radians. The amplitude is unchanged between input and output for each component. Therefore, the magnitude of the Fourier transform of $\hat{x}(t)$ equals that for $x(t)$, and the angle of the Fourier transform of $\hat{x}(t)$ is less than that for $x(t)$ by $\pi/2$ radians at each positive frequency. As mentioned above, in the time domain $x(t)$ and $\hat{x}(t)$ look different.

The human ear is sensitive to the distribution of signal content in the frequency domain but is insensitive to the phasing of the individual frequency components. Two different audio signals sent to a speaker will sound approximately the same if the magnitudes of their Fourier transforms are the same, even if the angles of their Fourier transforms are different. Therefore, $x(t)$ and $\hat{x}(t)$ sound approximately the same. This fact is exploited in SSB technology.

0.2 Quadrature Phase Splitter

The Hilbert transform that will be used in these experiments is incorporated into a module called the Quadrature Phase Splitter.

$$\cos(2\pi ft + \theta_1) \longrightarrow \boxed{\begin{array}{c} \text{Quadrature} \\ \text{Phase} \\ \text{Splitter} \end{array}} \longrightarrow \cos(2\pi ft + \theta_1 + \theta_Q)$$

$$\cos(2\pi ft + \theta_2) \longrightarrow \qquad\qquad \longrightarrow \cos(2\pi ft + \theta_2 + \theta_Q - \pi/2)$$

This module has two inputs and two outputs. A sinusoid on the first (upper) input appears on the first (upper) output. The angle of the frequency response between first input and first output is θ_Q. This represents a delay, so for small, positive frequencies θ_Q is negative. θ_Q is an implicit (and nonlinear) function of frequency. (The fact that the angle of the frequency response is a nonlinear function of frequency means that there is phase distortion. However, this Quadrature Phase Splitter is only used for voice communication, which is insensitive to phase distortion.) The amplitude is unchanged from input to output.

A sinusoid on the second (lower) input of the Quadrature Phase Splitter appears on the second (lower) output. The angle of the frequency response between second input and second output is $\theta_Q - \pi/2$. The amplitude is unchanged from input to output.

If the upper sinusoid and the lower sinusoid are of the same frequency (as indicated in the diagram), the difference in phase between the second and first outputs is $\theta_2 - \theta_1 - \pi/2$ radians, where θ_1 is the phase of the first input and θ_2 is the phase of the second input. (The common phase term θ_Q cancels.)

If the two inputs are connected together (as they will be in the SSB modulator), so that $\theta_1 = \theta_2$, then the difference in phase between the second and first outputs is $-\pi/2$ radians. That is to say, with the two inputs of the Quadrature Phase Splitter connected together, the second output is the Hilbert transform of the first output.

0.3 Single Sideband Modulation

The present experiments use the phasing method for generating SSB carriers. This modulator, also known as the Hartley modulator, is shown below.
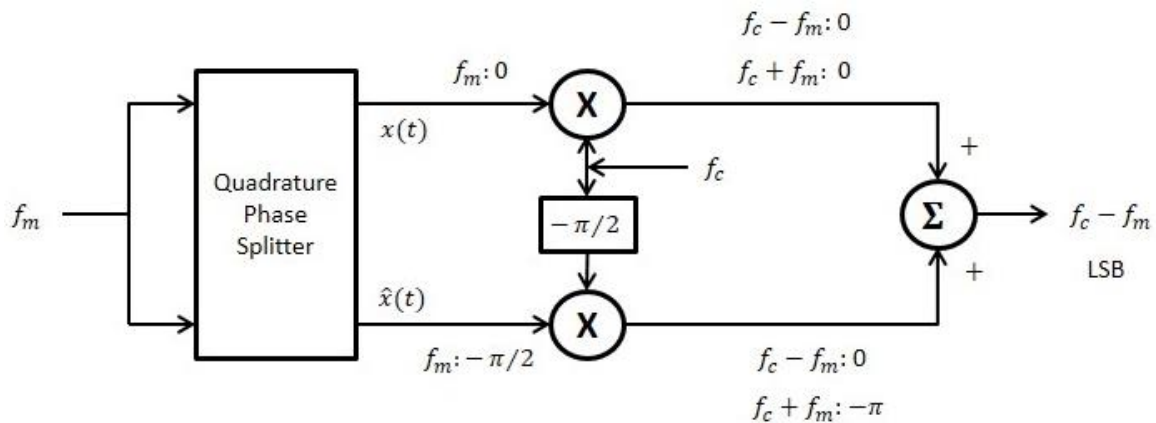
SSB modulator using the phasing method

In the Hartley modulator, both inputs of the Quadrature Phase Splitter receive the same (message) signal. The first (upper) output is a copy of the input message $x(t)$. The second output is the Hilbert transform $\hat{x}(t)$ of the first output.

The Hartley modulator is a linear (and time-varying) system. The principle of superposition holds for this system. Therefore, if one knows how the system responds to a sinusoid, the response of the system to a weighted sum of sinusoids can, in principle, be determined.

The best way to understand the Hartley modulator is to consider first a message signal that is a sinusoid of frequency f_m. In the above diagram the outputs of the Quadrature Phase Splitter are labeled with $f_m:0$ (upper branch) and $f_m:-\pi/2$ (lower branch). These labels indicate that both

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of these signals are sinusoids of frequency f_m and that the sinusoid on the lower branch has a phase of $-\pi/2$ radians relative to the upper branch.

Each of the two multipliers will produce a difference-frequency $(f_c - f_m)$ and a sum-frequency $(f_c + f_m)$ sinusoid. The upper and lower difference-frequency sinusoids will be in phase with each other, and the upper and lower sum-frequency sinusoids will be out of phase by π radians. The following equations demonstrate this:

$$\cos(2\pi f_m t) \cdot 2\cos(2\pi f_c t) = \cos[2\pi(f_c - f_m)t] + \cos[2\pi(f_c + f_m)t] \tag{2}$$

$$\cos\left(2\pi f_m t - \frac{\pi}{2}\right) \cdot 2\cos\left(2\pi f_c t - \frac{\pi}{2}\right)$$
$$= \cos[2\pi(f_c - f_m)t] + \cos[2\pi(f_c + f_m)t - \pi] \tag{3}$$

The phase relationships can also be recognized without writing any trigonometric equations. The reasoning is as follows. The phase of the difference-frequency sinusoid equals the phase of the higher-frequency input minus the phase of the lower-frequency input. For the upper branch, this is $0 - 0 = 0$; and for the lower branch, this is $(-\pi/2) - (-\pi/2) = 0$. The phase of the sum-frequency sinusoid equals the sum of the two input phases. For the upper branch, this is $0 + 0 = 0$; and for the lower branch, this is $(-\pi/2) + (-\pi/2) = -\pi$.

When the two multiplier outputs are added together, the difference-frequency sinusoids will reinforce each other (since they are in phase) but the sum-frequency sinusoids will annihilate each other (since they are out of phase by π radians and of equal amplitude). The output of the modulator is therefore a single sinusoid with frequency $f_c - f_m$ (when the input of the modulator is a sinusoid of frequency f_m).

The above analysis holds for any positive frequency f_m. For a general message signal, the input will consist of a weighted sum of sinusoids. For each of these input sinusoids, the output is a sinusoid with a frequency equal to the carrier frequency minus the input frequency. Also, the weighting of each output sinusoid will be proportional to the weighting factor of the input sinusoid. This is a description of the lower sideband (LSB).

With the modulator discussed above, there is no upper sideband (USB). Since the LSB contains all the information in the message signal, the USB is not necessary for conveying the information. This scheme is efficient in the use of spectrum since it occupies, for a given message signal, only half the bandwidth of a DSB carrier.

For this scheme to work, it is essential that the gain in the upper branch of the Hartley modulator match the gain in the lower branch. If these gains don't match or if the phase difference between the upper and lower sum-frequency sinusoids is not exactly π radians, then the sum-frequency sinusoids do not exactly cancel.

Is it possible to build a Hartley modulator that produces only the USB and not the LSB? Yes. If the final sum in the modulator is replaced with a subtraction, then the Hartley modulator generates a carrier with a single sideband, the USB. It is left to the reader to verify this claim.

Examining the Hartley modulator and using the fact that $\cos(2\pi f_c t - \pi/2) = \sin(2\pi f_c t)$, it is quickly determined that:
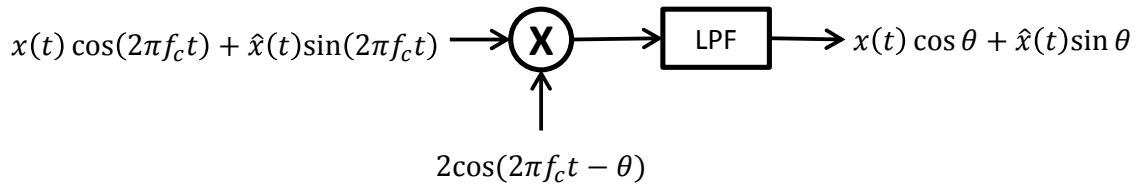
$$\text{SSB/LSB carrier} = x(t)\cos(2\pi f_c t) + \hat{x}(t)\sin(2\pi f_c t) \tag{4}$$

This expression is useful when investigating detectors and demodulators for SSB/LSB carriers. For SSB/USB the result is:
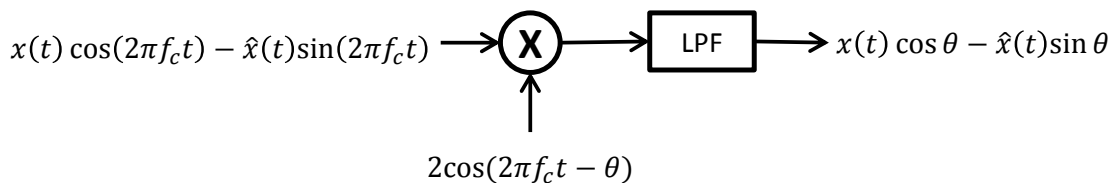
$$\text{SSB/USB carrier} = x(t)\cos(2\pi f_c t) - \hat{x}(t)\sin(2\pi f_c t) \tag{5}$$

0.4 Detection of SSB Carrier

Synchronous detection, the usual means of detecting a DSB carrier, can also be used for SSB. However, in the case of SSB with a voice message, it is not necessary that the local oscillator match the received carrier in phase. In the following, it is assumed that the local oscillator is $2\cos(2\pi f_c t - \theta)$. The phase term θ is included to model the fact that the phase of the local oscillator does not, in general, match that of the arriving carrier when detecting SSB.

$x(t)\cos(2\pi f_c t) + \hat{x}(t)\sin(2\pi f_c t) \longrightarrow \boxed{\times} \longrightarrow \boxed{\text{LPF}} \longrightarrow x(t)\cos\theta + \hat{x}(t)\sin\theta$

$2\cos(2\pi f_c t - \theta)$

Detection of SSB/LSB

$x(t)\cos(2\pi f_c t) - \hat{x}(t)\sin(2\pi f_c t) \longrightarrow \boxed{\times} \longrightarrow \boxed{\text{LPF}} \longrightarrow x(t)\cos\theta - \hat{x}(t)\sin\theta$

$2\cos(2\pi f_c t - \theta)$

Detection of SSB/USB

Since $\hat{x}(t)$ sounds (approximately) like $x(t)$, this detector's output, which is a weighted sum of $x(t)$ and $\hat{x}(t)$, sounds like $x(t)$. This is a successful demodulation, as long as $x(t)$ is voice. Moreover, the root-mean-square (rms) of the detector's output is constant and independent of θ.

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This conclusion is reached from the following considerations. The rms of $\hat{x}(t)$ is the same as that of $x(t)$ since the rms of a signal depends on the magnitude of its Fourier transform but is independent of the angle of the Fourier transform. Therefore, the rms of the detector's output is

$$[\text{rms of } x(t)] \cdot \sqrt{\cos^2\theta + \sin^2\theta} = \text{rms of } x(t) \tag{6}$$

This is independent of θ. (The identity $\cos^2\theta + \sin^2\theta = 1$ has been used above.) This result is valid for both SSB/LSB and SSB/USB. Therefore, the audio level out of this detector does not change if θ changes.

With SSB the local oscillator is not even required to match exactly the arriving carrier in frequency. If the frequencies are close but not an exact match, then the phase difference between them changes. If this change is relatively slow (that is to say, if the frequency mismatch is small), then the detector's output will continue to sound (approximately) like $x(t)$.

0.5 Single Sideband Demodulation

The detection scheme described above can work well for SSB with a voice message. However, it has a significant drawback: it works equally well for detecting the USB and the LSB. It might not be immediately obvious why this can be a problem. However, the purpose of using SSB is to improve spectral efficiency. If a transmitter only places signal content in the LSB, the span of frequencies just above the carrier frequency is available to be used by another transmitter. The detector described above might then respond not just to the desired message but also to another message intended for another receiver. Therefore, it is often desirable to have a demodulator that only responds to the LSB or the USB, but not both. This is what is meant by a single-sideband demodulator.

Here is a demodulator that responds to only the LSB:
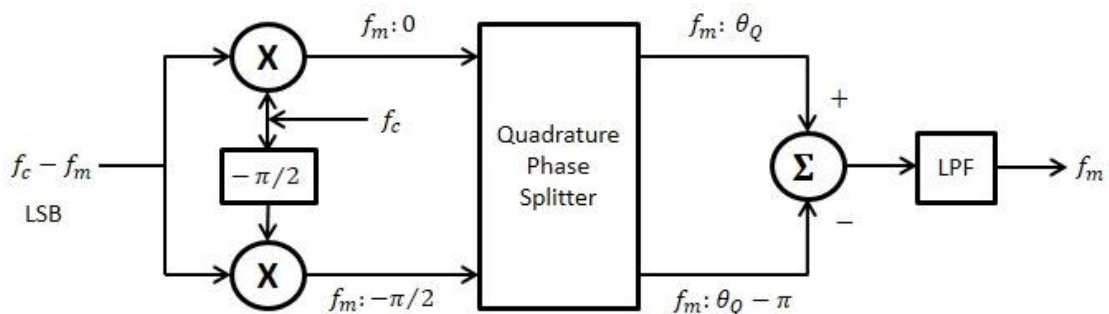
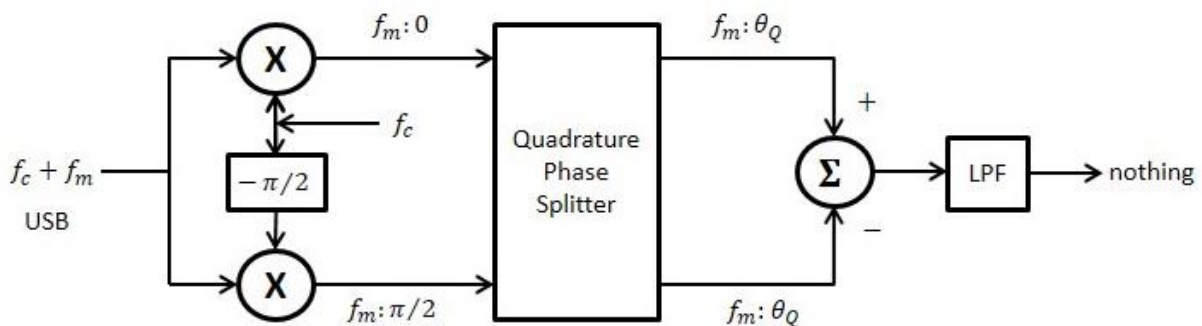SSB/LSB demodulator with input frequency $f_c - f_m$ ($f_m > 0$)

The following analysis shows that a frequency $f_c - f_m$ (with f_m assumed to be positive) at the demodulator input gets translated to a frequency f_m at the output, demonstrating that this circuit demodulates the LSB.

The output of each multiplier is the sum of two sinusoids, having frequencies f_m and $2f_c - f_m$. Only the difference frequency $f_c - (f_c - f_m) = f_m$ is shown in the above diagram. The sum frequency is undesired and filtered out by the low-pass filter. (The sum-frequency sinusoids could be filtered out earlier, immediately after each multiplier, but that would require two low-pass filters. In the interest of economy, the filtering is done by a single filter after the upper and lower branch signals are combined.)

From this point forward, this analysis only considers the difference frequency f_m (since the sum frequency will eventually be blocked by the filter). The phase at the output of the upper multiplier is $0 - 0 = 0$, and the phase of the first (upper) output of the Quadrature Phase Splitter is θ_Q. The phase at the output of the lower multiplier is $(-\pi/2) - 0 = -\pi/2$. The phase of the second (lower) output of the Quadrature Phase Splitter is $-\pi/2 + \theta_Q - \pi/2 = \theta_Q - \pi$. The two outputs of the Quadrature Phase Splitter are therefore out of phase by π radians. When these two sinusoids are subtracted, they reinforce. Thus, the output of this demodulator is a sinusoid of frequency f_m when the input is a sinusoid of frequency $f_c - f_m$.

In general, a carrier with SSB/LSB can be regarded as a weighted set of sinusoids having frequencies lying below the carrier frequency f_c. The above analysis shows that each component sinusoid, with frequency $f_c - f_m$, will be translated to an output frequency f_m. The weighting factors on the input will be reflected on the output. Therefore, the above circuit successfully demodulates a carrier with SSB/LSB.

In order for this circuit to qualify as a true single-sideband/LSB demodulator, it must reject the USB. The following diagram demonstrates that it does.

SSB/LSB demodulator with input frequency $f_c + f_m$ ($f_m > 0$)

The single-sideband/LSB demodulator can be modified to a single-sideband/USB demodulator by simply changing the subtraction to an addition.

1 SSB Modulation

You will generate first SSB/LSB, then SSB/USB.

1.1 Sinusoidal Message

Build a Hartley modulator for SSB/LSB. Use a 100-kHz sinusoid (Master Signals) for the carrier and a Phase Shifter for the phase delay of the carrier. Make sure that the Phase Shifter's slide switch (on the PCB) is set to "HI". Adjust the Phase Shifter so that for a 100-kHz sinusoid the output lags the input by 90°. Use the Quadrature Utilities module for the two multipliers. Use an Adder for summing the upper and lower branches.

Initially use the analog 2-kHz sinusoid (Master Signals) as the message signal. The actual frequency of this sinusoid is (100/48) kHz. This message signal will be connected to both inputs of the Quadrature Phase Splitter. Connect the first (top) output of the Quadrature Phase Splitter to Channel A and the second (bottom) output to Channel B. You should find that the second output is (approximately) the Hilbert transform of the first output.

> Channel A: first output of Quadrature Phase Splitter
> Channel B: second output of Quadrature Phase Splitter

Adjust the two gains of the (weighted) Adder so that the upper and lower branches make the same contribution to the rms voltage at the Adder output. You can do this by connecting the Adder output to the RMS Meter and adjusting each Adder gain knob with the other input disconnected.

Place the first output of the Quadrature Phase Splitter on Channel A and the output of the upper multiplier on Channel B. Verify that the output of the upper multiplier is a DSB carrier.

> Channel A: first output of Quadrature Phase Splitter
> Channel B: output of upper multiplier

Place the second output of the Quadrature Phase Splitter on Channel A and the output of the lower multiplier on Channel B. Verify that the output of the lower multiplier is a DSB carrier.

> Channel A: second output of Quadrature Phase Splitter
> Channel B: output of lower multiplier

Place the first output of the Quadrature Phase Splitter on Channel A and the output of the Hartley modulator on Channel B. Since the message sinusoid and the 100-kHz carrier are coherently related, it should be possible to stabilize the display.

∿ Channel A: first output of Quadrature Phase Splitter
Channel B: output of Hartley modulator

Observe the Hartley modulator output on the spectrum analyzer. The LSB should be stronger than the USB. Adjust (slightly) one gain on the weighted adder and adjust (slightly) the delay of the Phase Shifter in order to minimize the USB. You shouldn't have to adjust either very much. The idea is that the USB sinusoid on the lower branch should have exactly the same amplitude as the USB sinusoid on the upper branch and the phase difference between them should be exactly π radians.

▥ Channel B: output of Hartley modulator

You will use a Tuneable LPF in the detector (demodulator). Before placing the LPF in the detector, adjust LPF bandwidth to approximately 6 kHz. (The Tuneable LPF's clock output has a frequency equal to 100 times the bandwidth.) Use the Noise Generator module to get a quick display of $|H(f)|$.

▥ Channel A: Tuneable LPF output, showing $|H(f)|$

Build a detector consisting of a local oscillator, a multiplier, and a low-pass filter. Generate the local oscillator by placing a copy of the 100-kHz carrier at the input to a Phase Shifter (*not* the Phase Shifter used in the Hartley modulator). The output of this Phase Shifter is the local oscillator. You are allowing for a local oscillator whose phase does not match that of the carrier. This local oscillator is one input to the multiplier, and the other input will receive the signal to be detected (see below). Connect the multiplier output to the LPF set for a bandwidth of 6 kHz. The output of this Tuneable LPF is the detector output.

In the first instance, you will detect the DSB signal that appears in the upper branch of the Hartley modulator for SSB/LSB. (Here you are not using the output of the Hartley modulator; instead, you are using a DSB signal from the inside of the Hartley modulator.) Place this DSB signal on the input of your detector. Simultaneously observe the detector output and the message signal on the oscilloscope. Vary the phase of the local oscillator in the detector. You should find that the amplitude of the detected signal is sensitive to the phase of the local oscillator.

Now detect the SSB/LSB signal. (You will replace the DSB signal on the detector input by the SSB/LSB signal from the output of the Hartley modulator.) Connect the first output of the Quadrature Phase Splitter (that is, the message signal) to Channel A and the output of the detector to Channel B. If you vary the phase of the local oscillator in the detector, you should find that the amplitude of the detected signal is insensitive to the phase of the local oscillator.

Set the local oscillator to have a phase difference of 0° relative to the carrier. You can do this by bypassing the Phase Shifter in the detector.

> Channel A: first output of Quadrature Phase Splitter
> Channel B: output of detector (phase difference $= 0^\circ$)

Now set the Phase Shifter in the detector (which supplies the local oscillator) to a phase difference between input and output of 90°. You can do this with the oscilloscope. It is suggested that you connect the Phase Shifter inputs and outputs to the lower input ports of Channels A and B, so as not to disturb the message signal and detector output connections to the oscilloscope. (Of course, you'll then need flip two toggle switches on the PC-Based Instrument Inputs panel.)

> Channel A: first output of Quadrature Phase Splitter
> Channel B: output of detector (phase difference $= 90^\circ$)

> sinusoidal message

Change the SSB/LSB modulator to a modulator for SSB/USB. This only requires that a negative sign be introduced into the lower branch. This could be done by inserting a (negative-gain) Buffer Amplifier into the lower branch, but that would then necessitate readjusting the gains so that the upper and lower branches had gains with equal absolute values. A more convenient way to accomplish the change to SSB/USB is to throw the toggle switch on the Phase Shifter in the Hartley modulator. Throwing this toggle switch causes another π radians of phase to be introduced into the delayed carrier that connects to the multiplier in the lower branch. This is equivalent to introducing an extra -1 factor in the gain of the lower branch.

Place the first output of the Quadrature Phase Splitter on Channel A and the output of the SSB/USB Hartley modulator on Channel B. Since the message sinusoid and the 100-kHz carrier are coherently related, it should be possible to stabilize the display.

> Channel A: first output of Quadrature Phase Splitter
> Channel B: output of Hartley modulator (SSB/USB)

Observe the SSB/USB Hartley modulator output on the spectrum analyzer. The USB should be stronger than the LSB. Adjust (slightly) one gain on the weighted adder and adjust (slightly) the delay of the Phase Shifter in order to minimize the LSB. You shouldn't have to adjust either very much.

> Channel B: output of Hartley modulator (SSB/USB)

Detect the SSB/USB signal. Connect the first output of the Quadrature Phase Splitter (that is, the message signal) to Channel A and the output of the detector to Channel B.

Channel A: first output of Quadrature Phase Splitter
Channel B: output of detector (with SSB/USB signal at detector input)

You should find that the amplitude of the detected signal is insensitive to the phase of the local oscillator.

1.2 Audio Message

Use an audio signal from the Speech module as the message signal. Connect this message signal to the SSB/LSB Hartley modulator. View the spectrum of the SSB/LSB carrier.

Channel A: output of Hartley modulator (SSB/LSB)

Connect the SSB/LSB carrier to the detector. Connect the detector output to the headphones. Listen to the recovered audio message while varying the delay of the Phase Shifter in the detector. You should find that the quality and loudness of the detected audio is insensitive to the phase of the local oscillator.

Replace the local oscillator in the detector with the output of the VCO (voltage-controlled oscillator) module. Make sure the switch on the VCO module's PCB is set to "VCO". Set the toggle switch on the front panel of the VCO module to "HI". A knob on the VCO module permits you to adjust the frequency. Place a copy of the VCO output on the input of the Frequency Counter so that you can monitor this frequency. Adjust this frequency to approximately 100 kHz. You will not be able to make this frequency exactly the same as that of the carrier, but you should be able to get close.

You are now using a local oscillator for your detector that doesn't match the carrier in either phase or frequency. You should find, however, that if the local oscillator frequency is close to that of the carrier the detected audio sounds okay. Estimate the maximum difference between the frequency of the carrier and that of the detector's local oscillator that still permits a reasonable sound quality out of the detector.

2 Single Sideband Demodulation

A single-sideband/LSB carrier with a sinusoidal message signal is just equal to a sinusoid of frequency $f_c - f_m$, where f_c is the carrier frequency and f_m the message frequency. For example, with a 100-kHz carrier and a 5-kHz sinusoidal message, the modulated carrier is simply a 95-kHz sinusoid.

You can take apart the SSB modulator. You won't need it for the remainder of this experiment. Instead, you will simulate the output of an SSB modulator that has a sinusoidal message signal. You will use a VCO to simulate the SSB modulator.

Build a single-sideband/LSB demodulator. Use a 100-kHz sinusoid (Master Signals) for the local oscillator and a Phase Shifter for the phase delay of the local oscillator. Simultaneously observe the Phase Shifter input and output (with frequency 100 kHz) on the oscilloscope and adjust the delay until the output lags the input by $90°$. Use the Quadrature Utilities module for the two multipliers. Use an Adder for summing the upper and lower branches. Set the Tuneable LPF bandwidth to approximately 6 kHz.

Change the summation into a subtraction, as required by the SSB/LSB demodulator, by throwing the toggle switch on the Phase Shifter in the demodulator. Throwing this toggle switch causes another π radians of phase to be introduced into the delayed local oscillator that connects to the multiplier in the lower branch. After you have thrown the switch, the output of the Phase Shifter should appear to lead the input by $90°$, rather than lag it. Verify this. This result is equivalent to introducing an extra -1 factor in the gain of the lower branch.

Place the output of the VCO, which is used here to simulate an SSB carrier, at the input to the demodulator. Make sure the switch on the VCO module's PCB is set to "VCO". Set the toggle switch on the front panel of the VCO module to "HI". Initially adjust the VCO frequency to 95 kHz.

Adjust the two gains of the (weighted) Adder so that the upper and lower branches make the same contribution to the rms voltage at the Adder output. You can do this by connecting the Adder output to the RMS Meter and adjusting each Adder gain knob with the other input disconnected.

Connect the SSB/LSB carrier (the VCO output) to Channel A and the demodulator output to Channel B. Set the PicoScope for Spectrum Mode. Record the signal level (in dBu) of the demodulator output.

📊 Channel A: VCO output (simulating SSB/LSB carrier)
Channel B: SSB/LSB demodulator output

Change the VCO frequency to the following values: 96 kHz, 97 kHz, 98 kHz, and 99 kHz. (You will be simulating message sinusoids of frequency 4 kHz, 3 kHz, 2 kHz, and 1 kHz.) In each case, record the signal level (in dBu) of the demodulator output.

📊 SSB LSB demodulation

You should find that the signal level of the demodulator output remains approximately constant as you vary $f_c - f_m$, as long as $f_c - f_m$ remains less than f_c (that is, as long as this is SSB/LSB).

Change the VCO frequency to 105 kHz. This now simulates SSB/USB with a 5-kHz sinusoidal message signal. Connect the SSB/USB carrier (the VCO output) to Channel A and the SSB/LSB demodulator output to Channel B. Set the PicoScope for Spectrum Mode. This SSB/LSB demodulator should produce nothing more than a weak output at 5 kHz. Adjust slightly one of the gains on the Adder and the delay of the Phase Shifter in order to minimize the 5-kHz output.

 📊 Channel A: VCO output (simulating SSB/USB carrier)
      Channel B: SSB/LSB demodulator output

Change the single-sideband/LSB demodulator to a single-sideband/USB demodulator. This is most easily accomplished by throwing the toggle switch on the Phase Shifter in the demodulator. This effectively changes the sign of the gain in the lower branch, causing the subtraction to become an addition.

Initially set the VCO output to 105 kHz, simulating SSB/USB with a 5-kHz sinusoidal message. Connect the SSB/USB carrier (the VCO output) to Channel A and the SSB/USB demodulator output to Channel B. Set the PicoScope for Spectrum Mode. Record the signal level (in dBu) of the demodulator output.

 📊 Channel A: VCO output (simulating SSB/USB carrier)
      Channel B: SSB/USB demodulator output

Change the VCO frequency to the following values: 104 kHz, 103 kHz, 102 kHz, and 101 kHz. (You will be simulating message sinusoids of frequency 4 kHz, 3 kHz, 2 kHz, and 1 kHz.) In each case, record the signal level (in dBu) of the demodulator output.

 📊 SSB USB demodulation

You should find that the signal level of the demodulator output remains approximately constant as you vary $f_c + f_m$, as long as $f_c + f_m$ remains greater than f_c (that is, as long as this is SSB/USB).