Mixing Frequencies: A New Look

Photos help explain complex linear mixing to amateur radio operators and others

By John Wannamaker

One of the easiest ways to grasp a complex linear mixing situation is through a good illustration. Ink drawings that are particularly well presented help explain simpler results, but anything that involves manually summing many cycles of several frequencies has simply been too tedious a task to render by hand. Now we have photographs that offer more insight than can be explained with the proverbial 10,000 words. Some of these appear in print here for the first time, and all are accompanied by an explanation and comments to appeal to readers of various technical backgrounds.

If you currently have or have ever had difficulty understanding AM radio and sidebands, the material presented here may be just what you need to clear up any confusion in this area. Even experienced single-sideband operators may discover something new or clear up some point.

To create these photos, summing (linear mixing) was done with an operational amplifier. A special device was used to generate up to four sine waves simultaneously, each with independently adjustable frequency, amplitude and phase shift. Frequencies of the four oscillators I used were in the low audio range, but they can be reasonably projected upward to represent what happens at radio frequencies.

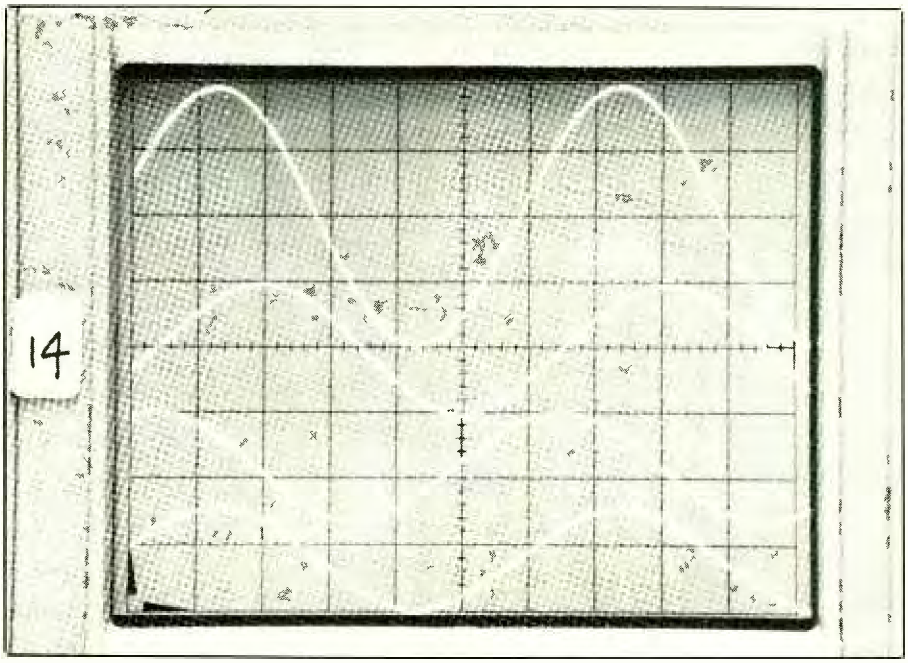

Fig. 1. Three sinusoidal waveforms (bottom) sum into a resultant waveform (top) of identical frequency.

Sine Waves Only

Figure 1 illustrates something that can be done only with sine waves. Here three sinusoidal waves of the same frequency (bottom trace), differing in amplitude and phase relationship, are summed to produce a sine wave (top trace) of the identical frequency. The only time the output could be otherwise is when the inputs sum to zero by precisely canceling each other out.

Summing of sine waves with different frequencies results in a complex waveform. Figure 2 shows how a fundamental frequency and its third, fifth and seventh harmonics combine (top trace) to begin formation of a square wave. In theory, the perfect square wave contains an infinite number of odd harmonics. (Apologies to readers who notice here that the fifth harmonic's amplitude is too low. Final press time was reached before it could be corrected for publication.) The slight variation in lateral symmetry of the resultant is due to a bit of distortion of the fundamental frequency.

In Fig. 3, a ramp can be seen taking shape. This ramp is composed of a fundamental frequency and its second, third and fourth harmonics. All harmonics, both odd and even, would are required to form a ramp waveform. Incidentally, this "recipe" must also specify amplitudes and phase relationships, properties that could change the shape if not selected correctly.

The heart of waveform analysis is this: If sine waves can be combined to form other waveshapes, then other waveshapes, no matter how they are generated, can be thought of as specific combinations of sine waves. This theory is supported by the photos in Figs. 2 and 3.

Anything that causes even the slightest distortion in an otherwise pure sine wave must by that very act create one or more additional frequencies. This is known as "harmonic distortion," where two frequencies are mixed nonlinearly. Amplitude modulation, where fairly large amounts of power are involved, is an example of this. AM creates sum and difference frequencies that become the upper and lower sidebands, respectively.

Figure 4 shows an often-used com-

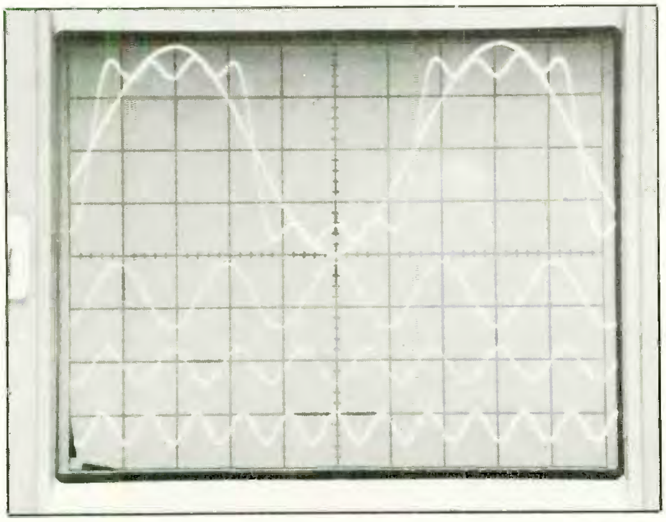

Fig. 2. Making of a square wave involves addition of fundamental frequency with odd harmonics. Third, fifth and seventh harmonics shown here are on the way toward making a square wave.

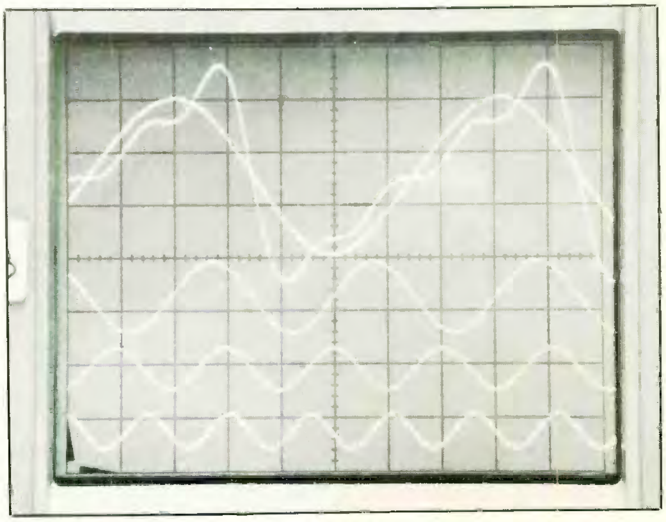

Fig. 3. Adding fundamental frequency and all harmonics produces a ramp waveform. Second, third and fourth harmonics shown here are on the way toward making a sawtooth-like ramp waveform.

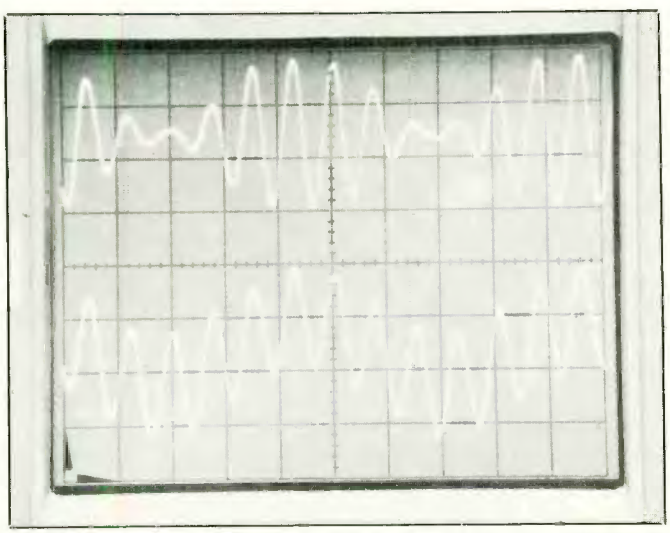

Fig. 4. Waveforms typically shown to represent heterodyning (top) and linear mixing (bottom).

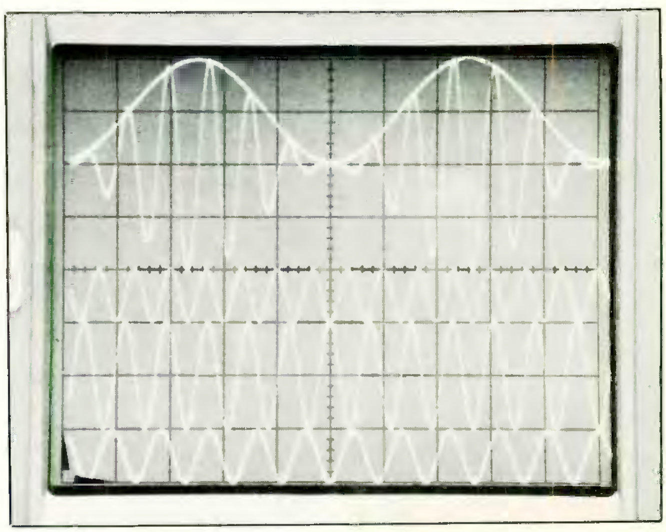

Fig. 5. Simulated carrier and sidebands mixed to reconstruct a nonexistent modulated waveform.

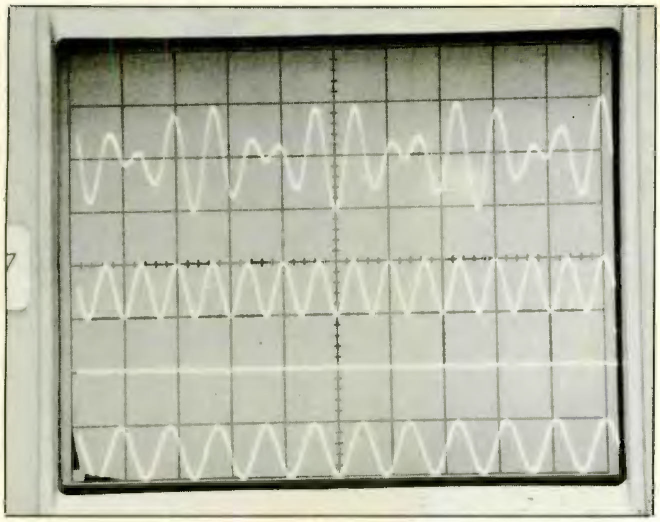

Fig. 6. With carrier reduced to zero, sideband reacts with sideband and introduces a frequency that is twice that of the true audio component.

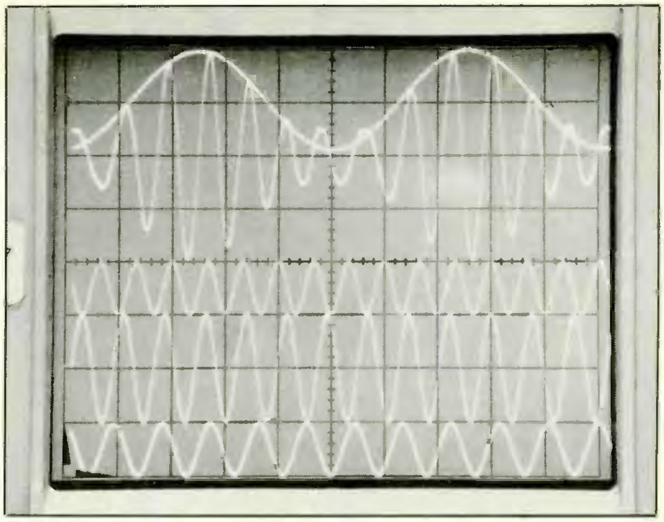

Fig. 7. This photo illustrates the effect on the modulation envelope when the carrier has been shifted in phase by approximately 30 degrees.

parison between linear mixing (bottom trace) and nonlinear mixing or heterodyning (top trace). In this case, linear mixing even looks easy to analyze.

If the highest frequency is filtered out, only the lowest remains and vice-versa. However, the modulated waveform needs some explanation. This waveform is the result of *linearly* mixing the component frequencies at the output of a nonlinear (heterodyning) circuit, and not even quite that because the lowest frequency component—call it the audio—is not included. Its effects can be seen, but it is not part of the summed values. Simple visual examination reveals that it is not possible to tell that sum and difference frequencies play any part in the waveform's shape.

Figure 5 shows a lower sideband (bottom trace), a carrier and an upper sideband as each might be separately received as an incoming signal. The receiving antenna acts as the linear mixer that sums these tuned-in frequencies (top trace). Collectively, they "recreate" a modulated envelope that never actually existed, since separate oscillators were used to generate them.

The audio that outlines the upper

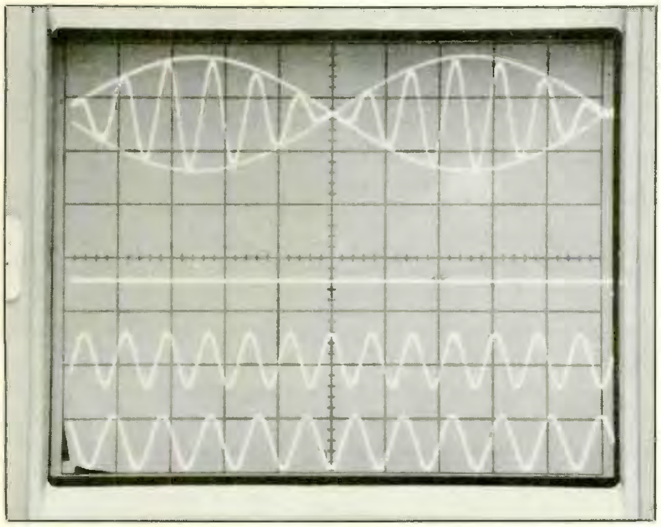

Fig. 8. Shown here is what the antenna presents to the receiver from a single-sideband reduced-carrier transmission (equal amplitudes).

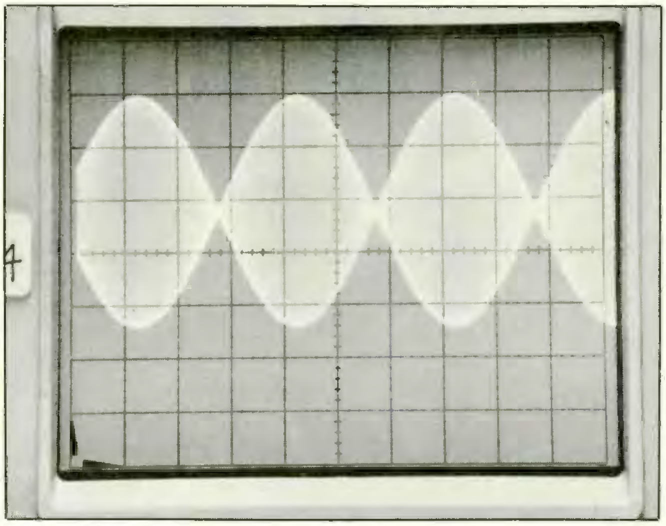

Fig. 9. Frequencies of 600 kHz and 602 kHz are shown here received with equal strengths; the results are similar to those illustrated in Fig. 8.

modulation envelope shown in Fig. 5 has been added for purposes of clarity. Although linearly mixed, each component frequency would be heterodyned with a receiver's local oscillator to produce its own intermediate frequency (i-f) . . . and combine linearly.

The following observations are worth making at this point:

(1) Carrier and sidebands do not vary in their peak-to-peak amplitudes and are true CW signals as long as the same modulation continues.

(2) While the phase relationship between the three signals is constantly changing, there is a repetitive pattern to this change that occurs at the frequency of the audio component.

(3) Both sidebands are in-phase with the carrier to form the modulated peaks, and both sidebands are out-of-phase with the carrier to form the valleys.

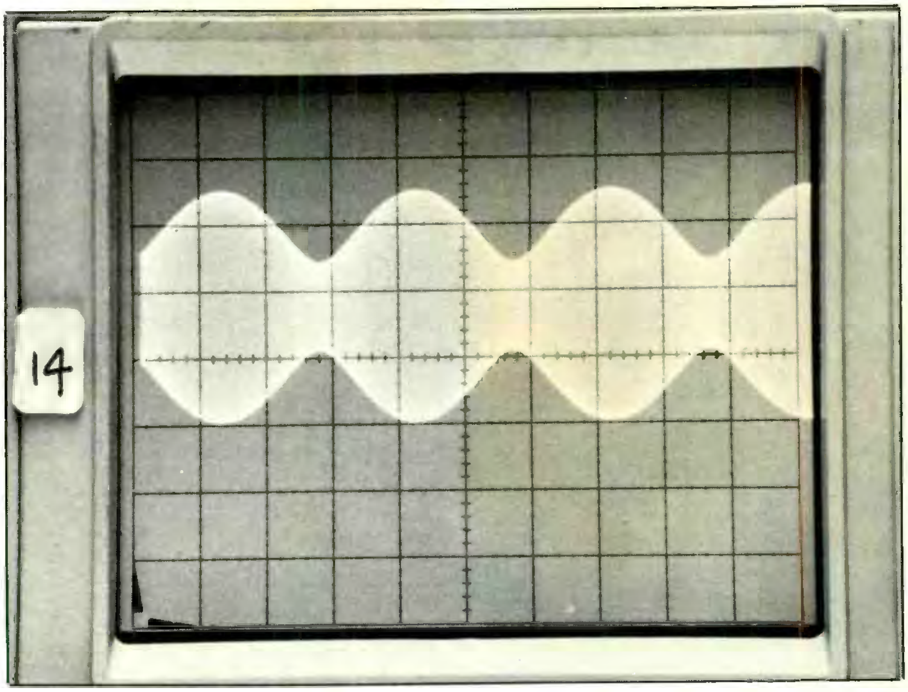

Fig. 10. Improved single-sideband envelope, where carrier has twice the amplitude of the sideband.

Nonsinusoidal Factors

When the carrier is completely eliminated, the receiving antenna has only the sidebands with which to work and combines them into the shape shown in Fig. 6. This modulation envelope has variations at twice the frequency of the true audio component, which can be seen for reference in Fig. 5. Not so noticeable here is the fact that the variations are not sinusoidal, the relatively few "r-f" cycles not being able to outline the shape clearly. (The single sideband photo shown in Fig. 9 gives a better idea of the pulsating waveform.)

When a signal that is equivalent in frequency and phase to the original carrier is inserted by the receiver, a modulation envelope more like the original is created when it combines with the sidebands. If its amplitude is insufficient, some of the second harmonic shown in Fig. 6 is revealed. If its amplitude is twice that of either sideband, a 100-percent modulated envelope will appear. If its amplitude is greater than this, something less than 100 percent modulation is recreated, but any detected audio would be essentially the same in peak value as under 100-percent modulation.

What happens to the recreated modulation envelope if a reintroduced carrier is shifted approximately 30 degrees from its proper phase is illustrated in Fig. 7. This apparent "filling in" of the envelope valleys continues to increase with phase shifts up to 90 degrees and the beat note between sidebands begins to become apparent. With a 90-degree shift, what would otherwise have been 100-percent modulation appears to be less than 20-percent modulation, and distortion is severe.

When a conventional receiver is receiving a single sideband with reduced carrier, both of the same amplitude, the signal illustrated in Fig. 8 is the best reconstruction that the receiver can manage. It is easy to confuse what the true audio component should be when examining this photo. Ideally, it would be the same as the audio shown in Figs. 5 and 7.

By covering the entire bottom half of the modulated signal, the true shape of the demodulated audio is revealed. What would be the negative peak of a sine wave is a very sharp peak, indeed. The recovered audio would (and did) look very much like the output of an unfiltered full-wave rectifier. What appears to be and actually is two overlapping sinusoidal waves are exactly one-half of the true frequency of the audio. This is not something that can be recovered, nor would it be desirable to recover it when voice or music is being transmitted.

Results shown in Fig. 8 seemed to be so very bad that they were double checked by actually transmitting and receiving CW signals of 600 and 602 kHz. The signals were followed through an old vacuum-tube receiver as they were "superheterodyned" in-

(Continued on page 90)

Mixing Frequencies *(from page 33)*

to intermediate frequencies and even individually checked there with a frequency counter.

The examination revealed one of the unsung marvels of the superhet: the intermediate frequencies maintain proper relative amplitude and phase relationships and thereby mimic the shape of the signal at the antenna very nicely. This test yielded the photo shown in Fig. 9, confirming the result shown in Fig. 8. A considerable improvement was realized when the amplitude of the sideband was reduced to half that of the carrier, shown in Fig. 10.

Further reducing the sideband for a 1:3 amplitude ratio gave additional improvement, but the modulation envelope never actually became sinusoidal, and the percentage of modulation decreased even more. Perhaps at near 0-percent modulation a sinusoidal variation in the envelope may almost be there.

This single sideband information may be of use to someone who is attempting to modify a conventional receiver. However, the secret to whatever success SSB operation enjoys is in an additional heterodyning step that is not found in, for example, the AM broadcast-band receiver. There is simply no way to recreate a good modulation envelope by *linearly* mixing carrier and one sideband. Acceptable audio more likely comes from generating a proper carrier and heterodyning it with the output from the final intermediate-frequency range. By filtering out all audio frequencies, only the difference frequency remains, and that is the audio. ME