Chapter 3: Amplitude Modulation

Chapter 3 Objectives

At the conclusion of this chapter, the reader will be able to:

- Explain conceptually how an AM signal is created.
- Use an oscilloscope to measure the percentage of modulation of an AM signal.
- Predict the frequency-domain characteristics of simple AM signals.
- Measure the various parameters of an AM signal using a spectrum analyzer.

Of all the methods of impressing information onto a carrier signal, AM is the oldest. It dates back to the beginning of radio. Although it's old technology, it is still widely used in the following applications:

- Local broadcast (535 - 1620 kHz in the USA)
- Aircraft communications in the 118-138 MHz band.
- Short wave broadcasts in the HF bands (3-30 MHz), which affords worldwide coverage.
- Analog television, in which an AM carrier is used for the picture, and a separate FM carrier frequency is used to carry the sound.
- Data communications, in which AM and PM (phase modulation) are used together in high-speed modems, the subject of a later chapter.

With all of these applications (and more), "Ancient Modulation" is hardly obsolete technology. *AM is an electronic fundamental!*

3-1 Generating an AM Signal

As you recall, radio uses a high-frequency sine wave called a *carrier* to move information from the transmitter to the receiver. Intelligence can be impressed onto a carrier signal in three ways:

- Amplitude Modulation (AM): The *amplitude* or *strength* of the carrier signal is changed in step with the information. (In place of the word *amplitude* we can substitute voltage, power, or current.)
- Frequency Modulation (FM): The *frequency* of the carrier is changed with the intelligence signal. The frequency changes are normally small and hard to see on an oscilloscope (but you probably already guessed, they are easy to see on a spectrum analyzer!)
- Phase Modulation (PM): The *phase angle* of the carrier signal is changed to convey the information. PM is very similar to FM, and is very hard to observe accurately on an oscilloscope.

Figure 3-1 shows two carrier signals that have been modulated by the same information signal. Note how the *shape* of the AM signal is quite distinctive. The information is actually contained in this shape.

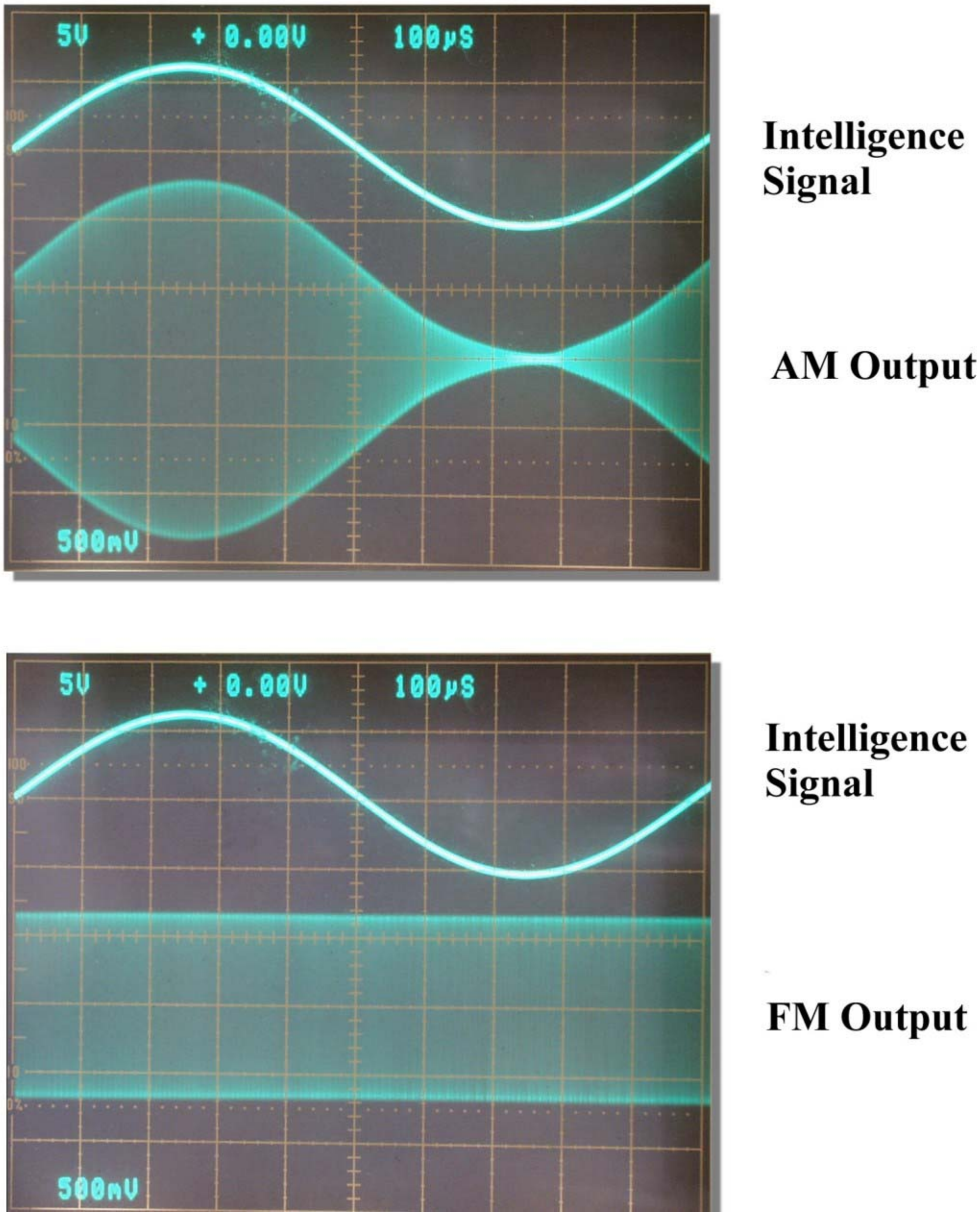

Figure 3-1: AM and FM signals on a scope

In contrast, the FM signal looks like a solid horizontal band. You really can't see much here at all! In fact, when the carrier frequency is much higher than the information frequency (as it is here), both FM and PM look identical on a scope. FM and PM signals have a constant power.

We need to use a spectrum analyzer to measure an FM or PM signal accurately. We'll learn how to do this in a later chapter.

Example 3-1

What is the frequency of the *information* signals in Figure 3-1? The horizontal timebase is set for 100 σS / division.

Solution:
The scope is measuring in the time domain, so we must first calculate the time period of the waveform:

$$T \mid (10\,div)(100\,\sigma s/div) \mid \underline{\underline{1\,ms}}$$

and the frequency is therefore:

$$F \mid \frac{1}{T} \mid \frac{1}{1\,ms} \mid \underline{\underline{1\,kHz}}$$

Example 3-2

Why do the modulated waveforms of Figure 3-1 appear as solid areas? Why can't we see the individual sine wave cycles of the AM and FM carriers?

Solution:
The *frequency* of the RF carriers is much higher than that of the information. In fact, the carrier frequency of both the AM and FM waveforms is 1 MHz. Recall that the information frequency is 1 kHz. Since 1 MHz is the same as 1000 kHz, *1000 cycles of carrier take place for every cycle of information*. Since the oscilloscope is adjusted to show one cycle of information, it also sees 1000 cycles of carrier. The carrier sine waves blend together, forming a solid figure.

Tip:
When observing modulated signals on a scope, it usually best to use two scope channels. One of the scope channels is connected to the information, and the other is connected to the modulated output. *The trigger must be set to the channel providing the information, in order to obtain a stable display*. Many people forget this and have trouble getting accurate scope readings of transmitter outputs!

Making an AM signal

Figure 3-2 illustrates the conceptual process of amplitude modulation. Almost all AM transmitters work this way. When analyzing an actual circuit, it helps to keep this picture in mind.

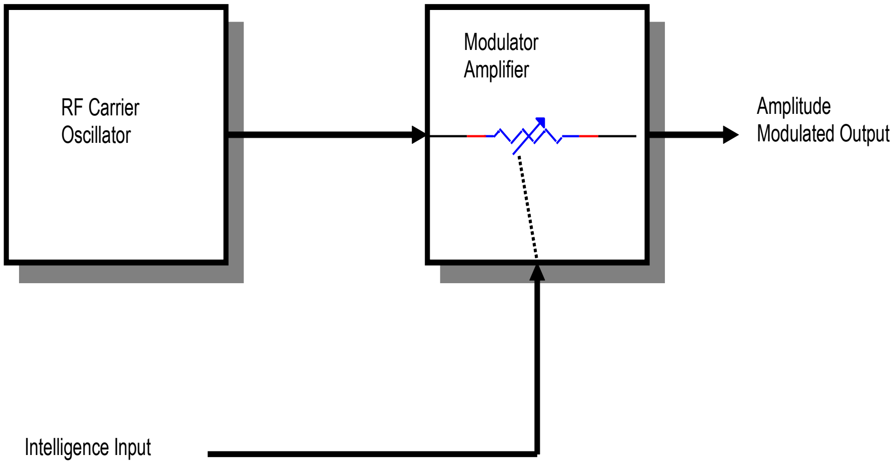

Figure 3-2: Generating an AM signal

The first stage in any transmitter is an *oscillator*. In a radio transmitter, it is usually called the *RF carrier oscillator*. The carrier oscillator converts the DC power supply energy into a radio frequency (RF) carrier wave. Oscillators will be studied in detail later.

The RF carrier wave contains no information until it is modulated. In order to amplitude modulate the carrier, its voltage (or power) must be changed. In order for the amplitude to be changed, the *voltage* or *power* gain of a subsequent stage must be changed.

The AM generator above has a special amplifier with a *variable* voltage gain called a *modulator*. This is really strange! The amplifiers you studied in fundamentals had a *constant* voltage or power gain, and only one input (this one has two!) An amplifier with a constant gain is called a *linear amplifier*.

What controls the gain of this amplifier? That's right -- there's a *second* input signal, the *information signal*. When the information signal goes positive, the amplifier's gain increases. This causes the output voltage (the AM signal) to swell or grow in amplitude. The opposite happens on the negative half-cycle of the information. The AM signal shrinks in amplitude because the amplifier's gain has decreased. Thus, amplitude modulation is created.

The variable-gain amplifier is a *nonlinear* amplifier because it has a gain that is not constant. One way of thinking of this amplifier is as a variable-resistor that controls the amount of carrier signal that gets through. The value of the "resistor" is controlled by the instantaneous value of the information signal.

A nonlinear amplifier distorts or changes the input signal. This is normally a bad thing! However, RF engineers carefully control this nonlinearity when they design modulators so that only a proper AM signal is produced.

A linear amplifier has a constant gain, and generates no distortion of the input signal. The graph of input-versus-output for a linear amplifier is a straight line (hence, the word "linear.") A nonlinear amplifier has a variable gain; its input-output graph is a curve. A nonlinear amplifier is always required to generate AM.

Section Checkpoint

3-1 List three applications of AM.
3-2 Why are FM and PM hard to observe on an oscilloscope?
3-3 What instrument is preferred for measuring FM and PM signals?
3-4 Why does the variable-gain amplifier stage in Figure 3-2 generate AM?
3-4 A non-________ amplifier stage is required to generate AM. (Fill in the blank)

3-2 Measuring AM Signals in the Time Domain

By interpreting the display of an AM signal on an oscilloscope, a technician can determine a lot about the operation of an AM transmitter. By examining the waveform, a technician can determine what type of information is modulating the transmitter, as well as the *percentage of modulation*.

How the Information is Conveyed

In an AM signal, the information is carried on top of the RF carrier. The actual shape of the carrier is altered by the addition of the information during the process of modulation. When we look at a modulated AM carrier wave, we tend to see an overall shape. The imaginary lines that make up this shape are called the *envelope*.

Can you tell what is significant about the envelope in Figure 3-3?

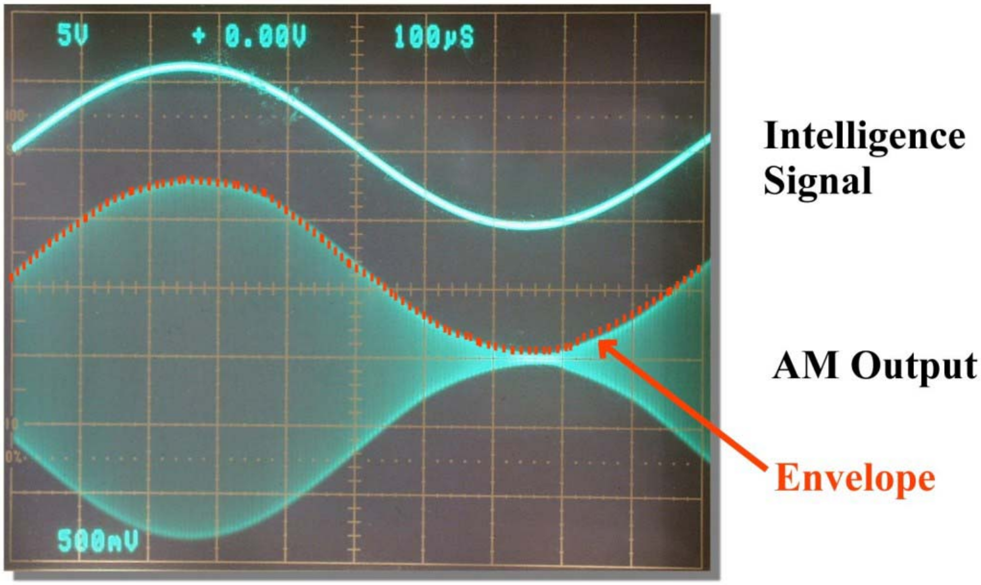

Figure 3-3: The envelope of an AM signal

AM Envelope is a copy of the information

Yes -- the envelope is copy or duplicate of the intelligence signal! No matter what the information is, the AM envelope will always appear as an exact copy of it. Take a look at Figure 3-4.

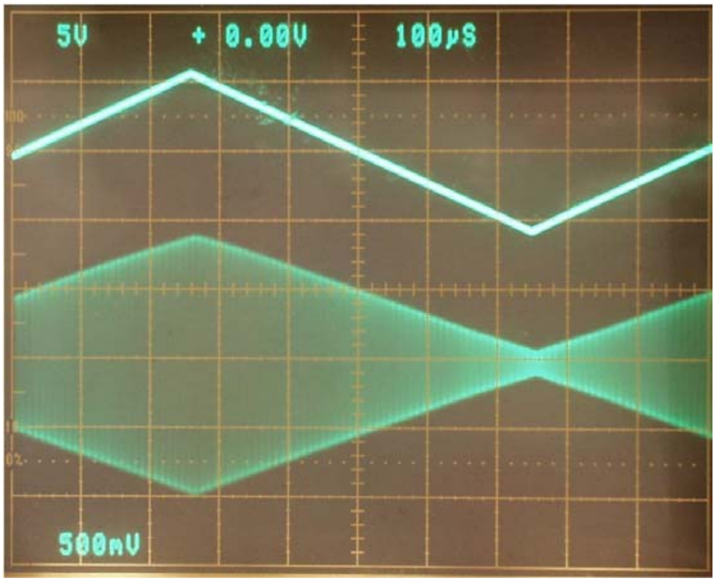

Figure 3-4: A triangular information signal

Again, the envelope looks just like the information signal on top. Another case might look like Figure 3-5.

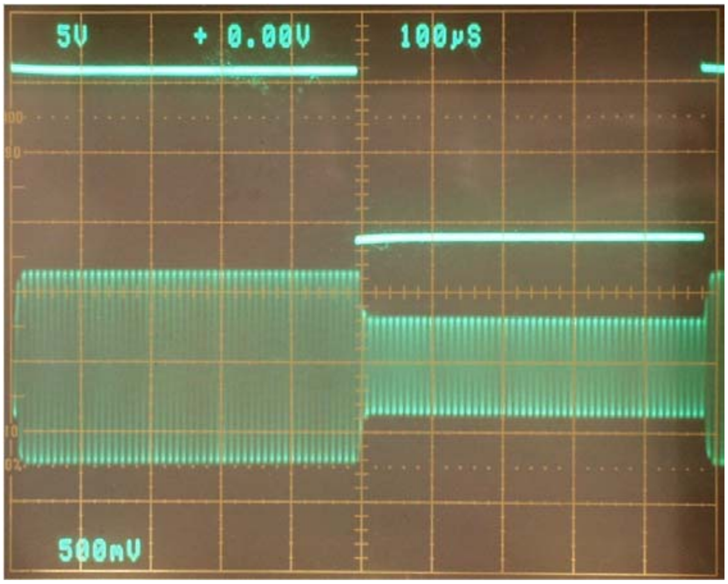

Figure 3-5: A square wave information signal

As you can see from Figures 3-4 and 3-5, the envelope always matches the shape of the information. Figure 3-5 is a special case; can you tell what the source of the information might be? If you're thinking *digital*, you're on the right track. The information signal of Figure 3-5 is *digital data*, which is sent as a sequence of binary ones (highs) and zeros (lows). We'll study digital data communications in a later chapter.

Percentage of Modulation and AM Modulation Index

In an AM signal, the *percentage of modulation* is a measure of how strongly the carrier wave is being changed by the information. For radio, the higher the percentage of modulation, the louder the signal will be in the receiver's loudspeaker. Because percentage of modulation relates to sound volume, it would make sense that a broadcaster would try to attain as high a percentage of modulation as practical.

The maximum percentage of modulation is 100%, which represents maximum intelligence voltage (or volume). 0% modulation means that no modulation is taking place; the transmitter is said to be *dead-keyed* or *unmodulated* in this case.

The *AM modulation index* is the *same* information as the percentage of modulation. It is given the symbol ***m*** and can have a value between 0 (0% modulation) and 1 (100% modulation). When we calculate percentage of modulation in an AM signal, we are really calculating the *modulation index*.

Remember that the maximum modulation index is 1 (which corresponds to 100% modulation). A signal that is over 100 percent modulated is said to be *overmodulated*, which is an illegal condition. Overmodulation distorts the information and causes excessive bandwidth to be used by the transmitter.

Example 3-3

What percentage of modulation corresponds to a modulation index *m* of 0.5 ?

Solution:
Since m=0 means 0% modulation and m=1 means 100% modulation, we get:

$$\%Modulation \mid m \Delta 100\% \mid 0.5 \Delta 100\% \mid \underline{\underline{50\%}}$$ [1]

Remember that modulation index and percentage modulation both represent the same measurement for an AM signal. (They are different quantities for FM, as we'll see later.)

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[1] Note that multiplying any value by "100%" is really multiplying it by 1. We do this because a percentage is more intuitive for most people than a fraction.

The AM modulation index is defined by the formula:

Definition of the Modulation Index

$$(3\text{-}1)\quad m \,|\, \frac{Vm}{Vc}$$

Where *Vm* is the information voltage, and *Vc* is the carrier voltage.

Equation 3-1 *defines* the modulation index, but is not very helpful in making oscilloscope measurements. This is a *frequency domain* definition. On a scope, it is difficult to separate the voltages *Vm* and *Vc* (but on a spectrum analyzer, it is quite easy, as we'll see).

Measurement of the Modulation Index

To measure the modulation index on an oscilloscope, the following formula is used:

$$(3\text{-}2)\quad m \,|\, \frac{V\max 4\, V\min}{V\max 2\, V\min}$$

Where *Vmax* is the maximum waveform voltage (the peak), and *Vmin* is the minimum waveform voltage (the trough) (See Figure 3-6). Note that since we're using an oscilloscope to obtain the measurement, Equation 3-2 is really a *time-domain* formula.

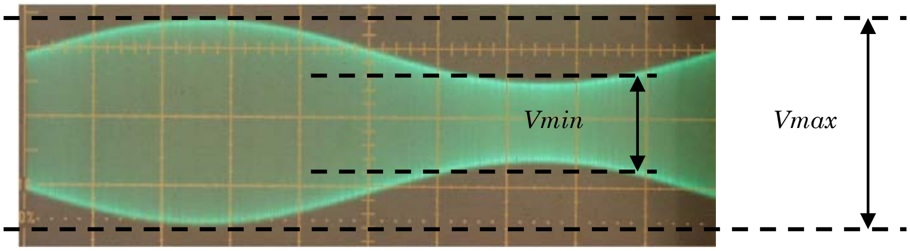

Figure 3-6: Measuring percentage modulation

Example 3-4

What is the modulation index and percentage of modulation in Figure 3-6? The vertical sensitivity is 1 volt/division.

Solution:
Since we're measuring from an oscilloscope, we use equation 3-2:

$$m \,|\, \frac{V\max 4\, V\min}{V\max 2\, V\min} \,|\, \frac{3\,Vpp\,4\,1\,Vpp}{3\,Vpp\,2\,1\,Vpp} \,|\, \underline{\underline{0.5}}$$

The percentage modulation is the modulation index expressed as a percentage:

$$\%Mod \,|\, 100\%\Delta m \,|\, 100\%\Delta 0.5 \,|\, \underline{\underline{50\%}}$$

Tip: To adjust an AM transmitter for 50% modulation, adjust the intelligence voltage so that the ratio of V_{max} to V_{min} is 3:1. (Notice how we have V_{max}=3 Volts and V_{min}=1 Volt in this case). Also, V_{max} and V_{min} can be measured in either peak or peak-to-peak units -- as long as they are both measured the same way.

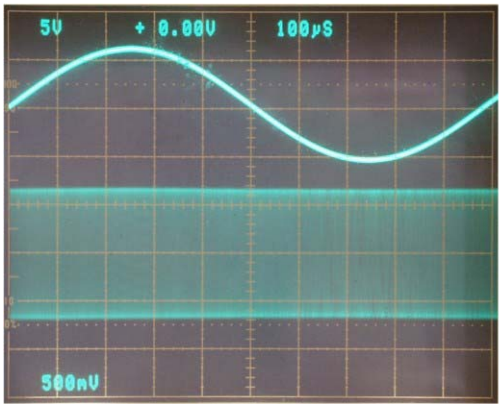

Figure 3-7: A Special Case for Examination

Example 3-5

What is the percentage of modulation in Figure 3-7? What is the condition of the transmitter? The vertical sensitivity is 1 volt/division.

Solution:
Since we're measuring from an oscilloscope, we again use Equation 3-2:

$$m \,|\, \frac{V\max 4\, V\min}{V\max 2\, V\min} \,|\, \frac{2.8Vpp\, 4\, 2.8Vpp}{2.8Vpp\, 2\, 2.8Vpp} \,|\, \underline{\underline{0}} \,|\, \underline{\underline{0\%Modulation}}$$

This is an example of an *unmodulated* transmitter. No information is being conveyed. We can also say that the transmitter is "dead keyed" or is transmitting "dead air." This is normally undesirable, especially in commercial broadcasting where time is money!

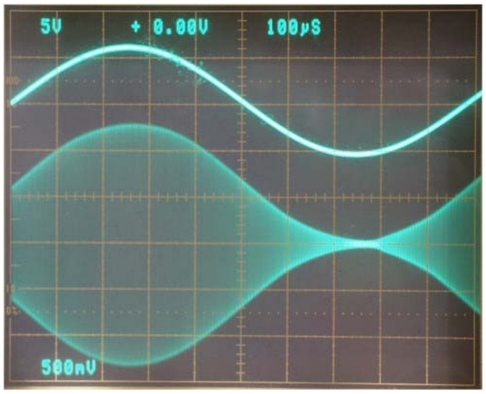

Figure 3-8: Another signal for analysis

Example 3-6

Without doing any calculations, what is the percentage of modulation in Figure 3-8?

Solution:
The *trough* in Figure 3-8 is nearly zero, and the envelope maintains the shape of the information. *This indicates that 100% modulation (or something very close) is being achieved.* No calculations are needed!

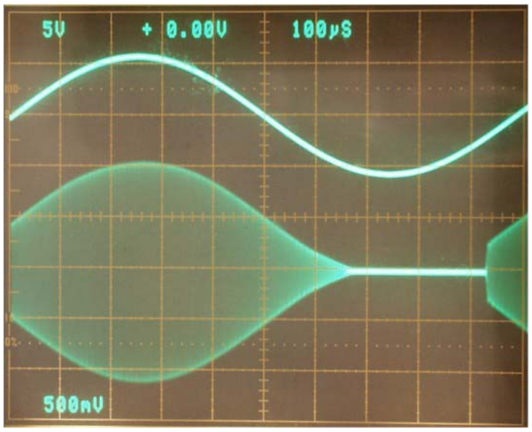

Figure 3-9: Too Much Information Voltage - Overmodulation

Example 3-7

What is wrong with the AM signal of Figure 3-9?

Solution:
This is an example of *overmodulation*. The intelligence voltage is too big to fit onto the carrier, and as you can see, it has caused the trough to flatten. There are two problems here. First, the *envelope* is no longer an accurate copy of the information. The transmitted information will sound distorted.

Second, *excessive bandwidth* will be used, which can cause *interference with adjacent stations on the band*. This effect is called *splatter*. It is hard to see it on a scope (but again, a spectrum analyzer gives a much clearer view of what is happening).

Overmodulation is not a good practice. It distorts the information, uses up precious bandwidth, and can be stressful on station equipment. It could have been avoided here by reducing the voltage (volume) of the information.

Section Checkpoint

3-5 What is the *envelope* of an AM signal? What is significant about the shape of the envelope?
3-6 If the information is a square-wave, what shape will the envelope of the resulting AM signal be?
3-7 To calculate the percentage of modulation of an AM signal from an oscilloscope screen, what two measurements are required?
3-8 What is the maximum allowed percentage of modulation for an AM signal?
3-9 Why do AM broadcast stations use as high a percentage of modulation as possible?
3-10 What are two consequences of *overmodulation?*

3-3 Frequency Domain AM Analysis

As you'll recall from Chapter 2, there are two ways of examining electronic signals. We can look at signals in either the *time* or *frequency* domains. AM signals are very predictable in the frequency domain, which is important. When we know the frequency domain picture, it's easy to calculate and measure the *bandwidth* and *total power* of an AM signal.

The Frequency Domain Revisited

Figure 3-10 shows a 100 kHz sine wave carrier in the frequency domain. How do we know this is a *sine* wave? Right, there's only one frequency present, 100 kHz. The sine wave is the only "pure" waveform, and it contains only one frequency. This particular sine wave is 10 volts RMS (about 14.1 volts peak).

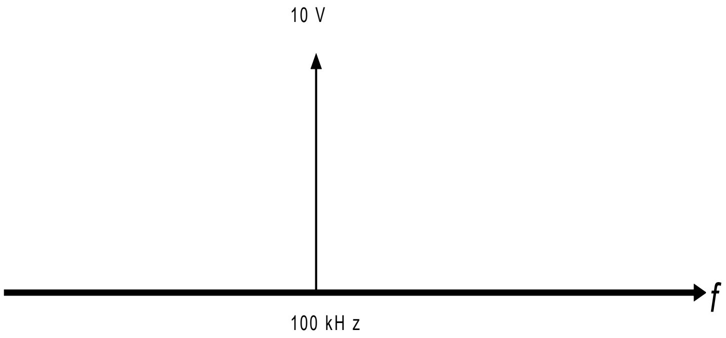

Figure 3-10: An unmodulated 100 kHz carrier

AM Sidebands

What happens when this carrier signal is amplitude modulated? In the time domain, we know that the instantaneous voltage of the carrier will be forced to grow and shrink in step with the information. The nonlinearity of the modulator (the variable-gain stage) causes this to happen. In the frequency domain, the rapidly changing amplitude shows up as new frequencies called **sidebands**.

***Sidebands* are new frequencies generated during the process of modulation. They are created by the nonlinear distortion introduced by the modulator amplifier. All modulation creates sidebands - whether it be AM, FM, or PM.**

Suppose that the 100 kHz carrier of Figure 3-10 is amplitude modulated by a 10 volt, 5 kHz information signal. The resulting frequency domain picture will look like Figure 3-11.

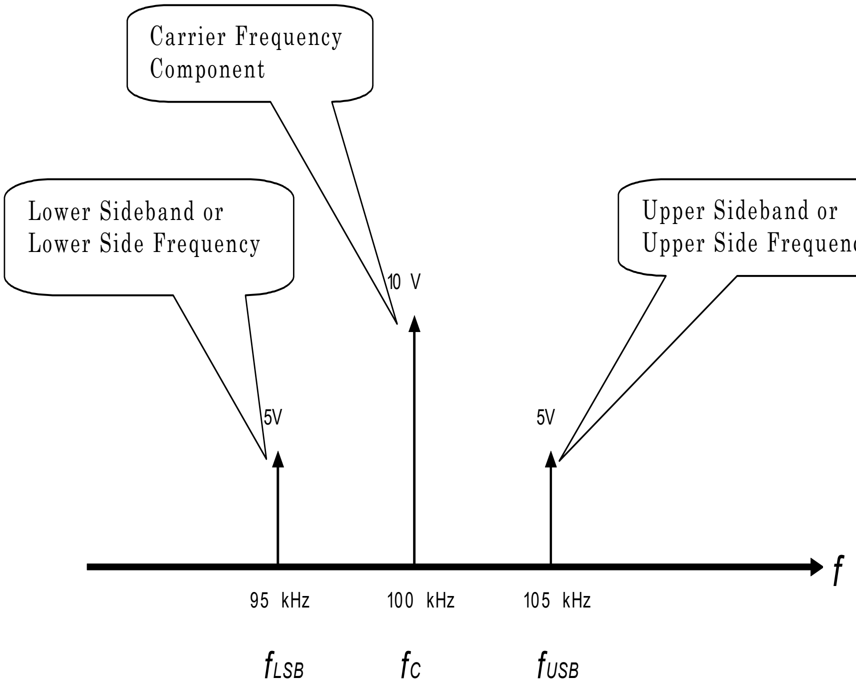

Figure 3-11: The 100 kHz Carrier Modulated with 5 kHz Information

Note that some people use the term *side frequency* and others use *sideband* to describe these new frequencies. A side frequency is an *individual* frequency that can be part of a *range* of frequencies in a *sideband*. Since each of our sidebands in this example have only one frequency each (95 kHz for the lower sideband and 105 kHz for the upper sideband), we can use either term to correctly describe the signal.

What are the Sidebands?

The result of Figure 3-11 leads to some important questions. For example, what has happened to the 5 kHz *information* signal? To get the AM modulated signal of Figure 3-11, two signals had to be applied to the modulator stage. These were the 100 kHz sine wave carrier, and the 5 kHz information. The 5 kHz information signal seems to have disappeared! In reality, *the information frequency (5 kHz) has been transformed into sideband frequencies (95 kHz and 105 kHz).*

This transformation takes place with the help of the nonlinear transfer characteristic of the modulator stage. Therefore:

The sidebands contain the information. They can be thought of as an "encoded" representation of the intelligence.

To calculate the frequencies of the sidebands, we use the following equations:

(3-3) $f_{usb} = f_c + f_m$

(3-4) $f_{lsb} = f_c - f_m$

In these equations, f_c is the carrier frequency, and f_m is the information frequency.

Sideband Voltages

The sidebands are the information expressed in a new way. Notice that we got *two* sidebands from *one* information frequency. Our original information *voltage* was 10 volts; yet the sidebands are only 5 volts each in Figure 3-11. Why is this so? Right -- because the information voltage causes *two* sidebands to form, its voltage must be *divided by two* in order to form each sideband. Therefore, we get:

(3-5) $V_{usb} = V_{lsb} = \frac{V_m}{2}$

Here, V_{usb} and V_{lsb} are the sideband voltages, and V_m is the information voltage.

Example 3-8

Calculate the *bandwidth* and *modulation index* of the AM signal shown in Figure 3-11.
Solution:
We know that bandwidth is calculated by finding the difference between the highest and lowest frequencies in a signal. Therefore, we get:

$$BW = f_{\max} - f_{\min} = f_{usb} - f_{lsb} = 105kHz - 95kHz = \underline{\underline{10kHz}}$$

Finding the modulation index is a little trickier, but not too difficult. Since we're working in the frequency domain, we will use equation 3-1:

$$m = \frac{Vm}{Vc}$$

We know that V_m and V_c are given in the original problem definition, however, we are asked to get the information from Figure 3-11. Finding V_c is easy; we just read it off the spectrum analyzer display as 10 volts.

Remember that each sideband comes from the information. Therefore, each sideband voltage is one-half of the information voltage. By using equation 3-5:

$$V_{usb} = V_{lsb} = \frac{V_m}{2}$$

$$Vm = V_{usb} + V_{lsb} = 2V_{usb/lsb}$$

Where $V_{usb/lsb}$ is the voltage of either sideband (since they're identical).

$$Vm = 2V_{usb/lsb} = 2(5V) = 10\ volts$$

Since we now know both V_m and V_c, we can calculate the modulation index:

$$m = \frac{Vm}{Vc} = \frac{10V}{10V} = \underline{\underline{1}}$$

The signal is 100% modulated.

TIP: You'll often see a basic equation such as 3-1 or 3-2 used in many different ways. Don't try to memorize all of these variations! Instead, just learn the basic equation, and concentrate on studying *how* we have applied it. *Look for basic principles*. For example, the basic idea here is that the information voltage "splits" into two sidebands during modulation. This will always happen in amplitude modulation.

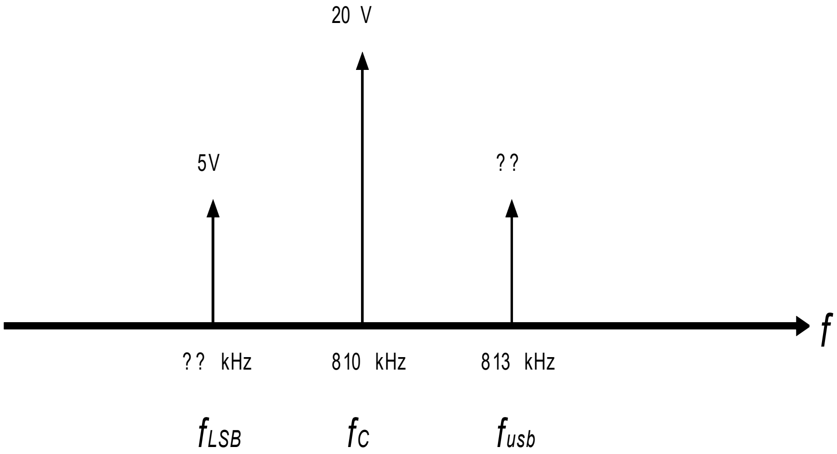

Figure 3-12: An AM Signal

Example 3-9

For the AM signal pictured in Figure 3-12, calculate the following:

a) The information frequency, f_m
b) The voltage in the upper sideband, V_{usb}
c) The bandwidth
d) *m* and Percent Modulation

Solution:
The information frequency is carried in the *difference* between either sideband and the carrier. The lower sideband frequency f_{lsb} is missing; however, we do know f_{usb}. By manipulating equation 3-3, we get:

$$f_m = f_{usb} - f_c = 813\ kHz - 810\ kHz = \underline{\underline{3\ kHz}}$$

The sidebands are identical twins; their voltages are always equal. Therefore:

$V_{usb} = V_{lsb} = \underline{\underline{5\ volts}}$ (The 5 volt value is given in Figure 3-12).

As we've done before, bandwidth can be calculated by:

$$BW = f_{\max} - f_{\min} = f_{usb} - f_{lsb}$$