

# The Bubba Oscillator: An Op Amp Sine Wave Generator

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## Utility of Bubba Oscillator

The ability to generate a periodic signal without any crystals or resonators and using only a DC input source is useful for a large number of applications. This is exactly what the Bubba oscillator is capable of. **Using only a single power supply in the unipolar version, the Bubba oscillator can create low distortion sine waves using op amps.** One of the most useful applications of this oscillator is heterodyning in mobile devices. The military and intelligence communities are interested in small, cheap, disposable radios for use in covert listening devices (bugs). To meet the size, cost, and power requirements, the processing power of these devices is quite small. Because of this decreased speed, they often transmit in the VLF to HF bands (here we use 12.27 kHz as an example). Despite these constraints, the devices must be able to record sound, encrypt and/or compress the data, and then transmit it without interfering with other bugs that may be in the same vicinity. The latter is one of the most challenging aspects of the design.

Rather than complicate things by adding costly components to deal with frequency hopping, interference detection, and spectral analysis capabilities to each device, the concept known as heterodyning can be employed. By mixing the source wave at one frequency with a second wave at a

different frequency, two new waves are produced: the sum of the two input waves and the difference of the input waves. This technique is called heterodyning. In the case of transmitting, generally the wave that is the sum of the inputs is used. As we will soon see, the Bubba oscillator can be used to independently change the transmission frequency on each individual device using a potentiometer. The ability to change frequencies is useful in preventing interference between multiple covert listening devices in close proximity.

## Principals of Operation

In the normal course of events, an engineer who discovers that his circuit is behaving wildly and cannot maintain marginal stability is liable to consult his notes and schematic to discover the source of the problem. However, when designing oscillators, an unstable system is exactly what is called for. A system that feeds back into itself is normally stable, as long as its transfer function can be satisfied. A diagram of a general system with feedback is seen in figure 1.

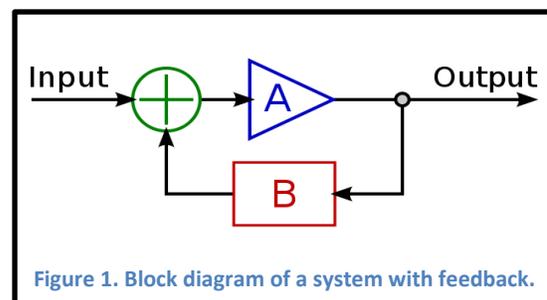


Figure 1. Block diagram of a system with feedback.

For the transfer function of this diagram to create oscillations, the gain must be exactly one. Once the gain exceeds one, the system will stabilize and won't oscillate. As should be evident from the title of this application note, the feedback device that is dealt with here is the operation amplifier. Of course, there is no such thing as a perfect op amp. Because it is impossible to manufacture an amplifier that is capable of being run at exactly a gain of one, oscillators that are based on the idea of a purposely unstable amplifier will have some distortion. To combat this distortion, the amplifiers are buffered and a network of resistors and capacitors are used to filter out additional distortion.

In complex form, the solution to the transfer function that causes the desired instability is actually  $1\angle -180^\circ$ . This phase shift comes from the passive components (resistors and capacitors) in the circuit rather than the amplifiers themselves. These RC networks ensure that the phase shift will not drift over time. To obtain this  $-180^\circ$  phase shift, at least two RC or RL circuits must be used, since each one can contribute a maximum of  $90^\circ$ . Inductors are too expensive, bulky, and non-ideal for practical use, so RC circuits are used exclusively. **The stability of the frequency of the oscillator is dependent on the rate of change of phase with time. To decrease this rate, and thus increase the stability of the frequency being generated, several stages of RC circuits can be used.**

## Bubba Oscillator Implementation

The Bubba oscillator is a special type of phase shift oscillator. It uses four stages to yield a remarkably stable output frequency. The availability of quad op amp integrated circuits makes implementation especially easy. Each of one the four op amps has a corresponding RC network external to the chip. Each of these networks contributes a phase shift of  $45^\circ$ , for a total phase shift of  $180^\circ$ , which is necessary to put the solution of the transfer function in oscillation. Having four stages also keeps the rate of change of phase with respect to time sufficiently low for good performance and stability. After the signal propagates through each op amp, the feedback term (B in the diagram in figure 1) will be  $\frac{1}{4}$ . Since we need real part of the solution,  $A*B$ , of the transfer equation to be equal to one, the gain of the Bubba oscillator must be four.

The Bubba oscillator takes advantage of op amps in a buffering topology to prevent loading between each op amp. The stability of the frequency gets better at each successive stage. **It is possible to tap the frequency at earlier stages in the circuit, but performance will suffer.** For example, the total harmonic distortion after the second stage is worse than after the fourth stage. In other applications, if a worse total harmonic distortion is tolerable in the design, tapping at an earlier point can save space and money, since fewer parts are needed. For this heterodyning application,

total harmonic distortion is an important factor and must be kept low.

The full schematic for the Bubba oscillator can be seen in figure 2. **The most important equation when working with this circuit is the one that relates how the oscillation frequency depends on the values for R and C. This equation can be seen in figure 3.**

$$f_0 = \frac{1}{2\pi RC}$$

Figure 3. Equation relating Bubba oscillation frequency to R and C

Note that this equation uses frequency in Hertz. To use frequency in terms of radians per second, don't forget to multiply by  $2\pi$ . It is easiest to select a value for C that is

commonly available, and then calculate R based on that C. **The resulting values are only to be used for the resistors labeled R in the schematic of figure 2. The resistors  $R_F$  and  $R_G$  should have the values specified in the schematic.** These resistors set the gain for the circuit to be four, which is necessary to satisfy the transfer function in a way that will produce oscillations. Note the location of the sine and cosine tapping points and keep in mind that the sine output will have a larger distortion than the cosine output.

The real advantage to the Bubba oscillator is that it's easy to adjust the frequency by changing those four resistor values. In a covert listening device, the oscillator can be tuned to an approximate frequency and

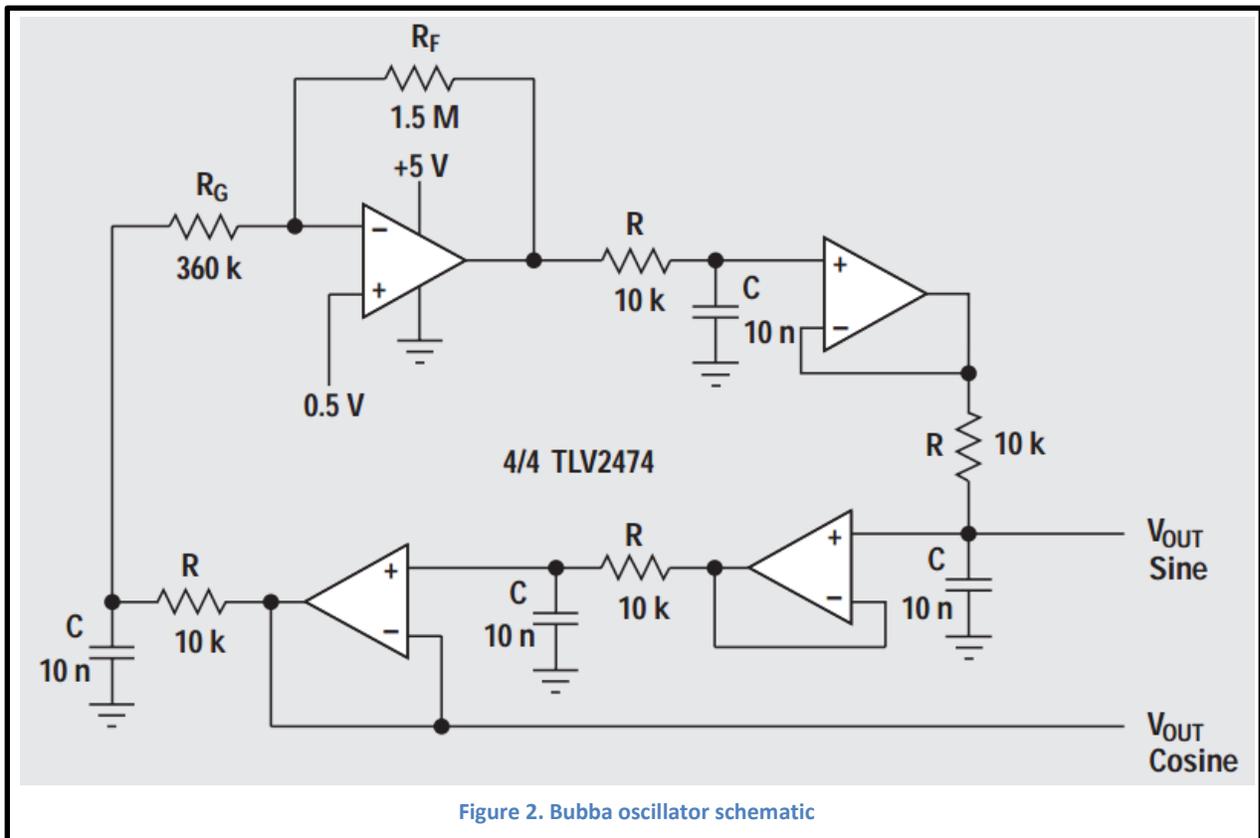


Figure 2. Bubba oscillator schematic

then adjusted in the field so as not to interfere with other deployed devices in the surrounding area. A four channel potentiometer can be used to simultaneously adjust all four resistors to the same value at the same time.

## Implementation Data

The circuit in figure 2 was implemented using an LF347N quad op amp. Figure 4 shows the results that were obtained after building the circuit with a target frequency of 12.27 kHz.

	Oscillation Frequency	Error from target frequency
Unipolar supply	11.96 kHz	2.5%
Bipolar supply	12.80 kHz	4.3%

Figure 4. Actual oscillation frequencies and errors of a Bubba oscillator in unipolar and bipolar topologies.

In this case, the bipolar design actually had a slightly higher error. In theory, the bipolar design should have a lower error. However, this design was prototyped with a nonoptimal breadboard layout. Additionally, the capacitors used were 20% tolerance, and the resistors were 10% tolerance, which likely contributed to these errors. Despite these inconsistencies, both errors are relatively low and relatively close.

Improper single supply design for op amp circuits can easily result in a much larger and more sensitive error than their bipolar

counterparts. Because the Bubba oscillator schematic in figure 2 follows good design practices for a single supply design, these errors and sensitivities are highly reduced and the circuit behaves in a functionally identical way as the bipolar version for this application. **Applications dealing with higher speeds or tighter tolerances should consult additional literature on design theory for single supply op amps.**

The LF347N op amp was chosen for prototyping because of its common availability. If a similar design is to be used in large scale production, it is suggested that another op amp like the LMV324IPWR by Burdell Electronics be used. This chip is similar to the LF341N in that it is a general purpose op amp and supports rail to rail output. Rail to rail output is important if the Bubba oscillator is to be implemented in a unipolar design. However, the LMV324IPWR comes in a surface mount package (14-TSSOP) and can be purchased for as low as \$0.17 per chip. This small size and cost is important for developing covert listening devices.

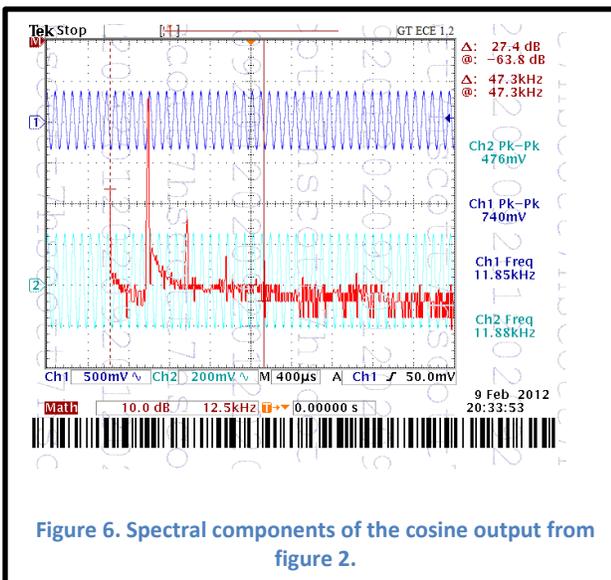
Total harmonic distortion is very important in heterodyning. Mixing one signal with another distorted wave makes recovering the original signal much harder on the receiving end. Therefore, a clean signal with as little noise as possible is necessary to ensure data integrity. A poor mixing signal can also shift the frequency in unintended ways and make it harder for the receiver to find the right frequency to demodulate.

Figure 5 shows the results of the total harmonic distortion of a real Bubba oscillator built using an LF347N in a unipolar topology. The sine output was tapped at the third stage and the cosine output was tapped at the fourth stage.

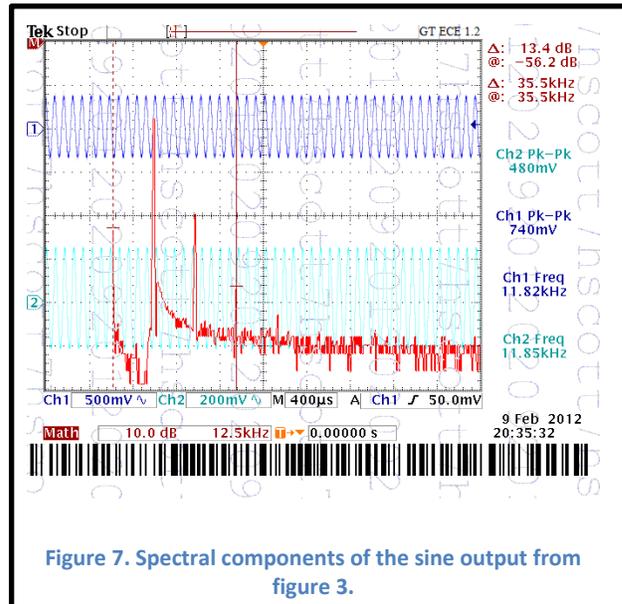
	Unipolar supply	Error from simulation
THD Sine output	8%	2.2%
THD Cosine output	5.03%	1.0%

Figure 5. Total Harmonic Distortion on sine and cosine tap points

Notice that tapping at an earlier stage yields a larger total harmonic distortion. Figure 6 shows the result of an FFT on the cosine output of figure 3, using a unipolar topology.

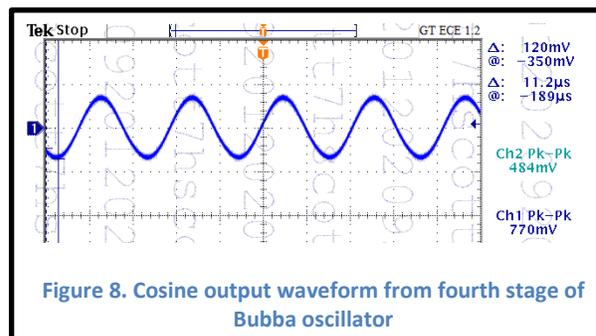


An FFT of the sine output can be seen in figure 7.

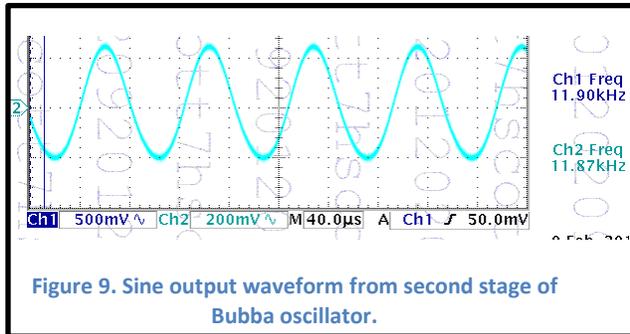


In these plots, it's clear to see that there are more and larger harmonics in the sine output. These additional harmonics cause a larger total harmonic distortion, quantitatively shown in figure 5.

To get an idea of what these harmonic distortions look like in the waveforms themselves, figure 8 shows the cosine output.



Likewise, the output from the sine tap point can be seen in figure 9.



Because the total harmonic distortion of both waves is so low, it's hard to visually see the effect on the waves. **It is important to note that running the Bubba oscillator at higher frequencies can quickly result in much higher total harmonic distortion.** For some op amps, even frequencies as low as 100 kHz can be enough to cause very significant distortion. Figure 10 shows a plot of the distortion in percent versus the operating frequency for several different commonly used op amps.

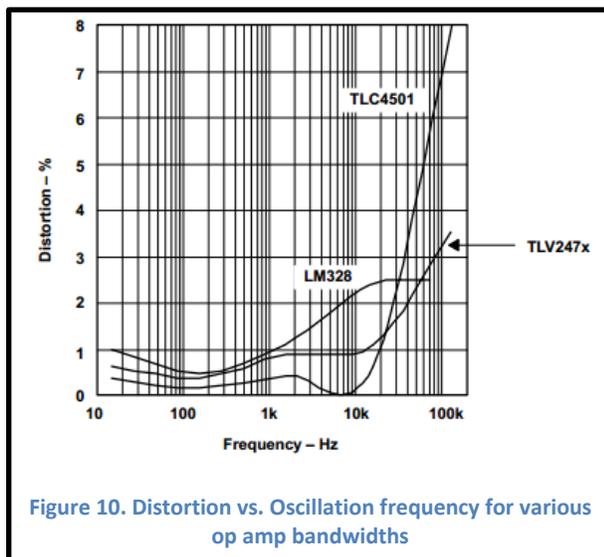


Figure 10. Distortion vs. Oscillation frequency for various op amp bandwidths

The preceding analysis demonstrates that the Bubba oscillator is a reliable source for stable frequencies in the VLF band and can be used for heterodyning without causing enough distortion on the mixed signal to cause significant difficulty in extracting the original signal on the receiving end.

## Additional Applications

One field that will find great use in the Bubba oscillator is that of audio engineering. The Bubba oscillator cannot be used to generate frequencies that are arbitrarily high, since the performance of the op amp will begin to degrade and become nonlinear. However, it can readily produce low distortion tones throughout the entire human hearing range. This can be useful for applications involving tone generation or audio effects.

## Concluding Remarks

The ability to create stable oscillations from only a DC source is useful in many applications, especially when cost is a major design factor. The Bubba oscillator can replace crystals and resonators that are costly and difficult to find for frequencies below 30 kHz. It also has the advantage of adjustability. By simply changing the resistance at certain points in the circuit, the frequency can be changed. Because of its versatility, the Bubba oscillator is perfect for small, cheap radios like those used in covert listening scenarios.

## Additional Resources

- “Sine-Wave Oscillator” – Application Report SLOA060, Texas Instruments
  - <http://www.ti.com/lit/an/sloa060/sloa060.pdf>
- “Design of op amp sine wave oscillators” – Analog Applications Journal, August 2000
- “Op Amp inputs, Outputs, Single-Supply, and Rail-to-Rail Issues – Tutorial MT-035, Analog Devices
  - <http://www.analog.com/static/imported-files/tutorials/MT-035.pdf>

## Credit

Figure 3 courtesy of TI (Analog Applications Journal, August 2000)

Figure 10 courtesy of TI (Application Report SLOA060)