HOMELAB PROJECT

Build Your Own Theremin

Using JFETs instead of vacuum tubes

Although the theremin was invented nearly 100 years ago, the instrument still has enthusiastic fans. It is played entirely without physical contact, and almost everyone will have heard one at some point. The original design from 1920, by Lev Termen, alias Léon Theremin, used vacuum tubes, but JFETs can equally well be employed. In this article we look at the development of an experimental design for a theremin that you can build yourself.

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The principle of operation of the theremin is straightforward and is based on the mixing of two RF signals to produce a beat frequency. One RF oscillator, called the 'pitch oscillator', has its frequency tuned by variations in the capacitance to the thereminist's hand thus adjusting the pitch of the note being played, while the other operates at a fixed frequency. The outputs of the two oscillators are taken to a demodulator which works on the same principle as an AM radio. Overall the circuit is very similar to a receiver for unmodulated Morse signals. For simplicity, then, our first experiment will use a ready-made radio receiver.

First experiments using the Elektor SDR shield

For our first experiments we will only build a single oscillator, whose frequency we can pull to a sufficient extent using the capacitance of a hand. To set this up we will use the Elektor SDR shield connected to an Arduino Uno running the standalone VFO software, along with an LCD panel on an Elektor extension shield. An arrangement like this has been described previously in Elektor for use at shortwave frequencies [1]. Here we use the shield as a direct-conversion mixer and we connect its output to an active loudspeaker, thus replacing the second oscillator and the mixer in the original theremin. It is easy to set the frequency of the beat oscillator very precisely (see **Figure 1**) and all we need now is the pitch oscillator. That will give use our first simple theremin, albeit without a volume control: an interesting application of the SDR shield.

The FET oscillator circuit shown in **Figure 2** operates at 420 kHz; moving your hand near to it will pull its frequency by up to 5 kHz. The antenna for the SDR is a length of wire simply placed close to the oscillator. The signal is so strong that only a weak coupling is required to the receiver. Instead of connecting a PC to the stereo output, we wire it directly to an

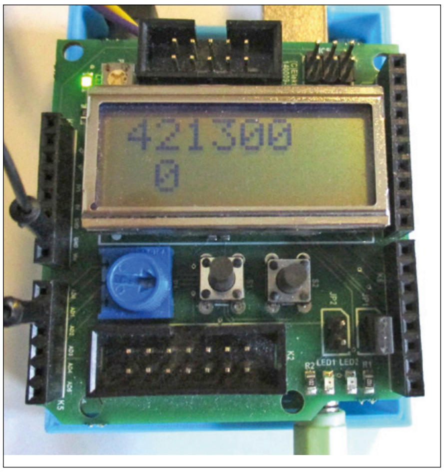

Figure 1. The receiver tuned to 421.3 kHz.

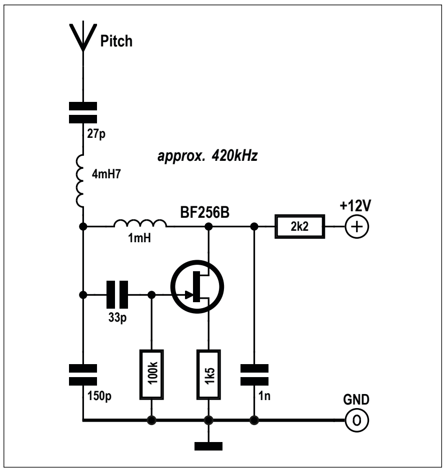

Figure 2. A simple pitch oscillator.

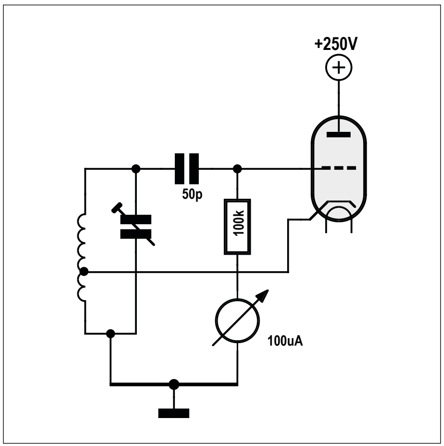

Figure 3. A grid dip meter using a triode.

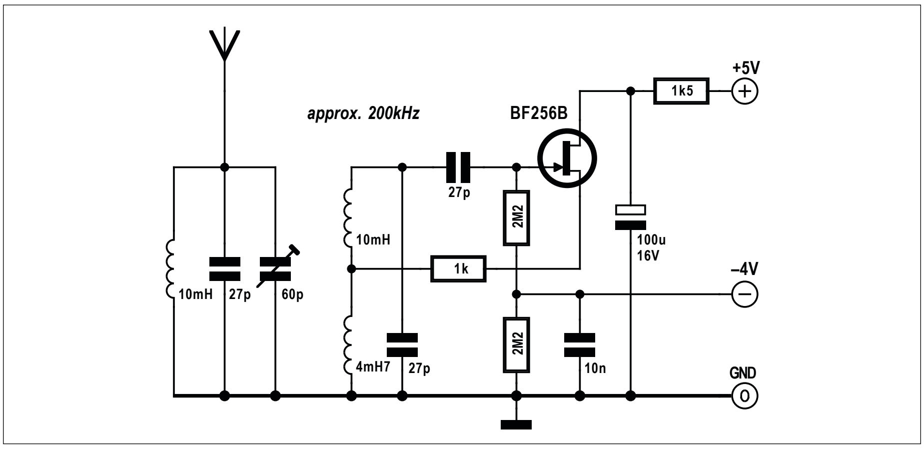

Figure 4. Modified FET dip meter.

active loudspeaker. The shield operates as a simple direct-conversion mixer without the need for any SDR software. The standalone software for the SDR shield and the extension shield allows the tuning to be adjusted easily and precisely. First it is necessary to use the buttons on the extension shield to locate the frequency of the oscillator and find the point where the beat frequency is zero. If you now move your hand close to the pitch oscillator its frequency will go down and the beat frequency will rise. And now it is just a question of a little practice, and you'll be able to play your first tune.

The connection to the antenna includes a 4.7-mH loading coil to increase its effective 'electrical length'. The result of this is to ensure that the very small extra capacitance introduced by the proximity of the hand, around one picofarad, can cause a sufficiently large change in frequency. A 1-mH inductor would require a capacitance of 143 pF for resonance at 420 kHz. With 144 pF of capacitance, the resonant frequency is 1.5 kHz lower. The load inductor considerably increases the size of this effect: you can visualize it as being equivalent to having a much longer antenna in the proximity of a much larger hand. The trick of using a loading coil was employed in the original theremin design and in variations on it ever since.

Putting it slightly more scientifically, a series resonant circuit has a low reactance near to its resonant frequency, which below this frequency corresponds to a large capacitance. The coil we have chosen here, in conjunction with an ordinary whip antenna, gives a measured resonant frequency of 600 kHz. This is not too far from the operating frequency of 420 kHz, which means that the capacitance of the hand has a noticeable effect. The result is that the sensitivity of the circuit to the capacitance of the hand is very good, with a useful working range of up to 30 cm. Because the oscillator frequency is low, stability is entirely adequate, and with a weak coupling to the SDR shield a pleasant sound is produced.

Testing the volume antenna

This simple theremin oscillator still has a shortcoming: there is no way to alter the volume of its output. The original design had two antennas rather than one, and the second antenna was operated by the player's left hand. As the hand approached the antenna the sound became quieter or even completely silent, making for a truly playable instrument.

The first idea that might come to mind is to pass one of the two oscillator outputs through a resonant circuit whose frequency is pulled by the volume antenna. Unfortunately, that will have the undesirable consequence of also pulling the pitch oscillator, resulting in an interdependency between pitch and volume.

A glance at older theremin circuits reveals an alternative approach, i.e. using a third oscillator that operates in similar fashion to a grid dip meter. A grid dip meter (**Figure 3**) is used to determine the resonant frequency of a circuit. A resonant circuit in the proximity of an oscillator coil draws energy from the oscillator circuit, reducing the amplitude of oscillation, which can be measured as a change in grid current. At the point of resonance the current 'dips', that is, falls to a very low value.

In the theremin the negative grid voltage of the oscillator is used to control the gain of a variable-mu tube in the audio signal path. This avoids potential problems of instability, as the dip frequency and the audio range lie far from the frequency of the beat frequency oscillators. In a tube-based circuit the amplitude of oscillations can be more than 10 V, and with a high value (around 1 MΩ) grid leak resistor the grid voltage might be around −10 V. If a second resonant circuit is weakly coupled in, then the grid voltage might dip to 1 V: this would correspond to maximum volume. If the resonant circuit is now detuned or damped, the negative grid voltage will rise significantly, and at −10 V the audio path will be completely blocked.

Our first attempt at a FET-based grid dip meter uses relatively large inductances (see **Figure 4**). The circuit does indeed oscillate with a large amplitude, and the output voltage is −4 V. The resonance dip effect does occur, but it is too weak: the voltage only changes by about 0.5 V. There is also a coupling effect, which also occurs with regular dip meters: the amplitude changes suddenly on one edge of the dip.

Tesla coupling

Looking at older theremin circuits, we can see that they also contain a kind of loading coil in the antenna

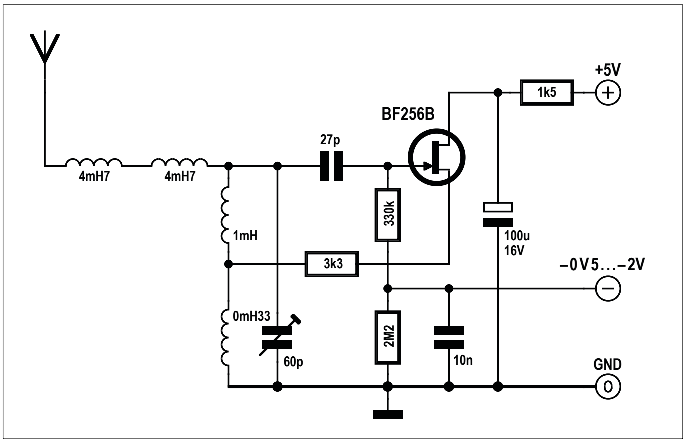

Figure 5. Oscillator with an antenna coil.

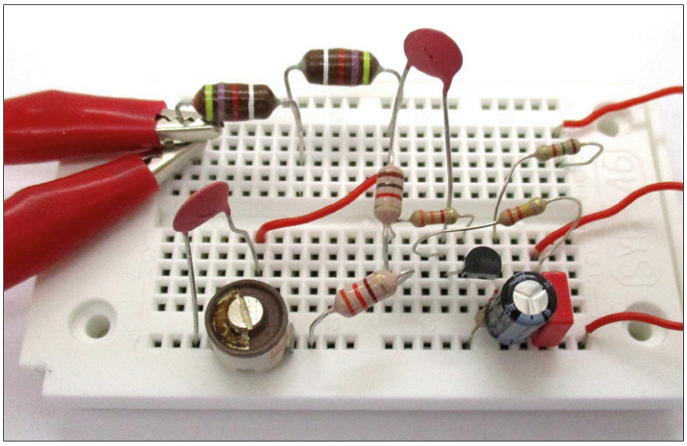

Figure 6. Prototype construction of the volume oscillator.

connection. On closer inspection this turns out to be a Tesla transformer: the coil has a self-resonance at the operating frequency and has a very large inductance to capacitance ratio. It is also strongly coupled to the oscillator, and in this case the oscillator (**Figure 5**) is tuned by the Tesla coil, whose resonant frequency will be pulled significantly even with tiny changes in capacitance.

When the circuit is in resonance the RF voltage on the antenna will be multiplied significantly. The secondary circuit draws a considerable amount of energy from the oscillator, which reduces its amplitude. The grid dip effect comes into play at voltages of up to –0.5 V, but with greater detuning or damping, for example if the antenna is touched directly, this effect disappears and the grid voltage falls by up to 2 V.

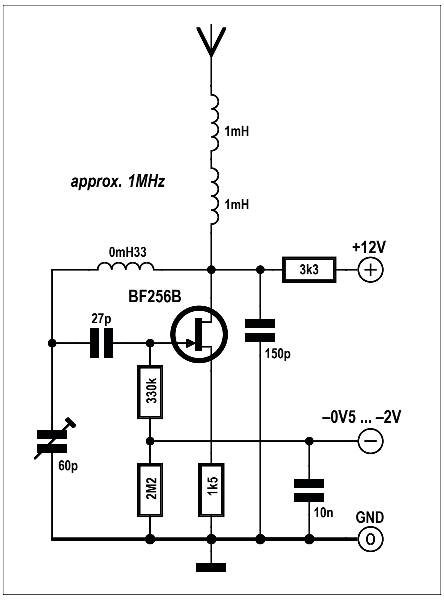

Figure 7. Alternative oscillator circuit.

The resonant frequency is easy to set, there is no longer any coupling effect and the control voltage range is large enough. For experimental purposes this oscillator can be constructed on a breadboard (**Figure 6**). A loop of cable terminated in crocodile clips can be used as an antenna.

Simplified oscillator circuit

The modified oscillator circuit shown in **Figure 7** avoids the need for a tapped inductor in the resonant circuit. Instead, the resonant circuit works using a capacitive voltage divider. By changing the ratios of the values of the individual capacitors it is possible to adjust the impedances at the gate and the drain of the FET. In the example shown the oscillator runs at around 1 MHz, which is also where the self-resonances of the two loading coils lie. As in the previous experiment the amplitude of the oscillator increases when the upper circuit is detuned or damped. The gate voltage then falls to –2 V.

The complete theremin

The complete circuit (**Figure 8**) includes the second oscillator, the mixer and a circuit for the volume antenna. The second oscillator is stabilized at 470 kHz by a ceramic resonator, and so it must be possible to set the adjustable oscillator to this frequency. A trimmer capacitor is provided for tuning.

The free-running oscillators now use 1 mH inductors. For resonance at 470 kHz a capacitance of 115 pF is needed; the capacitance of the antenna was measured at 5 pF, rising to 6 pF with a hand placed a few centimeters away. Calculation shows that this tiny change, just one picofarad, gives rise to a frequency change of 2 kHz, and only a small space near to the antenna is available to the player. The effect of the 4.7-mH loading coil is to increase significantly the change in capacitance seen at the lower end of the coil.

The dip oscillator also now uses a 1-mH inductor. The self-resonance of the loading coil for the volume antenna was found to be at 600 kHz, and so the free-running oscillator must adjusted to approximately this frequency, which requires a total capacitance of 70 pF. At 600 kHz the antenna circuit draws so much energy from the oscillator that the control voltage plunges to –2.5 V. If the antenna circuit is detuned by bringing a hand near to it the oscillator amplitude increases significantly, the control voltage reaching –3.5 V.

The 4.7 mH antenna coil requires a total capacitance of 26 pF for resonance at 600 kHz. The majority of this capacitance comes from the windings of the coil itself, only a small part being due to the antenna. Changing the capacitance by one picofarad by bringing a hand near to the antenna detunes the resonant frequency by 12 kHz, which is enough to generate the required dip.

The final element is the variable-gain amplifier. Its gain is controlled by its gate voltage: at –3.5 V the FET is fully off and there is no output signal, and with –2.5 V at the gate the circuit already has a considerable gain. In this common-gate configuration the signal is applied to the source connection of the FET and the output is coupled from the drain. The dip oscillator has to be adjusted so that it generates a suitable range of control voltages as you move your hand near the antenna, including turning off the amplifier completely. The final stage is an audio lowpass filter to minimize the amount of residual RF at the output.

The circuit can be constructed on the copper side of an uncoated printed circuit board (**Figure 9**). This has the advantage of providing a good ground connection and decoupling the individual stages. Wherever a ground is needed, the shortest possible path can be used. This construction method, used along with small pieces of prototyping board (see **Figure 10**), can also be employed for more complex and higher-frequency RF projects.

An interesting lesson from this project is that JFET-based oscillators are very stable in frequency, and insensitive to variations in supply voltage.

In all these experiments the circuit was earthed, as it was powered from an earthed bench supply. However, when the circuit was finished and mounted in its box (**Figure 11**) and the power switched over to batteries, a problem immediately reared its head: there was a strong interaction between pitch and volume. When the instrument was earthed, the problem immediately went away. It is evident that without an earth connection the two hand capacitances are effectively in series and so will inevitably affect one another. But with the earth connection in place the instrument is very playable: you quickly get used to using your right hand to control pitch and your left hand to control volume. ◄

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Web Link

[1] www.elektormagazine.com/160165

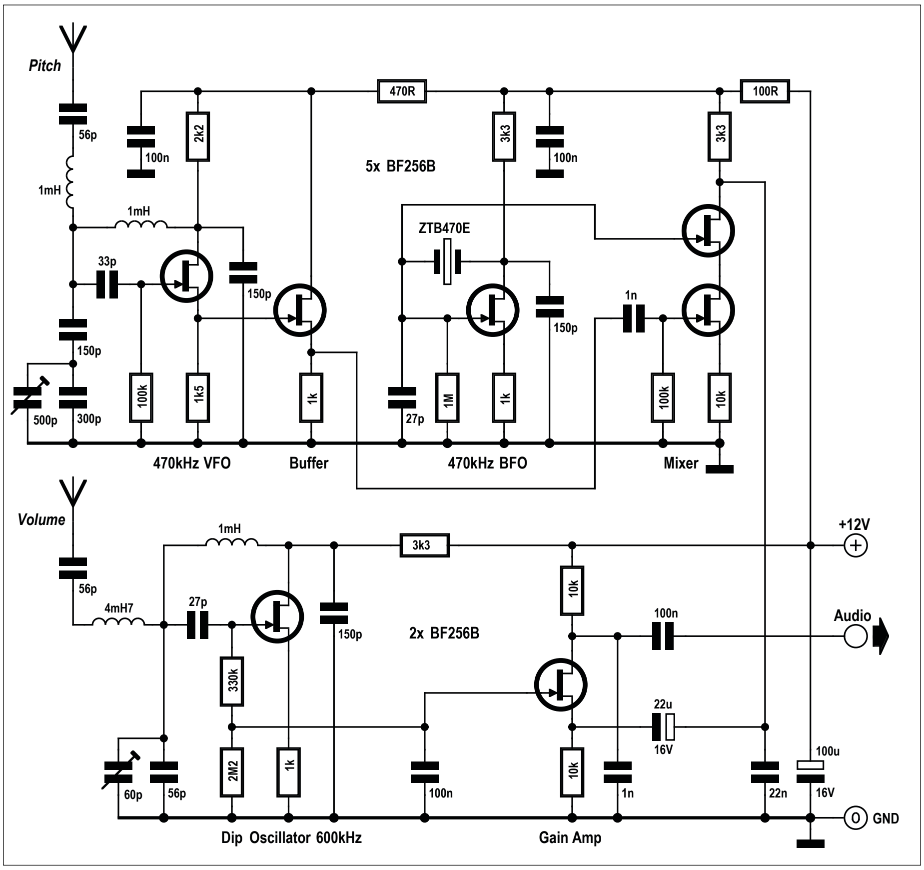

Figure 8. The complete JFET-based theremin.

The circuit can be built on an uncoated piece of printed circuit board.

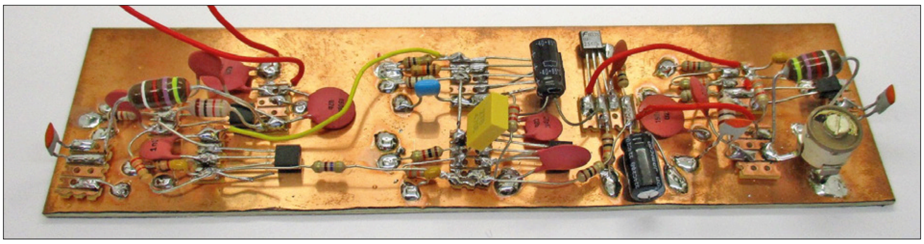

Figure 9. All the stages on one circuit board.

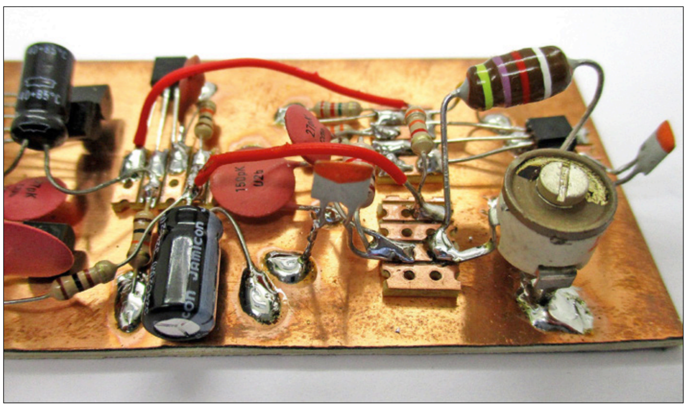

Figure 10. Close-up of the volume oscillator.

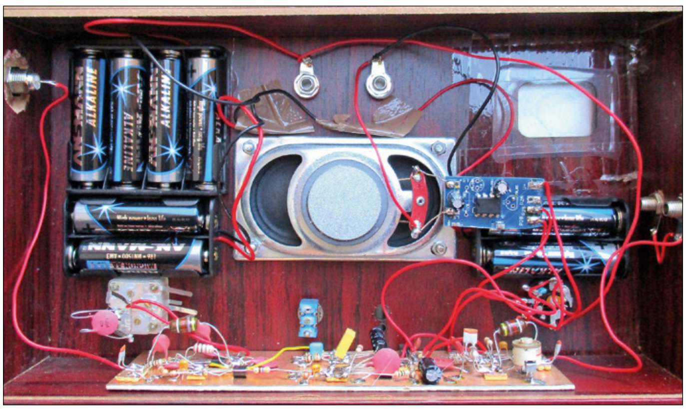

Figure 11. The instrument in its enclosure.