

[A guide to using FETs for voltage-controlled circuits, Part 4](#)

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Musical Effects Phasing Circuits

See [Part 1](#), [Part 2](#), and [Part 3](#) of this series.

The previous FET circuits pertained to voltage-controlled signal amplitude circuits. That is, the input signal's amplitude can be changed at the output via a control signal. This signal can be a DC signal, or a modulation signal. Note: The input signal levels should be kept below 150 mV peak to peak to avoid distortion for **Figures 29 through 32**. Although **Figures 29, 30, and 31** shows an LSK489 for the voltage-controlled FET, a VCR11 FET may provide better distortion performance.

We can further build a circuit that provides a voltage controlled phase at the output, or that provides phase modulation. See **Figures 29, 30, 31, and 32**, which are “all-pass” phase-shifting circuits.

Note that V_{in} for **Figures 29 to 32** has a very low output source impedance (e.g., $< 50 \Omega$) and is preferably provided by an amplifier such as an op amp.

For each circuit, $R_{17} = R_{18}$ to provide one path on unity gain inverting amplification via V_{out} and V_{in} . On another path with C_{14} , the FET (Q_{2B} in **Figures 29, 30, and 31**; and U_{2A} in **Figure 32**), and R_{19} , form a voltage controlled variable frequency high pass filter, via V_{phase_mod} .

Figure 29 shows a JFET voltage controlled phase shifting circuit.

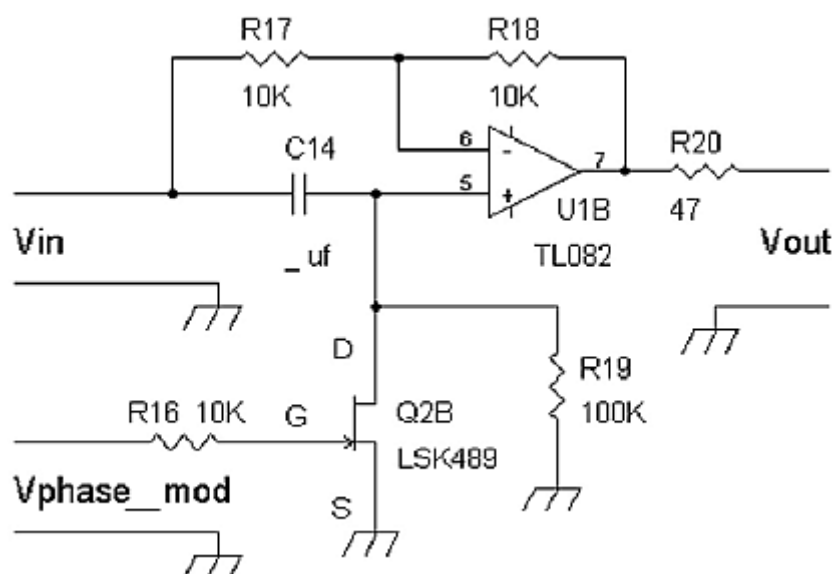


Figure 29 A basic phase-shifting circuit with a JFET and V_{phase_mod} normally connected to a

voltage source referenced to ground.

The gain, $|V_{out}/V_{in}| = 1$, but the phase, φ , in degrees of V_{out} referenced to V_{in} is:

$$\varphi = - [180 \text{ degrees} - 2\arctan(f/f_c)]$$

Where $f_c = 1/(2\pi RC)$ and $R = R_{ds}||R_{19}$ and $C = C_{14}$

With R_{ds} = drain to source resistance of the FET, Q1B.

For example if $f = f_c$, then $\varphi = - [180 \text{ degrees} - 2\arctan(1)] = - [180 \text{ degrees} - 2 \times 45 \text{ degrees}]$ or $\varphi = -90 \text{ degrees}$.

As an example, V_{phase_mod} = DC bias voltage plus an AC modulating signal.

The phase modulating voltage in this case is a negative voltage between 0 volts and the pinch off voltage, V_p . For an LSK489, the V_p can be - 3.5 volts. For example, $-3.5 \text{ v} \leq V_{phase_mod} \leq 0 \text{ v}$.

The input signal, V_{in} should be kept to < 500 mV peak to peak for low distortion in **Figure 29**.

However, if we want lower distortion, we can apply feedback via R_{fb} with the FET voltage controlled resistors (Q2B, Q2B, and U2A) shown in **Figures 30 to 32**.

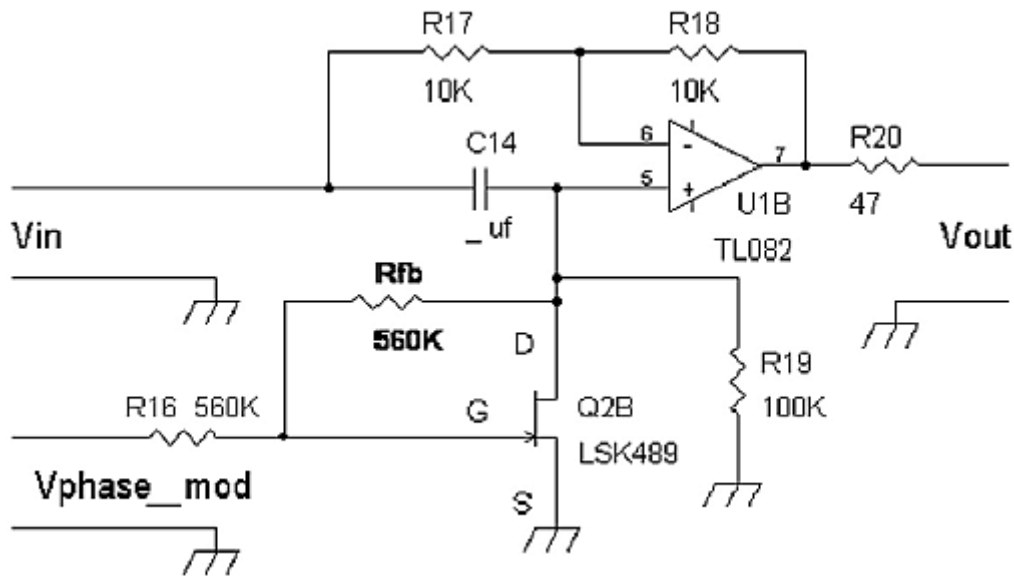


Figure 30 A lower distortion phase shifting circuit used a feedback network R_{fb} and R_{16} .

The gain, $|V_{out}/V_{in}| = 1$, but the phase, φ , in degrees of V_{out} referenced to V_{in} is:

$$\varphi = - [180 \text{ degrees} - 2\arctan(f/f_c)]$$

Where $f_c = 1/(2\pi RC)$ and $R \sim R_{ds}||R_{19}||(R_{fb} + R_{16})$ and $C = C_{14}$

With R_{ds} = drain to source resistance of the FET, Q2B.

Because the feedback network reduces the control voltage range by 50%, we have to increase the V_{phase_mod} 's voltage range:

$$2V_p \leq V_{phase_mod} \leq 0 \text{ v}$$

For an LSK489, V_p can be - 3.5 v, or

$2(-3.5 \text{ v}) \leq V_{\text{phase_mod}} \leq 0 \text{ v}$, which is:

$$-7.0 \text{ v} \leq V_{\text{phase_mod}} \leq 0 \text{ v}$$

An example $V_{\text{phase_mod}} = \text{DC bias voltage plus an AC modulating signal}$.

Although the feedback network reduces distortion, it allows a portion of $V_{\text{phase_mod}}$ to leak into the output, V_{out} . For example, if $V_{\text{phase_mod}}$ is a low frequency signal, and V_{in} is a higher frequency signal, V_{out} will include both a phase modulated version of the higher frequency input signal, but a low frequency signal related to $V_{\text{phase_mod}}$. The circuits in **Figures 31 and 32** fix this feed through or cross talk problem.

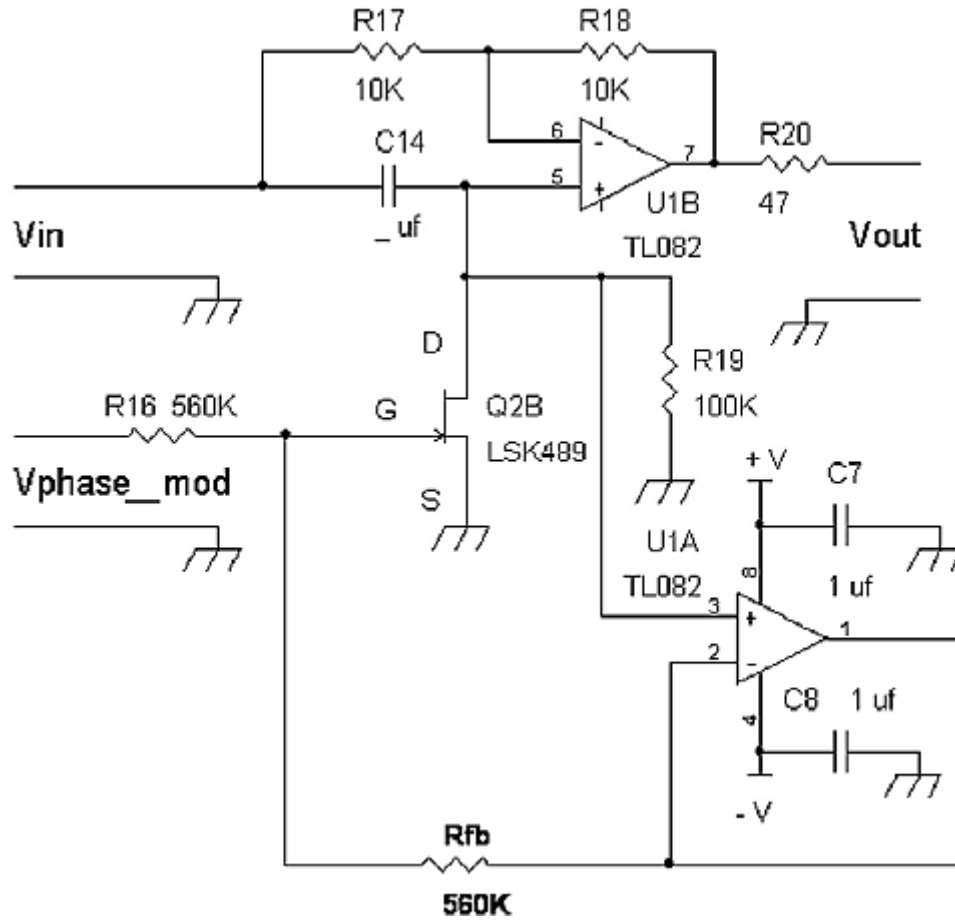


Figure 31 A voltage controlled phase shifting circuit with feedback and buffer amplifier U1A.

The gain, $|V_{\text{out}}/V_{\text{in}}| = 1$, but the phase, ϕ , in degrees of V_{out} referenced to V_{in} is:

$$\phi = - [180 \text{ degrees} - 2\arctan(f/f_c)]$$

Where $f_c = 1/(2\pi RC)$ and $R \sim R_{\text{ds}} || R19$ and $C = C14$

With R_{ds} = drain to source resistance of the FET, Q2B

By using a buffer amplifier, not only distortion is reduced and feed through or cross talk from $V_{\text{phase_mod}}$ to the output V_{out} is eliminated.

Again the control range is:

$$2V_p \leq V_{\text{phase_mod}} \leq 0 \text{ v}$$

For an LSK489, V_p can be -3.5 v , or

$2(-3.5\text{ v}) \leq V_{\text{phase_mod}} \leq 0\text{ v}$, which is:

$-7.0\text{ v} \leq V_{\text{phase_mod}} \leq 0\text{ v}$

An example $V_{\text{phase_mod}}$ is a DC bias voltage plus an AC modulating signal.

Again, to reiterate, for **Figures 27 to 31**, distortion can be lowered by using a VCR11 FET. Also as a reminder that input signal levels should be less than 150 mV peak to peak in circuit shown in **Figures 27 to 32**.

Figure 32 shows a voltage controlled MOSFET resistor phase shifting circuit.

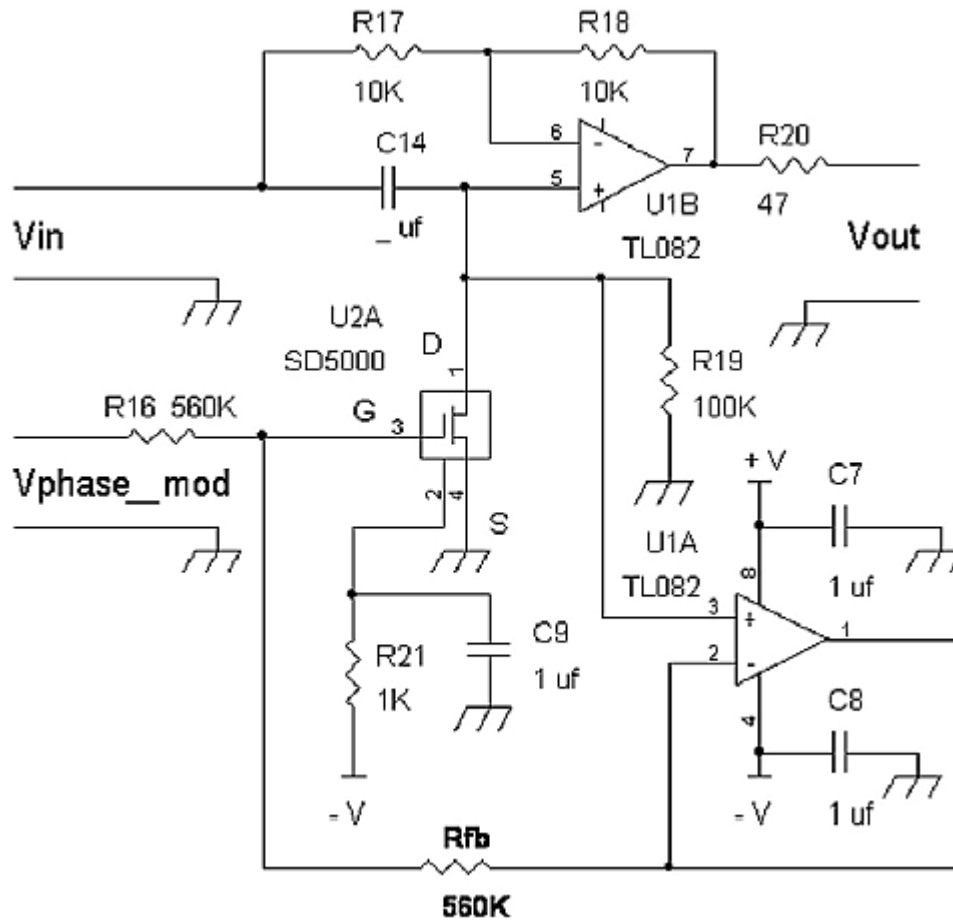


Figure 32 A MOSFET phase shifting circuit with feedback network and buffer amplifier for reduced distortion.

The gain, $|V_{out}/V_{in}| = 1$, but the phase, φ , in degrees of V_{out} referenced to V_{in} is:

$$\varphi = - [180 \text{ degrees} - 2\arctan(f/f_c)]$$

Where $f_c = 1/(2\pi RC)$ and $R = R_{ds} || R19$ and $C = C14$

With R_{ds} = drain to source resistance of the FET, U2A

Because MOSFET U2A is an enhancement device, $V_{\text{phase_mod}} > 0 \text{ v}$. The MOSFET usually turns on by +4.0 volts. However, the feedback, R16 and **Rfb**, network has a 50% loss so we need to double the voltage range for $V_{\text{phase_mod}}$ to 8 volts.

That is,

$$+0 \text{ v} \geq V_{\text{phase_mod}} \geq +8.0 \text{ v}$$

An example $V_{\text{phase_mod}} = \text{DC bias voltage plus an AC modulating signal}$.

Note again the buffer amplifier, U1A, prevents $V_{\text{phase_mod}}$ from cross talking into V_{out} .

For musical effects, sometimes distortion is desired, and V_{in} 's amplitude can be increased beyond 500 mV peak to peak to add distortion at V_{out} for **Figures 29 to 32**.

Musical effects with variable frequency gyrator bandpass filters

Musical effects with variable frequency gyrator bandpass filters

A basic building block to a Wah-Wah circuit is a variable frequency band pass filter. By modulating the band pass filter's resonant frequency, the input signal will have amplitude and phase variations. Using a low frequency signal impresses a "Wah-Wah" effect on a musical note.

For the circuits shown in **Figures 35 through 39**, the V_{in} input signal level should be less than 150 mV peak to peak.

Usually a parallel inductor capacitor (LC) tank circuit is implemented with a fixed inductor, L , (e.g., 100 mH to 1000 mH) while the capacitor is variable via a Miller capacitance multiplier effect. This variable capacitance, C_{var} , provides a variable resonant frequency given by

$$f_{\text{res_var_C}} = 1/[2\pi\sqrt{LC_{\text{var}}}]$$

Of course we can make an equivalent variable resonant frequency circuit with a fixed capacitor and a variable inductor (**Figure 34**).

$$f_{\text{res_var_L}} = 1/[2\pi\sqrt{(L_{\text{var}})C}]$$

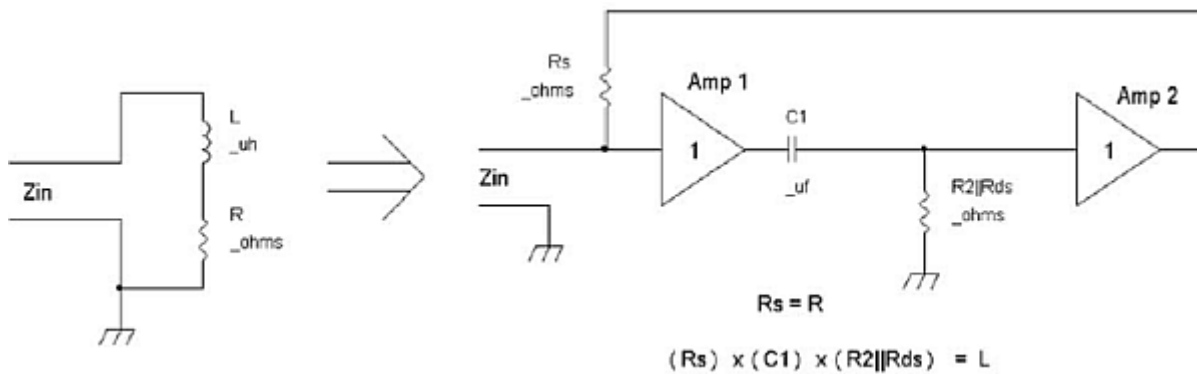


Figure 34 An inductor on the left side is implemented as a simulated inductor (gyrator) on the right side.

The gyrator's inductance $L = R_s \times C_1 \times R_2 || R_{\text{ds}}$, where R_2 is shown in **Figures 35 to 39** and R_{ds} is the drain to source resistance of an FET in **Figures 35 to 39**. The equivalent inductor series resistance R is R_s .

To understand how the gyrator on the right side works, we can observe an inductor's impedance magnitude at DC (0 Hz) and at very high frequencies.

At DC, an inductor's impedance magnitude is just the equivalent series resistance, R . See left side of **Figure 34**. Now let's look at the gyrator. At DC the capacitor $C1$ blocks any DC voltage into Amp 2's input. So at DC frequency, Amp 2's input is ground, which means its output is also ground. This means looking into Z_{in} of the gyrator at DC is just a resistor, R_s , that is grounded due to Amp 2's output being at 0 volts.

Now let's look at the impedance of the inductor on the left side when the frequency is very high.

$Z_{in} = R + j\omega L$, where j is an imaginary number with $j = \sqrt{-1}$, and $j^2 = -1$, and $\omega = 2\pi f$, with f = frequency in Hz.

As $\omega = 2\pi f \rightarrow \text{infinity}$, $Z_{in} \rightarrow \text{infinity}$

Now does the gyrator behaves in a similar manner when the frequency $\rightarrow \text{infinity}$?

On the right hand side the capacitor $C1$ has an impedance of $1/j\omega C1$. As $\omega = 2\pi f \rightarrow \text{infinity}$, the impedance of $C1 \rightarrow 0$, or becomes an AC short circuit at high frequencies. This means the input signal voltage at the input of Amp 1 is the same voltage at the input of Amp 2 because the gain of Amp 1 is unity. And since Amp 2 has a gain of 1, the voltage at R_s , top side is the same AC voltage as the input signal voltage at the input of Amp 1 and bottom side of R_s . Because there are equal AC voltages on both sides of R_s , there is no signal current flowing into R_s . This is the same as if there is an open circuit going into R_s for the input side. Because input impedance of Amp 1 is infinite, we then find that no AC current flows at the Z_{in} point, which means $Z_{in} = \text{infinite impedance}$ when $\omega = 2\pi f \rightarrow \text{infinity}$.

We now have the gyrator circuit that behaves like an inductor at DC and high frequencies. A detailed gyrator impedance derivation is shown in Appendix B. For now, let's look at how the gyrator that works like an inductor with one lead grounded is used in a band pass filter (**Figure 35**).

Note: For circuits that employ higher AC signal currents through the FET as a voltage controlled resistor, it was found that the VCR 11 FET performed better than others in terms of distortion in **Figures 35 and 36**. Basically FETs with larger pinch off voltages can handle larger signals. In general, the input signal level should be < 150 mV peak to peak.

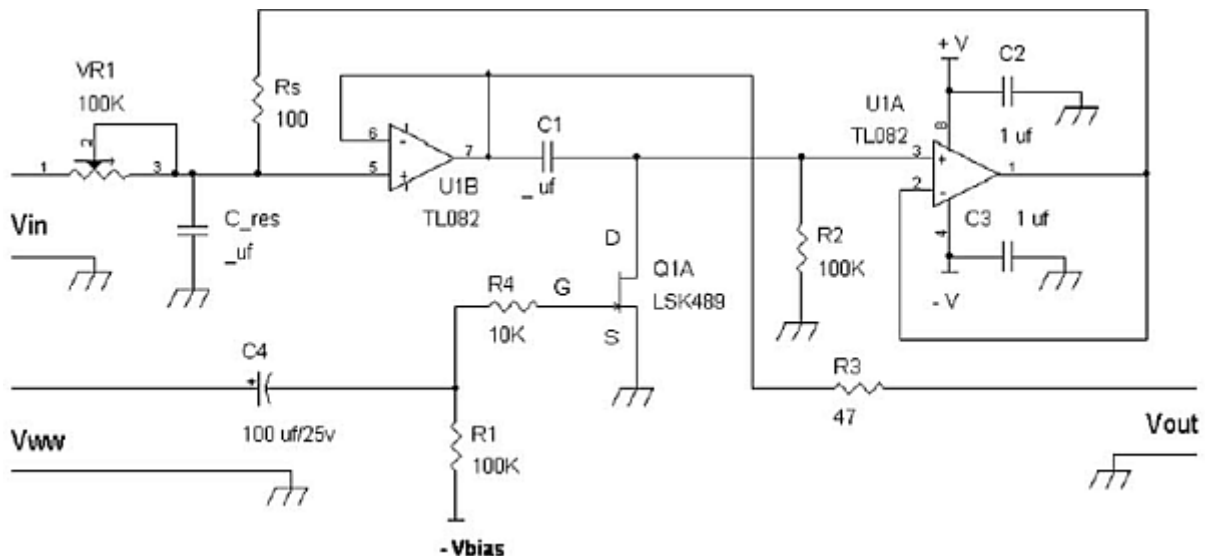


Figure 35 An active band pass filter circuit with a voltage controlled gyrator.

A quick look at the **Figure 35** shows a gyrator circuit having unity gain voltage followers U1B and U1A for Amp 1 and Amp 2 in **Figure 34**. The drain to source resistance of Q1A in parallel with R2 forms the equivalent resistor $R_{ds}||R2$ in **Figure 34**. R_s , which = $100\ \Omega$ in **Figure 35** is analogous to R_s in **Figure 34**. Since the gyrator forms an inductor to ground at the pin 5 U1B/ R_s junction and ground, a parallel LC circuit is implemented with capacitor C_{res} connected to the gyrator and to ground. V_{in} drives a series resistor via variable resistor VR1 to the parallel LC tank circuit where $L = R_s \times C1 \times R2 || R_{ds}$ and $C1 = C_{res}$. We can take the output of the band pass filter at the LC junction at pin 5 of U1B, but it would be better to take the buffered output via the voltage follower U1B's output at pin 7 and output resistor R3. This way any load at the output, V_{out} , will not affect the band pass filter's characteristics such as loaded Q or gain. Note that R3 is $47\ \Omega$ isolates the op amp from a capacitive load that may otherwise cause U1B to oscillate.

To reiterate, at the junction of R_s and pin 5 of U1B, we have an inductor referenced to ground. The inductance $L = R_s \times C1 \times R2 || R_{ds}$. The capacitor in parallel to this L is C_{res} .

For example if $L = 1\ H$ and $C_{res} = 0.033\ \mu f$, the resonant or peak amplitude frequency is

$$f_{res} = 1/[2\pi \sqrt{L(C_{res})}] = 1/[2\pi \sqrt{(1H)(0.033\ \mu f)}] = 876\ Hz = f_{res}$$

V_{in} is the input signal (e.g., musical note) with V_{ww} being the low frequency (e.g., 0.5 Hz to 5 Hz) "Wah-Wah" signal that is about 1 to 2 volts peak to peak.

V_{bias} sets R_{ds} of the FET, Q1A, which is typically a voltage between 0 and - 3.5 for an LSK489.

At audio frequencies a typical value for L is about 1 henry (1 H) so that the unloaded quality factor, Q_u , is still reasonably high at 10 or more that is determined by L, R_s , and the frequency of interest, f_{res} .

$$Q_u \sim 2\pi f_{res} L/R_s$$

For example, if $f_{res} = 1000\ Hz$ and $L = 1\ H$, and $R_s = 100\ \Omega$, then $Q_u = 6.28(1000)(1)/100 = 62.8$.

The unloaded Q_u is proportional to frequency, f_{res} . So, if we want a band pass filter with $f_{res} = 500\ Hz$ (half of 1000 Hz) then the unloaded Q_u drops from 62.8 to 31.4.

Typically, we want the unloaded Q_u is \gg loaded Q_{loaded} . Where: $Q_{loaded} = 2\pi f_{res} RC_{res}$ with $R = VR1$'s resistance.

In audio filtering usually a $Q_{loaded} < 10$ will work fine.

For example, if $L = 1\ H$ and $C_{res} = 0.033\ \mu f$,

the resonant frequency $f_{res} = 1/[2\pi \sqrt{(1H)(0.033\ \mu f)}] = 876\ Hz$

Suppose we set $VR1 = 25K\ \Omega = R$, then

$$Q_{loaded} = 2\pi f_{res} RC_{res} = 2\pi(876\ Hz)(25K\ \Omega)(0.033\ \mu f)$$

$$Q_{loaded} = 4.54$$

In practice Q_{loaded} will be slightly lower than 4.54 because the unloaded Q_u is not infinite. But for Q_{loaded} values within 10% or 20%, the approximation is OK. You can raise the Q_{loaded} value by

increasing VR1's resistance. Thus, changing VR1's resistance controls Q_{loaded} .

The - 3 dB bandwidth is $BW_{-3\text{dB}} \sim f_{\text{res}} / Q_{\text{loaded}} = 876 \text{ Hz} / 4.54$, which is:

$$BW_{-3\text{dB}} = 192.9 \text{ Hz}$$

So, let's now choose some component values for **Figure 35**, which will work for **Figures 36 to 39** also:

$$R_s = 100\Omega$$

$$C_1 = 1 \text{ }\mu\text{f}$$

$$R_{\text{ds}} \text{ from the FET Q1A} = 11\text{K}\Omega$$

$$R_2 = 100\text{K}\Omega$$

$$R_{\text{ds}} || R_2 = 11\text{K}\Omega || 100\text{K}\Omega = 10\text{K}\Omega$$

$$L = R_s \times C_1 \times R_{\text{ds}} || R_2 = 100 \times 1 \times 10^{-6} \times 10,000 \text{ H} = 1 \text{ H} = 1 \text{ Henry}$$

$$f_{\text{res}} = 1 / [2\pi \sqrt{L(C_{\text{res}})}]$$

As a suggestion only for the following frequencies, f_{res} , with $R_{\text{ds}} = 10\text{K}\Omega$, $R_s = 100\Omega$, $R_2 = 100\text{K}\Omega$ we have:

$$f_{\text{res}} \geq 700\text{Hz}, L = 1 \text{ H via } C_1 = 1 \text{ }\mu\text{f}$$

$$200 \text{ Hz} < f_{\text{res}} < 700 \text{ Hz}, L = 2.2 \text{ H via } C_1 = 2.2 \text{ }\mu\text{f}$$

$$f_{\text{res}} < 200 \text{ Hz}, L = 4.7 \text{ H via } C_1 = 4.7 \text{ }\mu\text{f}.$$

Note that C_1 should be a film capacitor such as polyester or mylar.

A quick look at a commercially available 2 H inductor rated at 100 mA shows a coil resistance of about 175 ohms (Hammond 154M). The gyrator or simulated inductor has an equivalent 100 ohm coil resistance at 1 H. In terms of inductance to coil resistance ratio, both are pretty close.

If we look back at [Figure 10](#), a voltage follower connected to the drain of an FET provides buffering for driving a feedback resistor that reduces the non-linear resistance of the drain to source resistance. Fortunately, in **Figure 35** we have a second voltage follower, U1A, that is part of the gyrator circuit, but can also serve as a buffer amplifier to linearize the FET's voltage controlled resistance (**Figure 36**).

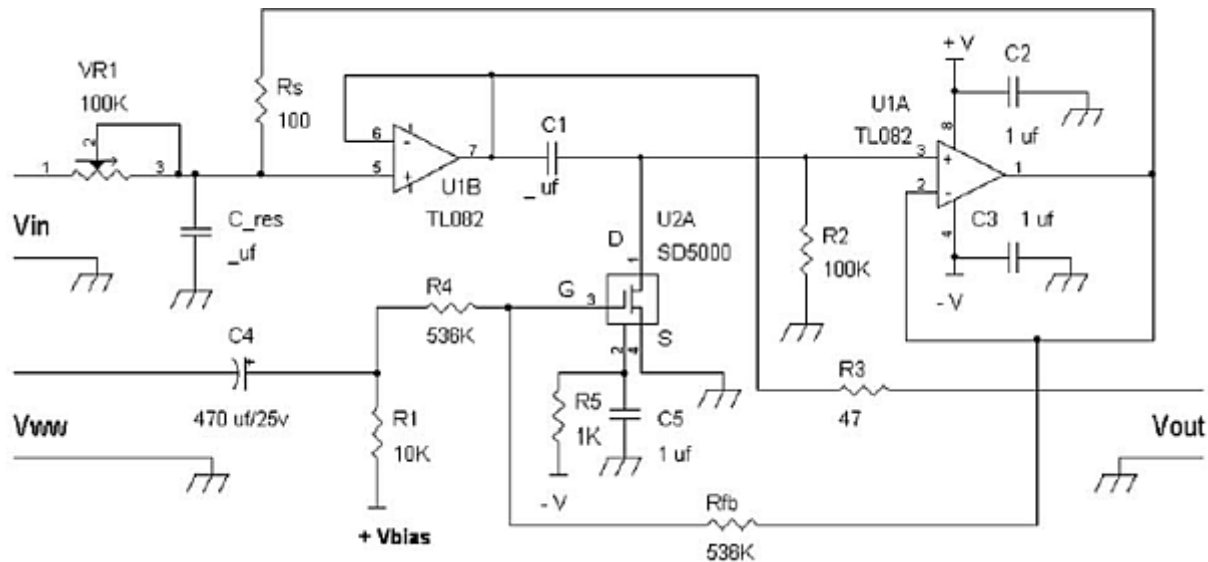


Figure 38 A voltage controlled MOSFET band pass filter with linearized drain to source resistance.

The bias voltage and Wah-Wah signal, V_{ww} , will need to be doubled in range because of the voltage divider circuit R_{fb} and $R4$.

Figure 39 shows a more complete voltage controlled band pass filter with a “blend” control pot $VR2$.

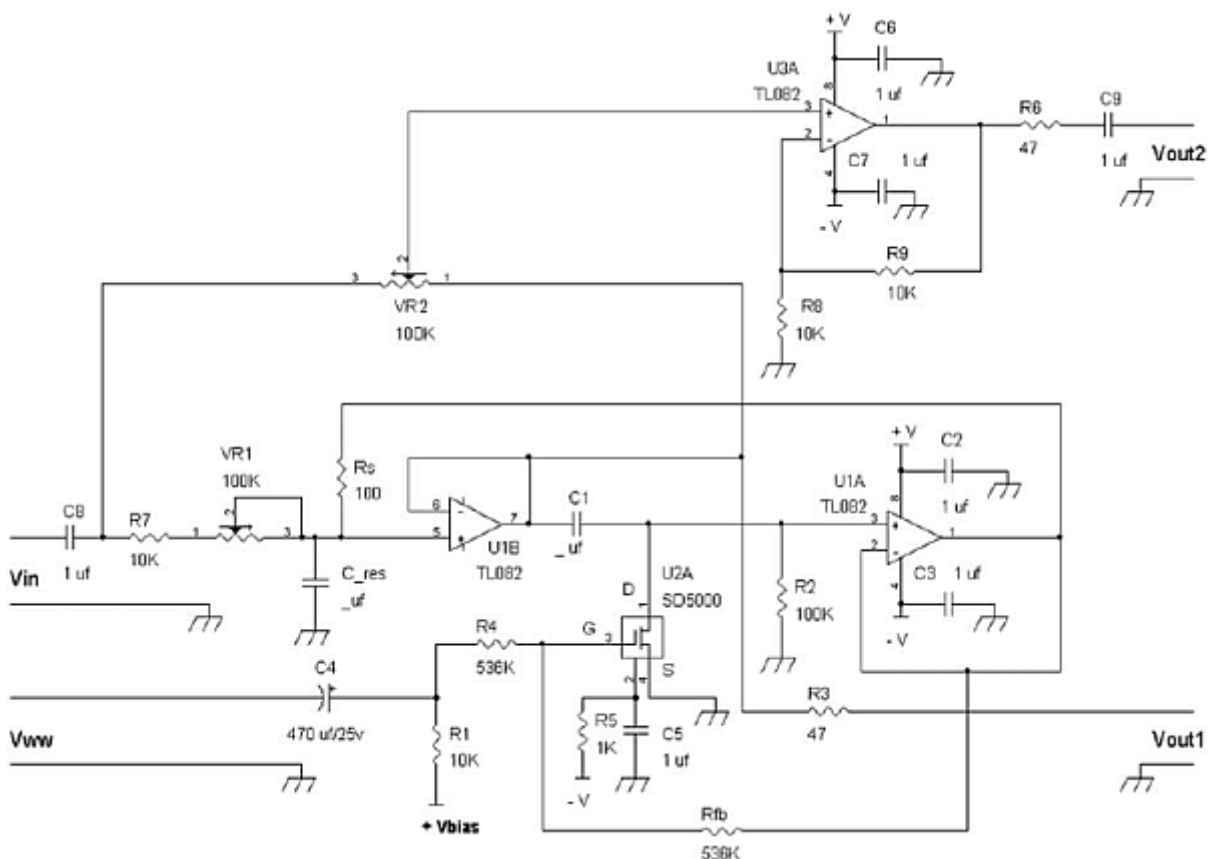


Figure 39 A blend control pot $VR2$ allows mixing part of the input signal with the band pass filter’s output.

By adding $VR2$ a blend of both the input signal plus the voltage-controlled band-pass filtered signal is provided via V_{out2} . By adjusting $VR2$ you can output via V_{out2} all of V_{in} , or a mixture of V_{in} with the band pass filtered signal, or all of the band-pass filtered signal.

Vout1 provides only the voltage-controlled band-pass filter output.

We now turn to a more “automatic” way to bias FETs. Unlike bipolar transistors that have a base-emitter turn on voltage in a narrow range, 0.6 volt to 0.7 volt, FETs can have much wider ranges for the pinch off voltage, V_p in depletion mode or the threshold voltage, V_{th} for enhancement mode devices.

However, we can take advantage of having matched JFETs or MOSFETs by using one the two (or four) FETs as a reference device for biasing.

Stay tuned for the final part of this series which will discuss bias servo circuits for automatic set up and some final tips and thoughts, plus appendices with some very useful equations and their derivations.

[Ron Quan](#) is an author, design engineer, and inventor with over 75 US patents.

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